Fluvial Geomorphic Assessment of the South River Watershed, MA

Prepared for

Franklin Regional Council of Governments
Greenfield, MA

South River

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EXECUTIVE SUMMARY

A fluvial geomorphology assessment was conducted on South River in Franklin County, Massachusetts to determine the causes of channel instability and identify restoration options to better manage riverine problems. The South River watershed has a long history of human land use, including significant manipulation of the river channel itself. More than 30 mills were active in the watershed during the 18th and 19th century with each associated with a dam built across the river to provide water for powering the structures. Considerable lengths of the channel were also straightened and cleared of boulders and wood as part of this process and in an effort to reduce flooding in the event of a catastrophic dam breach. While these numerous mills, cornerstones of the watershed's proud history, are no longer in use today, the legacy of this period continues to impact river function, habitat, and public safety in at least three important ways. First, the erosion of high banks of silt- and clay-rich impoundment sediments accumulated behind the now breached mill dams increases downstream sediment delivery to water bodies already impaired by excess sediment loading. Second, damaging flood flows passing through previously straightened water courses are unable to spread out across adjacent floodplains due to channel incision or confining berms. Finally, the quality of aquatic habitat is poor for great lengths of the river, because the river channel remains largely devoid of the pools, cover, and flow complexity created when large boulders and wood are present in the channel. River restoration efforts that simultaneously address these issues of increased sediment loading, exacerbated flooding and erosion, and degraded aquatic habitat have the greatest chance of long-term success.

Analysis of historical aerial photographs and maps, surveying of cross sections, and mapping of erosion, bars, channel straightening, and other channel features were used to delineate and characterize 94 discreet channel segments along the river. The condition of 10 geomorphic and habitat features, including pools, wood, and riparian vegetation, were used to identify and quantify the need for restoration in each. With the needs identified, typical designs for 13 restoration treatments (e.g., berm removal, riparian improvements, flow diversion) were developed and rated along with a "Do nothing" for their ability to address the highest priority needs in each segment, so the best approaches for restoring each segment could be identified. Twenty restoration project concepts were developed from the assessment results and restoration planning process.

While the full benefits of river restoration will be realized after several projects are implemented, initial restoration efforts are being focused on a two-part project in the village of Conway where Tropical Storm Irene inundated portions of Main Street (Route 116) and washed away a new retaining wall protecting the Main Street bridge abutment. The first phase of the proposed restoration project encompasses 1,400 feet of river downstream of the bridge and will lower a 0.8 acre portion of a town-owned field at the downstream end by as much as 2 feet to allow flood flows, otherwise confined to the incised channel, to spread out across a narrow floodplain. Further upstream where the river is confined by higher banks of glacial deposits, three boulder weirs and four boulder deflectors are proposed to focus flow into the center of the channel or divert flow onto the lowered portion of the floodplain. While the proposed project will directly address bank erosion problems faced by the adjacent private landowners, the proposed floodplain lowering will also serve to reduce the height that flood flows reach upstream, reducing the threat of inundation to Main Street. Furthermore, the boulder weirs and deflectors, by reducing bank erosion, and the floodplain lowering, by allowing floods to spread out and deposit fine sediment, will collectively reduce downstream sediment loading. The boulder weirs and deflectors will also add critically important structure to the stream channel, thus restoring pools, cover, and flow complexity to what is currently a plane-bed channel with uniform flow velocities and depths. A final project element, the addition of wood structures on the margins of the channel between the weirs and deflectors, will protect the banks from further erosion, encourage sediment deposition, and enhance cover and spawning habitat.

The project's second phase upstream of the bridge includes the partial removal of an old berm that will allow flood flows to spread out across a lowland area at the confluence of South River and Pumpkin Hollow Brook. The berm removal will thus reduce the chances that Main Street will be inundated in future floods and will provide a large area for fine sediment storage, thereby reducing downstream sediment loading. The two-phase project in the village of Conway must be seen as only the first of many projects, that taken together, will provide more significant watershed-wide relief from flooding and the environmental impacts associated with high sediment loads and degraded aquatic habitat. Improvements in public safety, aquatic habitat, and pollutant loading will only be possible with support from the citizens of Ashfield and Conway and continued funding from agencies concerned with emergency management and environmental restoration.

1.0 INTRODUCTION

This report describes a fluvial geomorphology assessment completed by Field Geology Services, LLC along South River in Franklin County, Massachusetts (Figure 1). From Ashfield Lake, South River flows 15.8 mi to its confluence with the Deerfield River and drains a total watershed area of 26.3 mi^2. Land use in the watershed is mixed with some agricultural and residential use on the valley bottom but largely forested uplands. Buildings and other human developments on the river's floodplain are concentrated in the villages of Ashfield, South Ashfield, and Conway. In addition, agricultural fields border much of the river's length, Route 116 approaches close to the stream at several locations, a total of 26 bridges cross the river, and 3 dams are still extant.

South River has a long history of mills that were built along its banks. A considerable length of channel has been manipulated with numerous dams constructed and the channel realigned and straightened. These alterations were likely accompanied with the removal of wood, boulders, and other obstructions in the channel. The history of land use along and within the river has created a legacy of channel instability, accelerated rates of sediment production, and degraded physical habitat (e.g., limited pools, low quality cover, little channel complexity) for brook trout and other aquatic species.

The geomorphic assessment of South River, including the development of restoration options, was undertaken to better understand continuing channel changes resulting from historic land use activities and to identify restoration techniques that will lead to stream channel equilibrium and associated improvements in physical habitat and sediment loading. The results of the geomorphic assessment are presented below prior to a discussion of the restoration planning process, a process based on the assessment findings. The assessment and restoration planning efforts are designed to fulfill the long-term project goals of increasing channel stability, enhancing physical habitat, improving water quality, and reducing downstream sediment loading.

2.0 FLUVIAL GEOMORPHIC ASSESSMENT

Fluvial geomorphic assessments are devoted to understanding how the natural setting and history of human land use in a watershed effect river channel processes and form (i.e., channel dimensions and shape). River channels are in constant adjustment as watershed conditions change, but eventually approach an equilibrium channel form where the channel's dimensions, although not necessarily its position, remain constant, absent a significant watershed perturbation. River channel adjustments may persist 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 rapid bank erosion and changes in channel position even while maintaining an equilibrium condition by balancing erosion with an equivalent amount of sediment deposition. Consequently, geomorphology assessments are essential for identifying sustainable management solutions related to channel instability, habitat degradation, and downstream sediment loading. River restoration projects are more likely to succeed with a thorough understanding of how the channel is responding to natural conditions and human activities in the basin and how the channel may respond to future management efforts. Therefore, geomorphic assessments must focus on both the natural and human conditions in the watershed that engender channel adjustments and describe the current channel conditions that reflect the ongoing evolution of the channel.

Identifying how conditions in one part of the watershed are linked to channel adjustments elsewhere are essential for developing restoration options that not only reduce hazards and improve habitat conditions at the site of restoration but also promote equilibrium conditions throughout the watershed. Within this context, the specific objectives of the South River geomorphic assessment are to: 1) characterize past and current channel conditions; 2) determine past and current human land uses that have resulted in ongoing channel adjustments; and 3) identify natural watershed conditions that control the character and rates of channel adjustment. The geomorphic assessment presented below consisted of seven parts: 1) reach and segment delineation; 2) review of existing materials; 3) watershed characterization; 4) analysis of historical aerial photographs and topographic maps; 5) mapping channel features; 6) topographic surveys and substrate particle size analysis; and 7) channel classification.

2.1 Reach and segment delineation

Since different portions of a river can respond differently to the same natural and human influences, the first assessment task is to subdivide the river into distinct reaches of varying length (Figure 2 and Appendix 1). Within a given reach, the river is likely 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 restoration techniques gained in one reach may apply to other “like-reaches”. The break points between different reaches are located at: a) large tributary confluences, b) grade controls (e.g., ledge across the channel), or c) abrupt changes in channel slope or valley confinement. The influence of human factors (e.g., dams, berms, riprap) is ignored when defining reach breaks, but is important when subdividing the reaches into shorter segments (see Section 3.1below; Appendix 1).

Reaches downstream of valley 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 less confined reaches (i.e., in wider portions of the valley) where the channel will predominantly encounter low banks of floodplain sediments. Reaches downstream of tributary confluences will generally have morphologies different than reaches immediately upstream of the confluence because of the higher discharge and input of sediment. The morphological impacts of tributary confluences, as well as valley constrictions and expansions, are generally most noticeable at or near the reach break itself. Consequently, the locations of the reach breaks are often points of the greatest channel instability where active bar formation, bank erosion, and channel migration are possible. For example, mid-channel bars typically form just downstream of valley expansions where the stream power to carry the sediment is lost with flow expansion. Bars are also commonly observed downstream from tributaries because of the excess sediment added at the confluence. Delineating the reach breaks and characterizing the morphological conditions present in each reach are critical for identifying the natural and human factors leading to channel instability and degraded aquatic habitat.

The identified reaches are further subdivided into shorter "segments" (Appendix 1), reflecting the location and occurrence of various human impacts (e.g., channel straightening, dams) and channel responses to those impacts (e.g., braided channel, bar deposition, redeveloping meanders). Segmenting the stream into smaller sections based on human impacts and channel response serves as the basis for identifying and prioritizing restoration options at various points along the stream. The reaches and segments are of uneven length and the breaks between each occur where there are observable changes resulting from various natural and human conditions, respectively.

Twenty-seven reaches were identified along the mainstem of South River using topographic maps and aerial photographs (Figure 2 and Appendix 1). Four of the reach breaks occur at tributary confluences, four occur at valley expansions, and six at valley constrictions (Table 1). The 27 reaches were later subdivided into 94 segments as described further in Section 3.1 below.

2.2 Review of existing studies

The South River watershed, located in southwestern Franklin County, Massachusetts has a long history of mills, dams, land clearance, and human modification. The Town of Ashfield was first settled in 1743 with the first dam built across South River in 1744 by the Huntstown Proprietors to power a corn grist mill. Further downstream, the first dam within the Town of Conway was built in 1762, the year of Conway's original settlement, to power a saw mill near the current site of the Main Street bridge. At least 28 more dams would follow. Only three remain extant (Appendix 1): the dam at Ashfield Lake, the CC Flagg sawmill (actively run until 1951), and the Big Dam, built in 1899 to power the Conway Electric Street Railway and later to provide electricity to the Town of Conway (Lee, 1967).

The South River watershed was an important manufacturing center with more than 50 mills in the town of Conway alone, many along South River. Manufacturing increased significantly in 1837 with the construction of several large mills and continued into the 1920's. Afterwards, mills became less important due to a combination of factors, including financial problems, natural disasters, and isolation from markets (Lee, 1967).

The history of flooding on South River and the human response to those floods has had a profound effect on river channel conditions in the towns of Ashfield and Conway. Examples of these influences extend over two centuries. On October 4, 1869 after a large rain event, the granite dam at the Tucker and Cook Reservoir, upstream of the village of Conway, breached with the ensuing flood destroying 14 bridges in Conway; only the Burkeville covered bridge remained standing. All of the mills along the river were also damaged (Pease, 1917). The reservoir breached for at least a second time on December 10, 1878. The human response to flooding, however, has possibly had an even greater impact on channel morphology than the flooding itself. Communal fears regarding the potential breach of this large reservoir prior to 1869 led to public backing of the "4-40 campaign" by which the river channel was straightened and widened to a width of 40 feet for a distance of 4 miles from the reservoir to a point well downstream of the village (Kantor, P., Conway Historical Society, 2011, personal communication). Whether the effort was undertaken or successful at reducing damages during subsequent flooding is unknown, but such activities were not uncommon throughout most of the 19th and 20th centuries in New England, the effects of which continue to influence channel stability many decades later.

In the past century, the floods of 1927, 1936, and 1938 are most notable prior, but preceded stream gauging. Widespread channel straightening and bank repairs identified during the mapping of channel features (see Section 2.5 below) were completed after these and other flood events. The potential impacts of floods and consequences of subsequent river management were recently revealed during Tropical Storm Irene flooding on August 28, 2011, the highest recorded discharge since gauging began in the 1960's and several times larger than the average peak discharge (Figure 3). Bank repairs completed earlier in 2011 (Figure 4a) upstream of the Main Street bridge in Conway were washed away by the flooding (Figure 4b). The resulting repairs (Figure 4c) have further constrained the channel, a condition addressed by conceptual restoration designs developed through the restoration planning process (see Sections 3.0 and 4.0 below). Field data for the geomorphic assessment were collected prior to August 2011, so the impacts of Tropical Storm Irene and subsequent river management are not reflected in the assessment results. However, extreme bank erosion (Figure 4b) and reactivation of landslides on high banks of glacial deposits (Figure 5) were subsequently noted.

2.3 Watershed characterization

River channels adjust to changes in water discharge, sediment loading, and wood inputs brought about by natural conditions (e.g. floods, landslides) and human activities (desnagging of wood, dams) in the watershed. Basic morphometric measurements such as channel gradient, valley confinement, and watershed size provide a framework for interpreting the assessment information and determining whether the existing channel morphology is consistent with natural conditions or reflects adjustments that have resulted from human impacts. Ascertaining the difference between the existing channel conditions and what might be expected under natural conditions with minimal human influence is important for implementing sustainable restoration projects that reduce flood hazards, effectively manage downstream sediment loading, and improve aquatic habitat.

As a whole, the watershed area of South River is 26.3 mi^2 and the river's gradient averages 0.013 ft/ft. With a relief of 1,666 ft between the watershed's highest point and the river's outlet to the Deerfield, severe flooding is possible in response to intense rainfall such as during Tropical Storm Irene. Mass failures in glacial sediment on steep slopes (Figure 5) and channel incision through valley-bottom impoundment sediments (see Section 2.5 below) results in high sediment loads on South River. While rivers often display a steady decrease in slope and valley confinement downstream, the complex geology and glacial history of South River gives rise to abrupt changes in slope, confinement, and watershed area (Figure 6). The steepest portion of South River is actually at the downstream end of the river where it flows through a bedrock gorge before reaching the Deerfield River. As discussed in Section 2.1 above, many of the reach breaks are located at these areas of rapid change. Identifying where rapid changes in valley confinement, channel gradient, and drainage area occur is critical for understanding the distribution of gravel bars, bank erosion, and areas of rapid channel migration. The location, extent, and character of erosion, deposition, and channel migration on South River have been characterized through an analysis of historical aerial photographs and topographic maps (Section 2.4 below), channel features mapping (Section 2.5 below), and topographic surveying and substrate particle size analysis (Section 2.6 below).

2.4 Historical aerial photographs and topographic maps

Historical aerial photographs and topographic maps can be an important tool for studying changes in channel morphology through time. Visual inspection of changes on South River was made by comparing aerial photographs from 1952, 1971, 1992, 2003, 2009, and 2011 following Tropical Storm Irene (Appendix 2). Historic topographic maps from 1894 and 1937 were also consulted for further evidence of channel changes (Appendix 2). The history of South River's channel position was further extended and refined by consulting the 1871 Beers Atlas and a 1903 trolley line map (Appendix 2).

At least 67 percent of South River's length was artificially straightened prior to 1886-7 (Appendix 1), the year of surveying for the earliest map available (i.e., 1894 topographic map). Artificial channel straightening was a common practice on New England's streams in the 19th century, especially those with numerous dams and mills constructed on them such as South River. Sometimes the straightening can be demonstrated by comparing channel positions between different years. Multiple generations of straightening on South River are evidenced on the 1903 trolley map where the straightened 1903 channel position is shown alongside the trace of the also straightened "old line of river" (see 1903 map in Appendix 2). Artificial straightening that occurred prior to the earliest maps of a given area can usually be verified by the presence of one or more of three tell-tale features: 1) straight segments longer than the wavelength of adjacent meanders; 2) straight reaches that “hug” the valley sides despite an adjoining wide floodplain on which meanders could form; and 3) the presence of former meanders adjacent to the straightened channel (Figure 7). Such evidence exists on South River, but former meanders are less commonly observed due to infilling for agricultural development and impoundment sedimentation behind mill dams.

Meanders have subsequently reformed naturally along many artificially straightened channel segments on South River (Figure 8). In New England, two primary mechanisms, referred to as breakouts and buildouts, are responsible for the natural reformation of meanders along artificially straightened channels (Field, 2007). Breakouts occur where log jams, ice, or sediment clog the channel and force floodwaters to breakout onto the floodplain with enough stream power to scour a new meander across the floodplain surface. Breakout meanders typically form where flow can more easily overtop the channel banks such as in backwater areas behind constrictions or very low gradient reaches as behind (former) dams. Buildout meanders, in contrast, form as the stream is diverted around sediment building out into the channel at the confluence of tributaries (or otherwise being deposited along one side of a river channel). Erosion of the bank opposite from the location of sediment accretion leads to the formation of a new meander over time. Meander reformation on South River occurs by a combination of these processes and continues today in many areas, although an artificially straight condition persists in others. Understanding how meanders reform can help predict which portions of the remaining straightened segments may be prone to severe erosion. Rapid meander formation by either the breakout or buildout process can result in a shift in river position of tens of feet across the floodplain in a single flood event. Rapid meander reformation tends to occur at reach breaks where rapid changes in valley width, gradient, or sediment loading (from tributaries) are present (Figure 6).

The impact of former dams and mills on South River are still visible on aerial photographs. The former impoundments behind dams are characterized by lighter tones on the photographs due to the fine-grained impoundment sediments exposed at the surface that have yet to be completely obscured by vegetation encroaching into the former mill ponds (Figure 9). Essentially, the “ring around the tub” is still visible and covers at least 30 percent of the river’s length (Appendix 1). As the mill dams have fallen into ruin, the channel has incised through these sediments, causing bank erosion and increasing fine-grained sediment loading downstream (Figure 10).

2.5 Mapping of channel features

Several channel features were mapped continuously along the channel of South River in order to: 1) identify locations of channel instability and sensitivity; 2) characterize physical habitat conditions; and 3) document the impacts of past human activities on channel morphology and evolution (e.g., channel straightening and dam construction). The mapped features include: 1) bank height (to determine areas of confinement and assess the potential for mass failures along the river); 2) bank stability (e.g., eroding areas); 3) bank composition (e.g., alluvial floodplain sediments, impoundment sediments, bedrock); 4) grade controls (e.g., dams, waterfalls); 5) past management activities (e.g., former mill dams, location of berming, channel straightening); 6) bar types (e.g., point bars, mid-channel bars); and 7) habitat features (e.g., woody material, log jams, deep pools). The mapping was completed using a hand-held ArcPad computer with an embedded Trimble GPS and loaded with 2008 digital orthophotos as a base map. The beginning and end points of mapped features (e.g., an eroding bank) were recorded, so GIS shapefiles could be created and analyzed (Appendix 1 and Table 2).

The ArcView GIS shapefiles of the mapped features detail the character of the channel bed and banks for all points along South River (Appendix 1). The GIS shapefiles can be used to compare the location and distribution of multiple mapped features. For example, bank height, composition, and stability for a given section of river can be viewed simultaneously, helping to demonstrate how impoundment sediments are particularly prone to erosion (Figure 11). Based on an analysis of the GIS shapefiles, a statistical summary was produced to reveal the percentage of stream length along which certain conditions are found (e.g., percentage of eroding banks) (Table 2). The significant channel instabilities created by natural channel changes and human impacts along South River are manifest in the 34 percent of the channel banks that are either eroding or armored to prevent erosion. The channel features mapping data were also used to establish and characterize the segments described in Section 3.0 below. As described below, the several mapped features demonstrate the significant impact mill dams and associated human activities have had and continue to have on channel morphology, channel adjustments, aquatic habitat, and the distribution of erosion hazards along South River.

2.5a Mill dams and impoundment sediments

In addition to historical maps showing the location of former mill dams on South River (Figure 12 and Appendix 2), remnants of these and other dams are still visible in the field (Figure 13a). A total of 30 dams or remnants of dams were mapped on South River (Appendix 2). The older dams were primarily log crib structures (Figure 13a), but the largest existing dam near the downstream end of the river is of concrete construction (Figure 13b). Canals adjacent to the river that once led to mill buildings are frequently observed with their upstream ends beginning at the sites of former mill dams (Figure 12).

While the former mill dams are situated at single discrete points along the channel, the impoundment sediments deposited behind the dams extend for long distances upstream and, therefore, exert a greater influence on current channel morphology and continuing evolution (Figure 9). South River encounters impoundment sediments along 30 percent of the total length of stream bank (Table 2 and Appendix 1). Impoundment sediments are prevalent on South River due to the numerous dams that were once present and the sometimes low valley gradients that enabled the impoundments to extend considerable distances upstream. The impoundment sediments are characterized by thinly laminated dark brown organic-rich silts and sands (Figure 10).

Exposures of the impoundment sediments often contain numerous logs generally concentrated at the base of the finer grained laminated sediments. The presence of wood, organic fine-grained sediments, and thin laminations are all consistent with rapid deposition behind historic dams. Older floodplain deposits, that may share many of these characteristics, generally do not contain heavy concentrations of wood nor would laminations be preserved in slowly deposited floodplain sediments subject to reworking by extensive and protracted bioturbation by animals.

The majority of the mill dams have fallen into disrepair and have been breached (Figure 13a) with the impoundment sediments, in some cases, providing the only remaining evidence on the ground of the dams' former presence. Where the dams have been breached, the river has carved through the layers of accumulated silt up to 12 ft deep, giving rise to long lengths of eroding banks of readily transported fine-grained sediment (Figure 10). The channels incising through these former impoundment sediments are still evolving towards an equilibrium channel condition, so the bank erosion is likely to continue for an extended period of time and lead to high sediment loading downstream (see Section 2.7 below). In contrast, in those few cases where the former mill dams are still standing, the impounded area upstream is characterized by wide shallow channels prone to rapid migration as flow is diverted around the large point bars and mid-channel bars deposited in the low velocity zones upstream of the intact dams (Figure 14).

2.5b Bar deposition

Since deterioration of the mill dams, as described above, South River has incised through the impoundment sediments, releasing a considerable amount of stored sediment back into the river channel. Sediment moving through the channel is accumulating in the form of numerous gravel/sand bars that are found along 36 percent of the channel's length and at the edges of islands representing another 8 percent of the channel's length (Table 2). The bar deposition is largely concentrated in unconfined reaches and impoundments, since the sediment transport capacity in the straighter confined reaches is generally too high for sediment accumulation. The most common bar type on South River is point bars forming along the low-velocity inside bends of meanders (Figure 14), but mid-channel bars and delta bars formed at the mouths of tributaries are also present (Table 2). The bars can reach widths greater than the width of the low flow channel and grow fast enough that the bars remain largely unvegetated (Figure 14). Without the sediment generated from the reworking of the valley-bottom impoundment sediments (see Section 2.5a above) or mass wasting events along the valley side slopes (see Section 2.5c below), South River would have fewer bars, less erosion, and greater channel stability.

2.5c Bank erosion, mass wasting, and bank armoring

Twenty five percent of the river banks on South River are eroding (Table 2). Most of this bank erosion, as described above, is the result of channel incision through impoundment sediments or flow deflection around bars deposited in the channel. Where the river flows against the valley sides and encounters high banks of glacial deposits, the river is capable of initiating landslides, larger scale mass failures that rapidly introduce large amounts of sediment and wood into the channel (Figure 15). Forty six mass failures are present on South River with most of these mass wasting events found in narrowly confined reaches of the river where the river is more likely to flow against the valley sides (Table 2 and Appendix 1).

The sediment generated from landslides and incision through former impoundment sediments represents excess sediment that the river does not have the capacity to move through the river system. This excess sediment can generally pass through naturally steep confined reaches or artificially straightened channels (steeper and confined by incision or berms compared to natural conditions), but tends to accumulate at points of decreasing sediment transport capacity such as at points of valley expansion, natural or artificial channel constriction, decreasing channel gradient, or channel blockage (i.e., log or ice jams). The bars deposited at these locations deflect flow into the adjacent banks and cause further erosion, setting in motion a series of channel adjustments that can lead to the reformation of meanders along artificially straightened channels (see Section 2.7 below). While the dynamic channel conditions created by the bar deposition increases flow complexity and aquatic habitat, the associated bank erosion also, unfortunately, results in the loss of valuable agricultural land and presents a public safety hazard when occurring near human infrastructure such as at bridges.

Concerns about erosion and its potential for land loss and infrastructure damage has led to the armoring of nearly 10 percent of the river's banks (Table 2). Armoring on South River comes in the form of concrete retaining walls found along portions of Route 116 (Figure 16a), stacked rock retaining walls (Figure 16b), and more traditional rock riprap (Figure 16c). A geocell retaining wall filled with soil to support plant growth was built upstream of the Main Street bridge in Conway (Figure 4a), but was washed away less than one month after completion during Tropical Storm Irene in August 2011 (Figure 4b) and replaced with boulder riprap (Figure 4c). Bank armoring usually extends over only the bank, but in one location (Segment 15A) the riprap was also placed over much of the channel bed. While protecting property and infrastructure, bank armoring prevents natural channel adjustments that are important for creating aquatic habitat and establishing long-term channel stability. Consequently, the use of bank armoring should be limited.

2.5c Wood and pools

South River is dominated by a pool-riffle morphology in unconfined meandering segments of the river with a plane-bed channel characterizing confined reaches and artificially straightened segments where flow energy is high. Deep pools are uncommon in confined reaches and straightened segments, but are sometimes associated with the outside bends of meanders. Bedrock or otherwise hardened banks can result in adjacent deep pools as the river's erosive energy is focused on the channel bottom. Scour at the base of concrete retaining walls at three locations along the river have created deep pools that threaten the stability of the walls and has initiated efforts by the Massachusetts

Department of Transportation to repair or replace the walls with additional scour protection (Field, 2010 and 2013). As meanders continue to develop along artificially straightened segments of the channel (see Section 2.7 below), more pools are likely to develop as the plane-bed morphology is transformed to pools and riffles.

Large pieces of wood (greater than 0.5 ft diameter and 6.0 ft in length) are found on average every 43 ft along the river (122 pieces/mi) (Table 2). While this figure is below the 175-225 pieces/mi believed to have occurred naturally on northeastern rivers (McKinley et al., no date), the amount of wood in the channel is considerable given the long history of sawmills and logging in the watershed. Wood is introduced to the channel through mass failures of high banks (Figure 15) and less commonly by erosion of low banks.

The wood in the channel of South River is unevenly distributed. Wood entering the channel is not retained for long periods in the higher energy confined and straightened segments, so large accumulations of wood occur in relatively short segments of the channel (where flow energy rapidly declines) with long lengths of channel devoid of wood entirely (Figure 17 and Appendix 1). Wood in the channel is important for creating flow complexity, scouring pools, providing cover, and segregating particle sizes such that fines are removed from spawning gravels. The uneven distribution of wood along South River implies such habitat elements are lacking for long lengths of river.

2.6 Topographic surveys and substrate particle size analysis

The topographic surveys and substrate particle size analysis had two objectives: 1) characterize the variety of channel conditions present on South River; and 2) guide future restoration designs. Detailed topographic surveys were completed with a Sokkia Set 5 total station at 5 sites on South River (Appendix 3). At each site, plan views of bank positions, cross sections, and longitudinal profiles of the thalweg (i.e., deepest part of the channel) were surveyed. Channel cross sections were used to establish the bankfull channel width, mean and maximum depth, and width:depth ratio (Table 3). The data were also used to classify the channel type using Rosgen's (1996) channel classification system, Montgomery and Buffington's (1997) channel-reach morphology method, and Schumm et al.'s (1984) channel evolutionary model. The gradient of the stream bed and water surface were measured along the channel's thalweg as part of a longitudinal profile at each survey site. The substrate particle size data presented in Appendix 4 were collected at each survey site using standard pebble count procedures (Wolman, 1954) and were used to determine the D_{50} particle size (Table 3). The data from the longitudinal profiles and substrate particle size analyses can also be used to calculate bankfull shear stress and sediment entrainment thresholds, essential values for determining stream sensitivity, guiding restoration design, and sizing in-stream habitat improvement structures.

2.7 Channel classification

Three primary channel types have been identified as a result of the geomorphic assessment tasks described above: 1) confined channels; 2) unconfined channels; and 3) channels within impounded areas (Appendix 5). The channel types, as described below, share many of the same characteristics of widely used channel classification systems (Schumm et al., 1984; Rosgen, 1996; Montgomery and Buffington, 1997), but also encompass the unique conditions, history, and long-term evolution of South River.

2.7a Confined channels

Confined channels are those where the banks on both sides of the channel are higher (sometimes much higher) than the bankfull stage (i.e., river level that is reached or exceeded on an annual basis and generally equates to the level of the floodplain in unconfined channels). The confining banks are typically composed of glacial deposits in upper sections of the river, but are largely composed of bedrock in the gorge area at the downstream end of the river. Since flows greater than the bankfull condition remain confined within the channel, high stream powers are experienced in the bouldery channel bottoms that typify this channel type (Appendix 5). Mass wasting of high banks of glacial deposits leads to the recruitment of wood and fine sediment in confined channels, but the high stream power means such material is not retained for long periods. The confined channels of South River represent Rosgen B-type and F-type streams (Rosgen, 1996) and have a plane-bed or step-pool channel reach morphology (Montgomery and Buffington, 1997). Channel evolution in confined channels occurs very slowly, so classification using the channel evolution model of Schumm et al. (1984) is not appropriate. However, the high stream power can lead to severe scour and undermining of structures built in such channels as evidenced by undermined highway retaining walls along Route 116 (Figure 18). Consequently, habitat restoration and bank protection efforts in confined channels will require construction of robust structures (i.e., use of large boulders and anchored logs).

2.7b Unconfined channels

Unconfined channels are free flowing channels bordering a floodplain across which flood flows can spread. Where the channel is able to access a floodplain, stream power in the channel essentially reaches a maximum once flows reach the floodplain level (i.e., bankfull stage) since river stage increases only slowly, even with large increases in discharge, once flow begins to spread out on a wide floodplain. Consequently, finer sediment and wood is more likely to be retained for longer periods of time in unconfined channel segments than in confined channels. The unconfined channels are alluvial channels or channels that flow through erodible floodplain sands and silts. Alluvial channels are capable of freely adjusting the position of the bed and banks in response to the accumulation of wood and sediment (or even ice) in the channel. The unconfined channels classify as Rosgen C-type or E-type channels depending on width:depth ratios. A plane-bed morphology predominates in straightened segments while pools and riffles are found in meandering sections.

Nearly the entire length of the unconfined channel segments on South River were artificially straightened in the past (see Section 2.4 above and Appendix 1). Artificially straightened channels in alluvial reaches are inherently unstable due to the increase in channel gradient and stream power associated with the shortened stream length. Over time, straightened stream channels undergo a series of channel adjustments that ultimately lead to the return of a stable, yet continually shifting, meandering planform that approximates the pre-straightening condition. As described in Section 2.4 above, the first stage in the evolution of straightened channels is the formation of an initial meander by either the buildout or breakout process with buildouts being the predominant process on South River. Sediment accumulation is the main driving force of meander reformation on South River, although wood and ice likely play a lesser role as well. The straightened channel configuration persists on many sections of South River with such segments prone to future meander formation (Figure 19a). The initial meanders to form are simple single bends that initially break away from the straightened channel, but ultimately reconnect to the straightened channel downstream (Figure 19b). Breakout meanders most readily develop where flows can easily overtop the channel banks such as in backwater areas behind constrictions (such as dams), low gradient reaches, or where bank heights are lowered through sediment deposition in the channel. Once meander development begins, further sediment deposition occurs in response to the increasing stream length with deposition on point bars on the inside of the meander bend and erosion on the outside. Through this process, meanders continue to grow and ultimately more complex multiple-bend meanders are created (Figure 19c).

The recreation of meanders leads to improved aquatic habitat and decreased sediment loading downstream in unconfined channel segments. The plane-bed channel morphology associated with straightened segments has uniform flow velocities across the channel, embedded substrate (i.e., fines covering or mixed in with coarse sediment), and shallow pool depths, while all of these conditions are vastly improved in the pool-riffle dominated meandering sections. The point bars that develop along the reformed meanders are locations of long-term sediment storage that decrease downstream sediment loading, although a portion of this sediment is replaced by erosion on the outside bends of the meanders. Despite the erosion on the outside bends of the developing meanders, the potential for rapid and extreme bank erosion must be considered lessened by the reformation of meanders. The initial breakout along a straightened meander has the potential to suddenly shift the location of the channel tens of feet during a single flood with the location of such an event along a long straightened segment somewhat unpredictable. In contrast, the location of erosion in meandering sections of the river can more confidently be expected on the outside bend of meanders and while tens of feet of bank might be lost to erosion over several years the potential for extreme bank loss during a single flood is greatly diminished once meander reformation begins.

2.7c Channels within impounded areas

If the downstream dam is still intact, channels within impounded areas are completely unconfined with high width:depth ratios, large gravel bars present, and flow sometimes split into multiple flow paths (Figure 14 and Appendix 5). Given the loss of stream power as flows enter the impoundment area, the rates of bar formation, channel migration, and meander formation are all accelerated compared to the unconfined channels described above. As a result meander formation evolves to a point where cutoffs may develop and oxbows formed (Figure 19d). At this climactic stage of meander evolution, meander growth will continue to occur but the overall channel sinuosity will fluctuate around an equilibrium value with the increasing channel length created by meander growth offset by the channel shortening associated with cutoffs. The unconfined channels within impounded areas classify as Rosgen C-type or E-type channels and are predominately characterized by a pool-riffle channel morphology.

In most cases the dams creating the numerous impoundment areas on South River are no longer intact and the channels within the impoundment areas are adjusting to the lower base level (i.e., the channels are regrading themselves to the base of the dam as opposed to the top of the intact dam). This regrading process consists of a series of sequential channel adjustments akin to the channel evolutionary stages described by Schumm et al. (1984). First, the channel incises a deep narrow channel through the impoundment sediment to create banks of fine-grained sediment over 12 ft high in places (Figure 10). The banks are highest just upstream of the former dam and become progressively lower further upstream as a sloping regarded channel is created through the former flat-bottomed impoundment. The incised channel at this stage would be characterized as a Rosgen G-type channel or in Stage II of Schumm's et al. (1984) channel evolution. Once the channel has regraded its slope, the stream power contained within the incised channel begins to act on the banks and a phase of channel widening begins. Considerable sediment is generated during this phase of channel evolution as the erodible banks of fine impoundment sediments collapse into the channel. The channel in this widening phase would classify as a Rosgen F-type channel and be in Schumm's et al. (1984) Stage III of channel evolution. Many of the channels in impounded areas on South River are currently in this phase of evolution and generate considerable sediment that can be transported through the impounded area to downstream locations, because stream power remains high in the still confined, albeit widened, channel. Widening continues until stream power declines to a point where the sediment generated from bank erosion can no longer be transported through the reach and sediment begins to accumulate as bars in the channel. This begins a process of meander formation as described in Section 2.7b above and illustrated in Figure 19 that ultimately culminates in a fully meandering channel planform. The outer bends of the meanders continue to impinge on the high banks of impoundment sediments as bars initially form, but eventually the banks recede to the point where flows are no longer confined by the incision through the impoundment sediments and a new lower floodplain develops below the old impoundment surface. This final stage of channel evolution is equivalent to Stage IV of Schumm's et al. (1984) channel evolution model and results in a Rosgen C-type or E-type channel. The high downstream sediment loading associated with incision and widening of impoundment sediments may eventually give way to long-term sediment storage with continued evolution of the channels within impounded areas.

The different stages of channel evolution that can be identified today at various points along South River (Figure 19) represent the stages that occur through time at a single location. Some areas progress through the stages of evolution much faster than others, explaining why fully redeveloped meanders are found in some locations while others remain in an artificially straightened condition. In general, evolution progresses faster where the channel has a lower gradient, lower banks, or where sediment accumulation is most rapid (i.e., at points of valley expansion or constriction). For these reasons, channel adjustments occur most quickly on channels within impounded areas, some segments experiencing, in only decades, all phases of Schumm's et al. (1984) channel evolution model: channel incision, widening, and meander formation. Understanding these processes of channel evolution can be used to anticipate the types, rates, and location of future channel adjustments, thus playing an important role in the restoration planning process (see Section 3.0 below).

2.8 Reach descriptions

Geomorphic assessment information was collected on each of the 27 identified reaches (Figure 2). In many cases, two or more reaches are closely interconnected such that conditions in one reach may influence morphological conditions in another. Consequently, the summary discussion below of the geomorphic reaches is subdivided into groups of reaches within the same zone of influence. Each zone of influence is generally bounded by grade controls (e.g., bedrock ledge, dam) on both the upstream and downstream end; such grade controls tend to limit the upstream and downstream extent of channel adjustments occurring in response to various human activities.

2.8a Village of Ashfield (Reach 27)

From the dam impounding Ashfield Lake, two narrow and straight river channels emerge. These former canals, built to power long since vanished mills, are the headwaters of South River. The two channels upstream of the Buckland Road bridge are separated by a long berm, confining the river and preventing floodplain access. The channel planform is almost entirely artificially straightened and the banks are extensively armored, with stacked stone walls commonly covering the natural bank material. Increased flow velocity and sediment transport capacity combined with high runoff could lead to backwatering at undersized bridges and culverts in the reach, increasing potential damages due to flooding and erosion during high flow events. Many of the buildings encroaching upon the river are likely built on artificial fill or impoundment sediments. The riparian buffer is poor to nonexistent in this highly residential reach.

2.8b Huntstown Proprietors mill dam (Reaches 26 - 25)

Reach 26 begins at a large mass failure of glacial sands along the left bank of the river. By transferring energy downstream, the artificially straightened channel upstream likely contributes to this slope instability. The two reaches in this zone of influence are relatively steep (i.e., 1.8 and 1.4 percent slope) and well forested. Despite the narrow valley, three old impoundments are contained within these two reaches, including the large Huntstown Proprietors Corn Grist Mill impoundment at the downstream end of Reach 25. Land use in the river corridor is a mix of forest, wetlands, and residential properties. Geomorphic and habitat conditions are highly variable in the two reaches with some segments exhibiting excellent meander planform dimensions, particle size segregation, flow complexity, pool depth, in-stream wood, floodplain access, and bank stability. Other segments, such as downstream of the Baptist Corner Road crossing, exhibit poor conditions due to channel incision, artificial channel straightening, bank armoring, and past removal of wood from the channel.

2.8c Mill Hill valley (Reaches 24 - 22)

Reaches 24 through 22 flow through a steep forested valley bounded to the northeast by Mill Hill and to the west by the Ashfield Plain. Reaches 24 and 23 are bedrock controlled with Reach 23 occupying a steep bedrock gorge. All segments are in good geomorphic condition with low fluvial erosion hazards. Very little need for restoration exists, and wood recruitment to the reaches is likely to occur over time as the riparian forest bordering the channel matures. Sediment accumulation in the lower gradient portions of Reach 22 is contributing to local bank erosion. Given the lack of infrastructure in the reach, the erosion can be considered a habitat benefit, because of the cover associated with the undercut banks and the trees recruited to the channel from the undermined banks.

2.8d Emmett Road impoundment (Reach 21)

Reach 21 occupies the impoundment upstream of a relict mill dam. The impoundment was drained when the dam was breached and is currently a wetland. The stream channel is highly sinuous with a relatively low gradient and many adjacent wetlands and beaver dams. Overbank flows are very common at the upstream end, but the banks, composed of fine-grained impoundment sediments, are up to 7.0 ft high at the site of the former dam at the downstream end of the reach. Geomorphic and habitat conditions are good and the potential for flood and erosion damages is low given the lack of nearby infrastructure in the stream corridor.

2.8e South Ashfield (Reach 20)

Reach 20 is the first dominantly agricultural reach along the mainstem of South River. A limited riparian forest and light residential land use is also present on the wide floodplain. The river is impacted by artificial straightening, agricultural runoff, sediment loading, bank destabilization, and a loss of riparian vegetation. The geomorphic condition of the individual segments in the reach is highly variable with the most impacted segments being the most heavily agricultural such as Segment 20A where livestock access to the stream channel and a lack of riparian buffer combine to destabilize the banks. In places, the channel is reforming meanders along previously straightened sections.

Reach 20 was also significantly impacted historically by mill dams, as South Ashfield was a center for mill industries along South River. At least 6 mills in the village center were present, powered by water from canals and penstocks that came from upstream impoundments on South River and Creamery Brook. Reach 20 is in a unique position from a management standpoint given its position in the upper watershed. The reach's relative lack of infrastructure makes this an attractive location for land conservation, riparian plantings, and in-channel restoration.

2.8f Creamery Brook confluence (Reach 19)

The Creamery Brook confluence is an extremely important point along South River, because several controlling factors that influence the river's morphology dramatically change. The drainage area of South River increases by 130 percent (from 2.9 mi^2 to 6.7mi^2) at the Creamery Brook confluence. As a consequence, South River downstream of the confluence has a much greater capacity to move sediment. Further increasing stream power in the reach is the dramatic narrowing of the valley downstream of Creamery Brook. The narrow valley is bounded by high glacial terraces with even the low flow channel occupying the entire valley width. The high stream power contained within a channel bound by mass-failure prone glacial deposits make Reach 19 a potential source reach for high sediment loads downstream.

Reach 19 has a step-pool and steep riffle-pool morphology with a 1.9 percent channel gradient. In-channel habitat is good with many deep pools, boulders, wood and other cover elements. The channel is well shaded by mature trees, although the riparian corridor is narrow in many places. Given the narrow valley and the encroachment of Route 116, limited restoration opportunities are present but the good habitat and lack of infrastructure greatly reduce the need for active restoration.

2.8g Town line (Reach 18)

The Town line reach, so named because it spans both the towns of Ashfield and Conway, occupies a wide lower gradient valley compared to upstream and downstream. Consequently, sediment delivered from Creamery Brook and the upstream reaches of South River is deposited here, creating a very dynamic river reach with channel migration and bank erosion driven by significant sediment deposition. Considerable channel straightening and bank armoring have been carried out in the reach both historically and more recently in an effort to limit erosion and flooding. Meander reformation in response to this past straightening results in flood and erosion hazards that threaten the reach. For example, an enlarged mid-channel bar formed downstream of the recently channelized and armored segments, 18E and 18D, is diverting flow into the adjacent bank, creating a hazard to both Route 116 and the riparian landowner (Figure 8).

This reach of the stream would have naturally been an anastomosed or multi-threaded channel. This morphology has been reestablished in Segment 18F and the river's geomorphic condition in this area, consequently, is relatively good. Other than Route 116, which encroaches fairly close to the river and crosses the river twice, little infrastructure is present to be impacted by the river. This lack of infrastructure coupled by its position upstream of more populated areas in the watershed make this reach a strong candidate for land conservation and/or projects that promote sediment storage.

2.8h Poland Brook to Hickory Hollow (Reach 17)

Reach 17 begins at the confluence of South River and Poland Brook, the largest tributary in the watershed. The addition of Poland Brook increases the drainage area by 74 percent (from 8.9 to 15.5 mi^2). Similar to the Creamery Brook confluence, Poland Brook results in a significant increase in the water and sediment discharge to the river at a major valley constriction. The constriction, prone to backwatering during high flow events, is made more severe by the additions of water and sediment from the tributary. The result is a very dynamic channel with erosion a potential threat to the bridge just upstream, Route 116, North Poland Road, and adjacent properties. Evidence of the potential erosion hazards can be seen in the form of mass failures along the high banks of glacial deposits and the partial collapse of a concrete retaining wall protecting Route 116 (Figure 18).

The dominantly step-pool reach flows through a narrow steep valley and ends where the valley begins to widen at Hickory Hollow. The reach contains several large mass failures, including one in Segment 17E that was likely initiated during the 2005 flood when the channel switched positions and began to flow against the steep slope of glacial deposits. Since the channel remains against the high bank, the mass failure continues to contribute a huge quantity of sediment to the river. Reoccupying the abandoned channel and shifting flow away from the high bank would reduce this downstream sediment loading problem while reestablishing pools and other habitat elements in the former channel.

2.8i Tucker and Cook Reservoir (Reach 16)

Reach 16 flows through the valley once occupied by the Tucker and Cook Reservoir. The granite block dam created a large reservoir that was used to power mills downstream in the village of Conway. The partially breached dam, still capable of creating a backwater effect at high flows, contains a large volume of sediment in the upstream impoundment. This sediment is exposed on enlarged gravel bars and in the easily erodible banks of impoundment sediments up to 12 ft high (Figure 10). While this reach is a site of deposition at the upstream end, deep incision of the impoundment sediments at the downstream end contributes considerable sediment to downstream reaches. As the incised channel evolves towards a more meandering planform (see Section 2.7 above), the stream banks and bar surfaces should further stabilize and downstream loading should be greatly reduced. The ideal restoration option would be one that accelerates this evolutionary process while simultaneously protecting infrastructure that is adjacent to the river in portions of the reach.

2.8j Burkeville (Reaches 15 - 14)

In the Burkeville section of South River, several changes in land use, historic channel modification, and geography occur that distinguish these reaches from those upstream. Land use changes include increased population density and some commercial development. This was true historically, as it is today; there are five historic dams mapped in a 0.5 mi length of river. These dams controlled the water supply for canals leading to the mills that once operated here. Dams and canals were not the only historic channel impacts; the entire length of channel was straightened, perhaps as part of the 4-40 campaign described in Section 2.2 above. Reach 15 flows through a wide valley, but its location downstream of the reservoir's dam and its extensive history of channel straightening has led to an incised stream channel without access to its floodplain.

Geomorphic and habitat function is severely impaired in the Burkeville reaches, including four of the most severely degraded segments in the watershed (see Section 3.0 below). The river is wide, shallow, and relatively featureless with moderately unstable banks. The poor riparian buffer and lack of a channel canopy leads to high water temperatures unsuitable for trout. In addition, invasive species including Japanese knotweed are well-established along the river banks.

2.8k Conway Gorge (Reaches 13 -12)

The valley narrows considerably as the stream descends into the Conway Gorge section of the river. Channel gradient increases in Reach 13 to 1.2 percent and, then again, to 4.3 percent upon entering the bedrock gorge within Reach 12. The high steep banks of glacial deposits in Reach 13 are almost entirely armored. Two large mass failures are present along the left bank that may undermine Delabarre Avenue that runs along the top of the slope. Route 116 runs along the right bank with the base of the road grade encroaching on the channel along the upper portion of the reach. Slope stability is not much of an issue given the bedrock walls in Reach 12, but, despite this natural stability, concrete was poured across the channel underneath the Route 116 bridge.

The step-pool and cascade dominated channel is in good geomorphic condition with plenty of deep pools and well sorted sediment. While the stream has no floodplain connection and does not retain much wood, this is natural for a high gradient narrowly confined channel. The Conway Gorge section includes the former Delabarre Woolen

Mill (built in 1837) (Lee, 1967) and the remnants of an extensive mill and dam complex that is visible upstream of the Route 116 bridge.

2.8l Main Street (Reach 11)

Downstream of the Conway Gorge and the Route 116 bridge a very steep, artificially straightened stream channel flows through the heart of the village of Conway. Several canals are present that once fed long since vanished mills. This reach was once at the center of the industrialized Conway, including three dam impoundments, a sawmill (built in 1762), a tannery, the R. Tucker and Company cotton warp factory, and many other mills (Lee, 1967).

Several active mass failures in the reach supply sediment downstream to the lower gradient agricultural reaches, exacerbating bank instability, flooding, and erosion. The river is beginning to reform meanders in Reach 11 as channel bars aggrade and vegetate, a process that will increase sediment storage and decrease downstream sediment loading. The forested riparian zone supplies ample wood to the channel and provides a good canopy to keep summer water temperatures lower. The condition of Segment 11A is significantly more degraded than the rest of the reach with considerable bank erosion and armoring due to channel incision and the presence of a large granite block berm that blocks floodplain access (Figure 20). The berm severely limits the floodplain area available for the river to spread out and reduce its erosive force, a condition that potentially contributed to the scour around the Main Street bridge abutments during Tropical Storm Irene immediately downstream (Figure 4b). The retaining wall protecting the abutments has failed at least twice, most recently during Tropical Storm Irene, demonstrating the potential hazards created by confined flows. Many of the buildings encroaching upon the river in this reach are built upon artificial fill or impoundment sediments deposited behind the former mill dams. The high erosion and flood hazards in this area threaten not only the Main Street bridge, but also the residential, commercial and municipal buildings in the center of town. Given the considerable infrastructure at risk, the downstream end of Reach 11 and upstream end of Reach 10 just downstream have been identified as a priority area for restoration (see Sections 3.0 and 4.0 below).

2.8m Conway agricultural zone (Reaches 10 - 8)

Pumpkin Hollow Brook flows into South River just upstream of the Main Street bridge and marks the upstream end of Reach 10 and the Conway agricultural zone. This section of South River is lower gradient and occupies a relatively wide alluvial valley except for a short segment at the upstream end confined by glacial deposits and channel incision due to straightening. The characteristic meandering planform of wide alluvial valleys has been altered by extensive straightening and channelization, although an abandoned oxbow meander in Segment 9d is a remnant of the natural channel pattern (Figure 7). Along straightened segments, the river is redeveloping meanders as the channel evolves towards an equilibrium pattern. The process of meander reformation is particularly pronounced in the Conway agricultural zone where the channel flows across a wide gently sloping valley. Meander development is accelerated at the tight meander bends found where straightened segments end (e.g., Segments 10D, 9B, and 8A). Meander development also accommodates sediment deposition on the numerous enlarged bars found in this section of the river. This is the case at the former Harris Farm (Segment 9B) and at South River Miso and the Natural Roots CSA (Segment 8A).

In the past, efforts were undertaken to arrest the meander reformation and associated erosion including restraightening of the channel, bank armoring and gravel removal. The work was performed at various times and locations by the U.S. Army Corps, the Town of Conway, and local landowners themselves. This near annual "maintenance" helped keep bank erosion in check, kept the stream locked into its unnatural straightened form, increased sediment loading downstream, and allowed the severest erosion hazards to persist. By keeping the river in an unstable condition, the frequently managed channels remained primed for breakout meanders to develop whereby the channel could potentially shift tens of feet during a single flood.

Five dams are mapped in the three reaches of the Conway agricultural zone, including the extant dam at the former C.C. Flagg saw mill (operated until 1951). The legacy of channel modification has led to severely impaired geomorphic and habitat function in these reaches with three of the most severely degraded segments in the watershed in this zone. The river is wide, shallow, and relatively featureless with unstable banks. The riparian buffer is generally absent or dominated by invasive species such as honeysuckle, multiflora rose, Japanese knotweed, and bittersweet vines. Where a forested buffer exists, the band of trees is usually one tree wide and threatened by old age or bank erosion. Given the heavy agricultural land use in this zone, the riparian corridor is often mowed or hayed right to the top edge of the bank. The lack of a channel canopy through these three reaches leads to high summertime water temperatures unsuitable for trout.

2.8n Bardwells Ferry Road (Reach 7)

Just downstream of the Natural Roots CSA, the Bardwells Ferry Road continues north above the banks of South River. The valley becomes slightly narrower at this point, but the river's slope remains low. As in the zone just upstream, South River has experienced a long history of modification including several documented episodes of channel straightening and realignment. The riffle-pool channel is incised through alluvial, glacial, and impoundment sediments, losing some of its floodplain connection as a result. The exposed impoundment sediments, where they occur, are eroding severely and increasing downstream sediment loading. Three of the most impaired segments in the watershed are within this zone, Segments 7C, 7B, and 7A. The wide shallow channel is still actively widening with little flow complexity. Pools are filled with unsorted sand and gravel and coarser riffles are embedded with fine sediment.

The USGS maintains a stream gage just upstream of the lower Reeds Bridge Road bridge in Segment 7A. The peak discharge data from the gauge are shown in Figure 3.

This is also the former location of two dams and several mills, including a gristmill (see 1903 trolley map in Appendix 2).

2.8o Conway Station (Reaches 6 - 4)

At the upstream end of Reach 6, South River turns and begins to flow to the southeast as it enters the Conway Station reaches. This section of the river is significantly steeper and more confined than adjacent upstream reaches. Bedrock outcrops along the river bed and banks in the narrow valley. Long unstable sections of high banks of glacial deposits are also present with large mass failures adding significant quantities of sediment to the river. This is particularly evident in Reach 6 where 5 mass failures up to 40 ft high were mapped (Appendix 1). One such failure along the right bank threatens to undermine a section of Reeds Bridge Road. The river has an intact forested riparian zone. With the exception of Reach 6, geomorphic condition is good with good flow complexity, sediment sorting, deep pools, nice tree canopy, and ample in-stream wood. Human infrastructure was more prevalent historically than today; a former dam was present near the downstream end of Reach 6 and two bridges once crossed the river in the Conway Station section.

2.8p Big Dam impoundment (Reaches 3 - 2)

Big Dam (Figure 13b), as the largest existing dam in the watershed is locally known, was built in 1899 to power the Conway Electric Street Railway and later provided electricity to the Town of Conway (Lee, 1967). Under current low flow conditions the pond upstream of the dam extends over 1,300 ft to the upstream end of Reach 2, but the influence of the impoundment on river flow and sediment transport extends well into Reach 3. The low-gradient sinuous channel flows through a well forested river corridor. Much of the river channel is bedrock controlled, particularly in Reach 3. Erodible glacial and impoundment sediments make up the remainder of the stream banks with 5 mass failures mapped in the Big Dam impoundment reaches. Segments 3B and 3A have a nice wide forested floodplain, while the floodplain in Reach 2 is vegetated with invasive Japanese knotweed and tall grass.

The size of the impoundment has likely changed over time with the concrete dam replacing an older lower dam structure. Additionally, flashboards may have once been installed on the present dam, which would have raised the water surface elevation above its current state. The impoundment is currently filled almost completely with sediment. The penstock that delivered water from the dam and the ruins of the powerhouse are still visible in the forest downstream of the dam.

2.8q South River State Forest (Reach 1)

Downstream of Big Dam, South River flows through a bedrock gorge down to its confluence with the Deerfield River. The river channel is very steep, particularly in

Segment 1C, where the stream cascades over a series of bedrock falls. In most places, the stream channel completely fills the 90-foot wide valley with only a few isolated sand bars and pockets of floodplain forest present on the valley floor.

Geomorphic and habitat conditions are very good, especially in the cascade and step-pool channels of Segments 1C and 1B. Segment 1A is a riffle-pool channel with a much lower gradient. The lower portion of the segment is influenced by backwatering from the Deerfield River; pool depths, sediment sorting, and flow complexity are negatively impacted as a result. Being within the South River State Forest, the riparian forest is completely intact with a nearly full canopy over the river and considerable wood in the channel. Big Dam upstream is a fish passage barrier that isolates fish communities in this reach from the rest of the watershed upstream. Segment 1A is crossed by a pedestrian bridge constructed in 2009 on the Mohican Trail.

3.0 RESTORATION PLANNING

The 94 segments delineated with the assessment data (see Section 3.1 below) form the basis for developing and evaluating restoration options that will reduce flood and erosion hazards, improve aquatic habitat, and control downstream sediment loading. The most appropriate restoration options for each segment were identified through an eight step process detailed below: 1) segment delineation; 2) restoration needs; 3) restoration treatment options; 4) treatment prioritization; 5) determining appropriateness; 6) cost effectiveness; 7) treatment selection; and 8) segment prioritization. The selection of restoration options for each segment through this eight-step process has been organized using an Excel document with several linked tabs; each of these tabs is described in the first *Explanations* tab (Appendix 6). The restoration ranking process provides guidance in the selection of segments needing restoration and the best treatments to use in those segments, but the final selection and development of restoration projects also depends on other less quantifiable factors not incorporated into the restoration process.

3.1 Segment delineation

Designating river segments along the channel (Appendix 1) facilitates the selection of appropriate restoration options, because a single restoration design can usually be applied to the entire length of a given segment. Segments were delineated in the field during the mapping of channel features and represent distinct morphological elements along the channel such as a mid-channel bar, artificially straightened section of channel, breakout meander, presence of a confining berm, or absence of a forested riparian buffer along the river bank (Appendix 6 – *Segment characteristics* tab). Each segment has a uniform morphological character that is distinct from the immediately adjacent segments upstream and downstream but may be similar to other segments elsewhere. The segments represent subdivisions of the geomorphic reaches; each segment is identified first by the reach number and then by a sequentially-alphabetized letter starting from the downstream end of the reach. For example, the third segment from the downstream end of Reach 3 is designated as Segment 3C. The several reaches that were not segmented because of uniform morphology throughout were treated as single segments in the planning process. Further information on the types, distribution, and exact location of features within each segment can be gleaned from the GIS data (Appendix 1) and the *Segment characteristics* tab.

3.2 Restoration needs

The need for restoration within each segment was quantified by ranking the degree to which the segments possessed 10 geomorphic and habitat conditions typically associated with rivers that have reached a stable geomorphic state and possess high-quality physical habitat. A rating scale (ranging from 0 to 5) was developed for each of the 10 conditions to reflect the geomorphic and habitat needs of a given segment with a higher score reflecting a greater need for geomorphic and habitat improvements. The 10 geomorphic and habitat needs are outlined below with the scoring rubric used to assign the ratings (see also the *Explanations* tab). A high score generally indicates that habitat quality and geomorphic stability are poor. For example, a high score for Condition 7 indicates that the segment has little capacity for self-adjustment or the ability to develop improved habitat conditions over time. Some limitation on self-adjustment can be the result of natural channel confinement.

Condition 1 - Floodplain access

0 = floodplain access on both sides of channel
3 = floodplain access on one side
5 = no floodplain access

Condition 2 - Meander development

0 = well-developed meanders, high sinuosity
3 = meanders developing, cutbanks eroding, low sinuosity
5 = no meander development, straight channel

Condition 3 - Particle size segregation

0 = presence of large boulders (for cover and pool habitat), fine sediment and organic matter deposited on floodplain and channel margin (for greater soil fertility and macroinvertebrate taxa richness), coarser sediment in channel (for oxygenation), presence of active bars (for spawning along edges)
3 = 2 out of 4 present
5 = no boulders, no floodplain access, no active bars, highly embedded substrate

Condition 4 - Flow complexity

0 = presence of multiple flow conditions across the channel or in close proximity (i.e., fast deep flowing water near fast shallow, slow deep and slow shallow flows) characterized by deep pools (for cover and overwintering habitat),

shallow riffles or steps (for feeding and oxygenation), and side channels (for nursery habitat)
3 = missing 2 out of 4 flow types
5 = almost entirely fast shallow flow (i.e., continuous riffle; plane-bed morphology) with limited pools and side channels

Condition 5 – Quality of pools
0 = well developed deep pools (for cover and overwintering habitat)
3 = shallow pools only
5 = no pools

Condition 6 - Wood in channel
0 = plentiful wood in channel (for creating cover, increasing flow complexity, carving pools, and trapping other organic matter, fine sediment, and spawning gravels)
3 = four or more pieces of wood in channel
5 = no wood in channel

Condition 7 - Capacity for adjustment
0 = stream transporting bedload, capable of transporting bank material and adjusting planform morphology (for creating flow complexity), truly alluvial
3 = not capable of transporting bank material on one side, non-alluvial
5 = confined on both sides with no capacity to transport bank materials and adjust planform

Condition 8 – Riparian vegetation
0 = mature vegetation growing along approximately 75 percent of the channel banks (for shading and recruitment of organic matter to the channel), well-developed riparian zone, intervention would yield little possible improvement in channel shading
3 = mature vegetation along approximately 25 percent of the channel banks, decent riparian zone could be improved
5 = no mature vegetation on channel banks, poorly developed riparian zone providing very little shade

Condition 9 – Bank erosion
0 = less than 2 percent of the banks are eroding (stable banks reduce fine sediment inputs to the river, support healthy riparian vegetation growth, and provide cover)
3 = 20-34 percent of the banks are eroding
5 = more than 50 percent of the banks are eroding

Condition 10 – Bank armoring
0 = less than 2 percent armored (allows for channel adjustment to achieve geomorphic stability and create flow complexity)
3 = 16-25 percent armored

5 = more than 35 percent of the banks are armored

The *Needs* tab in Appendix 6 was developed to tabulate each segment's score for each of the 10 categories described above. The GIS shapefiles completed as part of the channel features mapping (Appendix 1) form the basis for assigning a score to some of the 10 needs categories (e.g., wood, erosion, armoring), while the scores for other categories were assigned directly in the field, using the scoring rubric above, immediately upon completing channel features mapping of a given segment. The total needs score of a segment, included in the "Total" column of the *Needs* tab (Appendix 6), is the summation of all 10 individual needs scores. The segments with the highest total needs scores represent the segments with the greatest overall need for improved geomorphic stability and aquatic habitat, although other segments may have a greater need for a specific category. For example, Segment 14A has the highest total needs score on South River with a value of 38 but only a value of 3 for the "Quality of pools" category, while Segment 18E with a lower total needs score of 28 has a higher needs score of 5 for the "Quality of pools" category. The total needs scores provide a quantitative means of identifying those segments with the widest range of needs over multiple categories. For the purposes of restoration planning on South River, segments with a total needs score of 30 or greater are generally considered high priorities for restoration, although other factors were also considered in selecting 20 sites for the development of conceptual restoration plans (as presented and explained in Section 4.0 below).

3.3 Restoration treatment options

Having identified the geomorphic and habitat needs for each segment, the next step in the restoration planning process is to select restoration options that are best suited to address those needs. A finite number of treatment options are available for mitigating flood and erosion hazards, improving aquatic habitat, and reducing downstream sediment loading. For South River, 14 possible restoration treatment options were identified that might be effective in addressing the various geomorphic and habitat needs (Appendix 6 – *Explanations* tab). Design typicals were created to provide more details on each treatment option except for the "Do nothing" option (Appendix 7). Some of the listed treatments embody multiple techniques that can be refined during a later detailed design phase. For example, a range of bank stabilization methods could be defined as "Bank bioengineering" with a decision, for example, to use willow stakes, root wad revetments, or log deflectors delayed for a later time. The 14 possible treatments cover a range of options from the "Do nothing" alternative through passive methods such as "Riparian improvements" to more active approaches such as "Bank cutting/Flow diversion".

Each restoration treatment was rated for its potential usefulness for addressing the 10 geomorphic needs described in Section 3.2 above. The 14 restoration options were scored on a scale from 0 to 5 to assign an effectiveness score with higher numbers representing a greater likelihood that the treatment under consideration will improve a given geomorphic and habitat condition (*Treatments* tab). The scoring for each treatment option is not specific to South River and was based on best professional judgment garnered from a similar restoration planning effort in New Hampshire (Field, 2009) and observations of restoration projects nationwide. The individual effectiveness ratings assigned to each of the 10 geomorphic and habitat conditions were added together to arrive at a total effectiveness score for each treatment option. The highest total effectiveness score displayed in the "Total" column is for "Engineered log jams", indicating that this treatment is the most effective at addressing multiple geomorphic and habitat needs simultaneously (e.g., creating pools, increasing flow complexity, providing wood in channel). However, other treatments may be more effective at addressing a specific geomorphic or habitat need (e.g., riparian improvements are more effective at developing a canopy for shading than engineered log jams). The "Total" row at the bottom of the table on the *Treatments* tab provides an indication of whether a given need can be treated by multiple treatments. For example, the highest score of 36.1 for "Flow complexity" indicates multiple options are available for improving flow complexity on South River while the lowest score of 24.4 for "Riparian improvements" indicates limited techniques are available for creating a better forest canopy over the river.

3.4 Treatment prioritization

To select the restoration treatment that best addresses the geomorphic and habitat needs of a given segment, the treatment effectiveness scores (*Treatments* tab) were compared with the geomorphic and habitat needs of each segment (*Needs* tab) (Appendix 6). To ensure the greatest needs (i.e., those needs assigned the highest value) are the focus of restoration, a threshold value of 4.0 was applied to the *Needs* tab such that only those geomorphic or habitat needs with a score of 4.0 or higher were considered for treatment (see *Needs* tab - "Threshold needs" column). For example, the threshold needs for Segment 5A listed in the "Threshold needs" column are floodplain access, capacity for adjustment, and bank erosion as these three conditions out of 10 are the only ones that scored a 4.0 or higher. Although another need scored as high as 3.0 (i.e., meander development), meander development was not considered as a need requiring treatment with the threshold value set at 4.0. The threshold value could be set at a lower value in the future to consider treatment of less acute geomorphic and habitat needs.

A threshold value was also assigned to the restoration effectiveness scores. A threshold value of 2.5 was set for the treatment options, so only the most effective restoration options for a given need would be considered for implementation. Those treatments with a score of less than 2.5 for addressing a particular geomorphic or habitat need were not considered as a treatment option for that need. Treatments that met the threshold for a specific need were assigned a " 1" on the "Treatments that pass threshold" table at the bottom of the *Treatments* tab with "0" assigned to treatments below the threshold value of 2.5. The highest value in the "Total" column on the right-hand side of the table is eight for particle size segregation and indicates eight treatment options have a high capacity (i.e., effectiveness scores greater than or equal to the threshold value of 2.5) to positively effect particle size segregation, while the lowest value of four for both riparian vegetation and wood in channel indicates suitable treatment options for addressing these needs are more limited. The "Total" row at the bottom of the

"Treatments that pass threshold" table provides a sense of which treatment options have the greatest value in effectively addressing multiple needs with "Bank cutting/Flow diversion" and "Engineered log jams" each able to address eight needs. The "Riparian improvements", "Bank bioengineering", and "Bar apex boulders" options, in contrast, are able to effectively address only two needs each. These three options, while limited in their broad utility, may, of course, prove very important in those segments where poor conditions exist for the needs these treatments best address.

An automated matrix-based process was developed in Excel to determine which treatment options best address (i.e., treatment effectiveness score of 2.5 or higher) a significant geomorphic or habitat need identified for a given segment (i.e., threshold needs score of 4.0 or higher). For each segment, the number of significant geomorphic and habitat needs that can be effectively treated using a given treatment option is recorded on the *Recommendations* tab (Appendix 6). All of the treatments that address at least one geomorphic need in the segment are listed under the "Recommended treatments" column on the *Recommendations* tab. For example, a value of six is recorded under "Boulder deflectors" for Segment 16C, because this treatment option effectively addresses six threshold needs in the segment. "Boulder deflectors" is thus listed as a recommended treatment in Segment 16C along with the 12 other treatments that effectively address at least one threshold need in the segment. A visual inspection of the table reveals that Segments 16C, 14A, 7C, and 7B are the only four segments where all of the treatment options except for "Do nothing" are recommended. Sixteen segments have no recommended treatment, because these segments have no needs that met the threshold value and, thus, can be considered segments with good geomorphic stability and aquatic habitat.

The cumulative total listed in the bottom "Total" row of the *Recommendations* tab provides a sense of the treatment's applicability along the entire river and the breadth of needs addressed. "Bank cutting/Flow diversion" has the highest total score of 189 reflecting how important this treatment option may be in addressing multiple needs in numerous segments on South River. In contrast, the lowest score of 35 (aside from 0 for "Do nothing") for "Bar apex boulders" suggests this treatment option may prove less useful.

If a specific geomorphic or habitat need becomes the primary focus of restoration (e.g., riparian improvements), the recommended treatments that best address that condition can be identified by referring back to the *Treatments* tab to determine which treatments exceed the treatment effectiveness threshold of 2.5 for the need of interest. In general, however, implementation of any of the recommended treatments in a given segment will improve the geomorphic and habitat condition of the river to some degree. The treatment addressing the most needs in a given segment would presumably provide the greatest improvements to channel condition, thus highlighting the value of the *Recommendations* tab.

The "Recommended treatments" column on the *Recommendations* tab lists all of the treatments that may be useful for addressing threshold needs in a given segment, but does not identify the most effective treatment. A clearer picture of the treatment option that best meets the broadest range of needs in a given segment can be drawn from the *Priority treatments* tab (Appendix 6) with the listed scores derived by summing the individual treatment effectiveness scores for all of the threshold needs in the given segment. For example, the total score of 11.8 (referred to here as the recommendations score) for "Engineered log jams" in Segment 20A can be reconstructed by first referring back to the *Needs* tab and noting that quality of pools, wood in channel, riparian vegetation, and bank erosion are the four geomorphic and habitat conditions that exceed the needs threshold of 4.0 in Segment 20A. The ability of "Engineered log jams" to address each of these conditions is indicated by the effectiveness scores recorded on the *Treatments* tab. For "Engineered log jams", the sum of the effectiveness score values for the four threshold needs in Segment 20A is 11.8 (i.e., 4.6 + 5.0 + 0.4 +1.8). (Note that the recommendations score can incorporate values from geomorphic needs for which the given treatment does not meet the treatment threshold of 2.5 as is the case in this example from Segment 20A where "Engineered log jams" does not meet the treatment threshold for the priority needs of riparian vegetation and bank erosion). The "Do nothing" option is listed as the priority treatment for the 16 segments with no threshold needs.

A ranking or prioritization of the recommended treatments for each segment is possible by comparing the recommendations scores; the three highest scoring treatments for each segment are listed on the *Priority treatments* tab. Continuing with the example from Segment 20A, the recommendations score for "Engineered log jams" is 11.8 and since this is the highest total in the segment, "Engineered log jams" is listed as the highest priority treatment. "Bank bioengineering" (score = 11.4) and "Rock weirs" (score = 10.9) are, in turn, the 2nd and 3rd ranked treatment priorities (Appendix 6). The recommendations scores for Segment 20A are not particularly high. The third ranked treatment priority in Segment 27C, for example, is "Boulder supported log jams" with a score of 14.8, significantly higher than the highest ranked treatment in Segment 20A. These differences between segments indicate that some segments will likely prove more responsive to the proposed restoration treatments than others. Regardless of the absolute values, however, the *Priority treatments* tab provides a priority listing of treatments for any segment that may be under consideration for restoration.

Ranking treatments based on thresholds ensures that the greatest needs in a segment are being addressed. However, in those segments with multiple needs, ranking treatments based on thresholds may leave many issues unaddressed if the threshold need(s) in that segment are treated with a technique that is well suited for that need but has limited effectiveness for addressing other needs. For example, "Floodplain lowering" is the highest ranked priority treatment in Reach 24 (an unsegmented reach) (see *Priority treatments* tab), because this treatment is very effective at addressing the reach's two threshold needs of floodplain access and capacity for adjustment (see *Needs* tab). However, three additional needs (i.e., meander development, flow complexity, and quality of pools) are near the threshold value (each has a needs score of 3), but the priority treatment of "Floodplain lowering" is not particularly effective at addressing these needs. To address this limitation of treatment prioritization based on thresholds (i.e., *Priority treatments* tab), the *All needs priorities* tab was created to prioritize restoration options without regard to thresholds and, thus, provides an opportunity to identify the restoration options that best address the full range of geomorphic and habitat needs in a given segment, not just the threshold needs. The values in the *All needs priorities* tab are derived for each treatment option by multiplying the needs score for each of the 10 geomorphic and habitat conditions for a given segment by the treatment's effectiveness score for that condition and then summing the 10 resulting products. For example, the value of 66.8 assigned to "Floodplain lowering" in Segment 20E was derived by multiplying the needs score of 4 for floodplain access in Segment 20E (see *Needs* tab) with the score of 5.0 for the effectiveness of "Floodplain lowering" for addressing the need for floodplain access (see *Treatments* tab). The resulting product of 20 was then added to the nine other products similarly derived for "Floodplain lowering" for the remaining needs to arrive at the total value of 66.8 (e.g., a value of 2.4 x 3 = 7.2 is the result for meander development). The calculation of all the values for 14 different treatments of 10 needs in 94 segments was simplified through matrix multiplication with the greatest value in a particular segment representing the highest priority restoration option. Given that the value of 66.8 from the example above is the highest value in Segment 20E, "Floodplain lowering" is the highest priority recommended treatment when all of the segment's needs are considered, not just the threshold needs. In Segment 20E, "Floodplain lowering" happens to be the highest ranked treatment regardless of whether the prioritization is based only on the threshold needs (see *Priority treatments* tab) or based on all 10 needs (see *All needs priorities* tab). However, the second and third ranked priorities for the two different prioritization approaches are different in Segment 20E and a visual inspection of the two tabs reveals that many segments have different treatments listed as the highest priority. Consequently, when contemplating which treatment options to select, project stakeholders must decide whether to select treatments that will best address the priority needs or the full suite of needs in a given segment. The values assigned in the *Priority treatments* tab and *All needs priorities* tab can be compared within a single tab but cannot be compared between tabs, because the values on the two tabs are derived in a different manner.

3.5 Determining appropriateness

While both the *Priority treatments* tab and *All needs priorities* tab prioritize several restoration options, the identified treatments are not always appropriate or feasible for the given segments. For example, "Breach or remove berm", although frequently recommended as one of the three highest scoring treatments on the two tabs, can only occur in segments where berms are present. Similarly, "Placed wood on bar", although not listed as a prioritized treatment on either tab, would necessarily be restricted to segments where a sand/gravel bar is present. These examples demonstrate two of the four treatments that were screened for appropriateness. The other two screens were to confirm bars are present in a segment before recommending "Bar apex boulders" as a treatment and to confirm bank erosion was present before recommending "Bank bioengineering", a treatment used exclusively on eroding banks. The *Screening* tab indicates the presence or absence (with a "Y" for yes and "N" for no) of three channel conditions (i.e., berms, bars, or bank erosion) in order to screen for the appropriateness of these four treatment types in the various segments. The GIS data created from the channel features mapping (Appendix 1) was used to determine in which segments these conditions were present.

Using "if-then" queries in Excel that reference back to the *Screening* tab, treatments that are not appropriate in a given segment are assigned a value of "0" on the *Appropriateness* tab while appropriate treatments are assigned a value of "1". A "0" value is assigned only if the critical condition used to screen for a given treatment is not present in a segment. For example, since a berm is not present in Segment 26D (as indicated by an "N" under the "berms" column on the *Screening* tab), the "Breach or remove berm" treatment is not appropriate for Segment 26D (so indicated by a "0" under "Breach or remove berm" column on the *Appropriateness* tab). Most columns are completely populated with a value of "1" on the *Appropriateness* tab, because nine of the treatment types have not been screened at all. Only the four screened treatment types have "0" values, highlighting the segments where that treatment option should not be considered in future restoration efforts. All treatments where a value of "1" is listed on the Appropriateness tab remain as possible treatments for a given segment assuming that treatment is also recommended on the "Recommendations" tab.

The results of the *Appropriateness* tab were used to eliminate inappropriate treatments from the initial *Recommendations* tab and to update the list of recommended treatments as shown on the *Screened recommendations* tab, which eliminates only those originally recommended treatments that are not appropriate for the segment. A visual inspection of the two tabs reveals "Breach or remove berm" was initially recommended for 54 segments but is appropriate in only the 2 segments where a berm is present. The *Screened recommendations* tab is unchanged from the *Recommendations* tab for the nine treatments where no appropriateness screening was conducted.

3.6 Cost Effectiveness

In addition to determining whether particular recommended restoration options are appropriate for a given segment, the potential project costs are another important consideration in the restoration planning process. For example, "Engineered log jams" is frequently the highest ranked treatment (Appendix 6 – *Priority treatments* tab and *All needs priority* tabs), but widespread application of this treatment may not be feasible given the relatively high costs of construction. Other less costly options may provide nearly the same benefits in terms of addressing geomorphic and habitat needs and, therefore, are more cost effective or have a greater bang-for-the-buck. In order to more systematically evaluate the cost effectiveness of potential projects, the *Cost effectiveness* tab (Appendix 6) was created that rates the 14 treatment options in regards to their ability to: 1) be sustainable over time; 2) create in-stream habitat, 3) improve riparian habitat, 4) increase floodplain access, 5) improve conditions downstream of the project, 6) reduce downstream sediment loading by either controlling bank erosion or increasing sediment storage, and 7) protect infrastructure. Each of these seven attributes—some of which embody the geomorphic and habitat conditions described in Section 3.2 above—were rated on a scale of 0 to 5.0 with higher scores indicating a greater capacity for the treatment to bring about long-term improvements in channel stability, habitat, downstream sediment loading, and infrastructure protection. The individual scores for each attribute were summed to calculate the total aggregate value referred to as the "stability score".

In addition to rating the five channel stability and habitat attributes, the perceived relative costs of each of the 14 treatment options were also ranked on a scale of 0 to 5.0 with 5.0 reflecting the highest cost. The ratio between the stability score and cost ranking yields the cost effectiveness score. For example, the cost effectiveness score of 7.1 for "Boulder clusters" is derived by dividing 11.4 (the stability score displayed in the "Total aggregate value" column) by 1.6 (cost ranking for "Boulder clusters") (i.e., 11.4/1.6=7.1). The treatment rankings based on the cost effectiveness score are not segment dependent, so the rankings are the same for all segments. The cost effectiveness score for all treatments that are both recommended and appropriate for a given segment are shown on the *Cost prioritization* tab with the highest-ranked cost effective treatment for a segment listed under the "Highest ranked treatment" column. Note, however, that the cost effectiveness scores for any given treatment are the same regardless of segment (e.g., 10.5 for "Riparian improvements"). The relatively high cost effectiveness score of 8.4 for "Bank cutting/Flow diversion" points to the potential utility of this treatment in the segments for which this option is recommended. In contrast, "Engineered log jams" has the lowest cost effectiveness score at 4.4 and suggests the high cost (Cost ranking = 4.5) of building log jams will limit the application of a treatment that otherwise has many benefits as reflected in the high stability score on the *Cost effectiveness* tab. The cost limitation of "Engineered log jams" is underscored by the treatment's absence under the "Highest ranked treatment" column on the *Cost prioritization* tab despite its frequent presence as a priority treatment on the *Priority treatments* tab and *All needs priorities* tab. The "Do nothing" alternative, because of no cost, has the highest cost effectiveness score and highlights the importance of considering the "Do nothing" option as a viable alternative in all segments even though this approach has limited capacity to quickly improve aquatic habitat and channel stability.

3.7 Treatment selection

Through the restoration planning process detailed above, the best treatment options for addressing the geomorphic and habitat needs of a given segment can be selected in three different ways: based on acute (i.e., threshold) geomorphic and habitat needs (see *Priority treatments* tab), based on the full range of needs (see *All needs priorities* tab), and based on cost effectiveness (see *Cost effectiveness* tab). The *Summary* tab compiles all of these different prioritization approaches after passing them through the appropriateness screening process (see Section 3.5 above) such that only appropriate treatments for a given segment can be listed under the "Highest ranked treatment" column. Since the listed priority treatments in the *Priority treatments* tab and *All needs priorities* tab have not been screened for appropriateness, these tabs should be considered only as intermediate steps in the restoration planning process with the *Summary* tab being the best reference for identifying the highest priority treatments. The *Priority treatments* tab and *All needs priorities* tab still have value for identifying the 2nd and 3rd ranked treatment priorities in a given segment as long as the listed treatments are also confirmed to be appropriate by checking the *Screened recommendations* tab.

The “Highest ranked treatment” column on the *Summary* tab lists three treatments, representing the highest priority treatment based on all needs, threshold needs, and cost effectiveness (i.e., bang-for-the-buck) with the cost-effectiveness priority generally representing a less expensive option that produces similar geomorphic and habitat benefits. The project stakeholders must decide among these three prioritized treatments and all other appropriate treatments (shown in the “Appropriate treatments” column on the *Summary* tab) when developing restoration plans. In many cases, the same treatment option is prioritized by two of the different prioritization approaches as in Segment 19E where “Floodplain lowering” is recommended based on both all needs and threshold needs. The cost effective treatment, “Bank cutting/Flow diversion”, represents a more affordable approach to achieving similar results.

All three prioritization methods recommend the do nothing option in those segments where no threshold geomorphic and habitat needs are present (e.g., Segments 14A-14C). Sixteen of the 94 segments fall into this category and should be considered as segments in fairly good condition with limited need for restoration. Priority treatments beyond the do nothing approach could be identified for the 16 segments by lowering the currently assigned threshold value of 4. The ability to change threshold values on the *Needs* tab provides project planners the flexibility to prioritize restoration efforts based on specific conditions present in a given watershed.

3.8 Utilizing the restoration rankings

Without the process detailed above to rank restoration treatment options, selecting the best of 14 treatment techniques to address 10 geomorphic and habitat needs in 94 different segments would be daunting. However, the process is merely designed to provide guidance to project stakeholders who ultimately must make the final decision regarding the treatment options to implement. For restoration at the watershed level, the highest priority segments selected for restoration should not only lead to channel stability and sustainable habitat improvements within the segment, but should also improve conditions elsewhere. High rates of sediment delivery from upstream reaches are a common cause for channel instability and habitat degradation on rivers in New England. Consequently, high priority segments for restoration should be those where floodplain access, multiple side channels, or a meandering planform can be reestablished or further improved without endangering public safety. Such restoration efforts typically improve flood and sediment storage, thereby reducing downstream sediment loading and flooding while creating aquatic habitat in the restored segment (e.g., flood flow refuge and rearing habitat in side channels and pool formation within recreated meanders).

Budgetary or other constraints preventing implementation of the highest priority projects should not necessarily preclude implementation of less expensive or more easily completed restoration projects elsewhere. The approach to developing and evaluating restoration options described above will allow long-term restoration planning to continue at the watershed level while the more easily implemented projects (the "low hanging fruit") can move forward more quickly in selected segments. The results of the restoration prioritization (Appendix 6) are a tool that will enable project stakeholders to begin long-term planning and sequencing of restoration projects at the watershed scale.

To focus future planning efforts, a list of segments with a high priority for restoration was created based on the total needs scores, degree of bank erosion and armoring, and proximity to infrastructure. To be considered as a priority segment the segment had to pass through a two-step screening process. First, the segment had to meet just one of three criteria: 1) a total needs score of 30 or greater (as recorded under the "Total" column on the *Needs* tab); 2) bank erosion of more than 35 percent (i.e., erosion score of 4 or higher as recorded under the "Eroding" column on the *Needs* tab); or 3) a combined bank erosion and bank armoring score of 7 or more (i.e., the sum of the two values listed under the "Eroding" and "Armoring" columns on the *Needs* tab). The combined bank erosion and bank armoring score of 7 or more means at least 45 percent of the bank length in the segment must be unstable (i.e., either eroding or armored) (see scoring rubric on *Explanations* tab). A total of 43 segments pass through the first screening process by meeting at least one of these three criteria, only 18 of which have a needs score of 30 or higher (see *Segment prioritization screen* in Appendix 6). The addition of 25 others to this initial list based on bank stability reflects the concern bank instability plays in erosion hazards and downstream sediment loading.

To be considered as a priority segment, however, the 43 segments that passed through the initial screening process must also be within 100 ft of critical infrastructure (defined here as a main road, bridge, or residential or commercial development). This second infrastructure screen ensures that restoration in prioritized segments, in addition to focusing on channel stability, aquatic habitat, and sediment loading issues, is potentially protecting infrastructure. A scoring rubric was developed to indicate how close a segment was to infrastructure or other human land uses with a "0" assigned to segments where no infrastructure or agricultural was within 100 ft, a "2" for segments within 100 ft of agricultural lands, a "3" for segments within 100 ft of a secondary road, a "4" for segments within 100 ft of a main road or bridge, and a "5" for segments within 100 ft of a residential or commercial development. A hand entered value was recorded for each segment under the "Infra score" column (for infrastructure score) on the *Segment prioritization screen* tab after analyzing with GIS the most recent orthophotos (from 2009), road shapefiles, and segment shapefiles in Appendix 1. Those segments with a score of 4 or more were then flagged with a "yes" under the "Infra_threshold" column on the *Segment prioritization screen* tab to identify those segments within 100 ft of a main road, bridge, or residential or commercial development. The final step in the two-part screening process was to identify those segments that passed through both screens (i.e., met one of the three criteria in the first screen and were also within 100 ft of critical infrastructure). The 26 prioritized segments that resulted from this process are denoted with a “Pass” designation under the “Pass all thresholds” column on the *Segment prioritization screen* tab. The 26 segments are also shown ranked ordered based on the total *Needs* score on the *Prioritized segments* tab.

The highest ranked priority treatment based on the prioritization process described above is Segment 14A, but all 26 priority segments should be considered equally worthy of restoration despite the range in total *Needs* scores from 38 to 17. Opportunities to work in one segment should not be delayed simply because other higher ranked segments have not yet been restored. Additionally, within a given segment, all appropriate treatments should be considered in developing restoration designs as many other factors not embodied in the restoration planning process must also be considered. For example, a hypothetical landowner in Segment 19E who is willing to implement a low ranking yet recommended and appropriate treatment in the channel (e.g., “Boulder weirs”) may be unwilling to consider the three highest priority treatments requiring work on the floodplain (e.g., “Floodplain lowering” and “Flow diversion) (see Segment 19E on *Summary* tab). The in-channel treatment while perhaps not as effective as the floodplain options would still be worth implementing, because some of the segment’s needs would be addressed.

4.0 DEVELOPMENT OF RESTORATION DESIGNS

The restoration planning process described above provides a framework for identifying priority sites to conduct restoration and selecting treatments to use at those sites. However, the planning process embodies only some of the many issues that must be considered in making decisions regarding the location and type of restoration (e.g., habitat needs, proximity to infrastructure, cost effectiveness). The other factors not incorporated into the planning process include, but are not limited to: 1) landowner willingness and support; 2) the priorities of interested parties such as municipalities, non-profit groups, and potential funding agencies; 3) the need to vary treatments along the length of the river, so the benefits of multiple approaches can be realized; 4) construction access; and 5) best professional judgment based on watershed assessment data and lessons learned from other restoration projects. Using the results of the restoration planning process, restoration project concepts were developed for 20 sites that include 14 of the 26 prioritized segments (see *Prioritized segments* tab) with 6 other projects included for additional reasons beyond the scope of the restoration planning process (Table 4). The 20 listed projects recommend a range of treatment options and include projects in both Conway and Ashfield, the two towns along South River. While the 20 listed projects provide a focus for future restoration efforts, the restoration planning process (Appendix 6), by providing restoration recommendations for all segments, allows opportunities anywhere on the river to be pursued, regardless of priority, whenever there is a confluence of various factors such as landowner willingness, funding, and stakeholder support. Implementation of one or two projects will enhance local channel conditions immediately, but the additive impact of completing several priority projects, as well as others, will ultimately benefit areas beyond the project sites and lead to watershed-wide progress on managing flood and erosion hazards, enhancing aquatic habitat, and reducing downstream sediment loading.

The impacts of past floods can be an important factor influencing decisions on where to implement a restoration project. In this respect, Tropical Storm Irene was an effective agent of both geomorphic and societal change with the near loss of the Main Street bridge in Conway (Figure 4b) resulting in a renewed community focus on flood and erosion hazards in the watershed. Given the damages at the bridge and erosion of several properties downstream of the bridge, the first site selected for restoration and project design development were Segments 11A and 10E, immediately upstream and downstream of the Main Street bridge in Conway, respectively. The two segments, although not the highest ranked priorities, are on the list of 26 prioritized sites that passed through the screening steps in the restoration planning process (Appendix 6 – *Prioritized segments* tab) with several of the recommended treatments for those segments incorporated into the project design for the site (Appendix 8). (The two segments are also included as a single restoration project concept in Table 4). Aerial photographs were flown of the project site at the bridge for later use in developing topographic maps, so hydraulic modeling and final design drawings can be completed.

The design incorporates both in-channel and floodplain restoration measures. The in-channel treatments include boulder weirs, boulder deflectors, and small engineered log jams at the margins of the channel between the weirs (Appendix 8). The weirs are intended to focus flow in the center of the channel and thus reduce bank erosion while creating pool habitat in the confined portions of the segments immediately upstream and downstream of the bridge. By centering flow, the weirs will also improve protection of the bridge abutments. The small log jams (not shown on the plans for clarity) will encourage sediment deposition along the channel margins and increase cover habitat. The boulder deflectors at the downstream end of the project will be done in conjunction with floodplain lowering on the margins of the channel. The deflectors will divert flow towards the lowered floodplain and increase its effectiveness. The floodplain lowering, proposed to occur on land owned by the Town of Conway, will become an area of flood storage during high flows, thereby reducing flood stage and velocities both upstream and downstream. Hydraulic modeling to be completed during a later final design phase will be able to quantify the changes in flood height and velocity. Sediment deposition on the lowered floodplain will remain in long-term storage and thus reduce downstream sediment loading.

Upstream of the bridge, a berm is present that blocks access to a lowland area at the confluence of South River and Pumpkin Hollow Brook. The design calls for breaching this berm, so high flows can access this area. Increasing flood storage across this lowland area will increase sediment storage and further reduce flood flow heights and velocities. Breaching of the berm is likely to result in greater reductions in flood height and velocity than the floodplain lowering downstream of the bridge, but future hydraulic modeling will better quantify these changes. The project will be completed in two phases with the first phase to be completed downstream of the bridge where the riparian landowners are supportive of project completion. Once the downstream phase is implemented and the various proposed treatments tested, the second upstream phase of the project can be completed with landowner support. Completion of an initial project in the village of Conway demonstrating the benefits of river restoration should stimulate interest in completing other projects elsewhere on South River.

5.0 CONCLUSIONS

The South River watershed's rich history of mills and associated river uses, including dam construction and extensive channel straightening, has left a continuing legacy of aggravated flood and erosion hazards, degraded aquatic habitat, and high sediment loading. As numerous mill dams have fallen into disrepair, large volumes of sediment are being released into the river as the channel incises through the former impoundments behind these old dams. Considerable sediment is also derived from mass failures along high banks of glacial deposits in naturally confined portions of the river where flood flow velocities and scour are enhanced without a floodplain to dissipate flow energy. The sediment derived from former impoundments and mass failures tends to accumulate in areas where flow velocity declines rapidly. Sediment deposition near bridges and other infrastructure threaten the structures through bank erosion driven by gravel/sand bar growth. Straightened channels have a propensity to reform meanders along their length with the process of meander development beginning with potentially rapid shifts in channel position of tens of feet in a single flood. Where occurring far from infrastructure and other human resources, continued meander growth, despite the associated bank erosion, can positively impact the river by reducing flood flow velocities, improving aquatic habitat (e.g., greater pool depths, increased flow complexity, and improved particle size segregation), and reducing downstream sediment loading through long-term sediment on gravel/sand bars and emerging floodplains.

The specific geomorphic and habitat needs to be addressed by restoration have been identified for the 94 discreet channel segments identified during the assessment (Appendix 6). Design typicals have been created for 13 treatment options (not including "Do nothing" option) that each address a unique suite of geomorphic needs (Appendix 7). An eight-step restoration planning process was developed to link appropriate cost-effective restoration treatments with the geomorphic and habitat needs of priority segments. The restoration planning process was instrumental in developing a list of 20 restoration project concepts (Table 4) that if implemented over time will lead to long-term improvements in flood and erosion control, enhancements in aquatic habitat, and reductions in downstream sediment loading. Detailed designs were developed for the village of Conway to increase flood storage through floodplain lowering and partial berm removal. Along with associated in-channel measures including the use of boulder deflectors, boulder weirs, and small log jams, the proposed project will demonstrate how flooding and bank erosion can be controlled sustainably while simultaneously improving aquatic habitat and reducing downstream sediment loading. The results of the geomorphic assessment and restoration planning process for South River will remain useful in the coming years by targeting restoration treatments to the site-specific needs of the various identified channel segments on South River.

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FIGURES

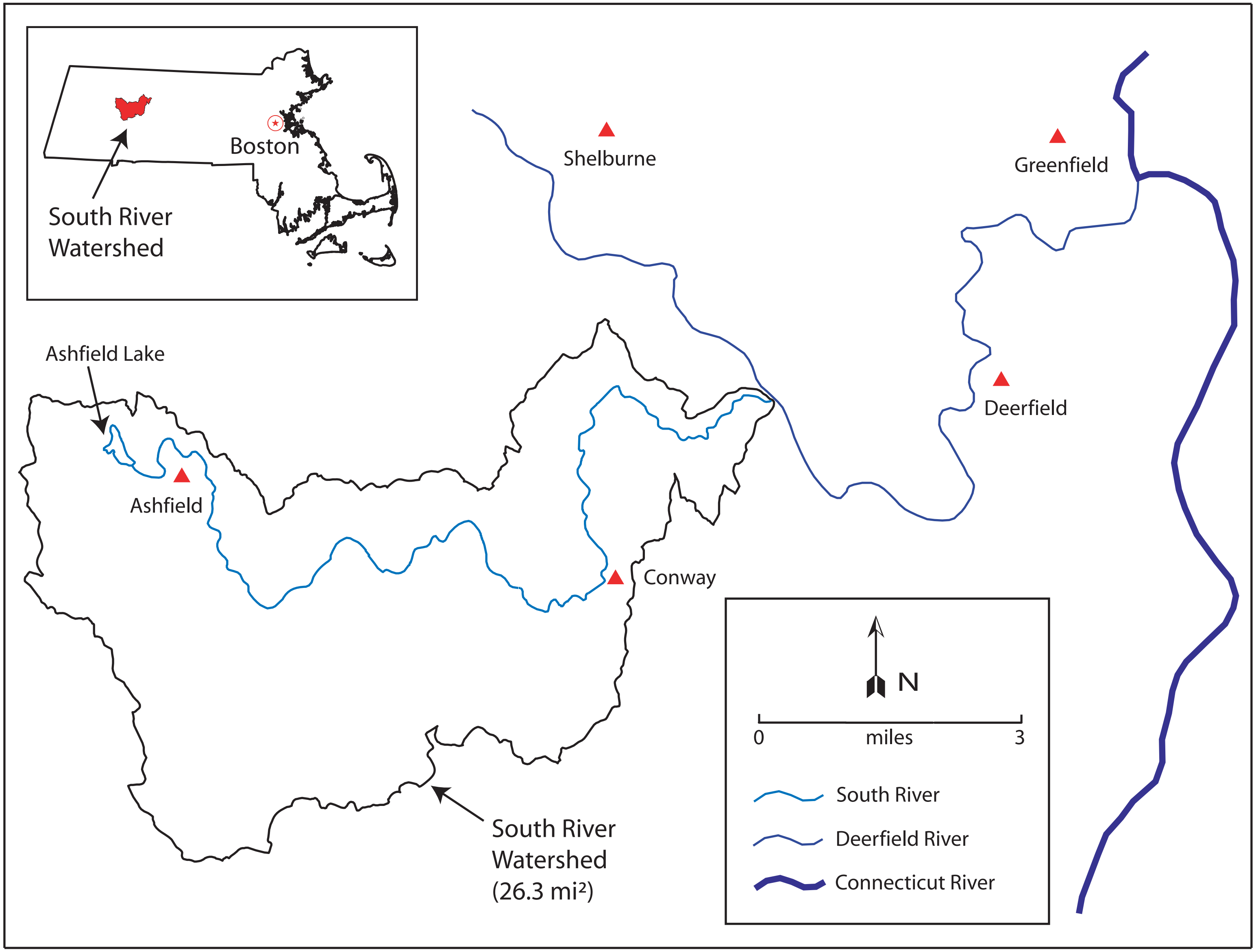


Figure 1. Watershed map of South River.

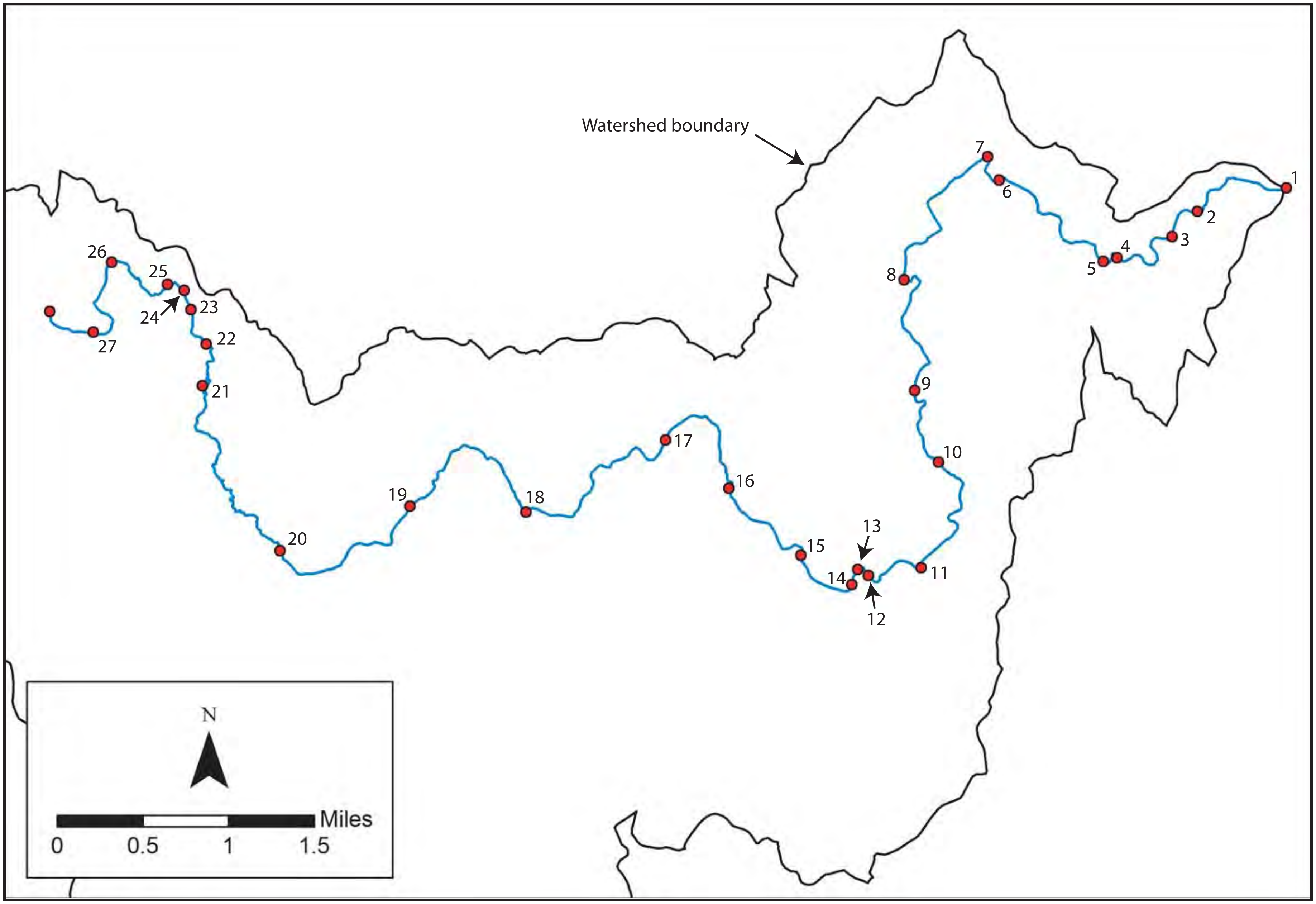


Figure 2. Location of reach breaks on South River.

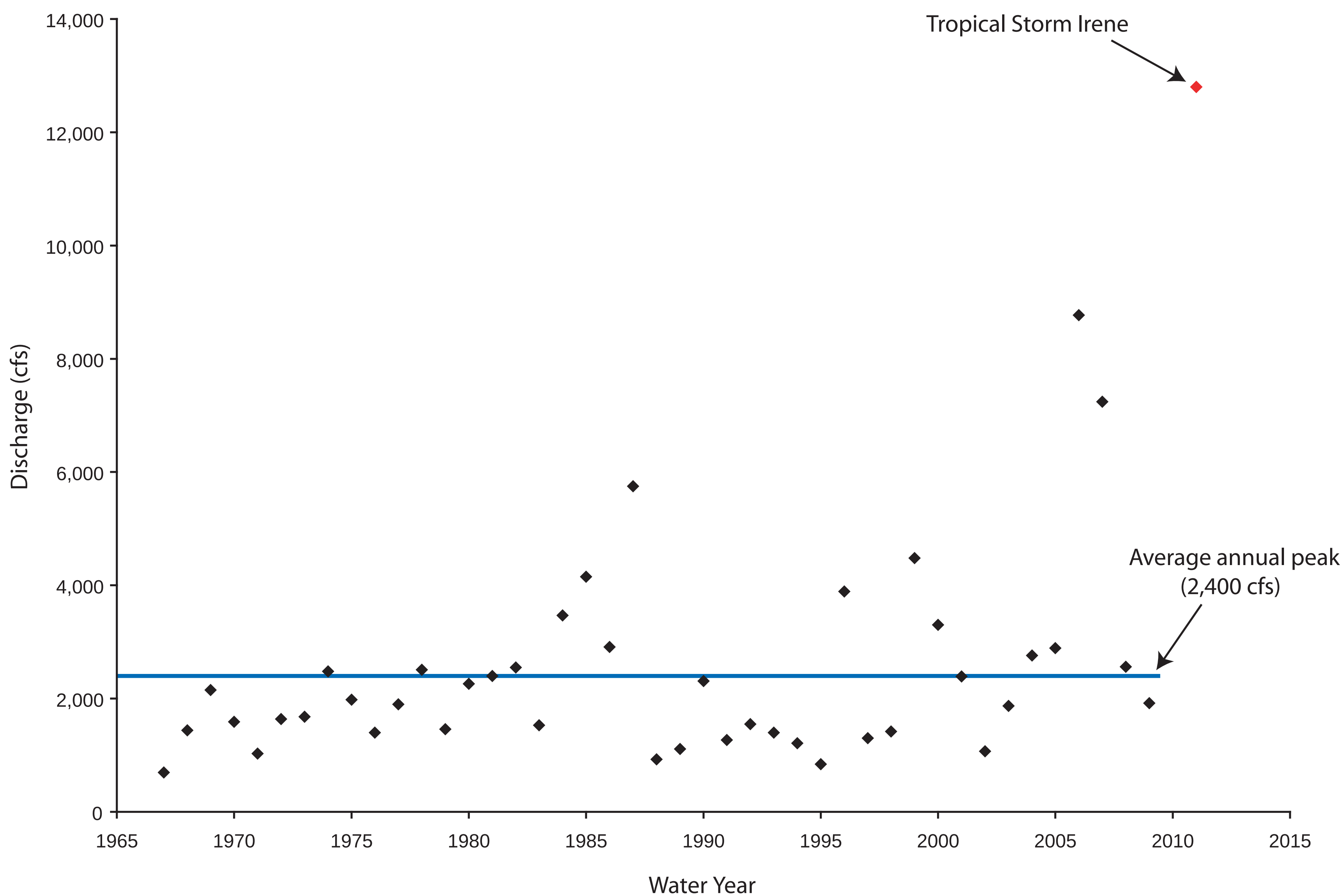


Figure 3. Annual peak discharge data for the South River including the historic maximum of 12,800 cfs recorded during Tropical Storm Irene on August 28, 2011.

Figure 4. Impact of Tropical Storm Irene flooding and subsequent river management as revealed just upstream of Route 116 Bridge where a) bank repairs completed in early August 2011 were b) washed away by flooding on August 28, 2011 with c) post-flooding bank repairs further constricting channel (photo “c” courtesy of M.Turre).

Figure 5. Landslides on high banks of glacial deposits were reactivated by Tropical Storm Irene.

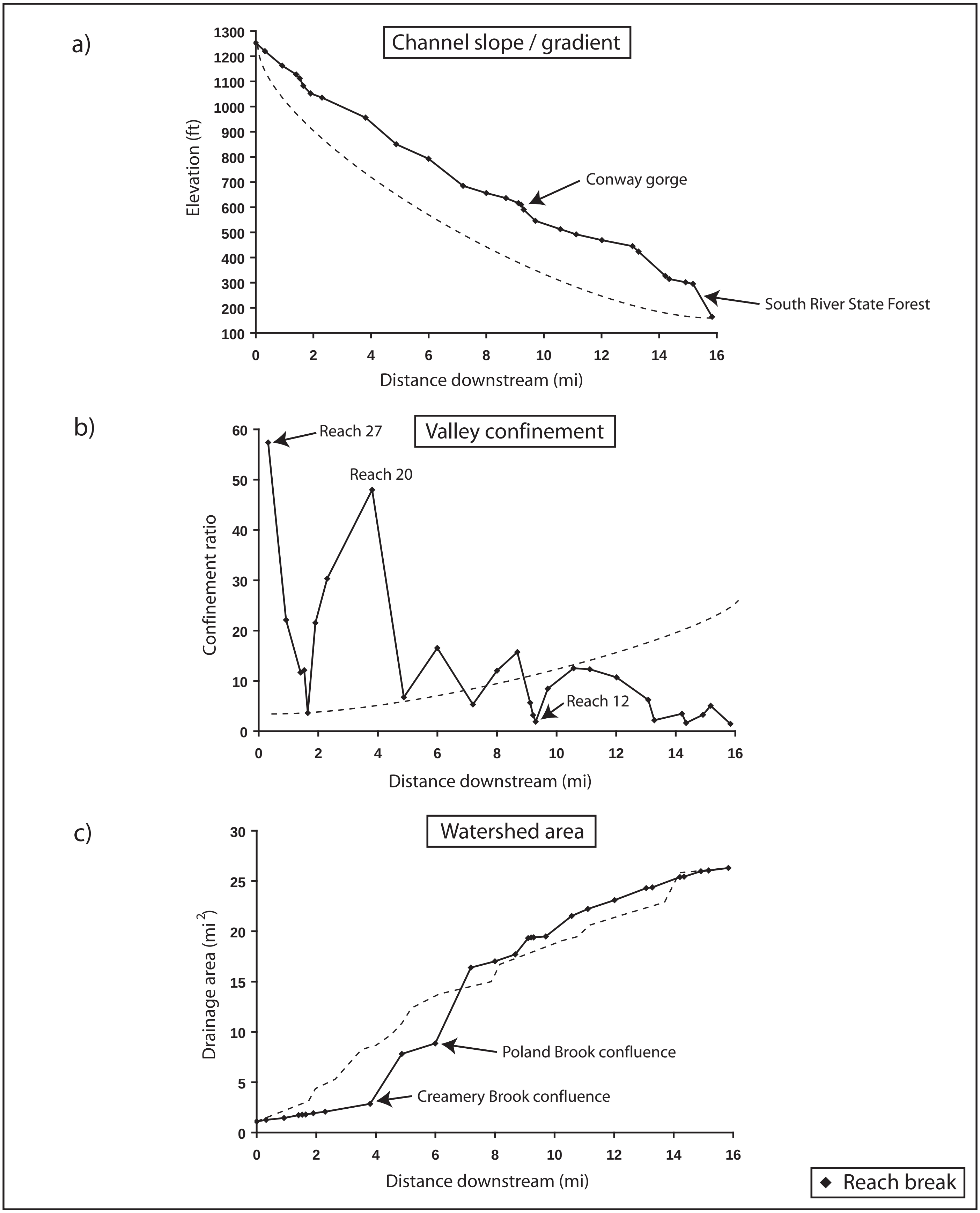


Figure 6. The complex geology and glacial history of South River gives rise to abrupt changes in a) slope, b) confinement, and c) watershed area along the length of the river. Note: dashed lines represent an idealized river equilibrium condition.

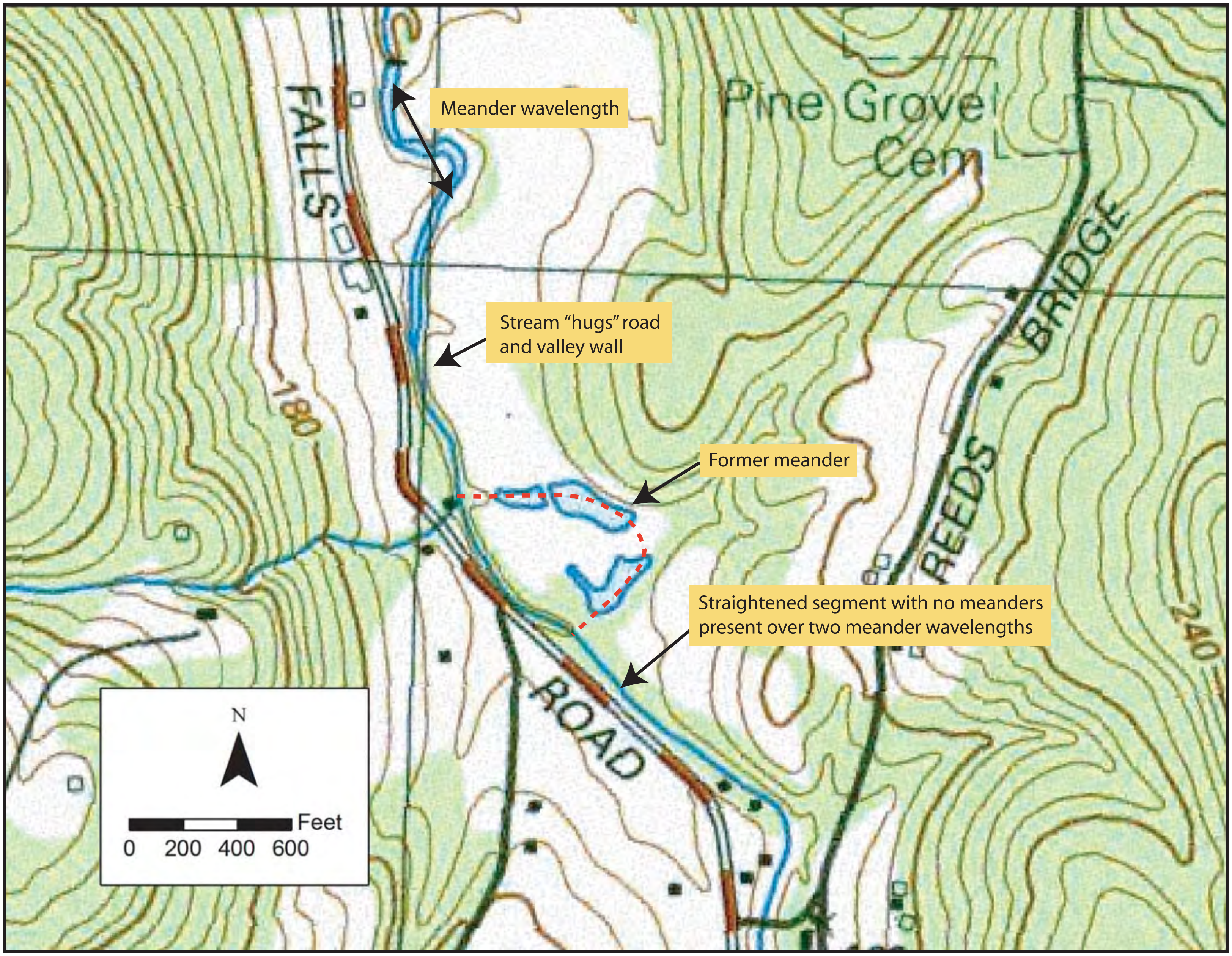


Figure 7. Evidence for artificial channel straightening on South River.

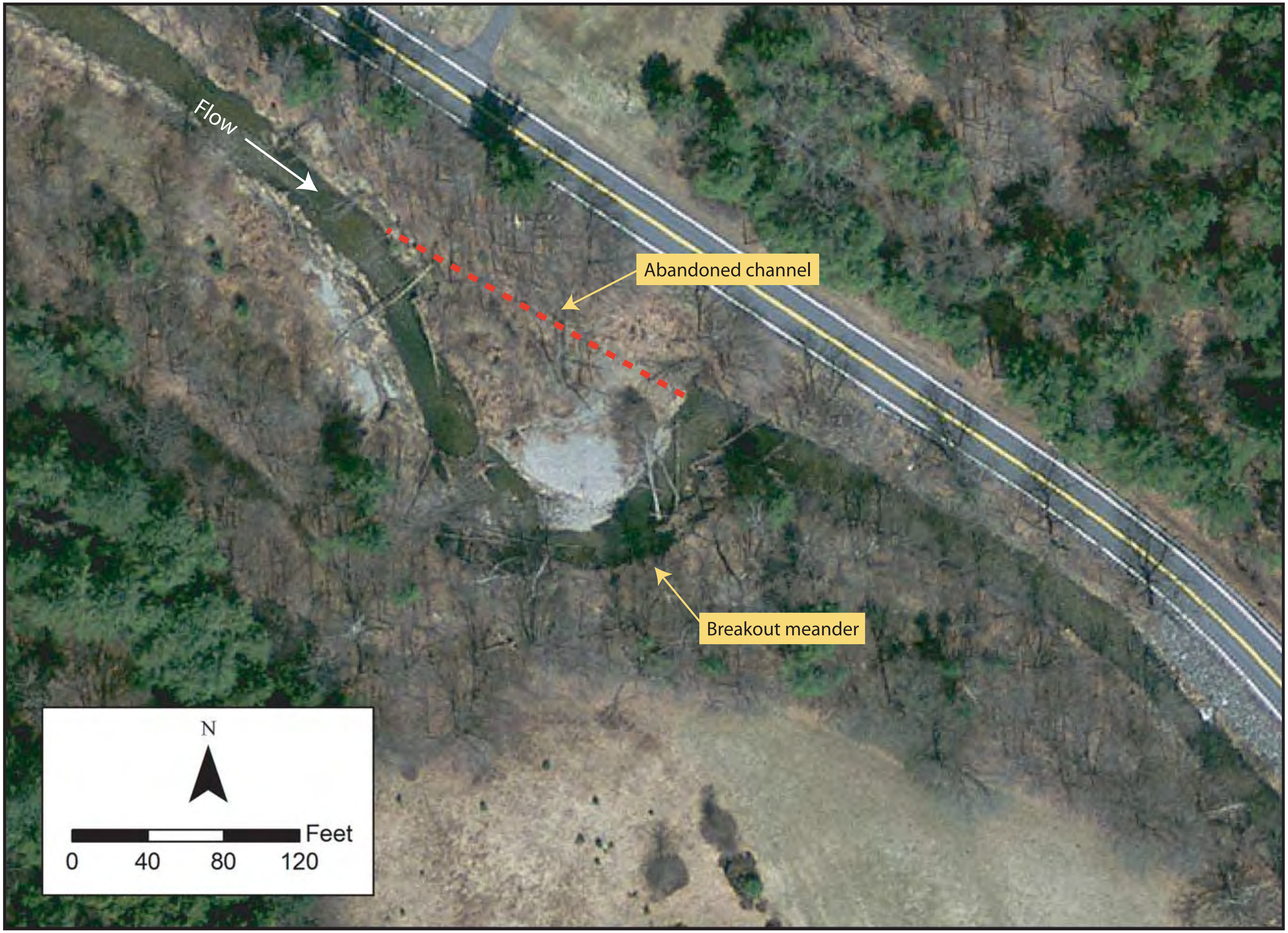


Figure 8. Reformed meander on straightened channel segment of South River.

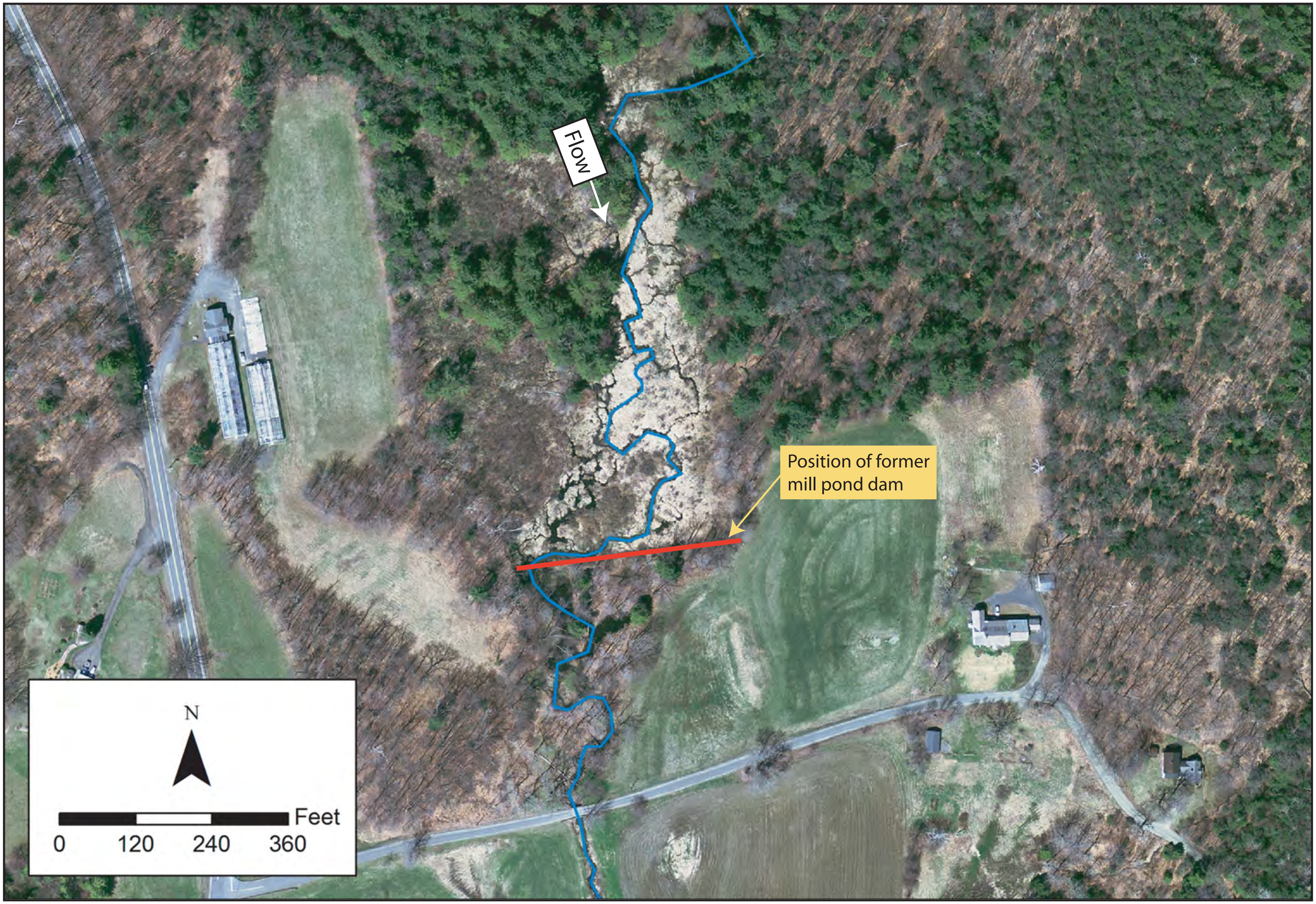


Figure 9. The position of former mill ponds can be identified on aerial photographs by the lighter tones associated with fine-grained impoundment sediments.

Figure 10. Impoundment sediments along an eroding bank exposed by channel incision through a former mill pond.

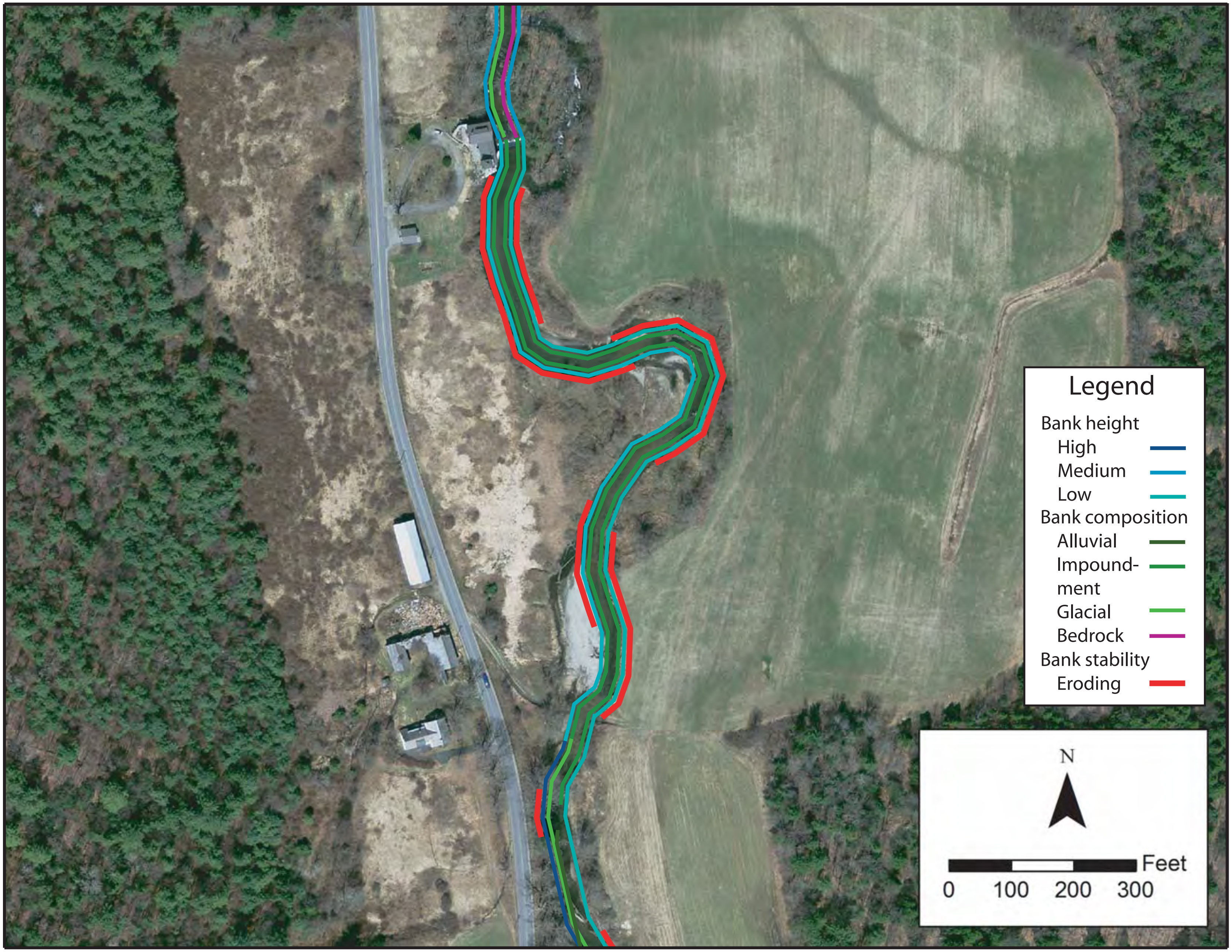


Figure 11. Comparison of bank composition (inner line), height (middle line), and stability (outer line) along a portion of South River.

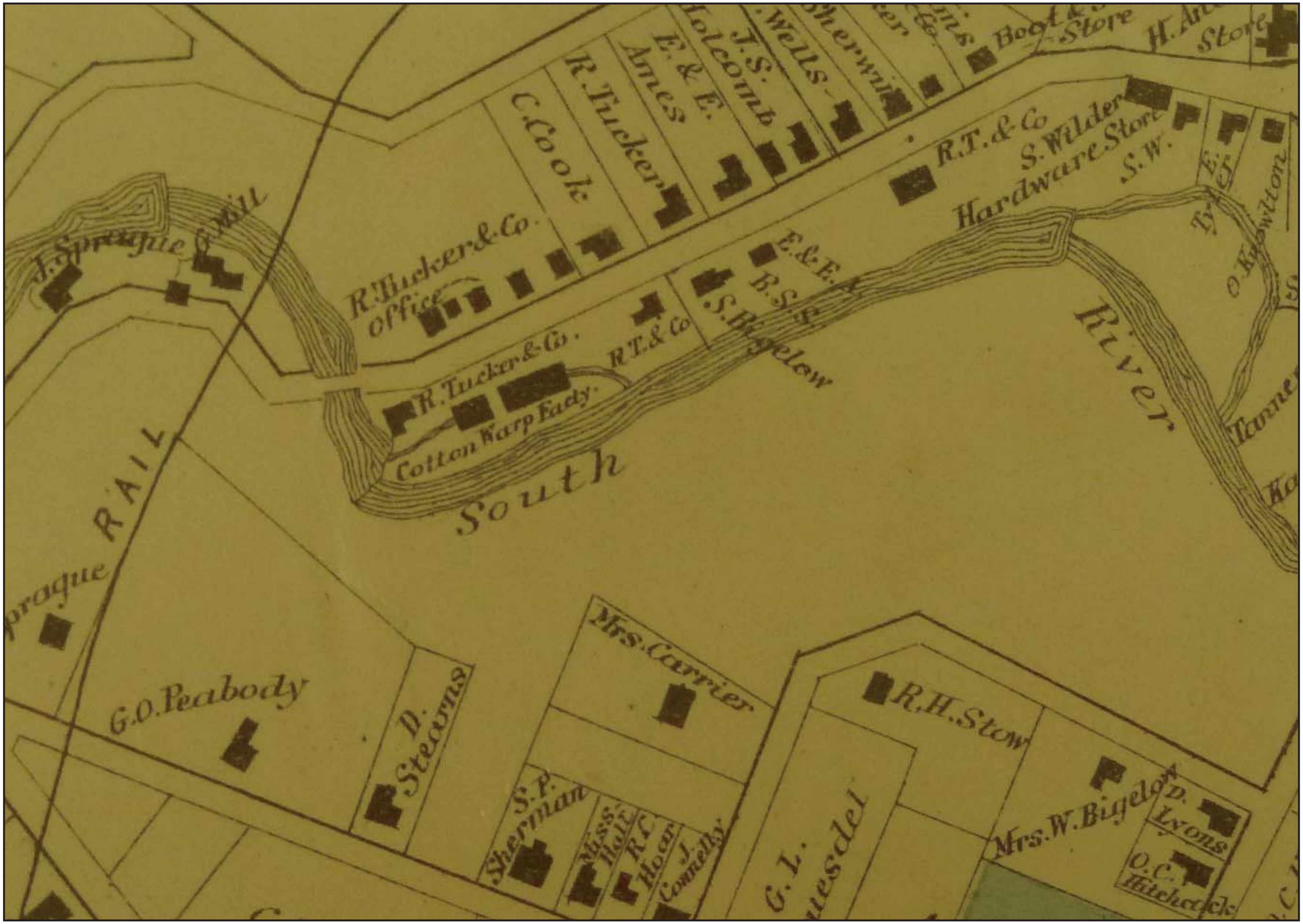


Figure 12. Historical map from 1871 (courtesy of Conway Historical Society) showing location of mill dams on a portion of South River along with other associated channel manipulations such as canals.

a)

b)

Figure 13. Former dams on South River are a) primarily log crib structures while b) the largest existing dam is made of concrete.

Figure 14. Large bars form in the wide shallow channels developed in an impoundment area upstream of an old mill dam that remains intact.

a)

b)

Figure 15. Mass failures on South River introducing a) sediment and b) wood to the channel.

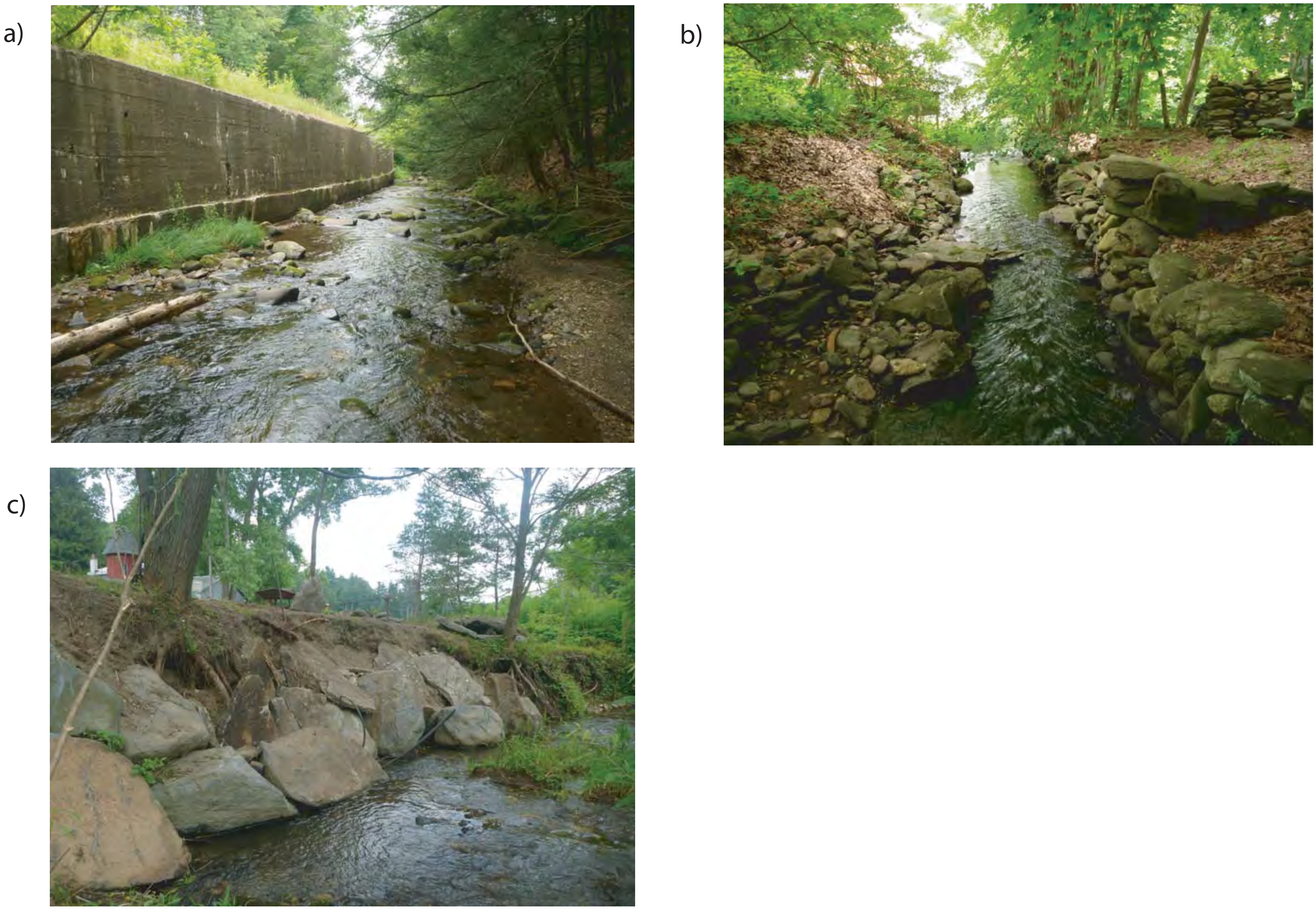
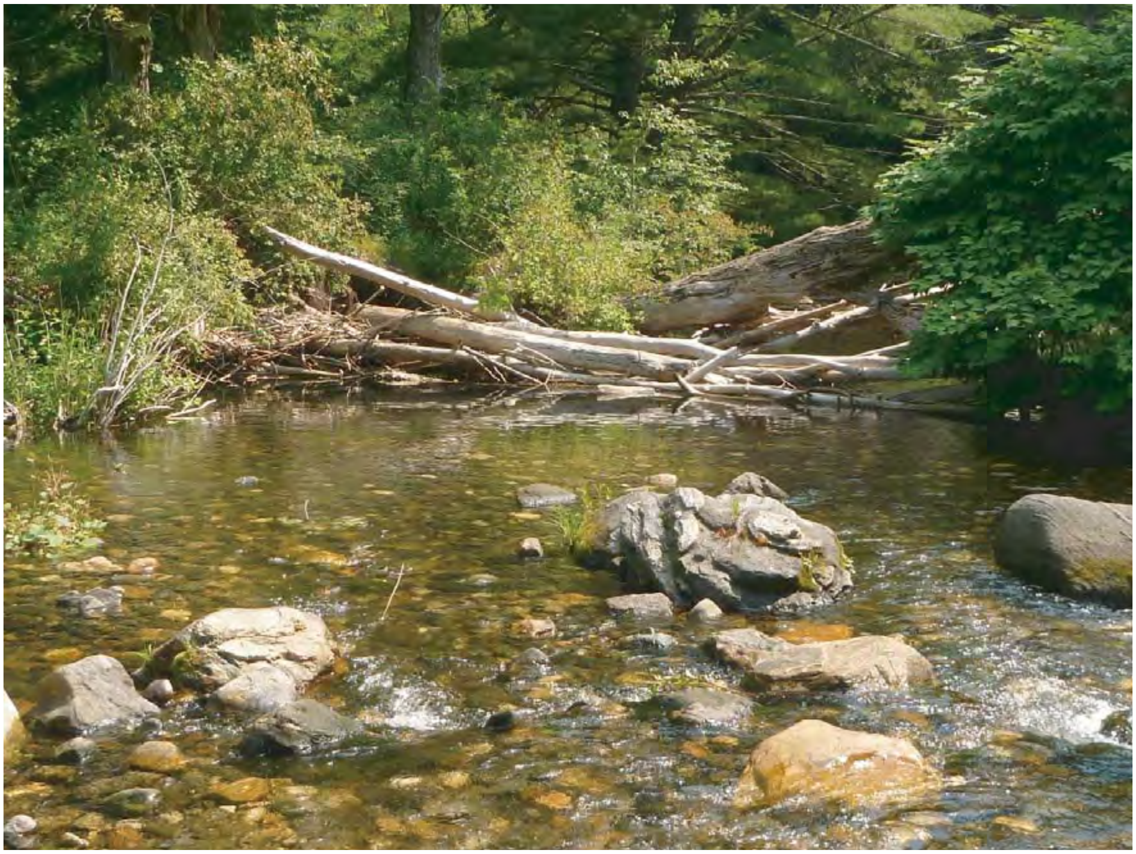


Figure 16. Bank armoring on South River comes in the form of a) concrete retaining walls, b) stacked rock retaining walls and c) rock riprap.

a)



b)

Figure 17. Wood is unevenly distributed on South River with a) large concentrations in short segments of channel and b) long lengths of channel devoid of wood entirely.

Figure 18. Scour undermines a concrete retaining wall on South River in Conway.

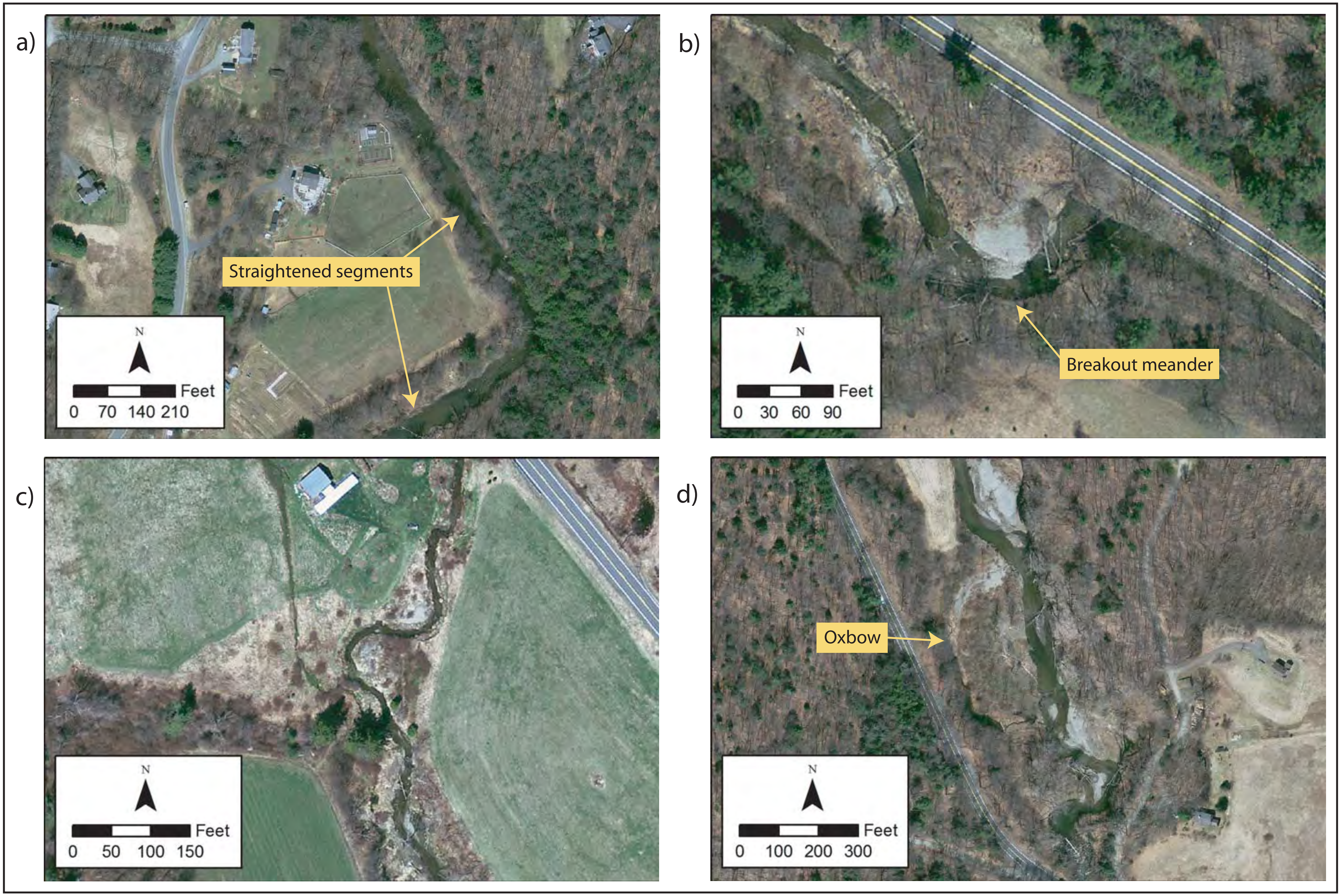


Figure 19. Artificially straightened segments on unconfined channels of South River evolve through several stages from a) straightened segments to b) segments with single bends that reconnect to the straightened channel to c) segments with multiple bends and to finally d) segments with migrating fully reformed meanders where oxbows may develop as meanders are ultimately cutoff.

Figure 20. Berm constructed of large granite blocks cuts off the channel's floodplain access immediately upstream of the Main Street bridge in Conway.

TABLES

Table 1. South River reach characteristics.

Reach	Drainage Area (mi2)	Reach length (ft)	Distance DS (mi)	Channel gradient (%)	Percent Change*	Predicted Channel Width$_{BF}$&	Valley width (ft)	Valley confinement$	Percent Change*	Reason for break†
US end	1.1	-	0.0	-	-	-	-	-	-	D
27	1.3	1674	0.3	1.96	-	13.9	800	57.4	-	VC, LU
26	1.4	3175	0.9	1.82	-7	14.9	330	22.1	-61	VC
25	1.7	2573	1.4	1.36	-25	16.3	190	11.7	-47	DR, P
24	1.8	645	1.5	2.39	75	16.5	200	12.1	4	G, CG
23	1.8	633	1.6	4.67	95	16.6	60	3.6	-70	G, CG
22	1.9	1343	1.9	2.25	-52	17.2	370	21.5	495	US
21	2.1	2103	2.3	0.81	-64	17.8	540	30.3	41	DR, P
20	2.9	7969	3.8	1.00	23	20.8	1000	48.0	58	T, VC
19	7.8	5618	4.9	1.89	89	34.1	230	6.7	-86	VC
18	8.9	5921	6.0	0.97	-49	36.3	600	16.5	145	T, VC
17	16.4	6318	7.2	1.70	76	49.0	260	5.3	-68	VC, CG
16	17.0	4259	8.0	0.68	-60	49.9	600	12.0	127	DR
15	17.7	3613	8.7	0.55	-18	50.9	800	15.7	31	T, LU
14	19.3	2276	9.1	0.88	59	53.1	300	5.7	-64	VC
13	19.4	508	9.2	1.16	32	53.2	170	3.2	-43	G, CG
12	19.4	463	9.3	4.25	266	53.2	100	1.9	-41	G, CG
11	19.5	2153	9.7	2.07	-51	53.3	450	8.4	349	T
10	21.5	4575	10.6	0.73	-65	56.0	700	12.5	48	VC
9	22.2	2888	11.1	0.70	-4	56.8	700	12.3	-2	D
8	23.1	4728	12.0	0.49	-30	57.9	620	10.7	-13	P
7	24.3	5606	13.1	0.43	-13	59.4	370	6.2	-42	CG, VC
6	24.4	1093	13.3	1.98	364	59.5	130	2.2	-65	BR
5	25.4	4897	14.2	1.97	-1	60.7	210	3.5	58	BR
4	25.4	729	14.3	1.67	-15	60.7	100	1.6	-52	CG, VC
3	26.0	2992	14.9	0.44	-74	61.4	200	3.3	98	US
2	26.0	1358	15.2	0.46	5	61.4	310	5.0	55	D
1	26.3	3512	15.8	3.74	714	61.7	90	1.5	-71	-

*Percent change from upstream reach
&Equation from published New Hampshire regional hydraulic geometry curve (REF)
$Valley confinement is the ratio of average valley width to reference channel width (from the regional curve)
†Reason for reach break: D = Existing dam site; DR = Former dam site; CG = channel gradient;
VC = valley confinement; T = major tributary confluence; P = planform; LU = land use;
BR = Bedrock ledge grade control; G = Gorge; US = upstream end impoundment

Table 2. Summary of channel features mapping.

Watershed Statistics						
Drainage area (mi^2)	26.3					
Channel Statistics						
Channel length (ft)	83624					
(miles)	15.8					
Reaches	27					
Segments	94					
	Length (ft)	%				
Artificially straightened	56095	67.1				
Stream Banks						
Bank stability	LB	%	RB	%	Total	%
Erosion	18211	21.8	22861	27.3	41072	24.6
Armored	10536	12.6	5162	6.2	15698	9.4
Bank Height	LB	%	RB	%		
low - (floodplain or leg seds)	42770	51.2	41838	50.0		
med (glacial terrace or leg seds)	24040	28.8	22119	26.5		
high (glacial / bedrock)	16751	20.0	19647	23.5		
	83561		83604	100		
Composition	LB	%	RB	%		
alluvial floodplain	21856	26.2	24425	29.2		
legacy / mill pond seds	24158	28.9	26190	31.3		
glacial sediments	31322	37.5	24339	29.1		
bedrock	6220	7.4	8606	10.3		
	83556	100	83560	100		
Depositional Features						
	LB	%	RB	%	Total	%
Point bars	17167	20.5	14769	17.7	31936	19.1
Side bars	1363	1.6	2101	2.5	3464	2.1
Delta bars	109	0.1	609	0.7	718	0.4
		%				
Mid-channel bars	11154	13.3				
Islands	6594	7.9				
Diagonal bars	683	0.8				
Point Features	Count					
Historic dam site	30					
Bridges (active)	26					
Beaver dams	6					
Mass failures	46					
Avulsions	4					
Oxbows	2					
Flood chutes	3					
Braiding	3					
Deep pool	209					
Debris jams	45					
Large wood (pieces)	1925					

Table 3. Data summary of representative topographic cross sections.

Segment	XS #	Channel $Width_{BF}$ (ft)	Mean $Depth_{BF}$ (ft)	Max $Depth_{BF}$ (ft)	X-S Area (ft^2)	W/D*	Wet P# (ft)	Hyd Rad$ (ft)	D_{50} (mm)	Notes
18D	1	104	2.2	5.4	226	48	107	2.1	2-4 (very fine gravel)	across point bar
17E	1	83	3.3	5.4	271	26	86	3.1	22-32 (coarse gravel)	main channel
11A	1	87	4.7	7.9	408	18	89	4.6	64-90 (small cobble)	berm us of Main St. bridge
10E	1	87	3.6	5.6	309	24	88	3.5	22-32 (coarse gravel)	ds of Main St. bridge
9C	1	82	2.9	4.9	236	29	85	2.8	22-32 (coarse gravel)	mass failure on LB
9B	2	143	2	6.4	286	72	147	1.9	22-32 (coarse gravel)	across mid-channel bar

*W/D = ratio of Channel $Width_{BF}$ to Mean $Depth_{BF}$

#Wet P = wetted perimeter or perimeter of the channel cross section

$Hyd Rad = hydraulic radius; cross sectional area divided by wetted perimeter

.

Table 4. Restoration project concepts.

Project Number	Coordinates	Reach / Segment	Town	Site Description	Project Description	Technical Feasibility	Segment Total Needs Score
1	42°31'40.62" N; 72°47'52.93" W	27C	Ashfield	210 foot long segment in residential village with no riparian buffer, adjacent to town park	Establishment of a riparian buffer through riparian planting of native species	Very high	30
2	42°30'55.57" N; 72°46'45.17" W	20D	Ashfield	Dynamic reach upstream of Village of South Ashfield prone to planform channel change	Corridor protection	High	14
3	42°30'35.40" N; 72°46'21.59" W	20A	Ashfield	Lack of riparian buffer downstream of Burton Hill Rd leading to degraded riparian and instream habitat, sediment loading to downstream	Establish / enhance riparian buffer with riparian plantings and no-mow zones along streambanks, fence livestock out of stream	Very high	31
4	42°30'25.85" N; 72°46'06.35" W	19F	Ashfield	Failing concrete retaining wall along Rt. 116 threatens road	Repair retaining wall, add boulder deflectors for scour protection, install rootwad habitat structures	Completed	24
5	42°30'34.03" N; 72°45'48.63" W	19D	Ashfield	Failing concrete retaining wall along Rt. 116 threatens road, downstream of Bullitt Road	Repair retaining wall, add boulder deflectors for scour protection, install rootwad habitat structures	Completed	30
6	42°30'49.08" N; 72°44'40.77" W	18A	Conway	Highly impaired channel upstream of North Poland Road bridge, agricultural land use	Instream structures paired with possible riparian conservation efforts to improve instream and riparian habitat and reduce downstream sediment loading	High	33
7	42°30'46.39" N; 72°44'32.79" W	17I	Conway	Failing concrete retaining wall along Rt. 116 threatens road, downstream of North Poland Road bridge	Construct new retaining wall, widen channel, build flooplain bench, add boulder deflectors for scour protection, install rootwad habitat structures	Scheduled for 2013-2014	29

Table 4 (continued). Restoration project concepts.

Project Number	Coordinates	Reach / Segment	Town	Site Description	Project Description	Technical Feasibility	Segment Total Needs Score
8	42°30'52.88" N; 72°44'10.03" W	17F-17E	Conway	Channel avulsion during 2005 flood activated large mass failures contributing excess sediment to stream	Restore river to historic channel course through bank cutting/flow diversion and engineered log jam	Moderate	27
9	42°31'12.94" N; 72°43'34.09" W	16C	Conway	Increased sediment transport capacity and flow velocity in straightened channel leading to degraded condition and high hazards	Restore geomorphic function and improve habitat value while lowering erosion hazards through combined instream and floodplain approach	Moderate	31
10	42°30'35.23" N; 72°42'42.94" W	15C	Conway	Increased sediment transport capacity and flow velocity in straightened channel leading to degraded condition	Use instream structures such as boulder deflectors and boulder-wood clusters to improve habitat and geomorphic function	High	36
11	42°30'39.29" N; 72°42'53.74" W	15B-14B	Conway	Degraded channel function in formerly impounded area leading to increased risk to road and ds infrastructure	Bank cutting/flow diversion and instream structures to restore channel complexity and reduce hazards to road and downstream infrastructure	Moderate	32
12	42°30'23.36" N; 72°42'30.58" W	14A	Conway	Straight featureless channel behind the town garage, location upstream of center of village is an asset	Instream structures such as boulder-wood clusters and boulder-supported log jams to increase sediment storage, reduce velocities and improve instream habitat	High	38
13	42°30'30.53" N; 72°41'53.38" W	11A	Conway	Upstream of the Main St Bridge in the Village of Conway; berm blocks access to floodplain and confines stream increasing hazards to adjacent infrastructure	Breach and remove portions of berm and construct weirs to restore floodplain access, increase sediment storage, reduce fluvial erosion risk to infrastructure	High	25
14	42°30'38.82" N; 72°41'42.74" W	10E	Conway	Downstream of the Main St Bridge in the Village of Conway; high sediment load and channel re-meandering represent severe fluvial erosion hazards	Floodplain lowering paired with instream weirs and deflectors to restore floodplain access, decrease velocity, bank erosion and downstream sediment transport, reduce flooding and erosion hazards	High	31

Table 4 (continued). Restoration project concepts.

Project Number	Coordinates	Reach / Segment	Town	Site Description	Project Description	Technical Feasibility	Segment Total Needs Score
15	42˚31'03.77" N; 72˚41'50.74" W	9D	Conway	Degraded channel function in straightened reach leading to increased risk to road and downstream properties	Re-activate abandoned oxbow meander to increase stream sinuosity and decrease sediment transport downstream	Moderate	32
16	42˚31'14.04" N; 72˚41'55.96" W	9C	Conway	Active mass failure threatens Shelburne Falls Road at top of slope	Stabilize mass failure with instream boulder and log deflector structures	High	28
17	42˚31'16.00" N; 72˚41'54.57" W	9B	Conway	Severely eroding bank at the former Harris Farm property, no riparian buffer	Riparian planting and establishment of a no mow zone with or without boulder deflector toe protection	Very high	15
18	42˚31'59.04" N; 72˚41'58.72" W	8A-7E	Conway	Extremely dynamic channel segments and tight meander breaking out of unstable straightened condition, very high erosion hazards	Bank cutting/flow diversion and instream structures to encourage re-alignment of channel to promote more stable geometry, limit erosion hazards	High	24
19	42˚32'30.95" N; 72˚41'37.64" W	7B-7A	Conway	Straightened channel incised into legacy sediments near lower Reeds Bridge, easy access and limited infrastructure	Alternating boulder-supported log jams to encourage meandering, increase flow complexity and provide sediment storage	High	33
20	N/A	Watershed	Ashfield and Conway	Japanese knotweed is primarily spread in floods like last year's TS Irene	Grassroots effort to eradicate invasive japanese knotweed using volunteers	Very high	N/A

Table 4 (continued). Restoration project concepts.

Project Number	Benefits	Stakeholders / Status	Costs	Next Steps	Photo
1	Improve riparian and aquatic habitat, increase canopy, reduce bank erosion	Town of Ashfield, landowner	$1K to $10K	Contact landowner	
2	Reduce potential losses through erosion hazards, provide sediment storage, moderate peak flows, reduce stress on downstream reaches	Town of Ashfield, landowner	Depends on value of land	Contact landowner	
3	Improve riparian and aquatic habitat, increase canopy, reduce bank erosion	Town of Ashfield, landowner / landowner receptive to idea	$15K to $25K	Follow-up with landowner	
4	Increase bank stability, reduce threat to Rt. 116, improve pool habitat, provide cover for fish, improve flow condtions and sediment sorting	Mass DOT / Project completed	Completed	Project monitoring	
5	Increase bank stability, reduce threat to Rt. 116, improve pool habitat, provide cover for fish, improve flow condtions and sediment sorting	Mass DOT / Project completed	Completed	Project monitoring	
6	Improving habitat quality could allow migrating fish and animals to pass through this degraded segment	Town of Conway, landowner	$50K to $250K	Contact landowner	
7	Reduce threat to Rt. 116, create floodplain storage, reduce velocities and sediment transport through reach, improve aquatic habitat	Mass DOT / Project scheduled for 2013-2014	Scheduled for 2013-2014	Final design and permitting	

Table 4 (continued). Restoration project concepts.

Project Number	Benefits	Stakeholders / Status	Costs	Next Steps	Photo
8	Reduce sediment loading to stream, stabilize slope, increase stream sinuosity	Town of Conway, landowner	$180K to $250K	Contact landowner	
9	Increase floodplain connection, reduce velocities and sediment transport through reach, lower erosion hazards	Town of Conway, landowner	$150K to $300K	Contact landowners to gauge interest, brainstorm	
10	Improve aquatic habitat, encourage meandering, increase sediment storage	Town of Conway, landowner	$80K to $120K	Contact landowner	
11	Reduce potential losses through erosion hazards, increase sediment storage, reduce sediment transport to ds reaches, lower flow velocities	Town of Conway, landowner	$180K to $250K	Contact landowner	
12	Increase sediment storage, reduce sediment transport to ds reaches, lower flow velocities, improve aquatic habitat	Town of Conway, landowner	$150K to $300K	Contact landowner	
13	Reduce potential losses through erosion hazards, provide sediment storage, moderate peak flows, reduce stress on downstream reaches	private landowners, Town of Conway, conceptual design and cost estimates completed	$254 K	Landowner permission, purchase land or easement	
14	Reduce potential losses through erosion hazards, provide sediment storage, moderate peak flows, reduce stress on downstream reaches	private landowners, Town of Conway, design completed and funding in place	$243 K	Vote by Conway residents to approve matching grant funds	

Table 4 (continued). Restoration project concepts.

Project Number	Benefits	Stakeholders / Status	Costs	Next Steps	Photo
15	Increase stream sinuosity, decrease hazard to Shelburne Falls Road, reduce sediment loading to stream	Town of Conway, landowner	$180K to $250K	Contact landowners to gauge interest	
16	Reduce imminent threat to major road, reduce sediment loading to stream thereby reducing pressure on eroding banks downstream	Town of Conway, Highway department, landowner	$175K to $200K	Contact town highway department	
17	Increase bank stability, protect agricultural land, improve riparian and aquatic habitat through establishment of riparian buffer and canopy	Town of Conway, landowner, farmer	$40K to $175K	Contact farmer and landowner	
18	Reduce potential losses through erosion hazards, provide sediment storage, protect agricultural land, reduce flood peaks	Town of Conway, landowner, farmer	$180K to $300K	Contact farmer and landowner	
19	Improve aquatic habitat, increase sediment storage, decrease flow velocities	Town of Conway, landowner	$250K to $300K	Contact landowner	
20	Eradicating knotweed or llimiting its spread will improve and protect the integrity and quality of the riparian zone, increase bank stability, protect native plant species	Towns of Ashfield and Conway, Friends of the South River, landowners	Low to no cost	Public outreach, organize volunteer labor	

APPENDIX 1

(GIS shapefiles – see attached CD)

APPENDIX 2

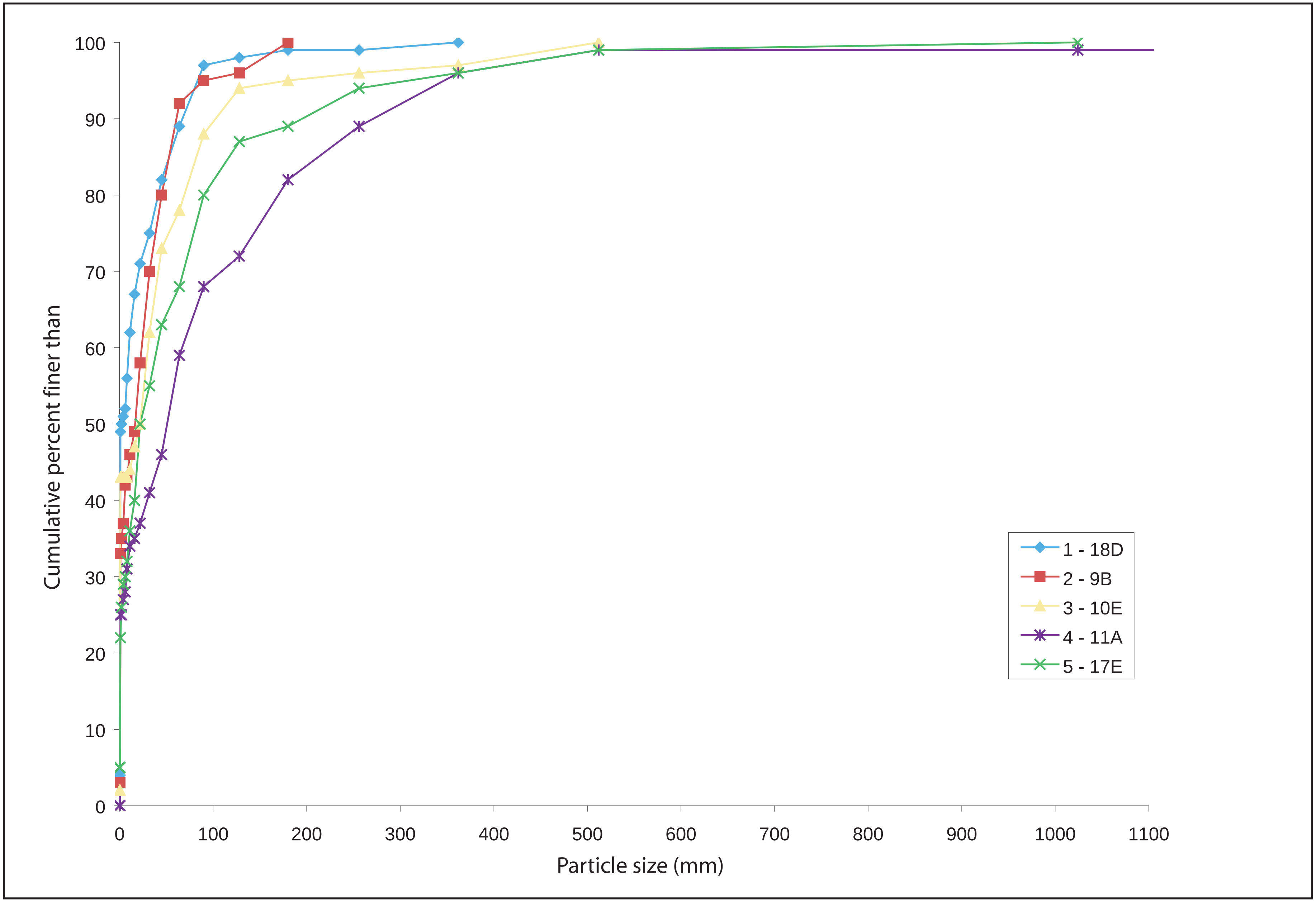
(Historical maps, aerial photographs and topographic maps – see attached CD)

APPENDIX 3

(Topographic survey data – see attached CD)

APPENDIX 4

(Substrate particle size data)



Appendix 4. Substrate particle size data.

APPENDIX 5

(Description of channel types)

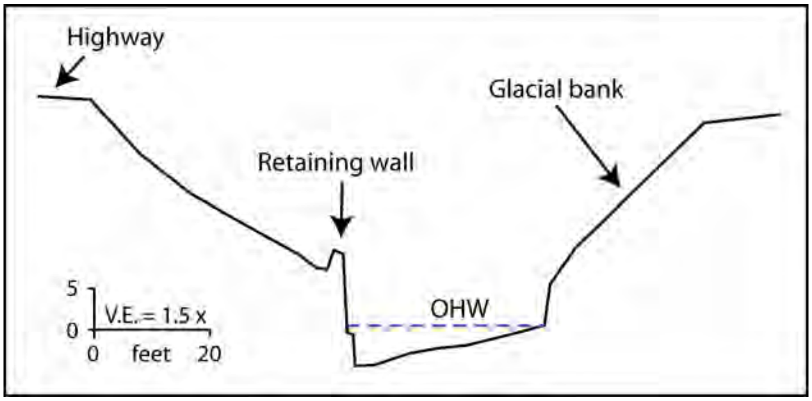
South River Channel Types – Confined Channels

Physical condition
- Single channel
- Limited gravel bars
- Very limited sinuosity
- High gradient/energy
- Confined by high banks
- Poorly formed boulder steps
- Occasional narrow floodplain bench
- Rosgen B and F stream type

Habitat Features
- Shallow pocket pools by boulders
- Mature riparian zone vegetation
- Poor particle size segregation

Restoration Proscriptions
- Boulder clusters
- Rock weirs w/ pool excavation
- Engineered log jams

Cross section



Ground photos

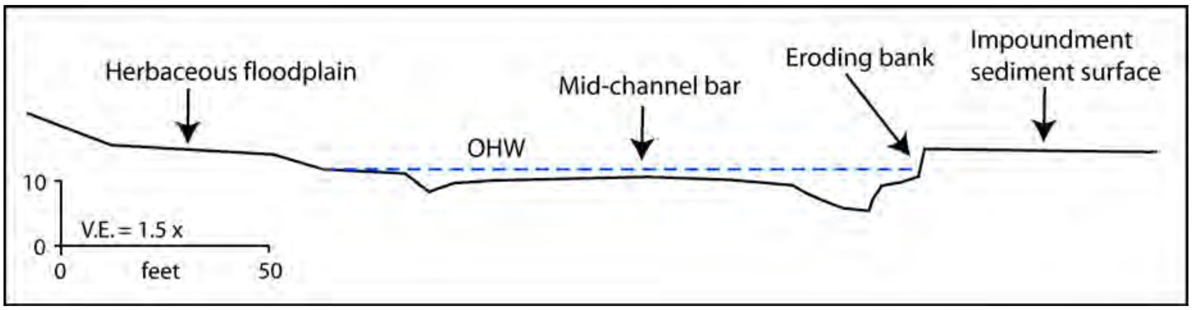
South River Channel Types – Channels within Impounded Areas

Physical condition
- Multiple channels
- Large mid-channel & point bars
- Moderate to high sinuosity
- Low gradient/energy
- Fair to well formed pools/riffles
- High channel migration rates
- Unconfined unless incised upstream of remnant dam
- Bank erosion on cutbanks and through channel widening following incision
- Rosgen C and E stream type when unconfined; Rosgen G and F when incised
- Stage III-IV channel evolution
- Several feet of fine grained bank material deposited behind mill dams
- Incision of impoundment sediments leads to downstream sediment loading issues

Habitat Features
- Deep pools along cut banks
- Poor riparian zone vegetation
- Good particle size segregation
- Excellent channel complexity where not incised

Restoration Proscriptions
- Deflectors to turn water away from bars & create meanders
- Wood additions on bars
- Log jams to divert flow to side channels
- Bioengineering of eroding banks to protect road/create bank cover
- Riparian zone improvements
- Remove impoundment sediments to broaden wetland areas

Cross section



Ground photos

South River Channel Types – Unconfined Channels

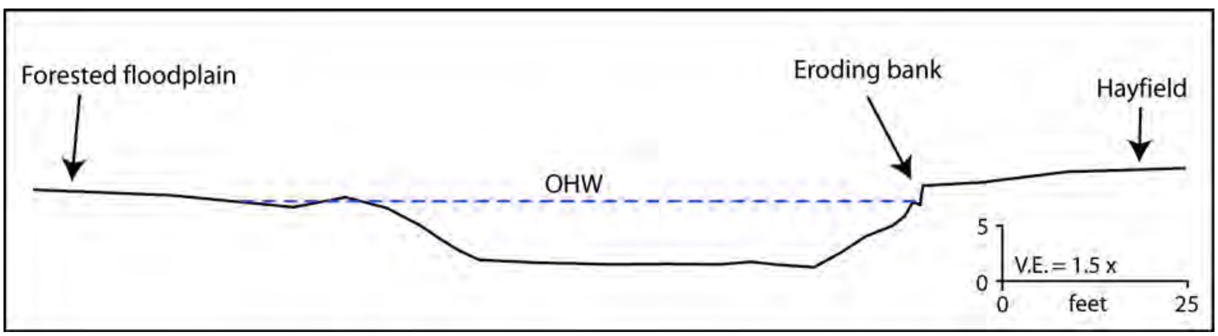
Physical condition
- Multiple channels w/ one dominant
- Small to large mid-channel bars
- Low to high sinuosity
- Occasional confinement by berms
- Fair to well formed pools/riffles
- Plane bed morphology in straightened channels
- Stage III-IV channel evolution
- Rosgen C and F stream type
- Meanders reforming

Habitat Features
- Shallow to deep pools on cutbanks
- Floodplain relief
- Poor to mature riparian zone vegetation
- Particle size segregation in meanders

Restoration Proscriptions
- Log jams to divert flow to side channels
- Wood additions on bars & in channel
- Log jams in pool areas for cover
- Breach berms
- Deflectors to turn water away from eroding banks near infrastructure

Channel Sub-Types
* Straightened channel
    - Bar formation leads to meanders as opposite bank scoured w/ severe deposition leading to breakouts
    - Adjacent side channels and wetland complexes in position of abandoned channels
* Breakout meanders
    - Straightened channel abandoned as new meander with high sinuosity scoured over floodplain
    - Point bars developed on inside of meander bend
    - Increased stream length decreases flow energy

Cross section



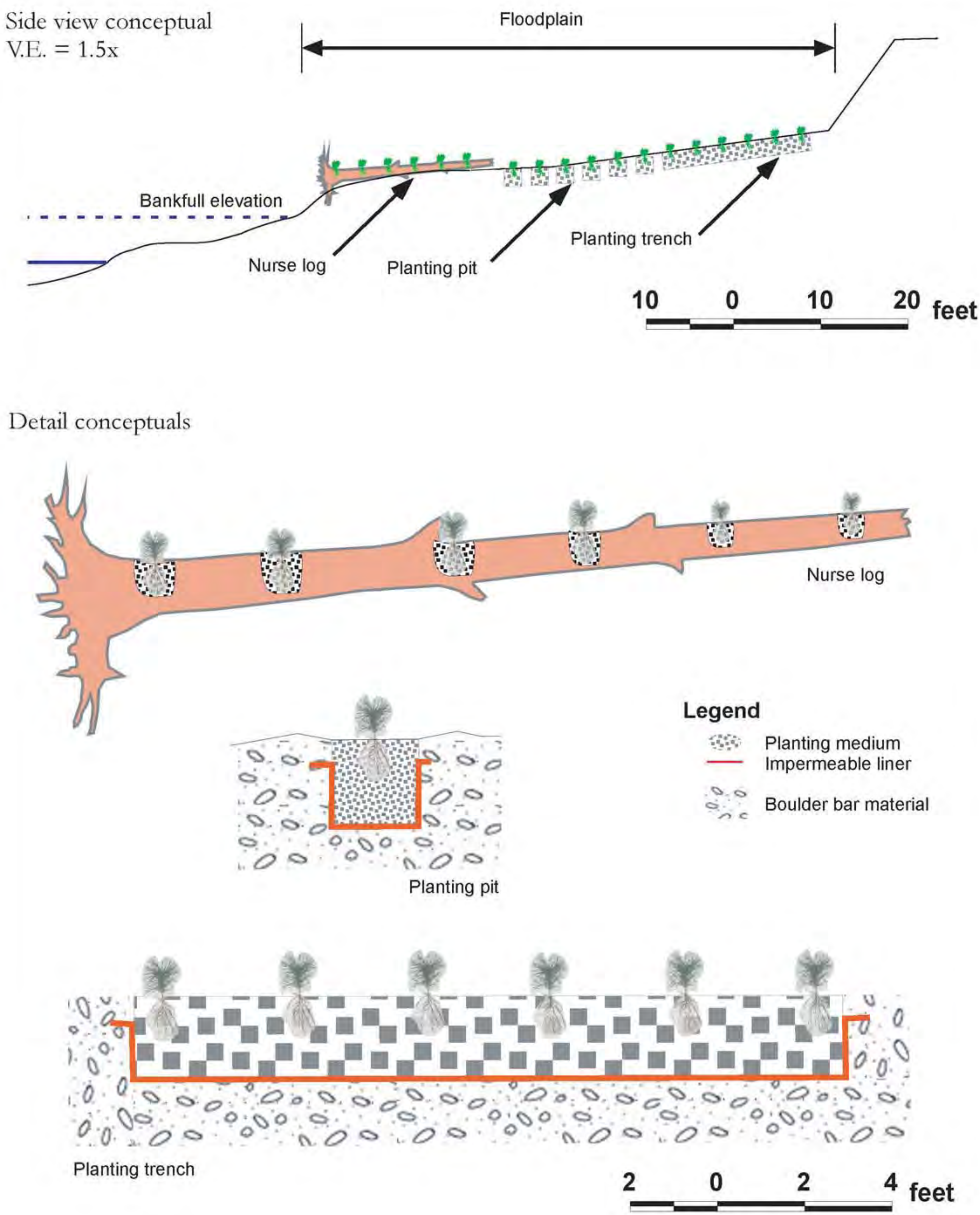
Ground photos

APPENDIX 6

(Restoration prioritization – see attached CD)

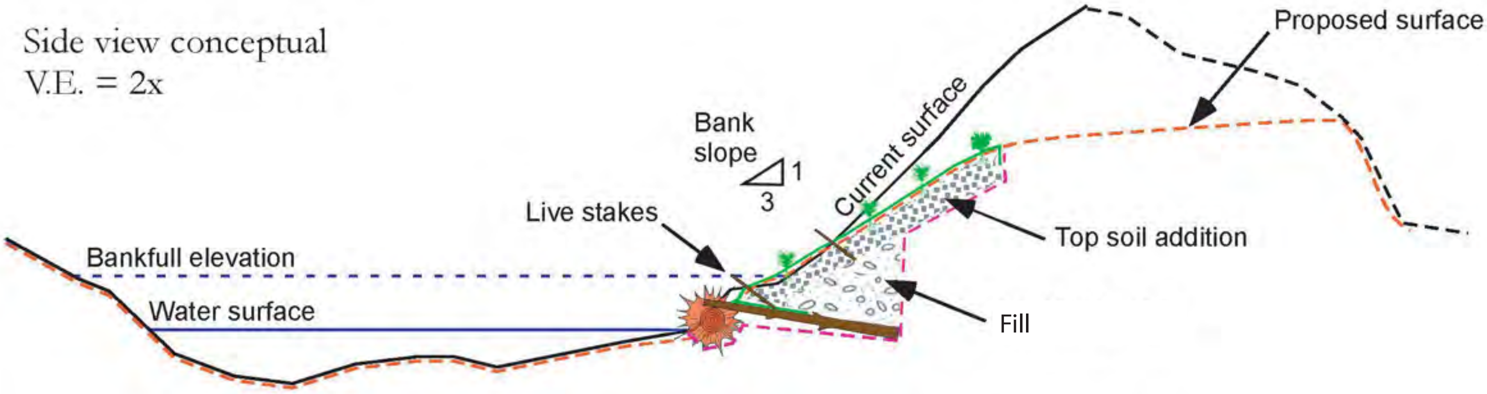
APPENDIX 7

(Design typicals of restoration options)



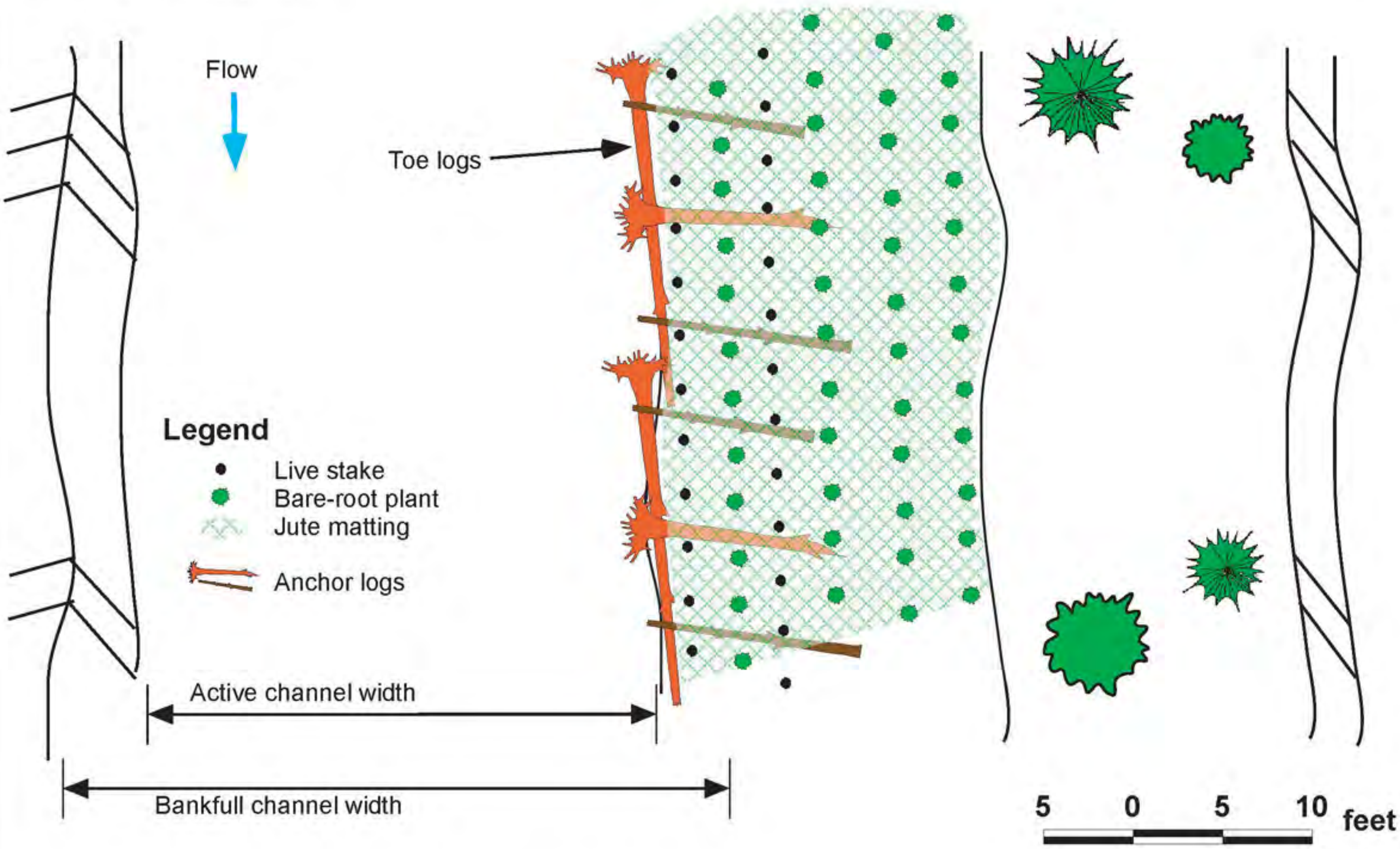
Treatment: Riparian improvements

Side view conceptual
V.E. = 2x

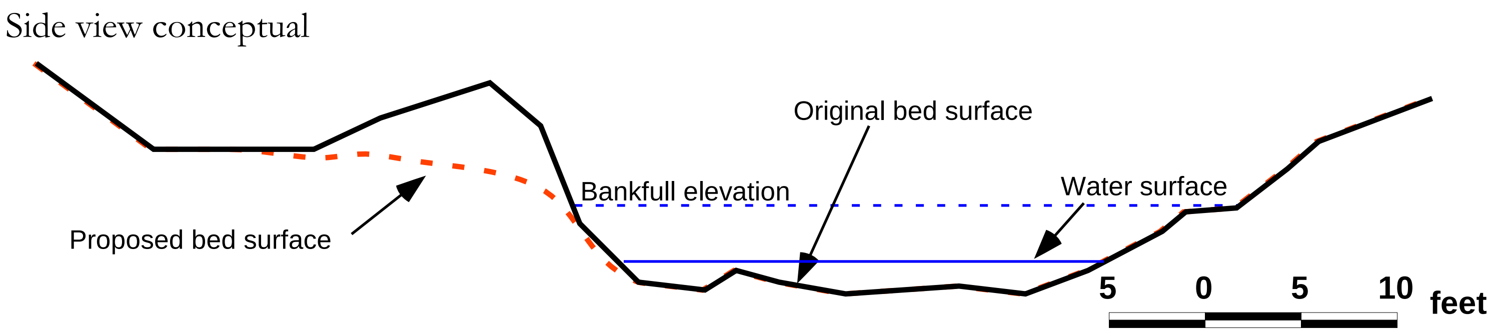


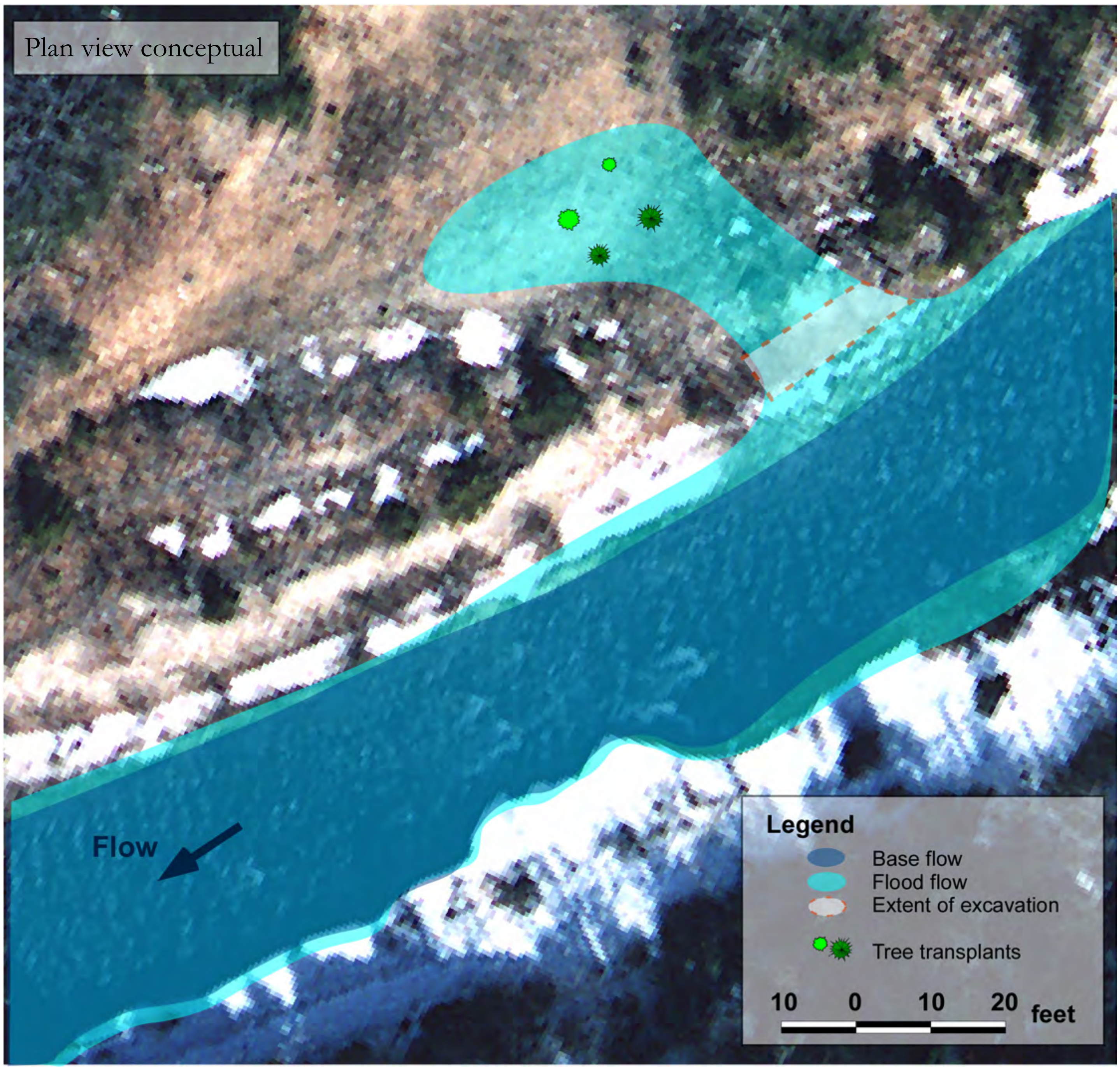
Length of bank treatment (ft)	Original bank slope ___:1	New bank slope	Total excavation (cyds)	Top soil amendment (cyds)	No. of toe logs	No. of anchor logs
100	1	2 : 1	287	234	6	18
100	2	3 : 1	177	234	6	18
200	1	2 : 1	573	234	13	39
200	2	3 : 1	354	234	13	39
300	1	2 : 1	860	234	19	57
300	2	3 : 1	531	234	19	57

Plan view conceptual



Treatment: Bank bioengineering

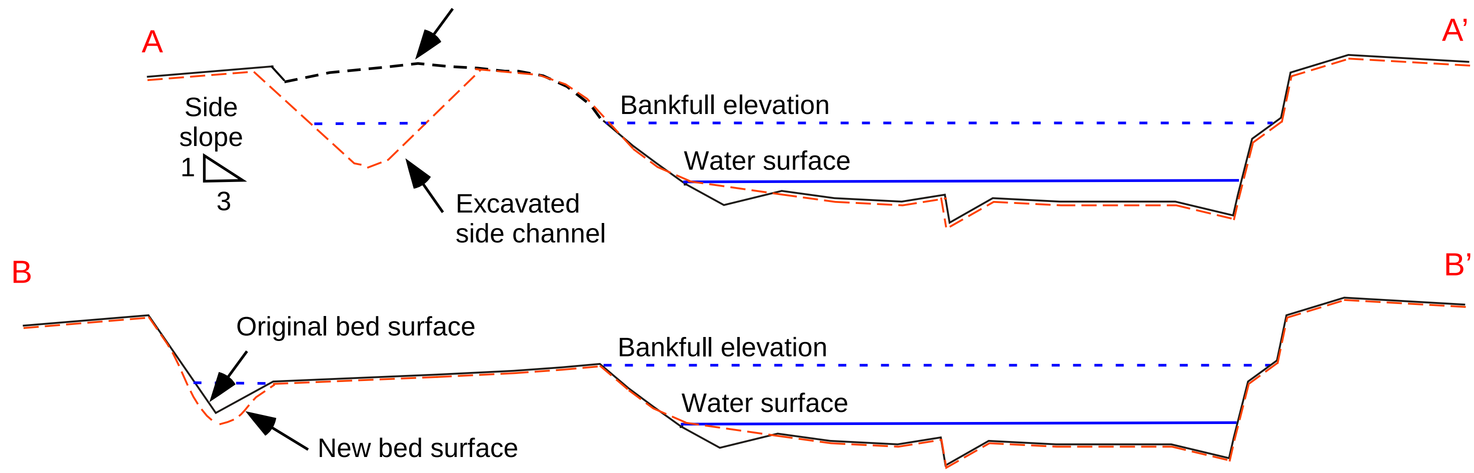




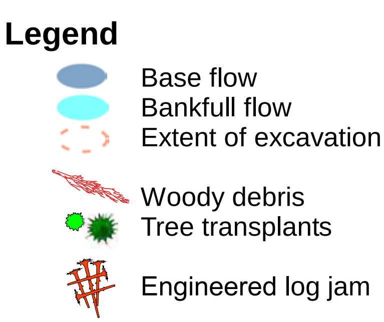
Treatment: Breach or remove berm

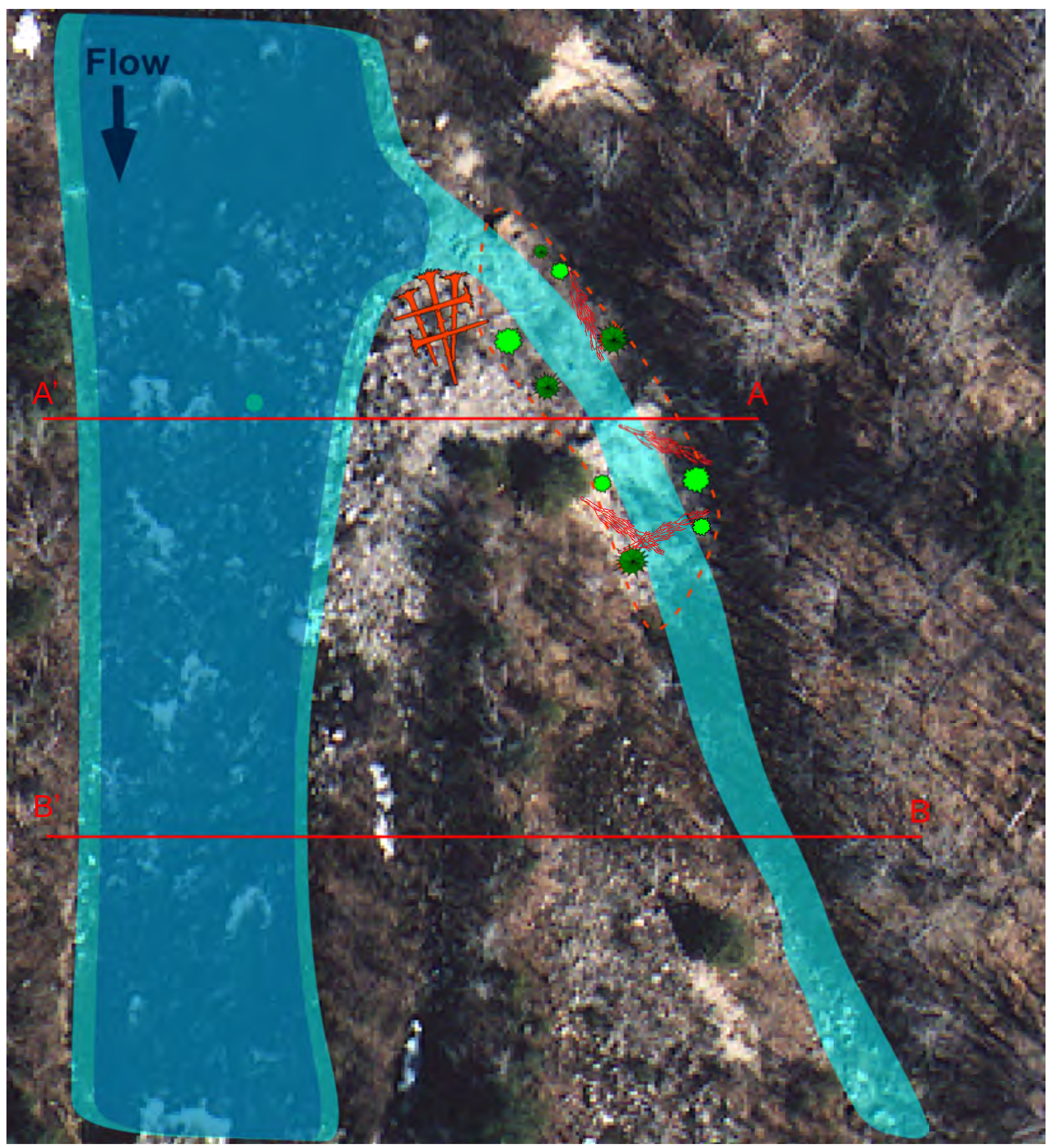
Field Geology Services
Fluvial Geomorphology

Side view conceptuals
1" = 20 ft, V.E. = 2x



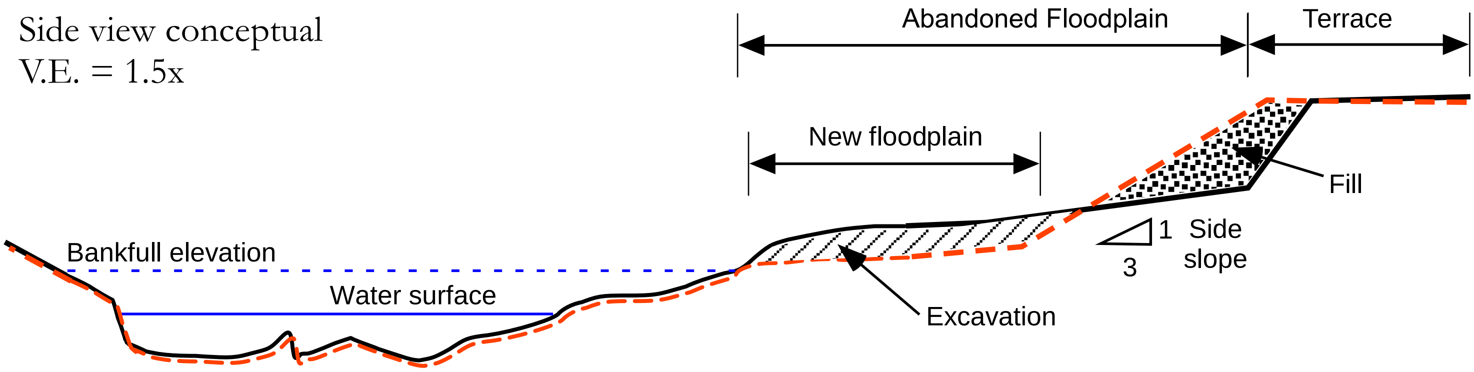
Plan view conceptual
1" = 40 ft





Treatment: Bank cutting / Flow diversion

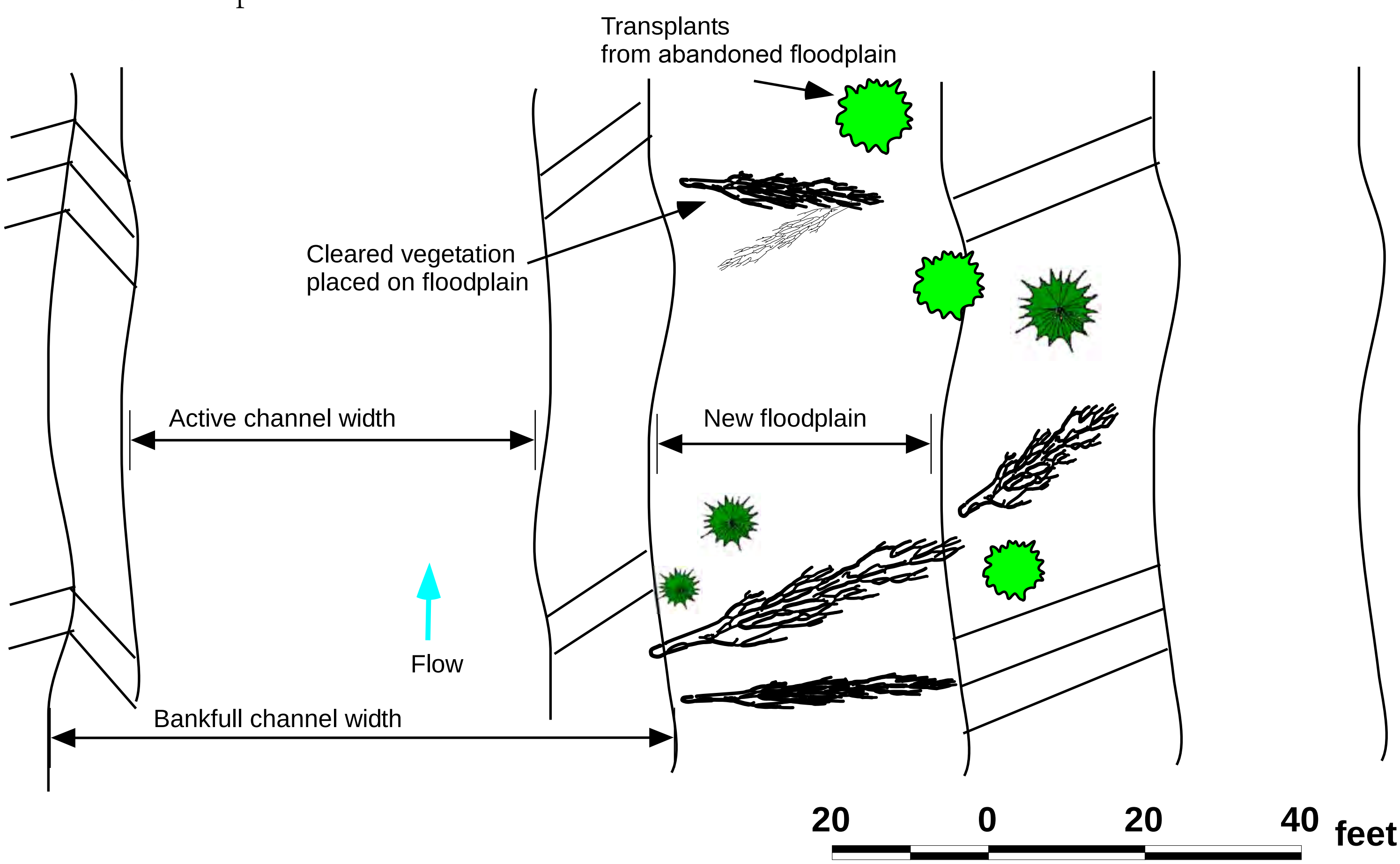
Side view conceptual
V.E. = 1.5x



Example dimensions

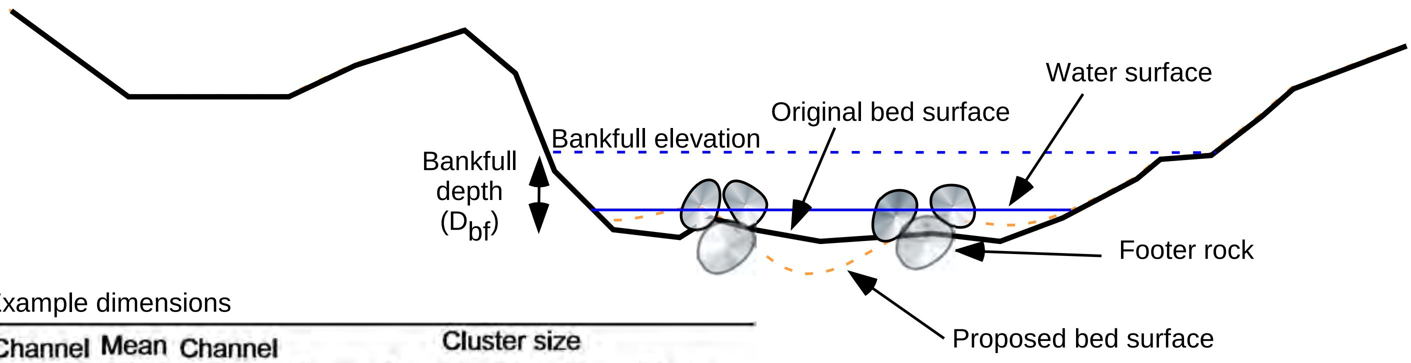
Mean height of boulder bar (ft)	Width of new floodplain (ft)	Terrace side slope	Excavation per unit length (cyds)	Excavation of 200' bar (cyds)	Excavation of 500' bar (cyds)
2	20	3 : 1	1.7	341	852
4	20	1 : 1	3.3	652	1630
2	30	3 : 1	2.4	489	1222
4	30	1 : 1	4.7	948	2370
2	40	3 : 1	3.2	637	1593
4	40	1 : 1	6.2	1244	3111

Plan view conceptual



Treatment: Floodplain lowering

Side view conceptual

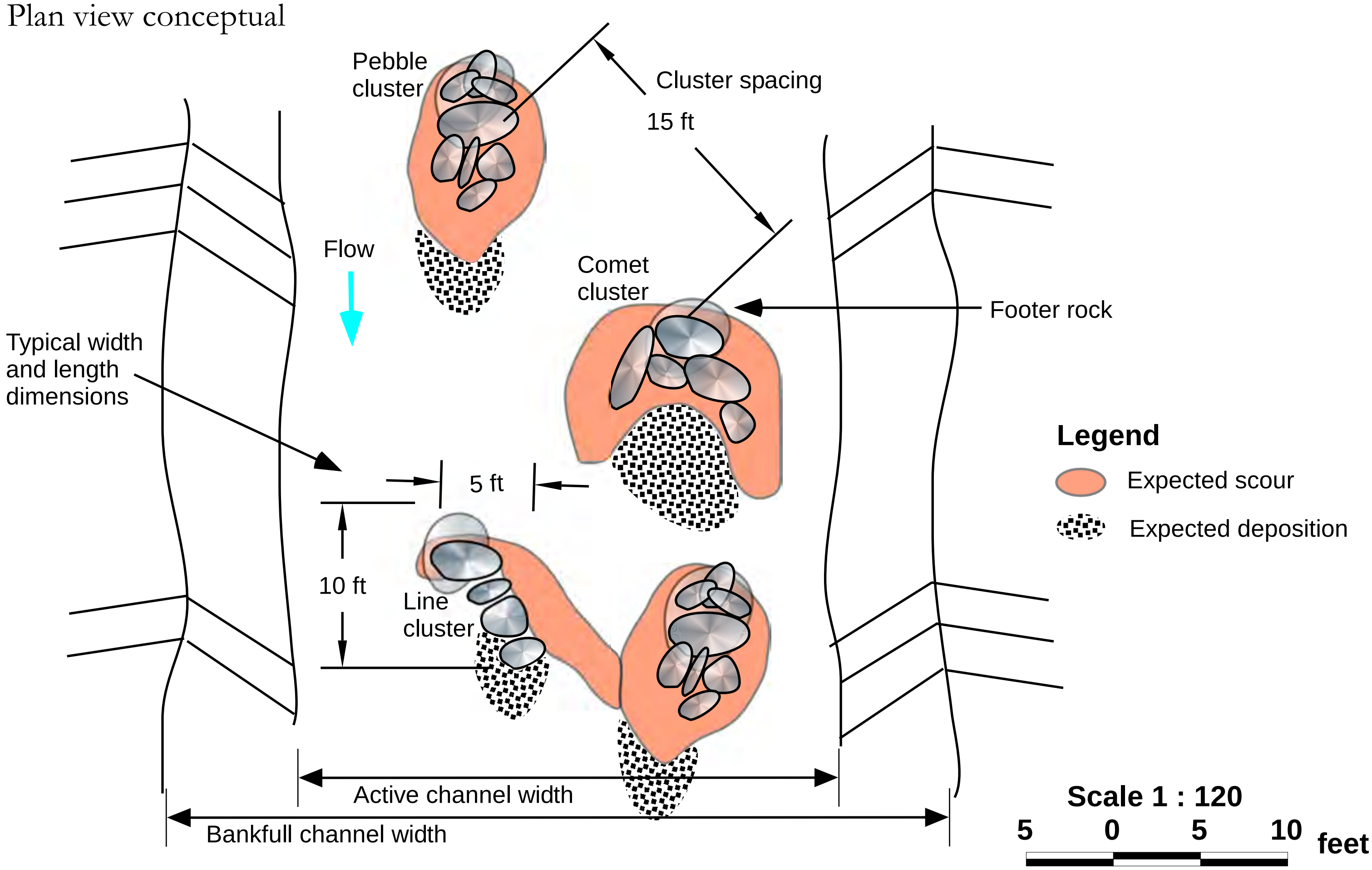


Example dimensions

Channel slope (%)	Mean D_{bf} (ft)	Channel width (ft)	d_{footer} (ft)	d_{key} (ft)	Cluster size length (ft)	Cluster size width (ft)	Cluster spacing (ft)
1.5%	2	40	3	2.5	10	5	15 - 80
1.5%	3	60	3.5	3	12	6	18 - 120
1.5%	4	80	4	3.5	14	7	21 - 160
3.5%	2	40	3.5	2.5	10	5	6 - 80
3.5%	3	60	4	3	12	6	8 - 120
3.5%	4	80	4.5	3.5	14	7	9 - 160

*Note: Cluster dimensions and spacing are averages and shall vary by several feet.

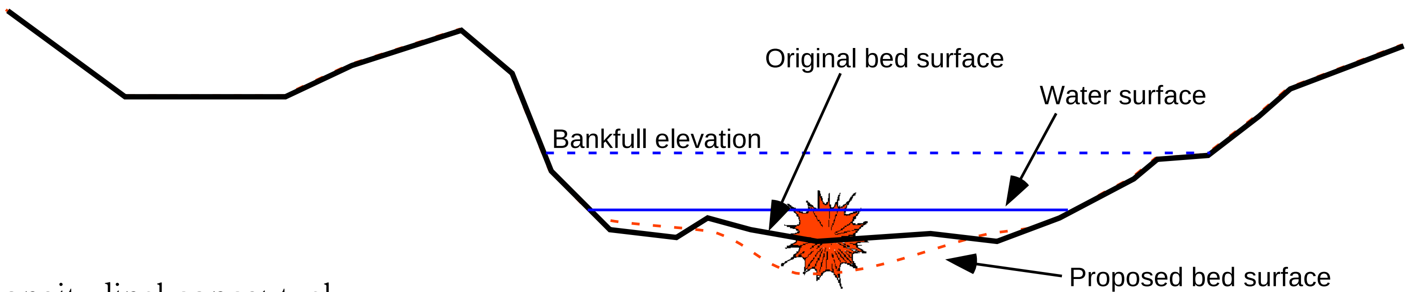
Plan view conceptual



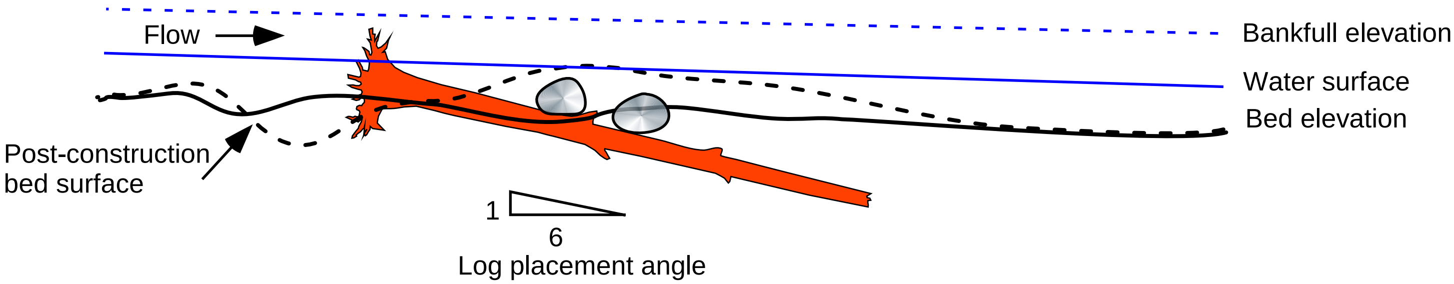
Treatment: Boulder clusters

Field Geology Services
Fluvial Geomorphology

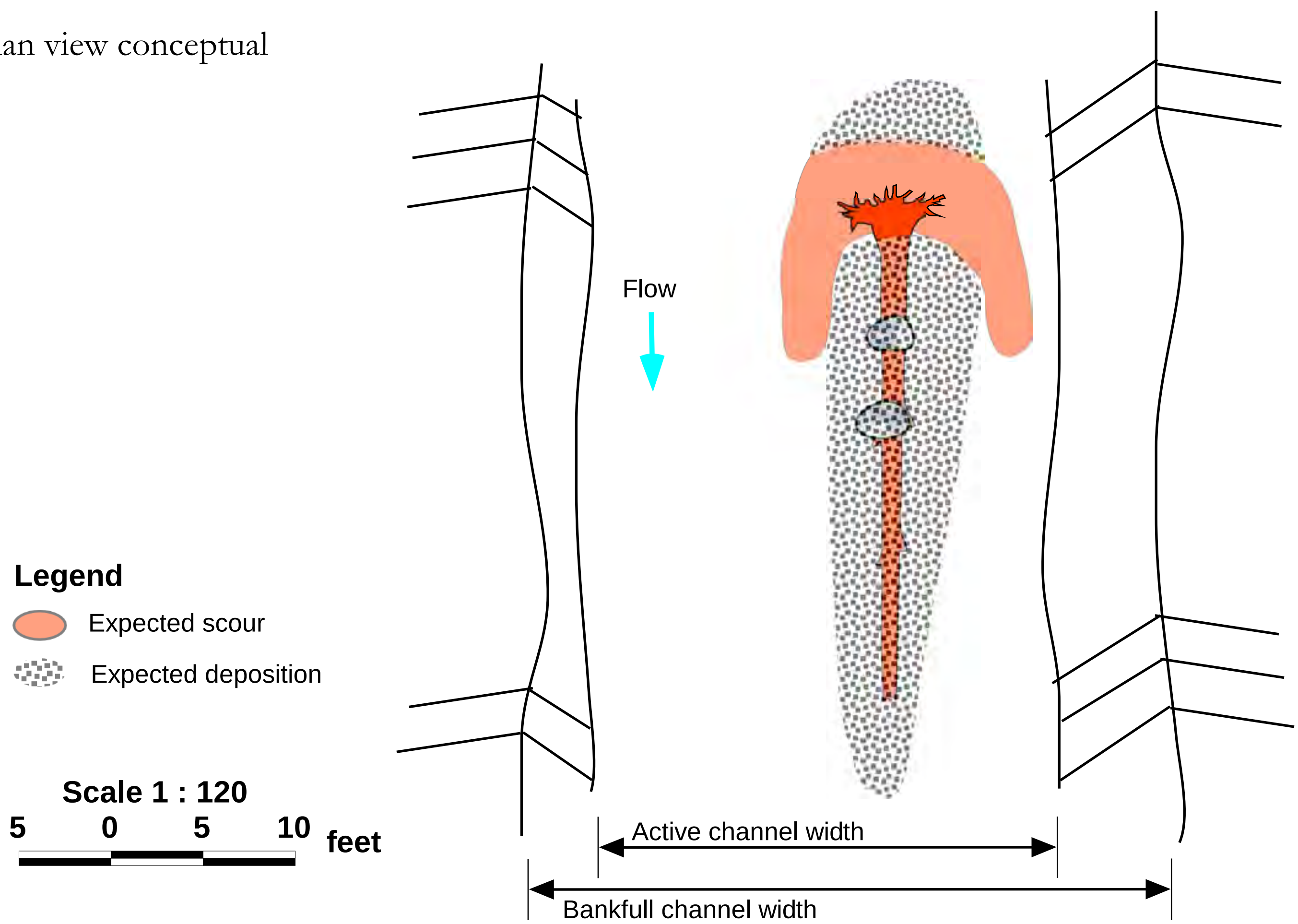
Side view conceptual



Longitudinal conceptual

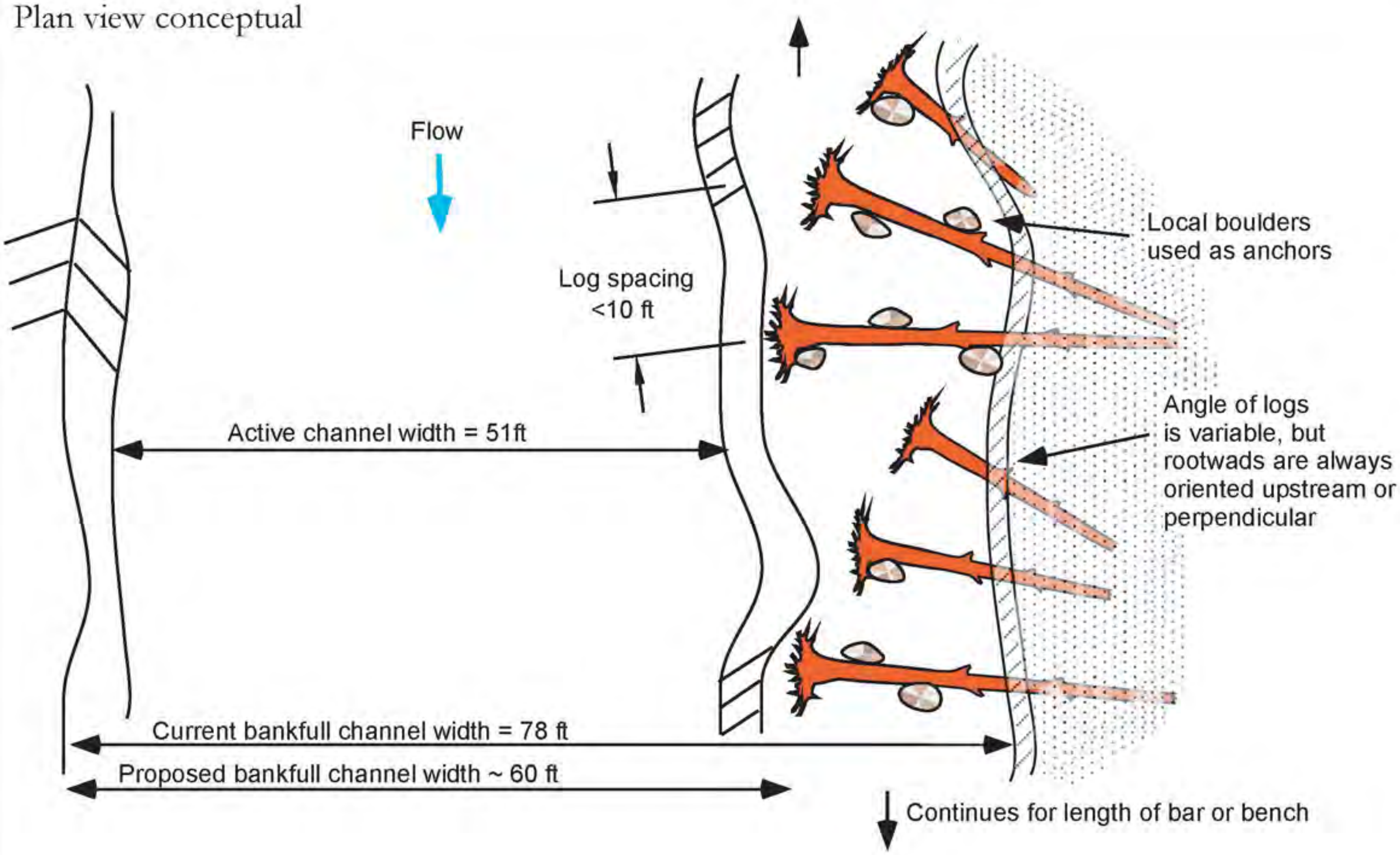


Plan view conceptual

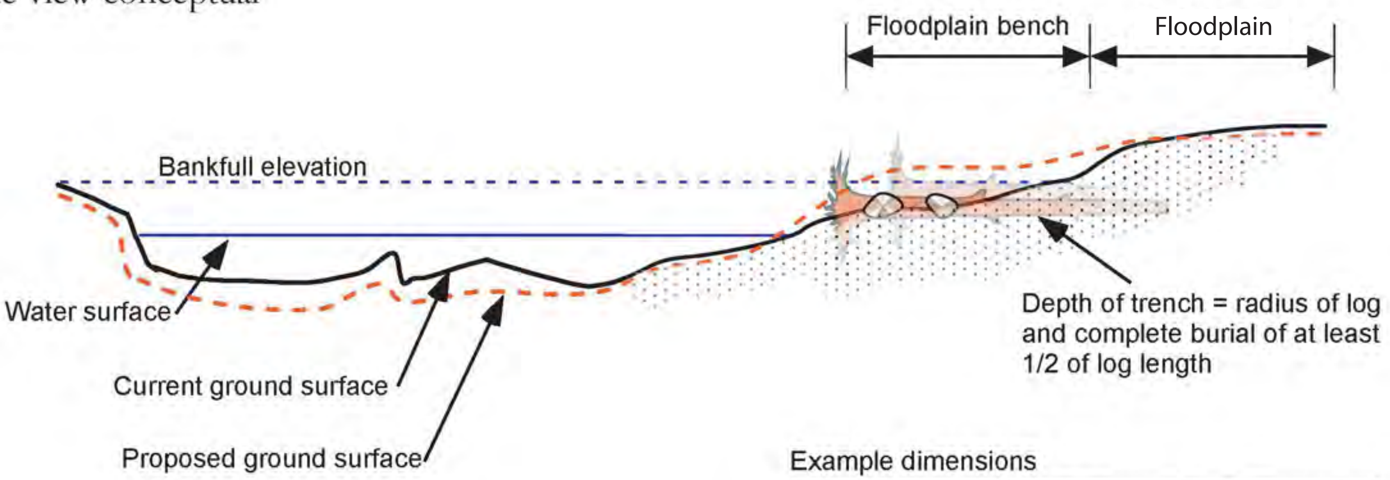


Treatment: Placed wood in channel

Plan view conceptual



Side view conceptual



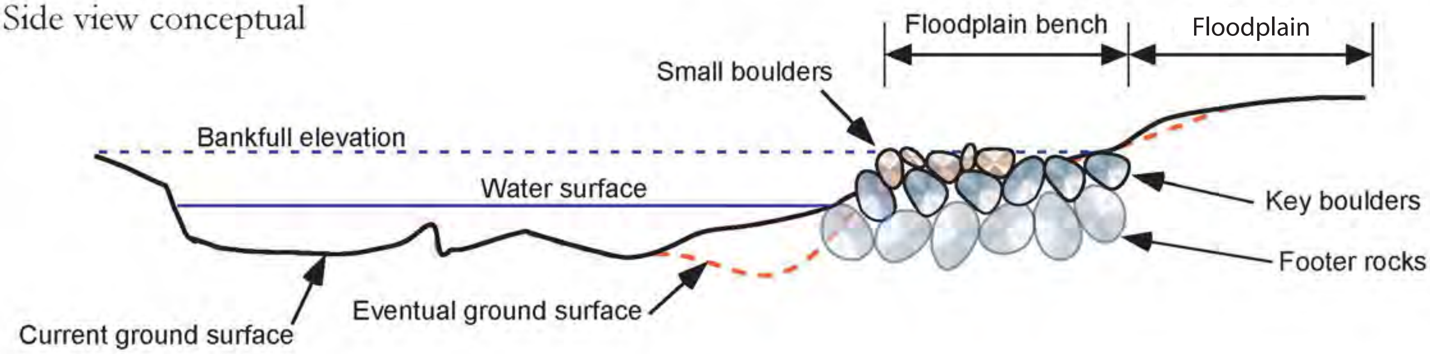
10 0 10 20 feet

Example dimensions

Log diameter (in)	Log length (ft)	Burial length (ft)	Trench depth (in)	Bank height (ft)	Excavation per log (cyds)
10	10	5	5	2	0.7
10	10	5	5	4	1.4
15	20	10	8	2	1.7
15	20	10	8	4	3.3
20	30	15	10	3	4.4
20	30	15	10	5	7.4

Treatment: Placed wood on bar

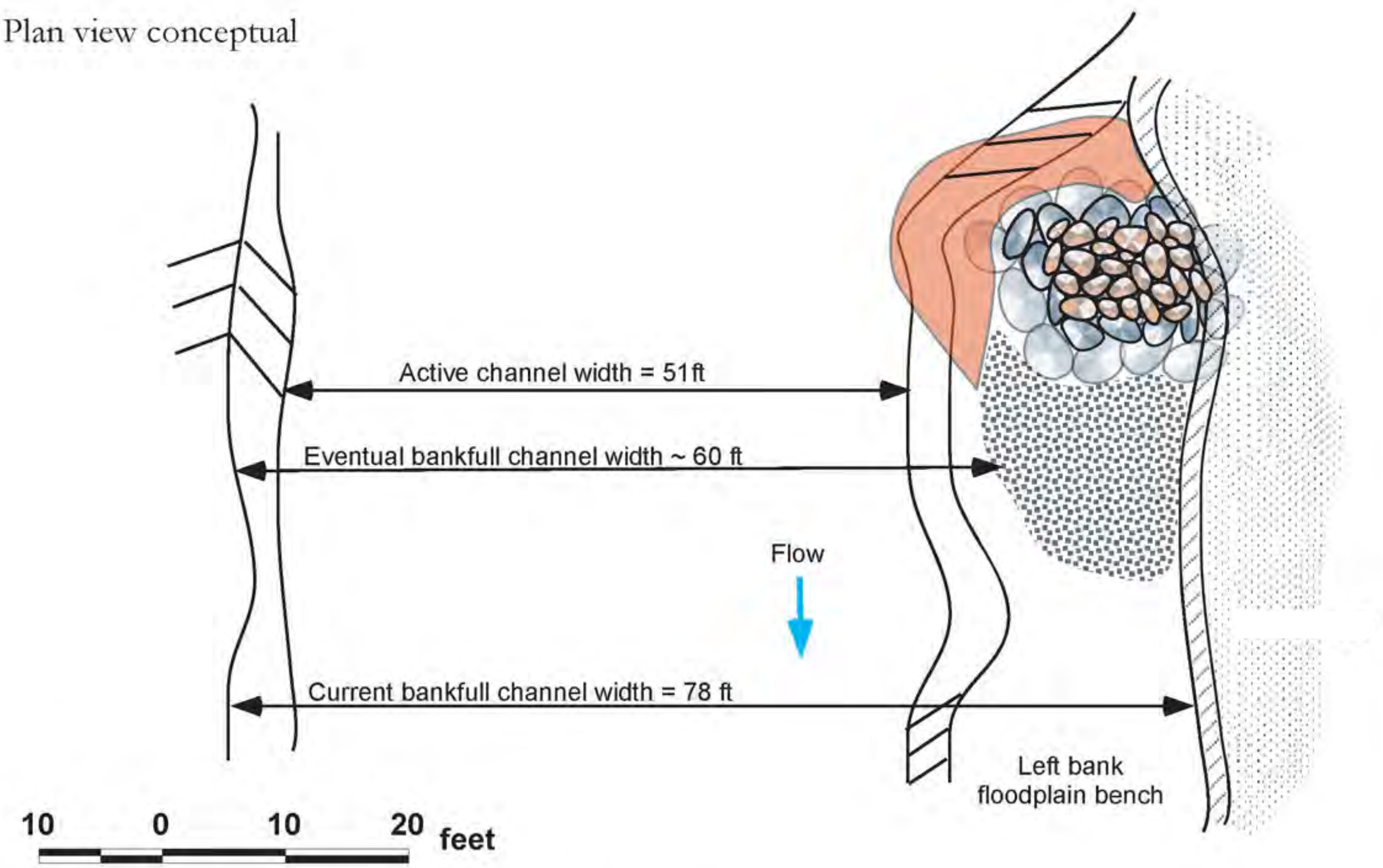
Side view conceptual



Example dimensions

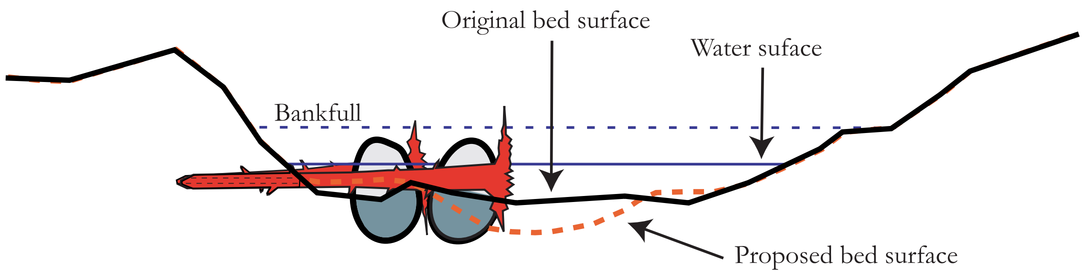
Bar width (ft)	D_{bf} (ft)	d_{footer} (ft)	d_{key} (ft)	Structure length (ft)	Excavation (cyds)	Footer rock (no.)	Key boulders (no.)	Small boulders (no.)
10	2	3	2.5	8	12	8	12	14
10	4	4	3	8	15	5	8	10
20	2	3.5	3	15	56	24	33	40
20	4	4.5	3.5	15	69	15	24	29
30	2	4.5	3.5	23	156	33	55	66
30	4	5	4	23	175	27	42	51

Plan view conceptual

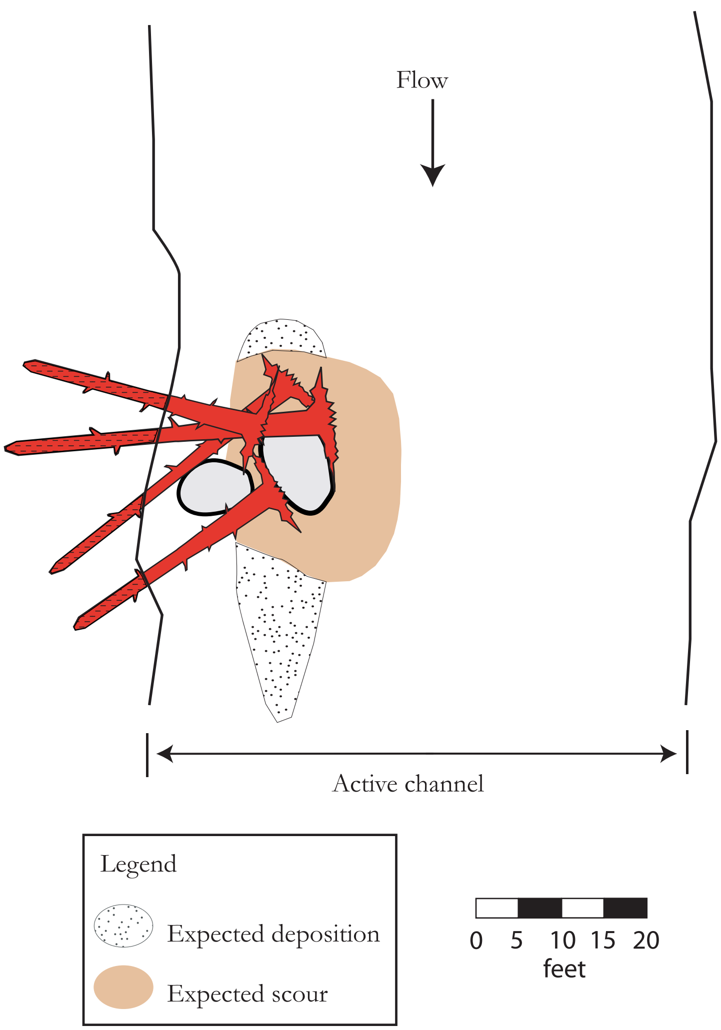


Treatment: Bar apex boulders

Side view conceptual



Plan view conceptual



Example dimensions

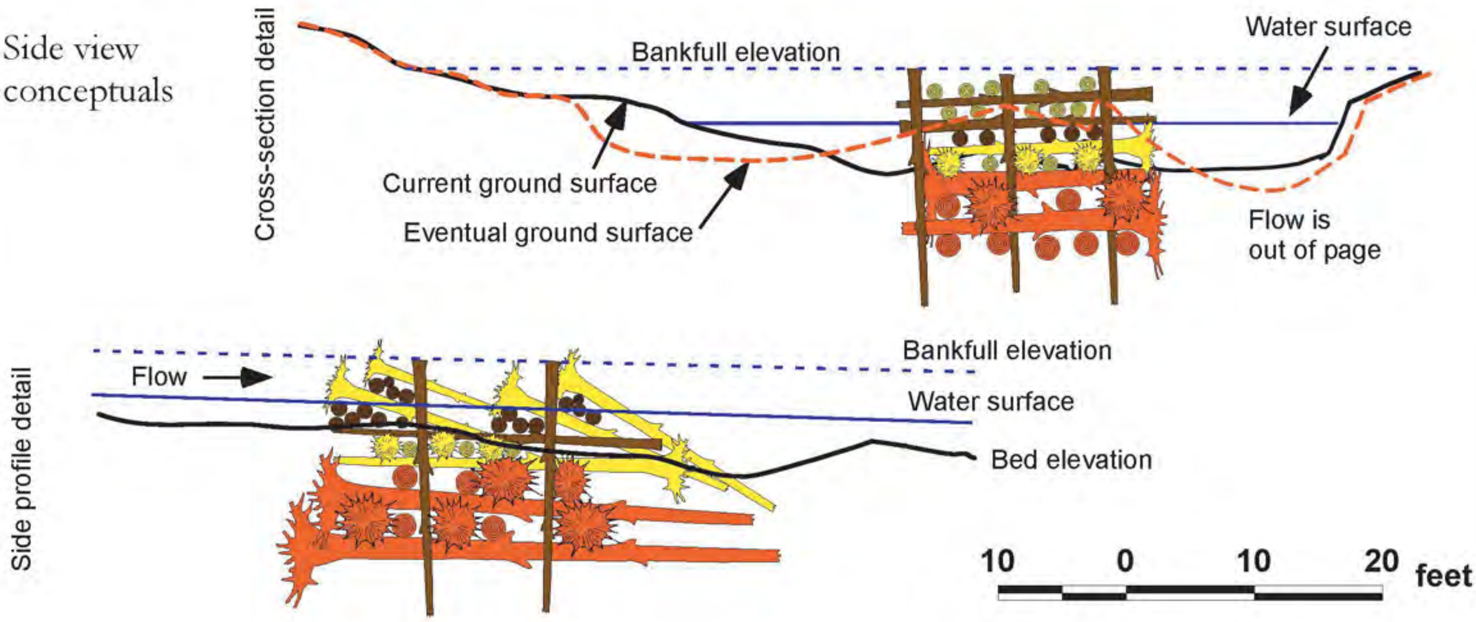
Bankfull channel width (ft)	Anchor log DBH (in)	Number of anchor logs
30	12	1
40	16	1 to 2
60	18	1 to 2
70	20	2 to 3
80	24	2 to 3

Example photo

Treatment: Boulder supported log jam

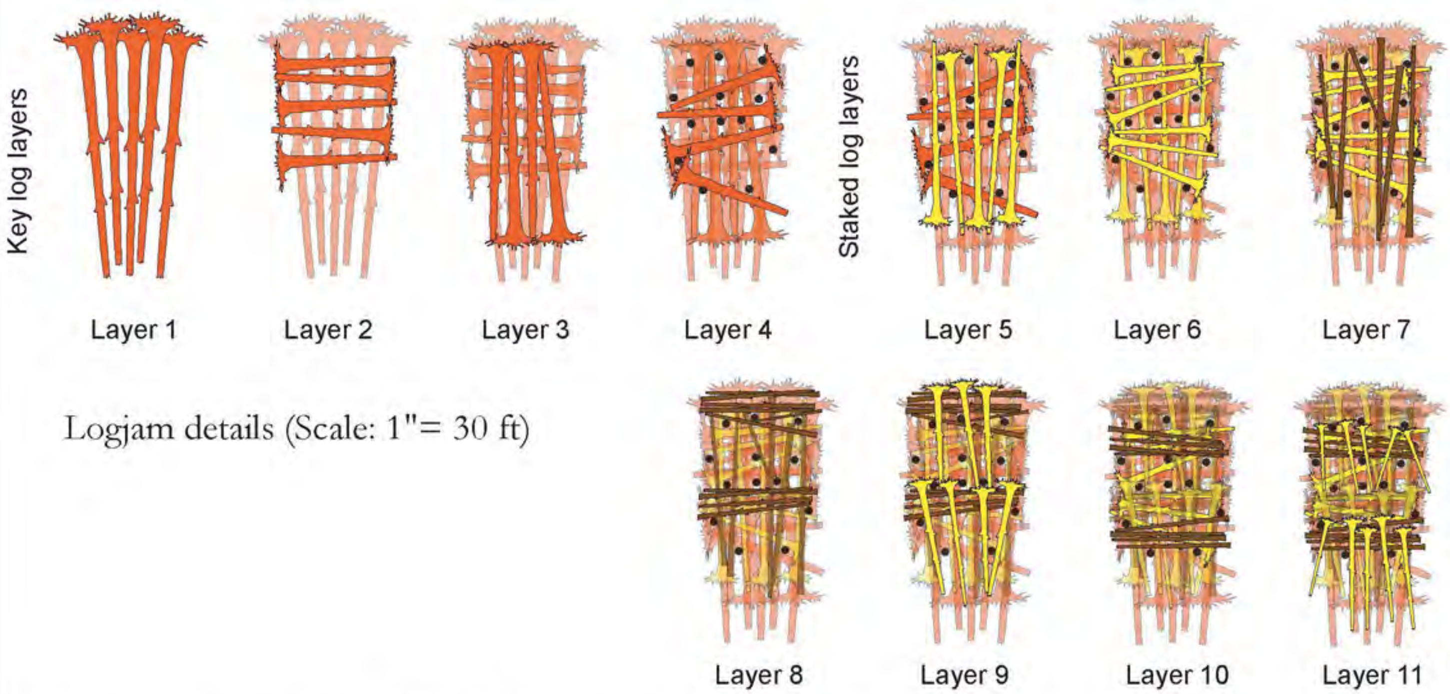
Field Geology Services

Side view conceptuals



Example dimensions

Channel width (ft)	Bankfull depth (ft)	Logjam width (ft)	Logjam length (ft)	Excavation (cyds)	Key logs (no.)	Stacked logs w/roots (no.)	Stacked logs w/o roots (no.)
60	3	15	30	167	11	22	19
60	5	15	30	167	14	22	19
80	3	20	40	296	14	28	24
80	5	20	40	296	18	28	24
100	3	25	50	463	17	34	29
100	5	25	50	463	22	34	29

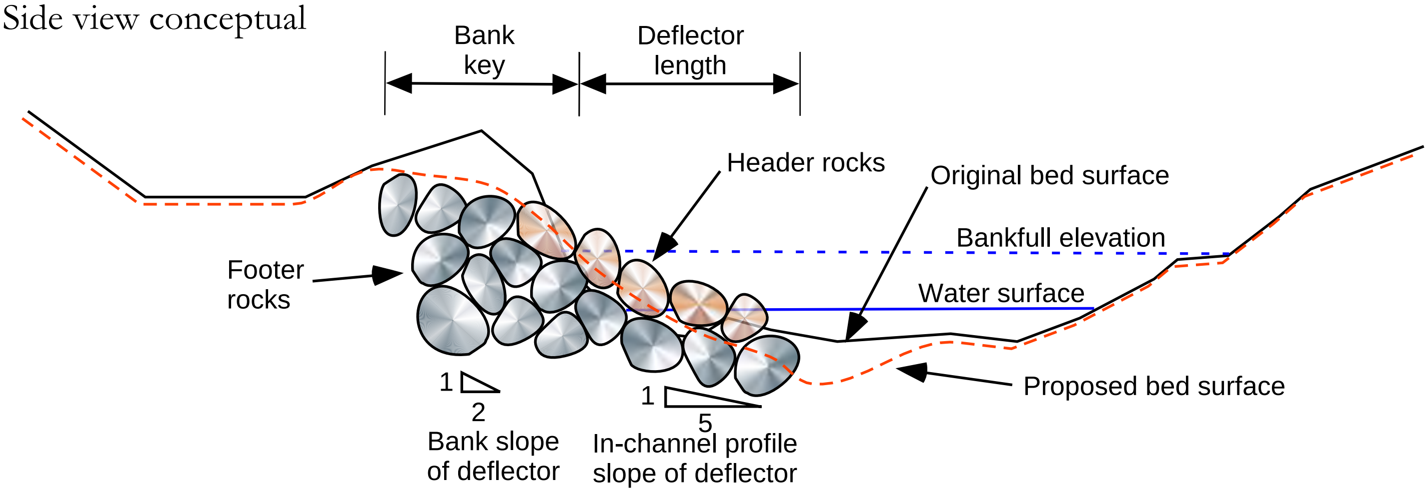


Logjam details (Scale: 1"= 30 ft)

Treatment: Engineered log jam

Field Geology Services

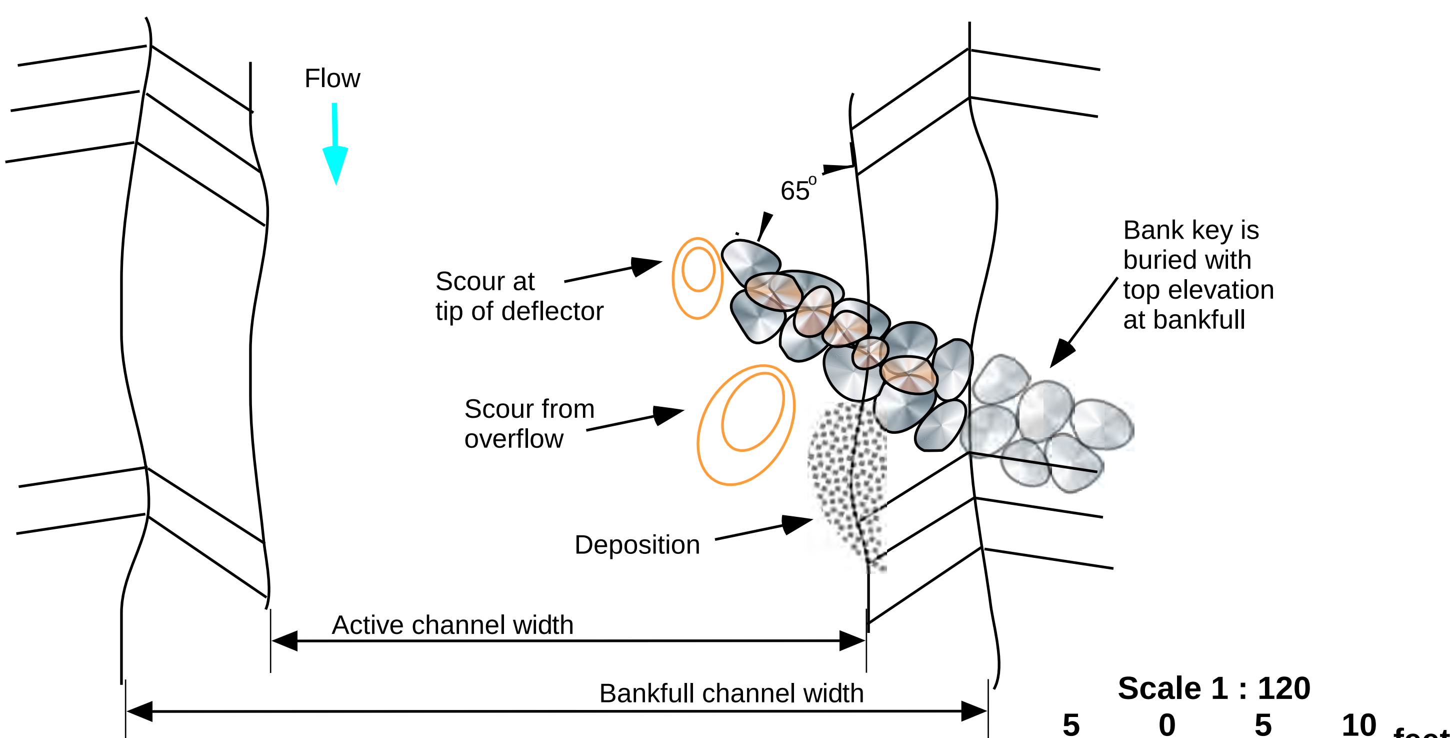
Side view conceptual



Example dimensions

Channel width (ft)	D_{bf} (ft)	d_{footer} (ft)	Deflector length (ft)	Deflector width (ft)	Deflector spacing (ft)	Bank key (ft)	Excavation (cyds)
40	2	3	10	6	50	5	13
40	3	3.5	10	7	50	5	18
50	2.5	3.5	13	7	63	6	22
50	3.5	4	13	8	63	6	30
60	3	4	15	8	75	8	35
60	4	4.5	15	9	75	8	46

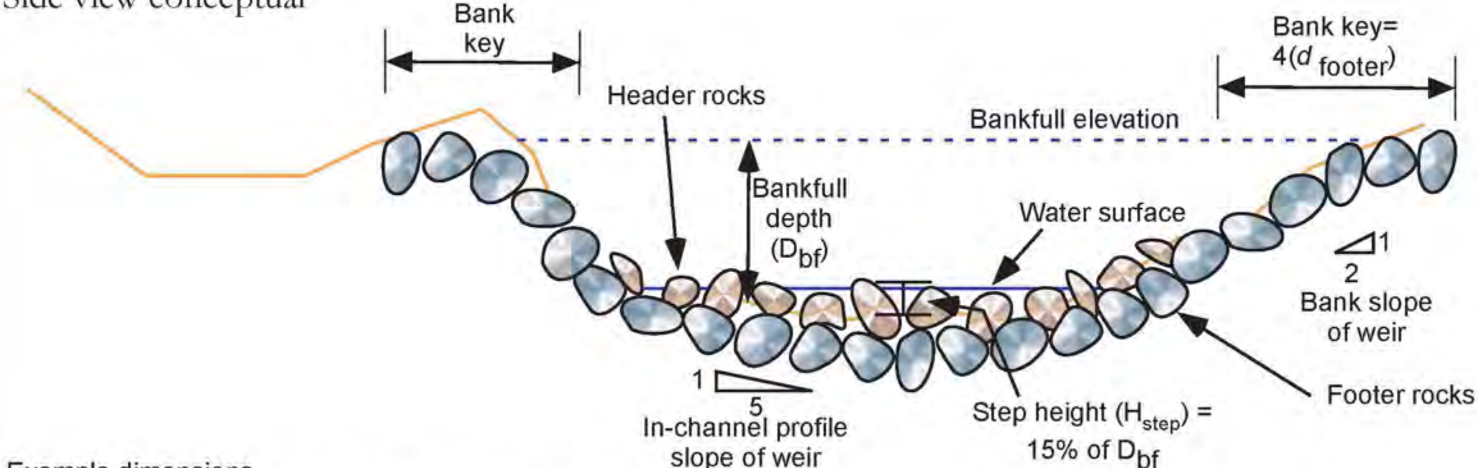
Plan view conceptual



Treatment: Rock (boulder) deflectors

Field Geology Services
Fluvial Geomorphology

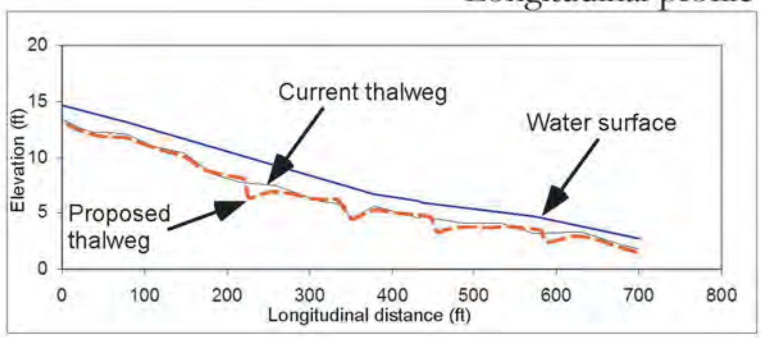
Side view conceptual



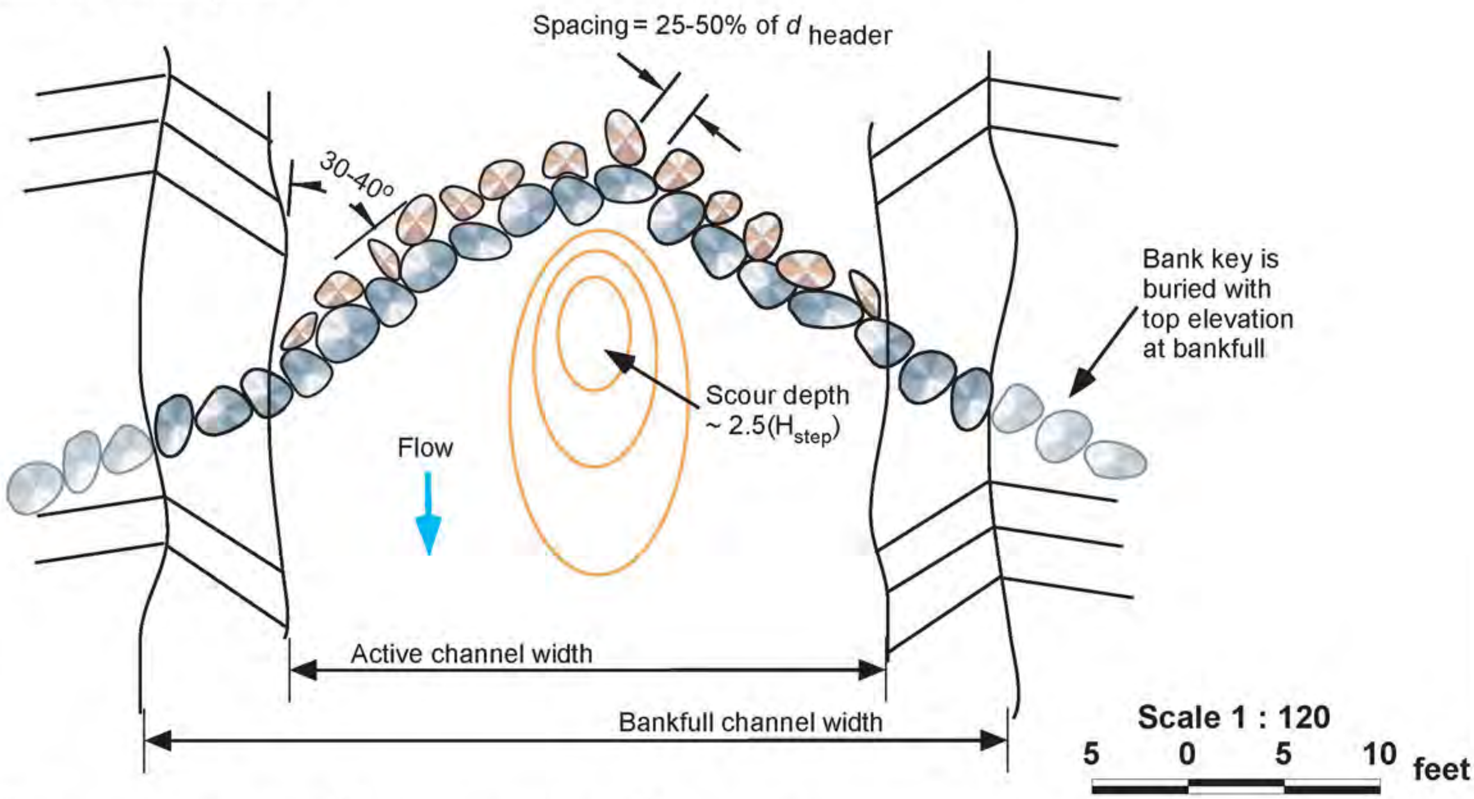
Example dimensions

Channel width (ft)	D_{bf} (ft)	d_{footer} (ft)	Step height (ft)	Bank key (ft)	Scour depth (ft)	Excavation per weir (cyds)
40	2	3	0.3	12	0.8	50
40	3	3.5	0.5	14	1.1	70
50	3	3.5	0.5	14	1.1	85
50	4	4	0.6	16	1.5	115
60	4	4	0.6	16	1.5	134
60	5	4.5	0.8	18	1.9	174

Longitudinal profile



Plan view conceptual



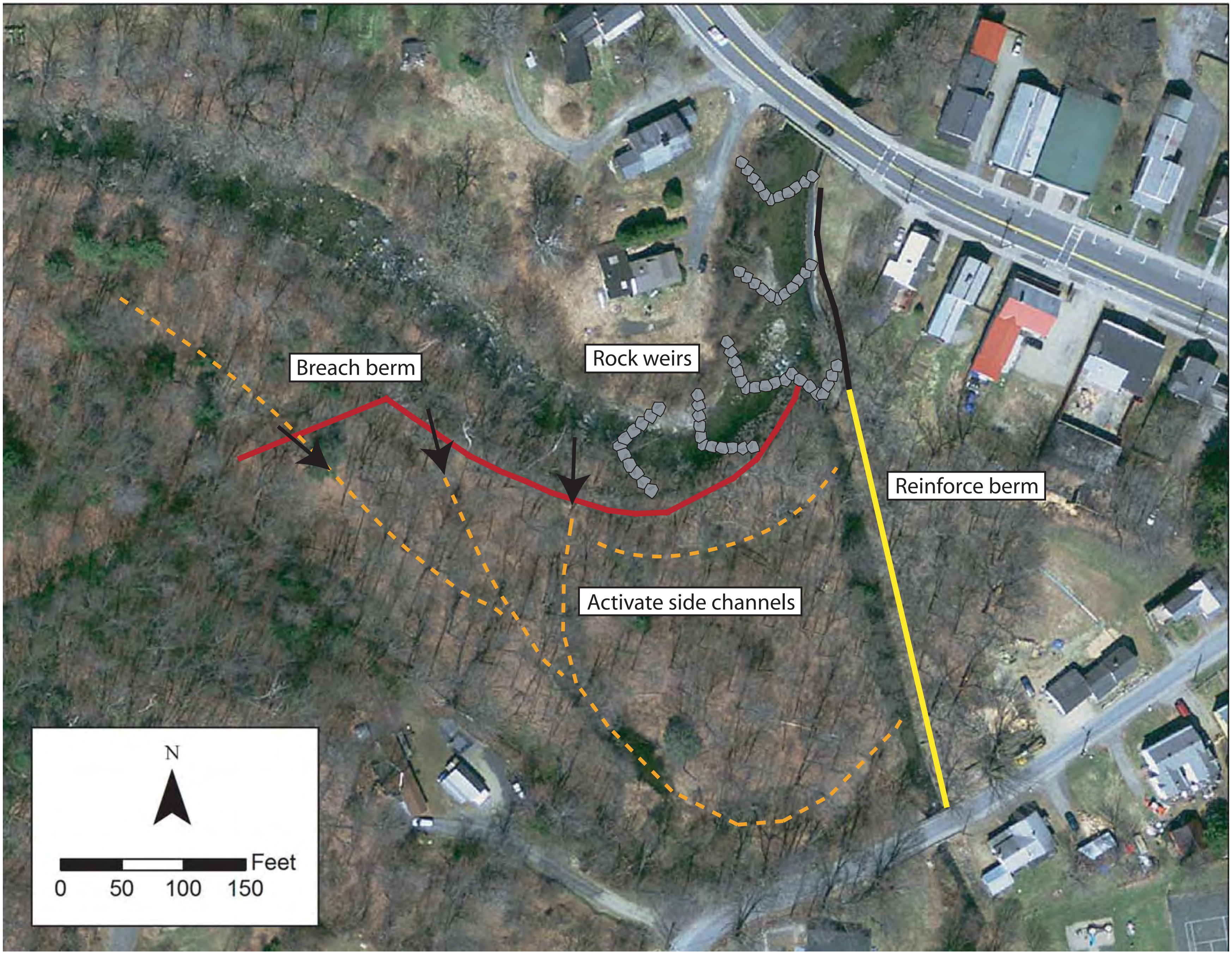
Treatment: Rock weirs

APPENDIX 8

(Restoration design plans for Segments 11A and 10E – see also attached CD)

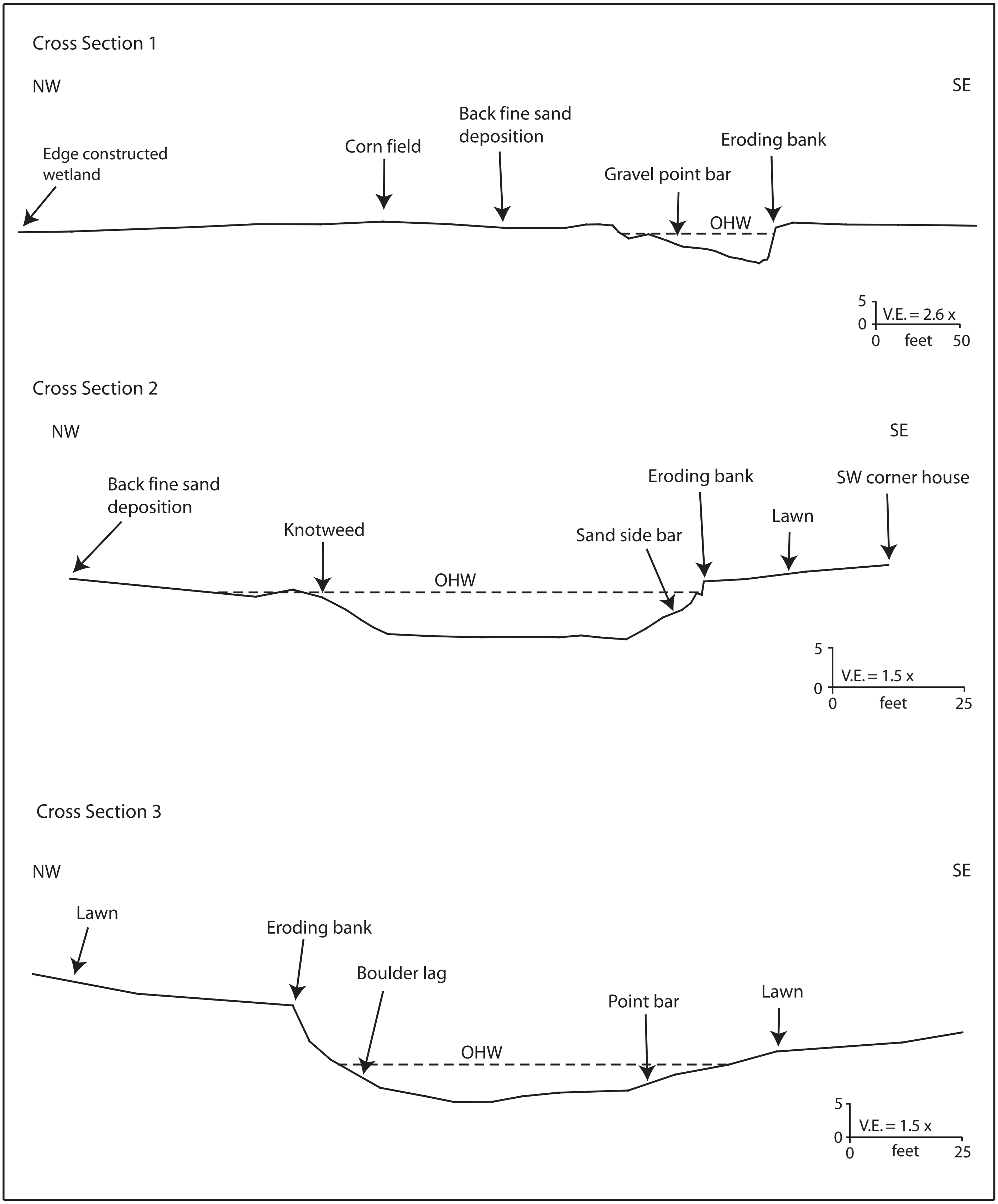
Phase 1 proposed planview map.

Field Geology Services

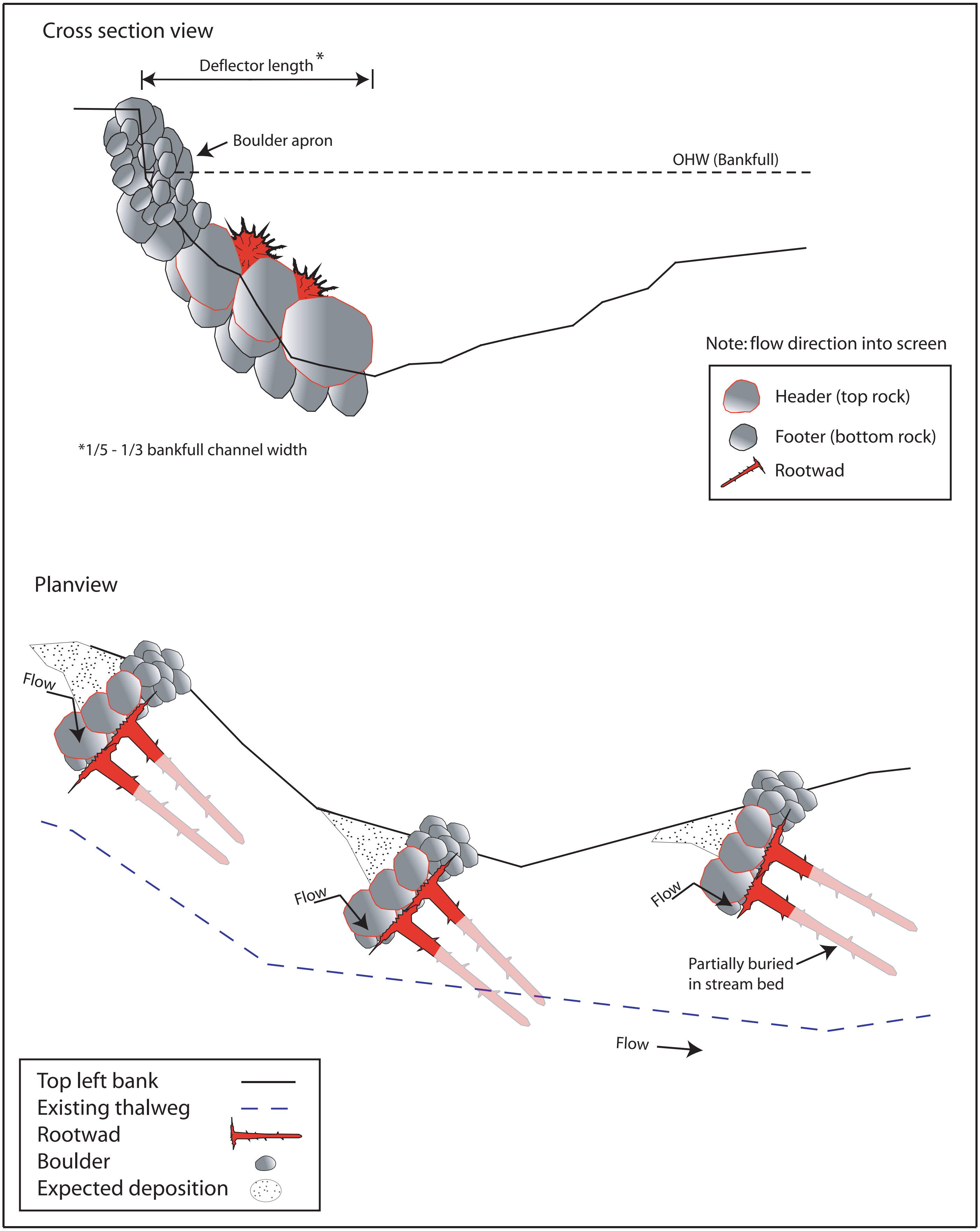


Phase 2 conceptual planview map.

Field Geology Services

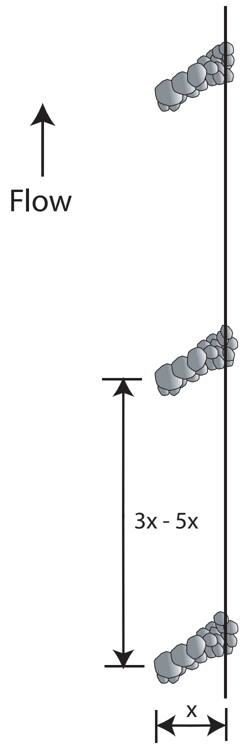


Phase 1 surveyed channel cross sections.

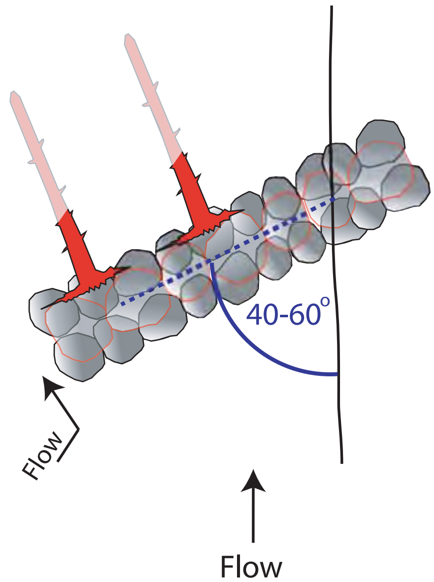


Boulder deflector design typical - sheet 1.

Planview spacing detail

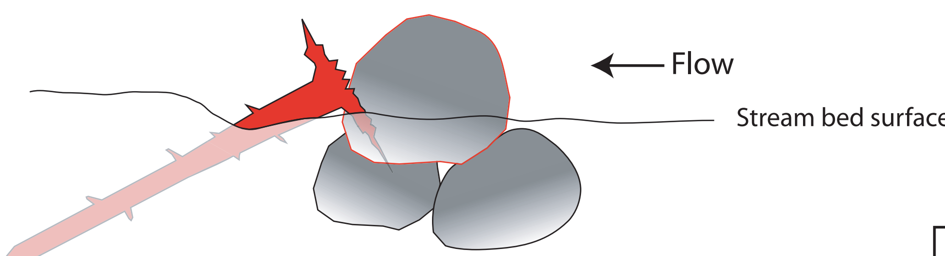


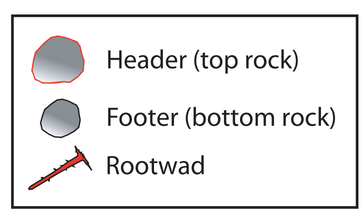
Planview angle detail



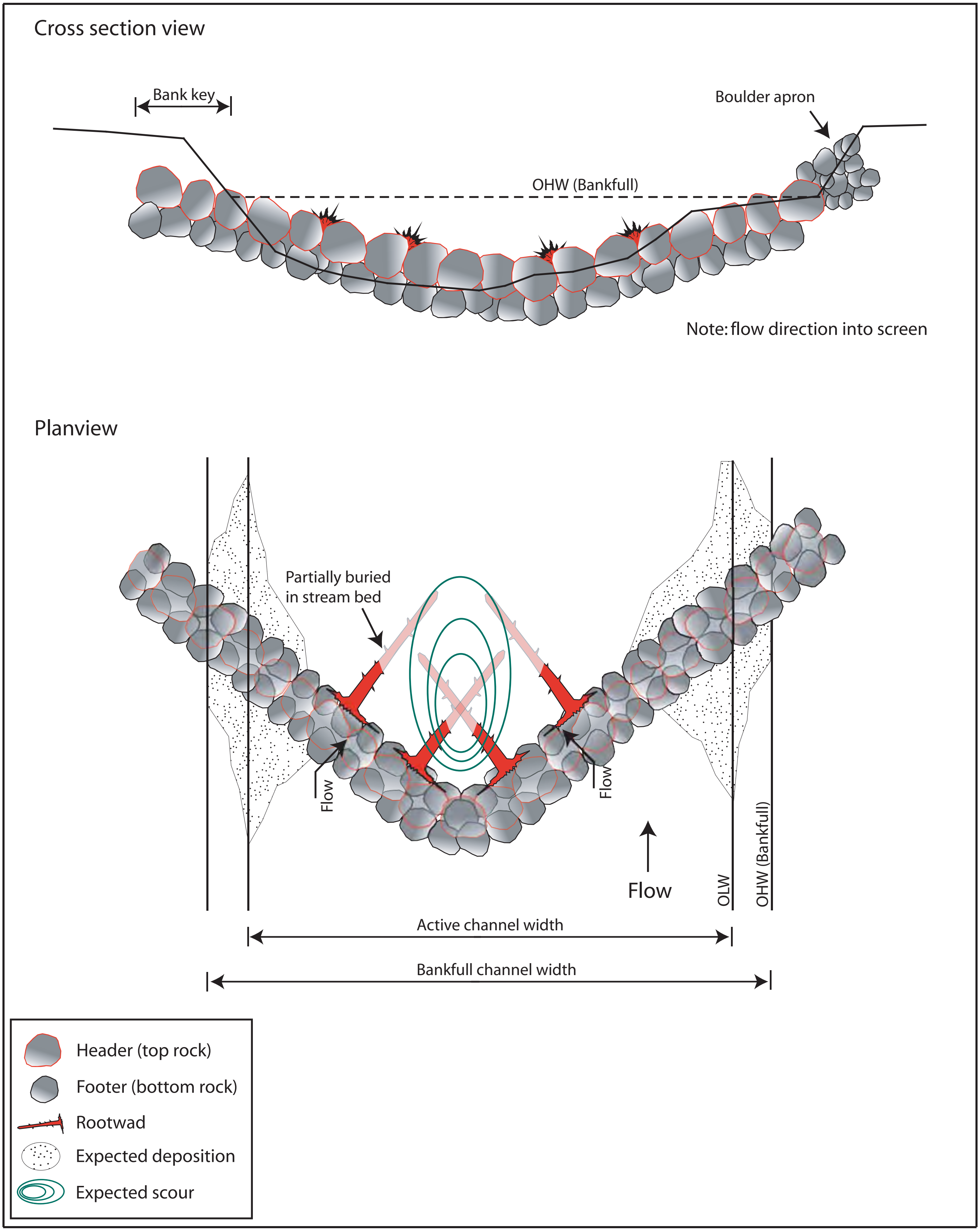
Example photo

Side view detail





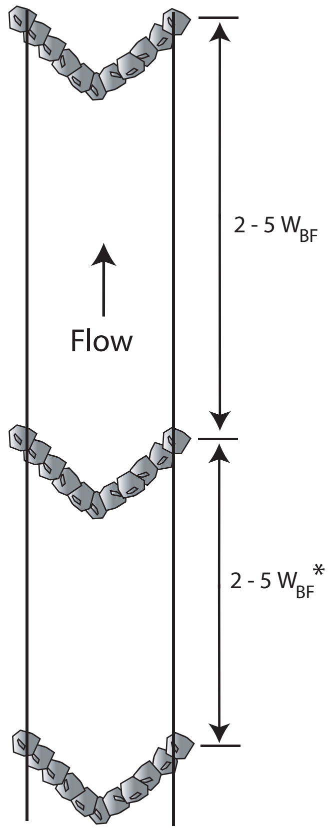
Boulder deflector design typical - sheet 2.



Rock weir design typical - sheet 1.

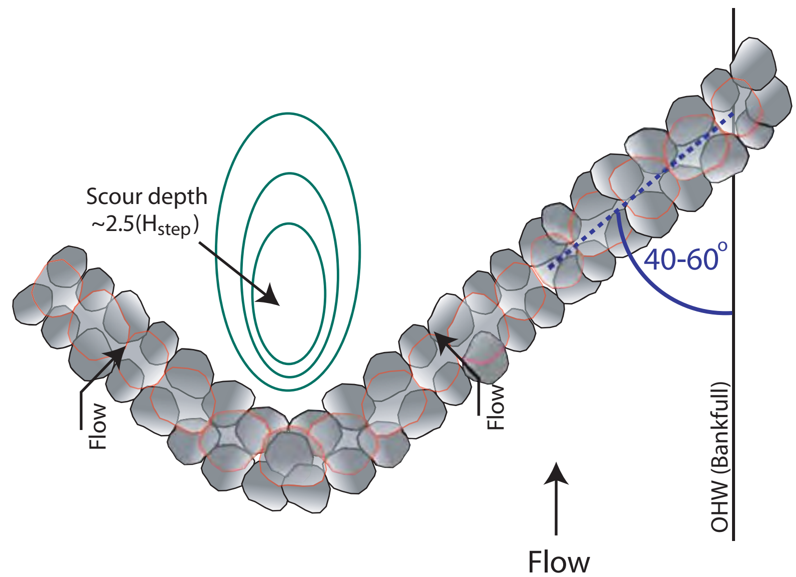
Field Geology Services

Planview spacing detail



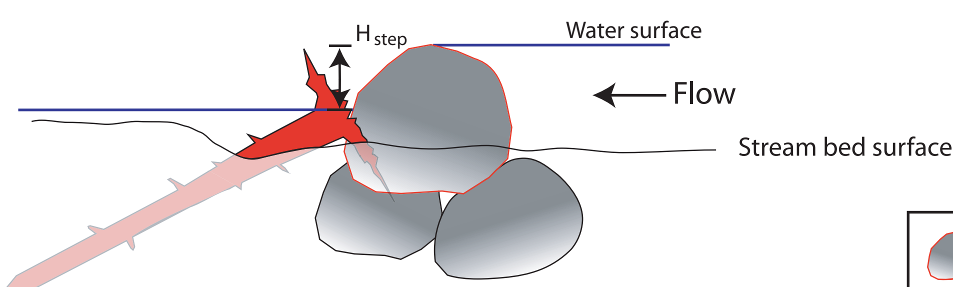
*Higher channel gradient requires closer structure spacing

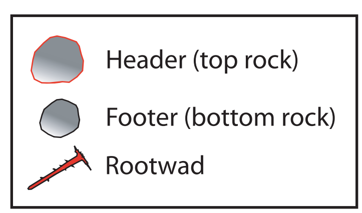
Planview angle detail



Example photo

Side view detail

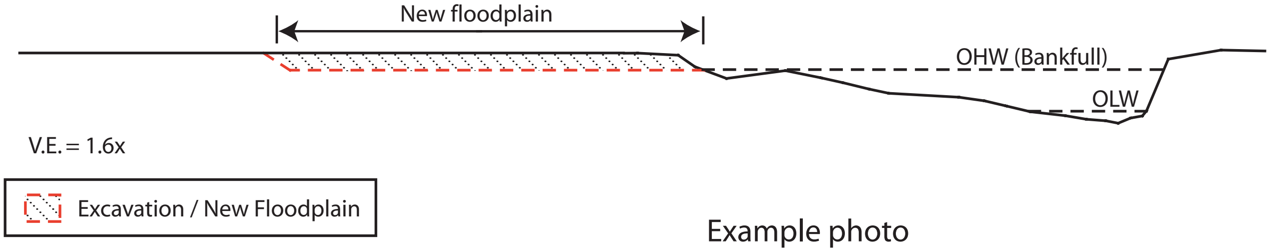




Rock weir design typical - sheet 2.

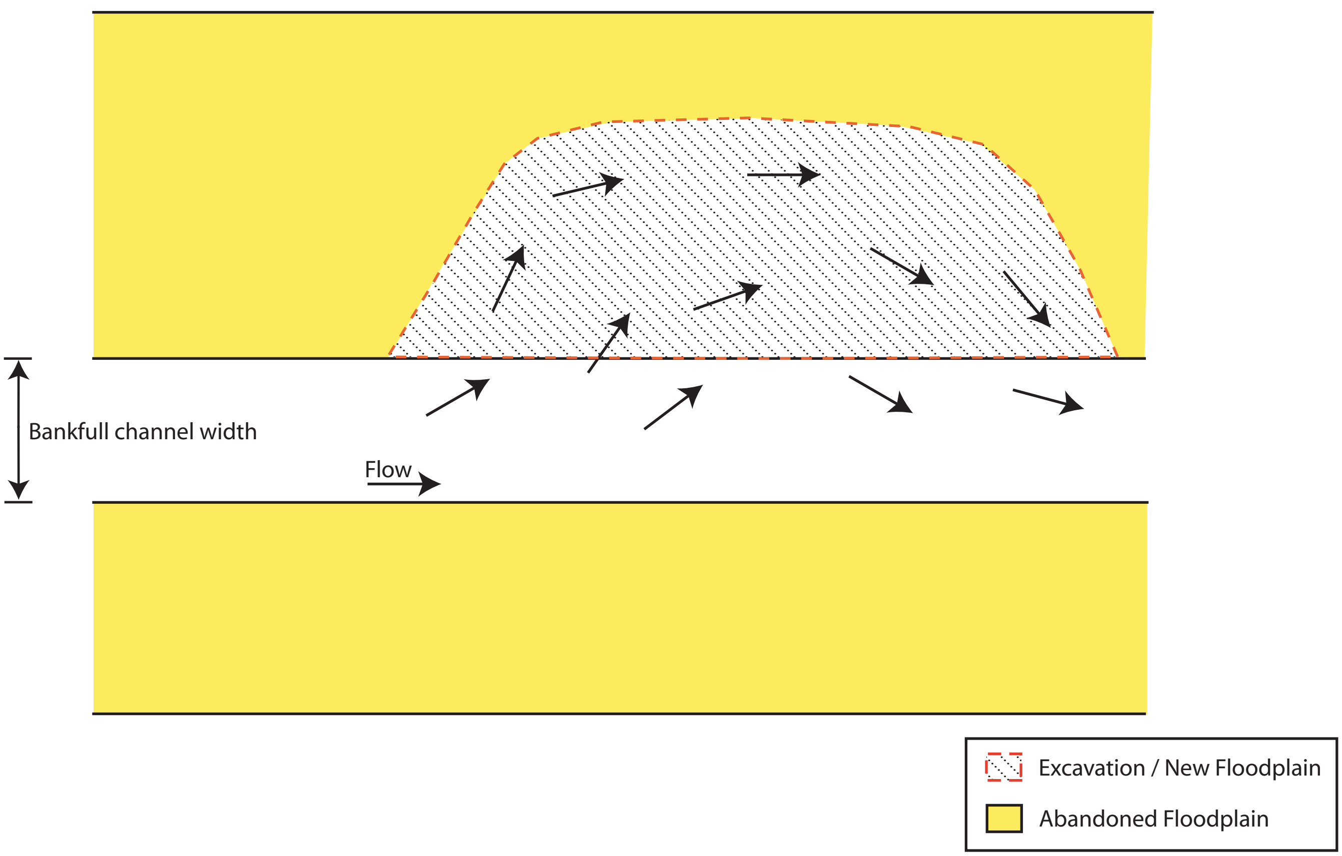
Field Geology Services

Cross section view



Example photo

Planview



Floodplain lowering design typical.