Fluvial Geomorphology Assessment and Restoration Options for Nash Stream Coös County, New Hampshire

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Nash Stream

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EXECUTIVE SUMMARY

A fluvial geomorphology assessment was conducted on Nash Stream in Coös County, New Hampshire to determine the causes of channel instability and identify restoration options to improve degraded aquatic habitat. The poor physical habitat conditions for trout and other aquatic organisms are largely the result of a large dam break flood in 1969 (with an estimated recurrence interval of 500 yrs) that deposited large boulder bars, leaving much of the stream channel confined and slowing the regrowth of trees in the riparian corridor. In addition, extensive channel straightening and berming of the channel occurred during the subsequent human response to the flood. These events continue to prevent the development of pools, recruitment of wood, and segregation of different particle sizes on the channel bottom, because flood flows cannot access floodplains or evenly dissipate energy around meander bends. In unconfined areas along the stream, meanders are reforming as flows are diverted around growing gravel bars and emerging bankfull benches. Larger meanders also form where flows escape the channel and carve new flow paths across the floodplain. Unfortunately, the presence of boulder bars is slowing these natural processes of channel adjustment along most of the stream, so stream restoration is needed to improve channel stability and aquatic habitat.

Analysis of historical aerial photographs, surveying of cross sections, and mapping of erosion, bars, channel straightening, and other channel features were used to delineate and characterize 95 discreet channel segments along the stream. The condition of eight geomorphic and habitat features, including pools, wood, and riparian vegetation, were used to identify and quantify the need for restoration in each segment. With the needs identified, typical designs for 17 restoration treatments (e.g., berm removal, riparian plantings, bioengineering) were created and rated for their ability to address the highest priority needs in each segment. While multiple treatments are potentially applicable to address the range of needs in a given segment, the priority treatment was selected by further considering appropriateness (e.g., berm removal can occur only where berms are present), cost, and access.

The process for identifying restoration treatments was used to focus discussions on treatment plans for the five upstream most segments on Nash Stream. A range of treatments were selected and final designs generated to improve aquatic habitat and lead to long-term channel stability. Addition of wood to the channel will occur through the chop and drop technique (i.e., the felling of trees in the riparian corridor) in areas of poor access with mature riparian vegetation, while trees will be partially buried with an excavator in areas of better access to ensure wood will not move downstream towards a bridge crossing the channel. Wood placed on bankfull benches will encourage deposition and vertical accretion of the surfaces in order to narrow the channel and increase low flow water depths. Boulder clusters will be placed in the stream channel to encourage and sustain pool development; rock weirs will accomplish the same results upstream of the bridge while maintaining a straight flow path, so bank erosion will not threaten the bridge abutments. Finally, berm removal will occur, where present, to increase floodplain access and reduce stream power in the channel. While treatments will vary with further restoration downstream, the process for prioritizing treatments of the upstream segments will be used to guide the selection of restoration options for the remainder of Nash Stream over the next several years.

1.0 INTRODUCTION

This report describes a fluvial geomorphology assessment completed by Field Geology Services along Nash Stream in Coös County, New Hampshire (Figure 1). From the site of the old Nash Bog Pond dam, Nash Stream flows 9.5 miles to the confluence of the Upper Ammonoosuc River and drains a total watershed area of 44.3 mi^2, the majority of which is part of the Nash Stream State Forest. Limited development occurs in the watershed, with only a few summer camps near the stream's edge. Nash Stream Road runs close to the stream for short distances at several locations and also traverses the floodplain in many spots. Only three bridges cross the stream downstream of Nash Bog Pond, one of which is primarily used by snowmobiles.

On May 20, 1969, after a period of heavy rain, the Nash Bog Pond dam breached catastrophically (Figure 2). The resulting flood—estimated as a 500-year event—carved a channel up to 400 feet wide that decimated the surrounding riparian forest and deposited thick boulder bars on which only sparse vegetation has grown over the past 40 years (Figure 3). The immediate post-flood response involved straightening the stream channel, removing boulders and wood, constructing berms along the banks, and other activities that were completed with an excavator. The flood and subsequent response has left poor physical habitat conditions for brook trout and other species along most of Nash Stream, including a limited number of pools, poor streambank cover habitat, and little channel complexity.

The geomorphic assessment, including the development of restoration options, was undertaken to better understand channel changes resulting from the 1969 flood and subsequent human response and to identify restoration techniques that will lead to stream channel equilibrium and sustainable improvements in physical habitat. The assessment consisted of eight parts: 1) reach and segment delineation; 2) review of existing studies; 3) watershed characterization; 4) analysis of historical aerial photographs; 5) mapping of channel features; 6) topographic surveys and substrate particle size measurements; 7) channel classification; and 8) regional curve analysis. The results of each component are described separately below and provide the basis for selecting restoration options that will help fulfill the project goal of improving physical habitat and water quality for brook trout and other aquatic organisms.

2.0 FLUVIAL GEOMORPHIC ASSESSMENT

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 (Figure 4 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". 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; these influences are used to later subdivide the reaches into segments (see Section 3.1 below; Appendix 1).

Reaches downstream of constrictions occupy more confined valleys where the river channel has a greater likelihood of flowing against glacial sediments exposed along the high valley walls. The potential for high rates of sediment production in these locations can affect channel morphology differently than 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 introduction 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. Consequently, the locations of the reach breaks themselves 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 from points of valley expansion 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", reflecting the location and occurrence of various human impacts (e.g., channel straightening, berming, gravel mining) 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.

Seventeen reaches were identified along the mainstem of Nash Stream using topographic maps and aerial photographs (Figure 4 and Appendix 1). Four of the reach breaks occur at tributary confluences, three occur at valley expansions, and three at valley constrictions (Table 1). The 17 reaches were later subdivided into 95 segments as described further below in Section 3.1.

2.2 Review of existing studies

On the morning of May 20th, 1969 the Nash Bog Pond Dam, a timber crib and earthen dam built in the late 1880s, was breached following a storm that dumped approximately 3.3 inches of rain over two days (Figure 2 and Appendix 2). The 200-foot wide failure occurred in the timber portion of the dam, which was probably 30 to 35 ft high (Appendix 2). At the time of failure the water was approximately 23 ft deep at the

dam. At the site of the breach the channel downcut 10 to 15 ft below the original reservoir bed, leaving vertical slopes 25 ft high. The failure released an estimated 2,500 acre-feet of water, or more than 100 million ft^3, which took about 3 hours to reach the confluence of the Upper Ammonoosuc River. Many large boulders greater than 3.0 ft in diameter were transported down the stream. The floodwaters and transported sediment caused damage in the towns of Odell, Stark and Groveton, including most of the Nash Stream Road and two bridges in Stark. This event and earlier floods on Nash Stream, such as in 1936, have greatly influenced the morphology of the Upper Ammonoosuc River and the Connecticut River 6.2 mi further downstream (Field, 2006). The impacts of these floods on Nash Stream, particularly the 1969 event, are the major focus of this report.

Prior to the 1969 flood, the Nash Stream Watershed had experienced a long history of land clearance and log drives (Appendix 2). The watershed has been a working forest since the mid 1800's with a railroad for logging built in 1852. In 1870, the Nash Stream Improvement Company was incorporated for the purpose of building a series of dams for log drives and for clearing the stream of boulders and snags. The largest of these dams, on Nash Bog Pond, was built prior to 1900. After a road was built to transport logs in the 1930's, the dam was maintained for seasonal camps built around the impoundment. The more permanent log crib dam that breached in 1969 at Nash Bog Pond was only one of at least three such structures still visible downstream of Nash Bog Pond (see Section 2.5b below). In addition, numerous temporary "splash dams" were annually constructed on the stream and its tributaries to aid the transport of logs downstream by providing surges of water when the dams were purposefully breached.

2.3 Watershed characterization

Channel adjustments to natural conditions and human activities in a watershed are driven by changes in water, sediment, and wood inputs. The old Nash Bog Pond is now a wide low gradient unconfined wetland. Nash Bog Pond largely ameliorates the impact of large changes in water, sediment, or wood inputs from the upper watershed such that upper watershed conditions have limited influence on channel morphology within the study area (Figure 1). Several tributaries enter Nash Stream below Nash Bog Pond. Most of the tributaries are well forested with the lower ends of these streams in an equilibrium, yet dynamic, condition with meanders created around log jams among other processes that form excellent physical habitat elements (Figure 5). The presence of wood in the channel and on the broad floodplains of the lower tributaries serves to store sediment and reduce peak discharges downstream. Consequently, tributary inputs are not negatively impacting the morphology of Nash Stream at present. The steep watersheds do however remain sensitive to land clearance, either through natural fires or human activities. Rare intense rainfall events could cause the rapid evacuation of large volumes of wood and sediment from the tributary watersheds. Such events are considered unlikely under the current climate and expected land use, so the influences of rapid sediment inputs from tributaries are not a constraint on the development of restoration plans (see Section 3.0 below).

Rapid sediment inputs from high eroding banks along the stream can greatly alter channel morphology downstream. While high eroding banks can occur in unconfined reaches if the channel migrates to the valley margin, a stream is more likely to encounter high banks in confined valley settings. High eroding banks composed of loose stratified sands, probably glacial outwash deposits, are present in Reach 5 on Nash Stream (Figure 6a). The large amounts of sediment produced from high banks typically leads to bar formation, channel migration, and bank erosion - channel processes that are often perceived as problematic because of potential threats to roads and other infrastructure. However, on Nash Stream where little infrastructure is present, the sediment being introduced from high banks rejuvenates these channel processes that are important for creating high quality physical habitat along previously altered reaches with poor physical habitat.

The type of channel response resulting from the stream flowing along the valley margins depends on the composition of the valley sidewalls (i.e., gravel, sand, clay, bedrock). While glacial outwash sands comprise much of the material along the valley margins, Nash Stream does encounter more erosion-resistant glacial-lake clays in some areas, leading to the formation of deep pools as the stream scours the channel bed rather than the resistant clay banks (Figure 6b). Very little bedrock is exposed along the length of Nash Stream below Nash Bog Pond, but deep pools would be expected where the stream did encounter ledge along the banks, similar to what is occurring where resistant clays are present. Depending on the conditions desired, restoration efforts could purposefully be designed to encourage the river to move towards the channel margins in order to create pools along resistant banks, or to generate sediment along erodible banks in order to enhance habitat-forming processes downstream.

Although channel adjustments can alter a stream's gradient, the valley slope over which the stream flows is largely a product of the watershed's geological and physiographic setting. In an idealized watershed, the stream's gradient gradually decreases downstream with a concave up longitudinal profile developed over time. However, Nash Stream, as throughout much of New England, encounters several areas where the channel gradient increases, largely in congruence with confined reaches downstream of valley constrictions (Table 1). For example, channel gradient decreases from 0.0242 immediately downstream of Nash Bog Pond to 0.0037 at Reach 9 where the valley is wide and unconfined, but then increases to as much as 0.0257 through the confined reaches downstream (Reaches 8 through 4). Gradients decrease again in Reaches 3 through 1 as the stream enters the larger Upper Ammonoosuc River valley. These watershed constraints on channel gradient and confinement must be accounted for in the development of restoration plans as restoration strategies that are appropriate for lower gradient unconfined settings may be ineffective for reaches in steeper narrower valleys.

To distinguish between the impacts of the 1969 flood and other human activities on Nash Stream, a portion of the neighboring Phillips Brook was also assessed as part of this project (Figure 1). Phillips Brook has a similar watershed area to Nash Stream, and the climate, watershed geology, and history of human activities are also assumed to be

similar due to their proximity. The only significant difference in the potential factors controlling channel morphology is that no catastrophic flood like the 1969 dam breach on Nash Stream has occurred along Phillips Brook. The morphology of Phillips Brook, therefore, may approximate conditions that existed on Nash Stream prior to the 1969 flood. This does not mean Phillips Brook represents a reference or equilibrium condition as Phillips Brook, like Nash Stream, has a long history of land clearance and log drives.

2.4 Historical aerial photographs

Historical aerial photographs can be an important tool for studying changes in channel morphology. Through geo-rectification, which utilizes ground control points to overlay older images onto the most recent image, the position of the channel for each image can be digitized in a GIS project and compared. For Nash Stream, the New Hampshire Fish and Game Department completed geo-rectification on the 1955, 1970 and 1986 photos, with the 2003 NAIP ortho-rectified aerial photographs serving as the basemap. No data on the rectification error was provided. The stream centerline was digitized in each series of images and the resulting shapefiles are found in Appendix 3 along with the original photographic images.

The maximum channel migration distance between each photo year was measured for all reaches using the stream centerline files and the average annual channel migration rate calculated based on the number of years between subsequent aerial images (Table 2). While the maximum rate of migration may be high for a specific point in a reach, channel migration in the rest of the reach may be minimal. Furthermore, with no information available on the error in the rectification process, channel migration of 50 ft or less, given the scale at which the maps were rectified, may reasonably fall within the margin of error. Consequently, very little migration may have actually occurred in those reaches where the maximum migration measured is 50 ft or less. Changes in channel sinuosity (i.e, the ratio between the channel length and valley length) for unconfined reaches were also calculated (Table 2). Significant changes in sinuosity cannot typically occur in confined reaches where limited space is available for meander development.

The largest observed changes in channel position occur between the 1955 and 1970 images and are assumed to be related to the dam breach flood of 1969, especially given the expansive lighter tones along the river on the 1970 image reflecting the fresh deposition of sediment. In 1955, the channel appears to be relatively stable in that the banks are well forested and expansive gravel bars are not visible in the channel. However, the impacts of past stream management can be seen in the form of channel straightening, presence of log-driving dams, and encroachment of the road close to the stream's edge. The presence of substantially enlarged unvegetated boulder bars defines the channel on the 1970 image, with the channel width changing from less than 80 ft prior to the flood to over 400 ft in many places after the flood (Figure 7). The extent of the flood is still demarcated in many places on recent aerial photographs by the edge of coniferous tree growth (Appendices 3 and 4). Presumably coniferous trees, along with other vegetation, growing closer to the channel were obliterated with passage of the flood

wave, and only sparse deciduous growth has recolonized the flood deposits over the past 40 years (Figure 3).

Channel migration in confined reaches between 1955 and 1970 was somewhat limited as the high valley walls were able to contain the floodwaters resulting from the 1969 dam breach. Channel migration during the same time period was much greater in unconfined stream reaches with a maximum of 510 ft measured in Reach 16 (Table 2). This equates to a migration rate of 34 ft/year, although most, if not all, of the migration is assumed to have occurred during the 1969 flood event. Channel migration, within the context of the large flood, probably did not occur through the slow recession of an eroding bank as is typically envisioned, but rather resulted from avulsions (i.e., rapid shifts in channel position) as new channels were carved through freshly deposited sediments during the waning stages of the flood. The recorded channel migration represents the distance between the pre-flood channel and the position of the new channel. During the flood itself, the old channel was either widened through extreme bank recession or was completely buried in flood deposits before a new channel was carved through these fresh deposits. In many instances, the 1970 channel position may reflect where the channel was excavated or moved to by excavators during the post-flood human response and not where the channel naturally formed after the flood. In Reach 16, meanders that likely formed during the waning stages of the flood were cut off as a straight channel was excavated through a boulder bar (Figure 8). In some cases, the new channel reformed or was placed during the post-flood response near the position of the old channel, resulting in low channel migration rates even in unconfined reaches (e.g., only 50 ft in Reach 14). However, the impacts of the 1969 flood were not necessarily any less severe in these areas.

Between 1970 and 1986, the stream channel underwent further morphological adjustments. While the rates of channel migration are greatly reduced from those resulting from the dam break flood, dramatic changes did occur in some reaches, with a maximum channel migration of 390 ft in Reach 8 (Table 2). The migration in Reach 8 is directly related to the formation of a new meander along a section of channel straightened after the 1969 flood (Figure 9). Straightened channels, with a higher gradient resulting from their shortened length, tend to have greater stream power and are prone to “breaking out” onto the floodplain with sufficient force to carve new meanders that are generally more stable than the abandoned straight section as the stream’s energy is more evenly distributed over a greater length. The “break outs” tend to occur at sharp bends (Figure 9) or areas where the channel becomes clogged with sediment, wood, or ice. The “break out” meanders form as floodwaters carve a new channel through the floodplain with undisturbed floodplain remaining as an island between the new meander and abandoned straight section (Figure 9). The channel migration in these instances again reflects a rapid avulsion process rather than steady bank retreat over time; steady bank retreat would erode all of the floodplain material between the former and present channel positions. In other locations, especially within former impoundment areas (see Section 2.5e below), bank migration may indeed be occurring through more steady bank retreat, but the maximum bank retreat in these places is likely much lower than where “break out” meanders have formed.

Bank migration rates between 1986 and 2003 are much lower and largely within the presumed margin of measurement error, indicating that the process of meander formation has slowed considerably. Immediately after the 1969 flood and post-flood straightening, the most unstable and sensitive sections of the channel (e.g., hard bends, low banks) quickly adjusted to a more stable meandering configuration. A considerable length of Nash Stream remains straightened, but the reformation of meanders along these less sensitive sections will require larger discharges or increased sediment or wood loadings to force flows onto the floodplain with enough force to carve a new channel. Therefore, bank migration rates may be expected to increase again in the future as wood loads in the channel increase either through purposeful additions during restoration or natural recruitment as riparian vegetation matures. The meander reformation process has probably been slowed considerably in the past 40 years, except in the most sensitive areas, because large amounts of wood were removed from the channel as part of the post-flood response (Appendix 2).

Changes in channel sinuosity through time largely reflect the same changes associated with channel migration. Channel sinuosity decreased in most unconfined reaches between 1955 and 1970 (Table 2) and is assumed to largely be the result of post-flood straightening undertaken after the 1969 dam breach (Figure 8). Those reaches where sinuosity increased between 1955 and 1970 are areas where the waning stages of the 1969 flood may have created meanders through the freshly deposited sediments but were not cut off by subsequent straightening. After 1970, channel sinuosity has increased, particularly before 1986, as meanders have reformed along the straightened sections of channel (Figure 9 and Table 2). The channel changes observed on the historical aerial photographs reflect how the channel adjusts to large flood events and human activities undertaken in response to such floods. An understanding of these adjustments provides clues to the types and location of restoration activities that can be undertaken to return the stream to an equilibrium condition under which sustainable high quality habitat can form.

Land use changes in the watershed have been minimal since 1955. The watershed has remained well forested during that time, with most of the riparian impacts appearing to be the result of the 1969 flood. A new road was constructed after 1970 on the west side of the valley, with a new bridge to access it. Several bridges were destroyed in the flood and most likely two log-driving dams at the downstream ends of Reaches 9 and 13. Gravel pit operations in the lower reaches of the watershed have expanded since 1955 with one pit, now several hundred feet from the channel, taking advantage of a high eroding bank formed by a meander created during the 1969 flood but later cutoff by post-flood straightening.

2.5 Mapping of channel features

Several channel features were mapped continuously along the channel of Nash Stream downstream of Nash Bog Pond in order to: 1) identify locations of channel instability and sensitivity; 2) characterize physical habitat conditions; and 3) document the impacts of past events (e.g., 1969 flood) and activities (e.g., dam construction). The

mapped features included: 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, non-alluvial glacial or lake sediments, bedrock); 4) grade controls (e.g., dams, waterfalls); 5) past management activities (e.g., location of berming, channel straightening); 6) bar types (e.g., point bars, mid-channel bars, floodplain benches); 7) channel reach morphology (e.g., pool-riffle, step-pool, etc.); 8) habitat features (e.g., woody debris, debris jams, deep pools); and 9) mature vegetation. These same features were mapped along 2.9 miles of Phillips Brook to provide a comparison with a neighboring watershed that did not experience a severe flood in 1969 (Figure 1). Field mapping on Nash Stream was completed using the 200-scale aerial photographs flown in 2005 as a base map to locate the beginning and end points of mapped features (e.g., an eroding bank); the 2003 digital orthophotos were used for mapping on Phillips Brook (Appendix 3).

All mapped channel features were digitized in ArcView GIS to provide a database detailing the character of the channel bed and banks for all points along Nash Stream (Appendix 4). The GIS shapefiles can be used to determine the exact location and distribution of any of the mapped features. 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 3). The data were also used to establish the segment breaks described in Subtask 2a and to characterize each segment (e.g., straightened segment).

2.5a Boulder bars

The legacy of the 1969 flood is well expressed in the composition of bank material. The stream channel encounters flood-deposited boulder bars along 42 percent of its length (Table 3). The presence of the boulder bars along the channel strongly controls the distribution of other mapped features: those with a direct impact on habitat quality and channel morphology. While the boulder deposits do not confine the channel in all locations, they largely explain why 37 percent of the channel is confined by banks 5 ft or higher. Where boulder bars and other surfaces are less than 5 ft high, berms were in some places constructed at the edge of the channel, totaling 5.0 percent of the total bank length (Figure 10 and Table 3). Considerably more berming is on the left bank (looking downstream), presumably to protect the road passing near the stream in several places. Channel confinement by boulder bars and berms ensures that greater stream power is retained within the channel, thus making difficult the retention of finer gravels for spawning or wood as pool-forming elements. Only one log jam and 55 individual pieces of large wood were mapped along 9.5 miles of stream, with very few of these associated with deep pools. Only 8 deep pools were observed and these were typically associated with the limited outcrops of bedrock (Table 3).

Banks 20 ft or higher are not associated with boulder bars but rather non-alluvial glacial deposits. However, meanders created by the 1969 flood—which are in part the result of flows being diverted around boulder bars—are partially responsible for bringing the channel into contact with these valley margin deposits. Where the stream channel

continues to flow against the valley sides, active mass failures occur along the high banks of glacial outwash sediments (Figure 11). These high eroding banks are a rejuvenation point along the channel where large amounts of sediment are quickly introduced to the channel. This source of excess sediment is not necessarily a negative impact to physical habitat because of the resulting channel migration and side channel formation.

Mature vegetation is growing along only 20 percent of the stream channel (Table 3), largely because revegetation of the boulder bars has progressed slowly since their deposition in 1969 (Figure 3). Vegetation growth is sparse in most locations given the coarse sediment and lack of organic matter, but mature vegetation does sometimes occur at the downstream ends of individual bars where the deposits might be thinner and the vegetation rooted in older soils below. Large ant colonies are found on many boulder bars and have brought considerable fine sediment to the surface (Figure 12a), providing a mechanism by which the soil fertility may be slowly improved. Flows occasionally inundate the boulder bar surfaces despite being several feet higher. This is possible because the boulder surfaces of the bars have a lower slope than the current channel and, as a result, bank heights are generally much lower at the upstream end of individual bars. (Stream channels typically create a lower slope during large floods as an adjustment to the greater discharge). While flooding over the boulder bars might be expected to deposit fine sediment and organic sediment over the boulder bar surface and speed the revegetation process, inundation of the bar surface, at least in one locality, appears to have stripped fines that had been brought to the surface by burrowing ant colonies (Figure 12b). Consequently, floods over the bar surfaces may in places be slowing the revegetation of the boulder bars. Brush purposefully laid down on the upper ends of a boulder bar in Reach 16 (just downstream of bridge) may help trap fines and speed the revegetation process.

The coarseness of the boulder bars limits the degree of bank erosion. Bank erosion was mapped along only 12 percent of the channel banks with much of this merely surface scour and not likely reflecting active bank retreat. Interestingly, however, the amount of bank erosion is similar to that mapped along Phillips Brook (Table 3). The limited erosion on Phillips Brook may be the result of the stream's energy being dissipated across wide low floodplain benches (see Section 2.6 below). On Nash Stream the high energy resulting from boulder bar confinement, berms, and channel straightening would be expected to result in more severe bank erosion except the bouldery banks resist erosion well.

2.5b Log driving dams

The legacy of the log drives preceding the 1969 flood is expressed in the extensive historic sedimentation behind two deteriorating wooden crib dams (Figure 13 and Table 3). The old dam that impounded Nash Bog Pond Dam is not included because the mapping of channel features begins just downstream of this point. Organic-rich, laminated silts deposited behind the two dams occur along slightly more than 9 percent of the stream channel. A bed of waterlogged wood including sawn logs is buried and exposed at the base of the silt banks, testifying to the historic age of the sediments.

Evidence that the impoundments behind the dams extended further upstream than the exposed organic-rich silts comes in the form of broad areas of sparse tree growth, extensive wetlands, and a brownish tone on aerial photographs (as opposed to the sparsely vegetated boulder bars with a whitish tone) (Appendices 3 and 4). Gravel bars and frequent channel avulsions characterize the upstream half of the former impoundments where lower gradients and loss of confinement are first encountered (Figure 14a). Channel incision into the organic-rich sediments in the lower half of the impoundment areas has exposed at least 6 rooted tree stumps (Figure 14b and Table 3). The presence of rooted stumps within the center of the channel indicates the stream has nearly returned to pre-dam levels but not, necessarily, an identical position.

2.5c Islands and bars

Nash Stream's flow is split around islands along slightly more than 25 percent of the stream's length (Table 3). In many cases, the smaller side channels are nearly dry during low flow periods, but likely provide important rearing habitat. The presence of islands along 11 percent of Phillip Brook's length suggests that the greater prevalence of islands along Nash Stream are the result of the 1969 flood carving new flow paths and/or new meanders forming along stream sections straightened after the flood (see Section 2.5 e below). In most cases, islands along Nash Stream are large, well forested and irregularly shaped (Figure 15a) as they represent areas of undisturbed floodplain cutoff from the rest of the floodplain after the formation of a breakout meander (see Section 2.4 above).

In contrast, the islands in four locations are narrow, poorly vegetated features with edges that are extremely straight and parallel (Figure 15b). In addition to their uniform shape, timber cribbing is found along the banks of the islands, suggesting they are artificially constructed features. The artificial islands separate the main channel from a side channel that are connected at the upstream end and by small channels cutting diagonally across the islands. The small diagonal channels probably formed after construction of the islands and are typically largest at the upstream end of the island and generally smaller downstream, if present at all. The artificial islands were constructed prior to 1969 and survived the dam break flood (Appendix 3). Although their exact purpose is unknown, the artificial islands are referred to here as sluicing islands because they may have been used to sluice logs more easily along the channel. Two of the islands occur immediately downstream of the two log driving dams.

While the islands have some, if not considerable, tree growth, unvegetated gravel bars are also common along Nash Stream. Several types of bars are present (e.g., point bars, delta bars, mid-channel bars) (Figure 16) along less than 25 percent of the stream's length (Table 3). The bars tend to occur most prominently at locations where the sediment transport capacity of the stream drops rapidly, such as at the downstream ends of straightened segments, upstream end of impounded areas, and areas where flow confinement is lost (e.g., downstream of boulder bars or berms). Gravel bar deposition is also prominent on Phillips Brook with a greater percentage of point bars compared with Nash Stream (Table 3). This may reflect that the reformation of a meandering planform

on Phillips Brook is further along than on Nash Stream where the channel has been more recently disturbed by the 1969 flood and post-flood straightening.

2.5d Bankfull benches

Narrow floodplain benches are inset within higher boulder bars and floodplains along less than 5 percent of the channel's length (Table 3). The floodplain benches, primarily found along straightened sections of channel, may have originally been bars that have accreted laterally to the channel margins. In other locations the floodplain benches are remnants of the old channel bed that was abandoned as the channel shifted laterally into the opposite bank or when a portion of an overwidened channel incised slightly, leaving a portion of the channel bed slightly elevated as a floodplain bench. The lateral extent of the benches represents the amount of channel narrowing that has occurred along the overwidened channels, with the new channel dimensions representing the emerging bankfull width of the channel.

In addition to the lateral accretion and narrowing of the channel, a vertical accretion and revegetation process has also begun whereby smaller shrubs and trees colonize the surfaces and enhance the trapping of finer grained sediments on the bankfull benches. While vertical accretion of the fine sediments trapped on the benches may eventually raise the surfaces to the floodplain or bankfull elevation, the occasional presence of small narrow gullies cut into the benches by high velocity flows indicate the floodplain surfaces have yet to reach the bankfull elevation. Consequently, the edge of the bankfull benches may accurately delineate the bankfull width of the channel but not necessarily the bankfull depth. The widespread presence of bankfull benches along Phillips Brook (Table 3) reflect that Phillips Brook, having undergone channel straightening longer ago than the 1969 straightening of Nash Stream, is further along in the evolution of a narrower bankfull channel. In addition to the greater length of time since channel disturbance, boulder bars do not confine the flows along Phillips Brook, so conditions are more conducive to the lateral accretion of sediments within the overwidened channels.

2.5e Reformed meanders

Both islands and bars are associated with new meanders that have reformed along artificially straightened sections of the channel. Given their shorter length compared to meandering flow paths, straightened channels have a greater slope and, therefore, generate greater stream power. Consequently, new meanders have a propensity to reform along straightened channels because flow escaping the channel does so with sufficient force to scour a new channel across the floodplain. Flows can escape the channel at hard bends that connect two straightened segments with different orientations (Figure 17a). Flows can also escape the channel where the channel becomes clogged by log jams and ice jams or where sediment backfills the channel and reduces the bank height, enabling high velocity flows to cross the floodplain. Meanders formed in this way are referred to as "break outs" as they form where flow leaves the channel and breaks out over the floodplain. An island is typically formed between the abandoned channel and new

"break out" meander, and a gravel bar is also typically present on the inside bend of the new meander (Figure 17a).

Meanders also reform when bank erosion occurs along one bank due to the deflection of flow around point bars and side bars deposited on the opposite bank of the straightened channel (Figure 17b). Meanders formed in this manner are most prevalent at the upstream ends of the impoundment areas (see Section 2.5b above), because the loss of sediment transport capacity entering the lower gradient impoundment areas leads to bar deposition in these areas. On Nash Stream, meanders formed in this way tend to be subtle features of low amplitude, while those formed by breaking out onto the floodplain are much larger and more pronounced.

2.5f Wood and pools

While over 90 percent of the stream channel is mapped as pool-riffle morphology, much of the channel appears as a plane bed system. Deep pools are scarce along the 9 mi of stream channel and they often occur in close association with bedrock, which is found along less then 1 percent of the stream (Table 3). Pools, not always of high quality, often occur around large boulders that are typically found in the steepest most confined sections of the stream (see Section 2.7 below). Individual boulders, however, were not mapped separately as part of the channel features mapping. Large woody material is scarce along the channel, because mature vegetation is growing along only 20 percent of the left and right banks of the stream (Table 3). The scarcity of pools is also due to the high stream power generated in the confined and straightened channels that tends to wash out any developing pools and reduces the potential for wood retention in the channel.

2.6 Topographic surveys and substrate particle size analysis

The purpose of the topographic surveys and substrate particle size analysis was three fold: 1) further characterize the conditions of the four identified channel types (see Section 2.7 below); 2) establish a regional curve for Nash Stream (see Section 2.8 below); and 3) guide future restoration designs (see Section 4.0 below). Detailed topographic surveys were completed with a Sokkia Set 5 total station along portions of 14 channel segments on Nash Stream; one to two cross sections were surveyed within each segment on Nash Stream for a total of 19 cross sections (Appendix 5). Two areas were surveyed on Phillips Brook with three cross sections completed at each site. Channel cross sections were used to establish the bankfull channel width, mean and maximum depth, and width:depth ratio. Selected representative cross sections were included in the regional curve analysis where well-developed bankfull indicators were present (see Section 2.8 below). 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 5 were collected at each survey site using standard pebble count procedures (Wolman, 1954). The data from the longitudinal profiles and substrate particle size analysis are useful for calculating bankfull shear stress and sediment entrainment thresholds, essential values for determining stream sensitivity, guiding restoration design, and sizing in-stream structures.

2.7 Channel classification

Four primary channel types have been identified as a result of the geomorphic assessment tasks described above: 1) confined channels; 2) slightly confined channels; 3) channels within impounded areas; and 4) unconfined channels (Appendix 6). Confined channels are those where the banks on both sides of the channel are higher (sometimes much higher) than the bankfull elevation. The confining banks are typically boulder bars or glacial terraces, but in some instances may be artificial berms built after the 1969 flood. Flows greater than the bankfull condition remain within the channel and the high stream powers thus created result in the bouldery channel bottoms that typify this channel type. Due to the confinement, width:depth ratios tend to be lower than the other channel types. Partially confined channels are similar to confined channels except that a bankfull bench is present between the confining banks. Although all of the flow energy is not contained within the channel, flow energy remains high and narrow gullies scoured across the bankfull benches. Partially confined channels are generally in a transitional state from a high width:depth ratio to a low width:depth ratio as the channel narrows and approaches an equilibrium bankfull width. This channel type is also characterized by the emergence of low-amplitude meanders as flow is diverted around the emerging bankfull benches. Channels within impounded areas are completely unconfined at the upstream ends with high width:depth ratios, large gravel bars present, and flow often split into multiple flow paths. The downstream ends are incised into impoundment sediments that are easily erodible, so, unlike the confined and partially confined channel types, high channel sinuosities develop. Breakout meanders with high width:depth ratios characterize the unconfined channel type with gravel bars and islands separating the newly formed high-amplitude meanders from the abandoned artificially straightened channel. Over time, the width:depth ratios would be expected to decrease as the gravel bars become vegetated and the vertical accretion of fines occur.

2.8 Regional curve analysis

Regional curves establish a relationship between the bankfull dimensions of a channel (i.e., channel width, depth, and area) at a given point along a stream and the drainage basin area upstream of that point. For a given drainage basin area, the channel dimensions at a particular location can be predicted once a regional curve is established from measurements of bankfull dimensions from other sites encompassing a wide range of drainage areas. A regional curve developed for New Hampshire is based on several sites around the state where the channel and watershed are believed to be relatively undisturbed, and thus the channel dimensions representative of equilibrium conditions (Figure 18a). Comparing the NH regional curve with the six surveyed cross sections on Nash Stream with well developed bankfull indicators shows that the regional curve predicts reasonably well the bankfull width of the Nash Stream channels, particularly those with larger drainage areas. For larger drainage areas, the bankfull depth and area on Nash Stream are consistently less than would be predicted by the regional curves. This is consistent with the findings that the lateral accretion of bankfull benches and bars has resulted in the development of the ultimate bankfull width, but that vertical accretion has not yet sufficiently progressed to accurately reflect the bankfull depth (see Section

2.5d above). Perhaps this is due to excess shear stress within the characteristically confined and straightened channels of Nash Stream that maintain channels with a high width:depth ratio.

Of the 19 channel cross sections surveyed on the mainstem of Nash Stream, six were chosen for inclusion in the development of a provisional regional curve of the Nash Stream mainstem (Figure 18b). These curves yielded regression equations for bankfull width, mean depth and cross-sectional area. The R-value for channel width was 0.93, which further verifies that the bankfull width dimensions on Nash Stream are approaching an equilibrium condition where strong bankfull indicators are present. Cross-sectional area, with an R-value of 0.87, had a similarly strong relationship with drainage area. The high R-values mean that drainage area can be used to predict channel width and cross-sectional area in a reasonably precise manner elsewhere on Nash Stream if the drainage area is known. Relationships between drainage area and mean channel depth, however, are not well developed as reflected in the low R-value of 0.19 (Figure 18b). The poor correlation between bankfull depth and drainage area indicates that the vertical accretion of bars and bankfull benches is ongoing and is in various stages of completion along Nash Stream. Therefore, drainage area cannot be used to precisely predict mean bankfull depth along the mainstem.

3.0 SELECTION OF RESTORATION OPTIONS

The long history of log driving, the 1969 dam break flood, and post-flood response have all led to severe physical habitat degradation along most of Nash Stream. In-channel wood and boulders are scarce because these were removed during these past activities and events. In addition, the high stream energy that persists due to channel confinement and straightening ensures that wood recruited into the channel is quickly removed. Wood recruitment to the channel is also severely limited by the slow growth of trees on the boulder bars and impoundment sediments along the channel margins. Mature vegetation is present along less than 25 percent of either bank and rarely along both banks simultaneously (Table 3 and Appendix 4). Without the in-stream structure that boulders and wood provide, pools and other cover elements are rare along Nash Stream. The amount of wood and occurrence of pools on Nash Stream is much lower than on streams of comparable size elsewhere in New Hampshire (John Magee, NH Fish and Game, written communication, 2009). Given the low fertility of soils on the boulder bars and the high stream energy, the recruitment and retention of wood in the channel is not likely to occur for decades without restoration.

The 95 segments delineated with the assessment data (see Section 3.1 below) form the basis for developing and evaluating restoration options that will lead to stream equilibrium and sustainable improvements in aquatic habitat. The most appropriate restoration option for each segment was identified through a seven step process detailed below: 1) segment characterization; 2) restoration needs; 3) restoration treatment options; 4) treatment prioritization; 5) determining appropriateness; 6) cost effectiveness; and 7) treatment selection. The selection of restoration options through this seven-step process led to the development of several Excel tables that are compiled as individual tabs in the

Summary of Overall Rankings (Appendix 7), each described in the *Explanations* table. The restoration ranking process is meant to provide guidance in the selection of which segments to restore and the treatments to be used. However, final decisions by the interested stakeholders must also consider: 1) the need to vary treatments along the length of the stream; 2) the potential positive and negative effects of treatments on adjacent reaches; 3) additional information not captured by the rankings summary (Appendix 7); and 4) best professional judgment.

3.1 Segment characterization

Designating stream segments along the channel (Appendix 1) is useful for identifying restoration options because a single restoration design can usually be applied to the entire length of a given segment. The results of the geomorphic assessment were used to define 95 segments, representing distinct morphological elements along the channel such as a mid-channel bar, artificially straightened section of channel, break-out meander, or presence of a bankfull bench. 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 16 is designated as Segment 16c.

The physical characteristics and channel type of each of the 95 identified segments are detailed in the *Segment Characterization* table (Appendix 7). A channel can still be classified as confined even when the bank heights are recorded as 0-4 ft if the low bank height is the result of a narrow bench that separates the channel from a high confining bank that is still within 10 ft of the river channel. Further information on the types, distribution, and exact location of features within each segment can be gleaned from the GIS data (Appendices 1 and 4).

3.2 Restoration needs

With the geomorphic character of each segment defined, the need for restoration within the segment was quantified by ranking the degree to which each segment possessed eight geomorphic and habitat conditions typically associated with streams that have, or can form over time, high-quality physical habitat. A rating scale (ranging from 0 to 5) for each geomorphic and habitat feature, as outlined below, was used to quantify the segment condition, with a higher score reflecting a greater need for restoration. In other words, a high score generally reflects that habitat quality is poor under current conditions; in the case of Condition 7, a high score indicates that the segment has little capacity for self-adjustment or the ability to develop improved habitat conditions over time.

Condition 1 - Particle size segregation

0 = presence of large boulders, fine sediment deposited on floodplain and channel margin with coarser sediment in thalweg, presence of active bars

3 = 2 out of 3 present
5 = no boulders, no floodplain access, no active bars

Condition 2 - Flow complexity

0 = fast deep, fast shallow, slow deep and slow shallow flows all present (needs to contain deep pools and good nursery habitat)
3 = missing slow shallow (nursery) or slow deep (eddies) flow
5 = almost entirely fast shallow flow (plane bed) with no nursery habitat

Condition 3 – Quality of pools

0 = a few good deep pools
3 = one deep pool or several shallow pools
5 = no pools

Condition 4 - Wood in channel

0 = plentiful wood in channel
3 = four or more pieces of wood in channel
5 = no wood in channel

Condition 5 - Floodplain access

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

Condition 6 - Meander development

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

Condition 7 - Capacity for adjustment

0 = stream transporting bedload, capable of transporting bank material and adjusting planform morphology, 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, 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

The *Needs* table was developed to tabulate each segment's score for each of the eight categories described above (Appendix 7). The *Segment Characterization* table (Appendix 7) and GIS shapefiles (Appendix 4) were the primary data sources for assigning scores. A total needs score, included in the *Segment Characterization* table (Appendix 7), was calculated by summing all eight individual scores for each segment. Segments with a total needs score of 32 or greater are considered high priorities for restoration.

3.3 Restoration treatment options

A finite number of treatment options are available for restoring channel equilibrium and aquatic and riparian habitat in any given watershed. For Nash Stream, a list of 17 possible restoration treatments was created that are believed effective in addressing the identified geomorphic and habitat needs (Appendix 7 – *Explanations* table). Design typicals for most of the treatment options were created that show construction details, list materials needed, describe treatment goals, illustrate potential effects on channel morphology, and estimate costs (Appendix 8). A unit cost per linear foot of stream was estimated based on the design drawings, which were created for a chosen segment with a specific length. Some of the listed treatments embody multiple techniques that can be refined during the detailed design phase. For example, a range of bank stabilization methods could be defined as "Bank bioengineering" with a decision to use fascine bundles, root wad revetments, or log deflectors delayed for a later time. The list of possible treatments includes the "Do nothing" alternative along with passive approaches such as "Riparian plantings" and more active approaches such as "Bank cutting/Flow diversion".

Each restoration treatment was rated on its effectiveness at potentially improving conditions related to the eight geomorphic features described in Section 3.2 above. The 17 restoration options were scored on a scale from 0 to 5, with higher numbers representing a greater effectiveness to improve the specified geomorphic conditions. A group of five project partners involved in the planning process each rated the treatments individually; the project partners were Dr. John Field (Field Geology Services), Mr. Nicolas Miller (Field Geology Services), Dr. Maeve McBride (SEEDS), Mr. James McCartney (Trout Unlimited), and Mr. John Magee (NH Fish and Game). The individual ratings were discussed as a group, the scores adjusted as discrepancies in the rating process were clarified, and a final average calculated from the individual scores to yield the final effectiveness ratings (Appendix 7 –*Treatments* table). The average scores for each geomorphic condition were added together to arrive at a total effectiveness score for each treatment option. The highest total score is for mid-channel log jams, indicating that this treatment is the most effective at addressing multiple geomorphic needs simultaneously. However, other treatments may be more effective at addressing a specific geomorphic need (e.g., riparian plantings are more effective at developing a canopy than mid-channel).

3.4 Treatment prioritization

To select the restoration treatment that best addresses the geomorphic needs of a given segment, the treatment effectiveness scores (*Treatments* table) were compared with the geomorphic needs of each segment (*Needs* table) (Appendix 7). In order to focus on those segments with the greatest needs and to simplify the comparison of numerous segments with varying needs, a threshold value of 5.0 was applied to the *Needs* table such that only geomorphic needs with a score of 5.0 were considered for treatment (see *Needs* table - "threshold needs" column). The threshold value could always be reduced in the future to consider treatment for less acute geomorphic needs. Similarly, to assist in the selection of only the most effective restoration options, a threshold value of 3.0 was set for the treatment effectiveness scores; those treatments with a score of less than 3.0 for addressing a particular need were not recommended as a treatment for that need (see *Treatments* table).

An automated process was developed in Excel to determine which treatment options effectively met (i.e., treatment effectiveness score of 3.0 or higher) a significant geomorphic need (i.e., threshold needs score of 5.0) within a given segment. For each segment, the number of significant geomorphic needs that can be effectively treated by a given restoration option is recorded in the *Recommendations* table (Appendix 7). All of the treatments that address at least one geomorphic need in the segment are listed in the table's "recommended treatments" column. No single treatment effectively deals with more than five geomorphic needs in any given segment, because either no more than five needs meet the threshold value of 5.0 or the given treatment does not effectively address all of the threshold needs; a combination of both factors is also possible.

The cumulative total listed in the final row of the *Recommendations* table provides a sense of the treatment's likely effectiveness along the entire length of the stream. Mid-channel log jams are the most frequently recommended treatment (recommended for use in 85 segments) with riparian plantings and bank bioengineering the least recommended treatments (recommended for seven segments each). A visual scan of the *Recommendations* table also shows mid-channel log jams typically addressing the greatest number of geomorphic needs within segments where this treatment is recommended.

If a specific geomorphic need becomes the primary focus of restoration, the recommended treatments that best address that condition can be identified by referring back to the *Treatments* table to determine which treatments exceed the treatment effectiveness threshold of 3.0 for the need of interest. In general, however, implementation of any of the recommended treatments in a given segment should improve the geomorphic condition of the stream in some way. The treatment addressing the most needs would presumably provide the greatest improvements to channel condition.

A clearer picture of the treatment option that best meets the broadest range of needs in a given segment can be drawn from the *Treatment scores (Recommended)* table

(Appendix 7) 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 18.0 (referred to here as the recommendations score) for mid-channel log jams in Segment 16F can be reconstructed by first referring back to the *Needs* table and noting that flow complexity, quality of pools, wood in channel, capacity for adjustment, and riparian vegetation are the five geomorphic conditions that exceed the needs threshold of 5.0 in Segment 16F. The ability of mid-channel log jams to address each of these conditions is indicated by the effectiveness scores recorded in the *Treatments* table. For mid-channel log jams, the sum of the effectiveness score values for the five threshold needs in Segment 16F is 18.0 (i.e., 4.8 + 4.6 + 5.0 +3.2 + 0.4). (Note that the recommendations score can incorporate values from geomorphic needs for which the given treatment does not meet the threshold of 3.0). While the *Treatment scores (Recommended)* table calculates a recommendations score for all treatments, the *Recommendations* table must also be consulted to see which treatments are recommended for each segment based on the threshold values set.

A ranking of recommended treatments is possible by comparing the recommendations scores; the four highest priority treatments for each segment are listed in the *Treatment scores (Recommended)* table. Continuing with the example from Segment 16F, the recommendations score for mid-channel log jams is 18.0 and since this is the highest total in the segment, mid-channel log jams are thus the highest priority treatment. Bar apex log jams (score = 15.0), placed wood in channel (14.7), and bank cutting/flow diversion (14.2) are, in turn, the 2nd, 3rd, and 4th ranked priorities, respectively. While the possibility exists that a priority treatment could be listed in the *Treatment scores (Recommended)* table without being recommended in the *Recommendations* table, the likelihood of this occurring is considered very low given that recommended treatments that have met certain threshold values will, as a consequence, score high. A visual comparison of the two tables did not identify any such discrepancies.

The *Treatment scores (All)* table prioritizes restoration options without regard to thresholds and, thus, provides an opportunity to identify which restoration options best address the full range of geomorphic needs in a given segment, not just the threshold needs. The values in the *Treatment Scores (All)* table are derived for each treatment option by multiplying the needs score for each of the eight geomorphic conditions by the treatment's effectiveness score for that condition and then summing the eight resulting products. The calculation of all the values for 17 different treatments in 95 segments was simplified through matrix multiplication with the greatest value in a particular segment representing the highest priority restoration option. A visual inspection comparing the two *Treatment scores* tables reveals only minor differences in the prioritized treatments.

3.5 Determining appropriateness

While both *Treatment scores* tables recommend and prioritize several restoration options, the identified treatments are not always appropriate or feasible for the given segments. For example, berm removal, although frequently recommended for treatment

(see *Recommendations* table), can only occur in segments where berms are present. Similarly, chop and drop projects would necessarily be restricted to segments where a mature riparian buffer is present. These examples demonstrate some of the if-then statements that can be created to query the geomorphic characteristics of the segments (Appendix 7 - *Segment characterization* table). A series of queries described in the *Explanations* table were established to systematically identify which of the recommended treatments in a given segment are actually appropriate (i.e., can be implemented). Queries were established for all but five of the treatments: do nothing, boulder clusters, placed wood in channel, bank cutting/flow diversions, and mobile wood additions. These treatments were not queried because either the treatments were deemed appropriate in most settings or insufficient data exists in the *Segment characterization* table to discern between appropriate and inappropriate conditions.

The *Appropriateness* table assigns a value of "1" for those treatments that are appropriate for a given segment and "0" if the treatments are not appropriate. The results of the *Appropriateness* table were used to eliminate inappropriate treatments from the list of recommended treatments and to update the list to include only recommended treatments that are also appropriate (see the *Recommended and appropriate* table). Comparing the number of segments that a treatment is listed in the *Recommendations* table, and then in the *Recommended and appropriate* table, provides a sense of how significant the process of determining appropriateness is in reducing the number of treatment options under consideration during the restoration planning process. For example, chop and drop was recommended for 80 segments but the treatment is appropriate in only 26 of those recommended segments.

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 selecting the best treatment(s) to implement. For example, mid-channel log jams are the most frequently recommended treatment (Appendix 7 – *Recommendations* table), but their widespread application may not be feasible given the high costs of construction. Other less costly options may provide nearly the same benefits in terms of addressing geomorphic needs and, therefore, be more cost effective. For example, in Segment 17, chop and drop, a much cheaper treatment than mid-channel log jams, has nearly the same recommendations score (4.6 compared to 5.0) (see *Treatment scores (Recommended)* table). To evaluate the cost effectiveness of potential projects, the project partners rated the 17 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, and 5) improve conditions downstream of the project limits. Each of these attributes—some of which embody the geomorphic conditions described in Section 3.2 above—were rated on a scale of 0 to 5.0 with higher "stability" scores indicating a greater capacity for the treatment to bring about long-term stream channel stability.

The averages of the individual project partner scores and the aggregate total of the five attributes (referred to as the stability score) are presented in the *Cost effectiveness* table (Appendix 7). In addition to rating the five attributes related to channel stability, the perceived relative costs of the treatments 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 (*Cost effectiveness* table). Treatments with the higher cost effectiveness scores should not be construed as better restoration options for those segments in which they are recommended and appropriate. The high score for the do-nothing approach reflects more strongly the low up front costs of taking no action rather than the capacity of doing nothing to improve long-term channel stability. The cost effectiveness scores do, however, provide another guidance tool for project partners in the restoration planning process. The relatively high score for chop and drop points to the potential utility of this treatment in the 26 segments in which this option is recommended and appropriate. In contrast, the relatively low cost effectiveness score for mid-channel log jams suggests the high cost will limit its application to only a few of the 52 segments where it is recommended and appropriate despite the high stability score. The treatment rankings based on the cost effectiveness score are not segment dependent, so the rankings are the same for all segments.

3.7 Treatment selection

The "highest ranked treatment" column in the *Summary* table (Appendix 7) highlights the priority, or highest scoring, treatment identified in three different tables (*Treatment scores (Recommended)*, *Treatment scores (All)*, and *Cost effectiveness*), but also lists the ranking scores for other recommended treatments in each segment (based on the *Recommended and appropriate* table). Identifying the treatment of choice took into account how easily equipment could access a particular segment. An access score, determined through stream buffering in GIS, was assigned to each segment based on the segment's proximity to roads or other access points such as driveways, logging roads and bridges. A value of "5" was assigned to a segment if any portion of that segment was within 50 ft of an access point. Segments with an access score of "4" are between 50-100 ft from an access point, a value of "3" assigned to segments between 100-200 ft from an access point, "2" for segments between 200-300 ft from an access point, "1" for segments between 300-400 ft from an access point, and "0" for segments more than 400 ft from an access point.

For those segments with poor access (i.e., an access score of 2 or less), the priority treatment listed in the "treatment of choice" column in the *Summary* table is chop and drop if it is recommended and appropriate for the given segment, regardless of other higher priority treatments. For those segments where chop and drop was not recommended and appropriate then the treatment of choice is do nothing. All other treatments are not considered feasible where access is poor, because of the likely difficulties in bringing in heavy equipment to the site. In actuality, poorly accessed segments can be treated with mobile wood additions from upstream segments, but the automatic selection process is not capable of evaluating multiple segment restoration options. Where access is good (i.e., an access score of 3 or higher), all treatment options

are feasible to implement and the treatment of choice is listed as "pick from list", providing the decision makers with the flexibility to select from the highest ranked treatments or any of the other recommended and appropriate treatments. If the same restoration treatment is listed as the highest ranked treatment by all three methods, then that treatment is listed in the "treatment of choice" column, although other recommended and appropriate options can still be considered and selected based on other variables that are not embodied in the automatic selection process.

The highest priority segments for restoration are those with the highest needs score displayed in both the *Needs* and *Summary* tables. With the highest needs score of 37, Segment 16F could be ranked as the first segment that needs restoring, but the 17 segments with a needs score of 32 or higher are all considered as high priorities for restoration. Given the acute need for improvements to the geomorphic and habitat conditions of these segments, an "inspection needed" column was created in the *Summary* table to draw attention to high priority reaches with poor access for which the treatment of choice is designated as do nothing. For the two segments requiring "inspection" (Segments 10D and 1C), consideration might be given to other treatment options despite the poor access since the geomorphic needs are so great. Similarly, the "professional judgment" column recommends a "review" if the treatment of choice is do nothing, but one or more other treatment types are listed among the highest ranked treatments. This "review" occurs for segments with poor access and includes not only the two segments requiring inspection but also lower priority segments (i.e., needs score of 31 or lower).

3.8 Utilizing the restoration rankings

Without the seven-step process detailed above to rank treatment options, identifying the best of 17 treatment techniques to address eight geomorphic and habitat needs in 95 different segments would be a daunting task. Despite the useful results, however, the process is merely designed to provide guidance to the project partners who ultimately must make the final decision on the treatment options to be implemented. For restoration at the watershed level, the highest priority segments selected for restoration should not only lead to channel equilibrium 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 streams in northern New England. Consequently, the highest priority segments for restoration will likely be those where floodplain access, multiple side channels, or a meandering planform can be reestablished such that sediment storage can occur within the segment, simultaneously reducing sediment delivery downstream while creating aquatic habitat in the segment (e.g., flood flow refuge and rearing habitat in side channels and pool formation within recreated meanders).

Budgetary or other constraints to the implementation of the highest priority projects should not necessarily preclude implementation of less expensive or more easily completed restoration projects elsewhere. The seven-step 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") consistent with these plans can move forward more quickly in selected segments. The results of the restoration prioritization are a tool that will enable project partners and stakeholders to begin long-term planning and sequencing of restoration projects at the watershed scale.

4.0 DEVELOPMENT OF RESTORATION DESIGNS

Adopting an upstream to downstream restoration philosophy, the initial restoration design efforts on Nash Stream focused on the five upstream most segments (Segment 16F-17), three of which are high priority segments (i.e., needs score is 32 or higher). Use of the treatment prioritization tables (Appendix 7) to guide the final selection of treatment options in these five segments, as described below, demonstrates how the restoration planning process will be valuable on the remaining segments over the next several years. Despite access scores of 5 and 3, the likely difficulties in negotiating the steep bouldery terrain of Segment 17 and 16I, respectively, with heavy machinery precludes the implementation of the placed wood in channel option recommended by the "All needs" and "Recommended" scores (Appendix 7 - *Summary* table). Consequently, chop and drop, the prioritized cost effective option in both segments, was selected as the final treatment option.

Although the cost effectiveness ratio is relatively high, the "All needs" recommendation of bank cutting/flow diversion for Segment 16H was ruled out because of the relatively high absolute cost (despite the perceived benefits). The most cost effective option, mobile wood additions, was also ruled out because of potential concerns of wood migrating to the bridge at the downstream end of Segment 16F. Consequently, placed wood in channel, a treatment that partially buries logs in the channel so they are less likely to migrate downstream, was chosen as one of the final treatment options. Although not listed as one of the highest ranked treatments, boulder clusters was also selected from the list of recommended treatments to be implemented in conjunction with the placed wood, because of their relatively low cost and potential to sustain in-stream habitat improvements in a reach with a very high needs score of 35. A decision was also made to treat the boulder bar with felled trees to help trap organics and encourage the growth of vegetation.

Access to Segment 16G with its bouldery substrate is not as easy as the access score of 5 would suggest, so the "All needs" and "Recommended" priority treatment of mid-channel log jams was not practical. The cost-effective option of mobile wood additions was ruled out, because of concerns with the downstream bridge. Consequently, placed wood on bars, or in this case on the floodplain bench, was the final treatment option selected. The purpose of the placed wood is to trap fines on the bankfull bench and vertically accrete the surface, reduce scour across the floodplain bench, and concentrate more flow in the channel, especially during low flow periods.

Finally, many of the recommendations for implementation were chosen in Segment 16F with the highest needs score along the entire stream. The "All needs"

priority of bank cutting/flow diversion was not chosen but the same benefit of increased floodplain access will be achieved through berm removal as one of the selected treatments. The "Recommended" priority of placed wood in channel will be implemented in conjunction with a non-prioritized recommendation of rock weirs. The placed wood will provide cover in the pools created by the weirs. The weirs were deemed appropriate just upstream of the bridge to help keep flows aligned with the bridge opening by discouraging meander formation. Boulder clusters will provide smaller pools between the weirs. The "cost effective" option of riparian plantings will also be implemented on the rejuvenated floodplain that will no longer blocked by the berm.

Once the treatment options for the five segments were selected, a site visit was conducted with GPS equipment to precisely determine the number and location of trees and boulder structures to be added to the stream. Project staging and equipment access were also important focuses of the site visit. Final design drawings were subsequently prepared for each segment (Appendix 9) and incorporated into a NH Department of Environmental Services Standard Dredge and Fill permit. While the final designs do not adhere exactly with the list of highest ranked treatments in the *Summary* table (Appendix 7), the results of the restoration planning process do provide a strong framework for discussing all of the recommended treatments. After first considering the prioritized options, the ultimately selected options are those that best address the site-specific conditions and constraints.

5.0 CONCLUSIONS

A long history of log driving, including a large dam break flood in 1969, has left aquatic habitat along much of Nash Stream in a degraded state with few deep pools, poor particle size segregation, and limited riparian vegetation to shade the stream or provide wood recruitment to the stream. Boulder bars deposited during the 1969 flood and human straightening of the channel in response to the flood confine high energy flows to the channel, limiting the potential for natural stream channel recovery. The specific geomorphic needs to be addressed by restoration have been identified for 95 discreet channel segments identified during the assessment (Appendix 7). Design typicals have been created for 17 treatment options that each address a suite of geomorphic needs (Appendix 8). A restoration planning process was developed to link the restoration treatments with the geomorphic needs and, thereby, identify the restoration options best suited for each segment. The list of possible treatments can be further refined by considering whether: 1) a given treatment is appropriate for the segment under consideration (i.e., berm removal can occur only where berms are present), 2) heavy machinery can access the site to construct certain treatments, and 3) the benefits of the treatment are worth the cost of implementation. The restoration planning process will provide guidance in the selection of the final treatment options along the length of Nash Stream. Final restoration designs for the five upstream most segments (Appendix 9) include: 1) the use of chop and drop to add wood into the channel where access is poor but mature riparian vegetation is present, 2) placed wood in channel where access is good but downstream infrastructure might be threatened by mobile wood, 3) wood on bars (actually on bankfull benches) to encourage vertical accretion of fines and narrowing of

the channel, 4) berm removal to improve floodplain access and reduce stream power in the channel, 5) boulder clusters to form and sustain pools, and 6) rock weirs to form and sustain pools but also to maintain a straight flow path and prevent scour around nearby bridge adjustments. The assessment results and restoration planning process developed will remain useful in the coming years as restoration treatments are selected based on their ability to promote channel stability and sustain improvements to aquatic habitat.

6.0 REFERENCES

Field, J., 2006, Fluvial geomorphology assessment of northern Connecticut River tributaries: Unpublished report submitted to the Connecticut River Joint Commissions, Charlestown, NH, 58 p.

Wolman, M.G., 1954, A method of sampling coarse river-bed material: Transactions of the American Geophysical Union (EOS), v. 35, p. 951-956.

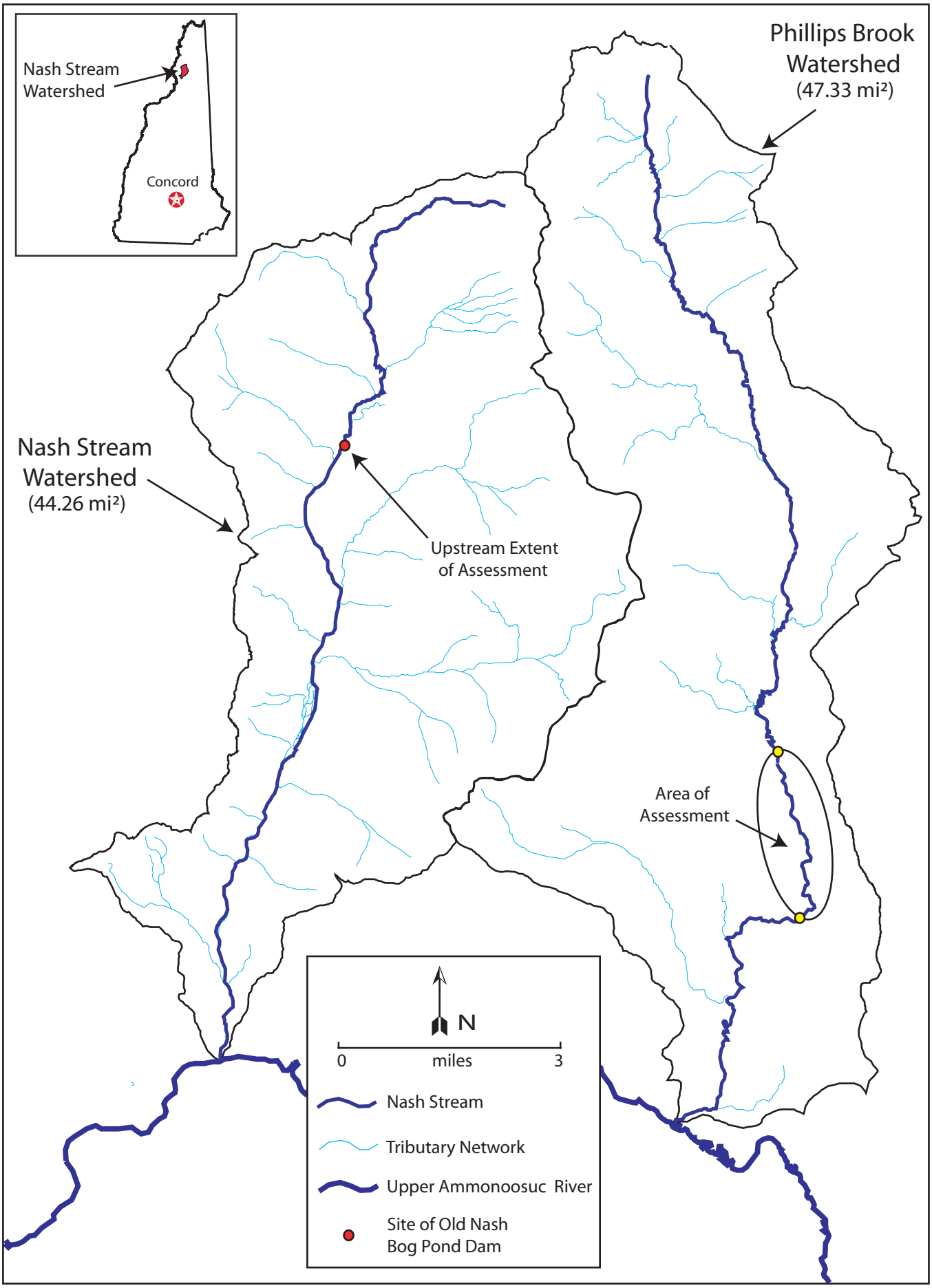
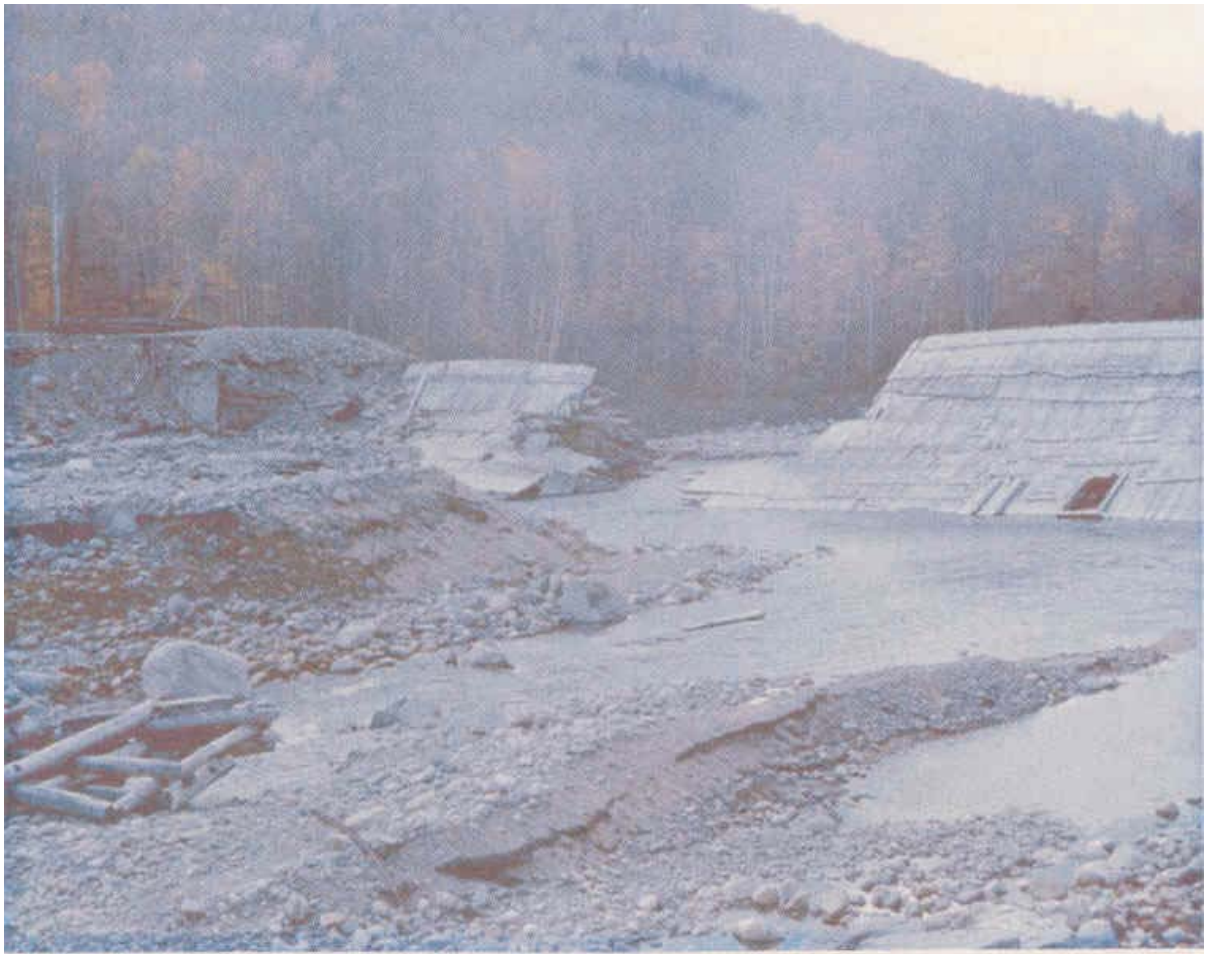


Figure 1: Watershed location map.

a)



b)

Figure 2: Dam breach photos from 1969 showing a) ruined dam and b) resulting impacts of flood on the stream channel.

Figure 3: Boulder bar with sparse vegetation (Reach 6).

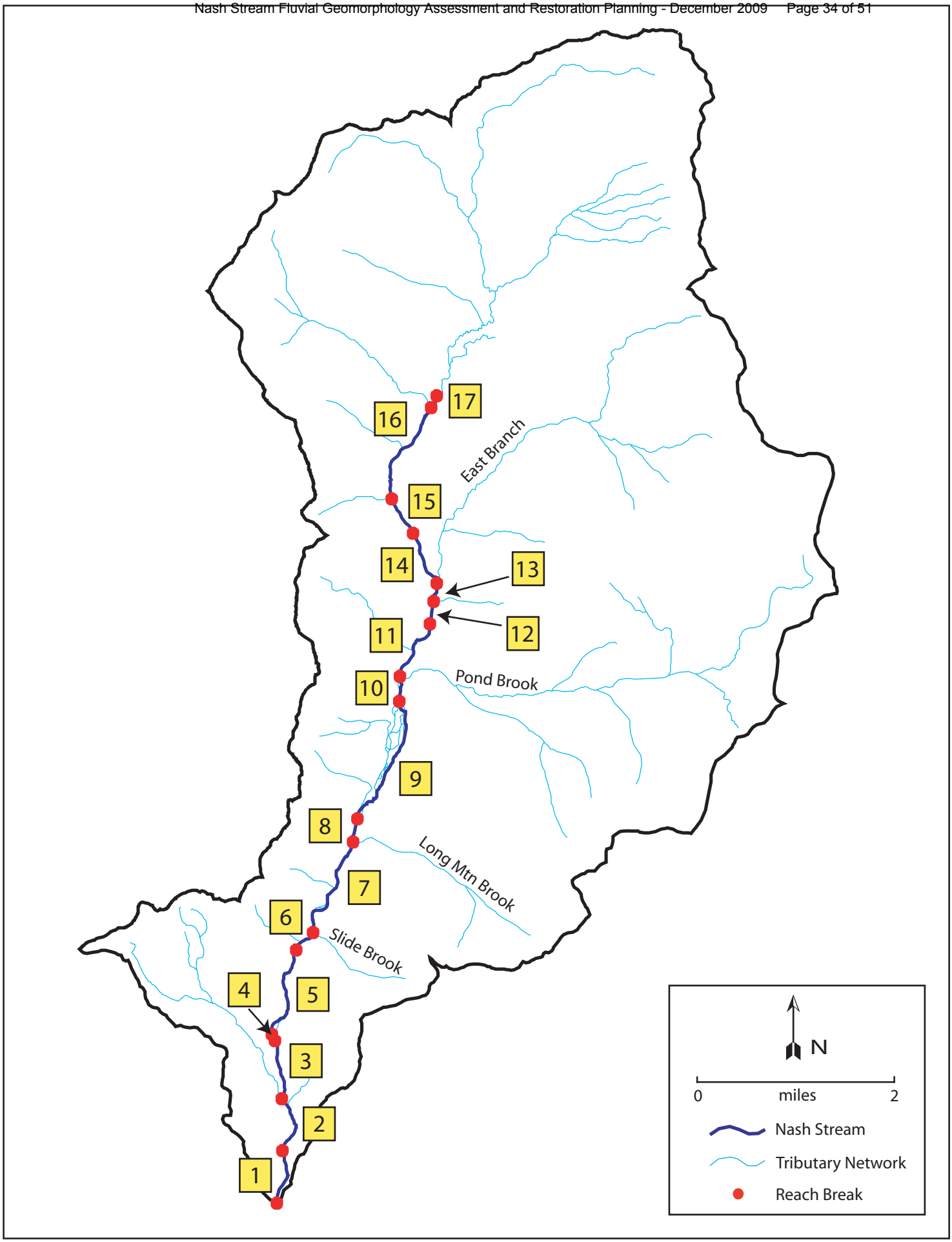


Figure 4: Reach location map.

Figure 5: Meander formation around log jam on tributary to Nash Stream.

a)

b)

Figure 6: Composition of stream banks along valley margins a) sand and cobbles (Reach 7) and b) glacial clay (Reach 2).

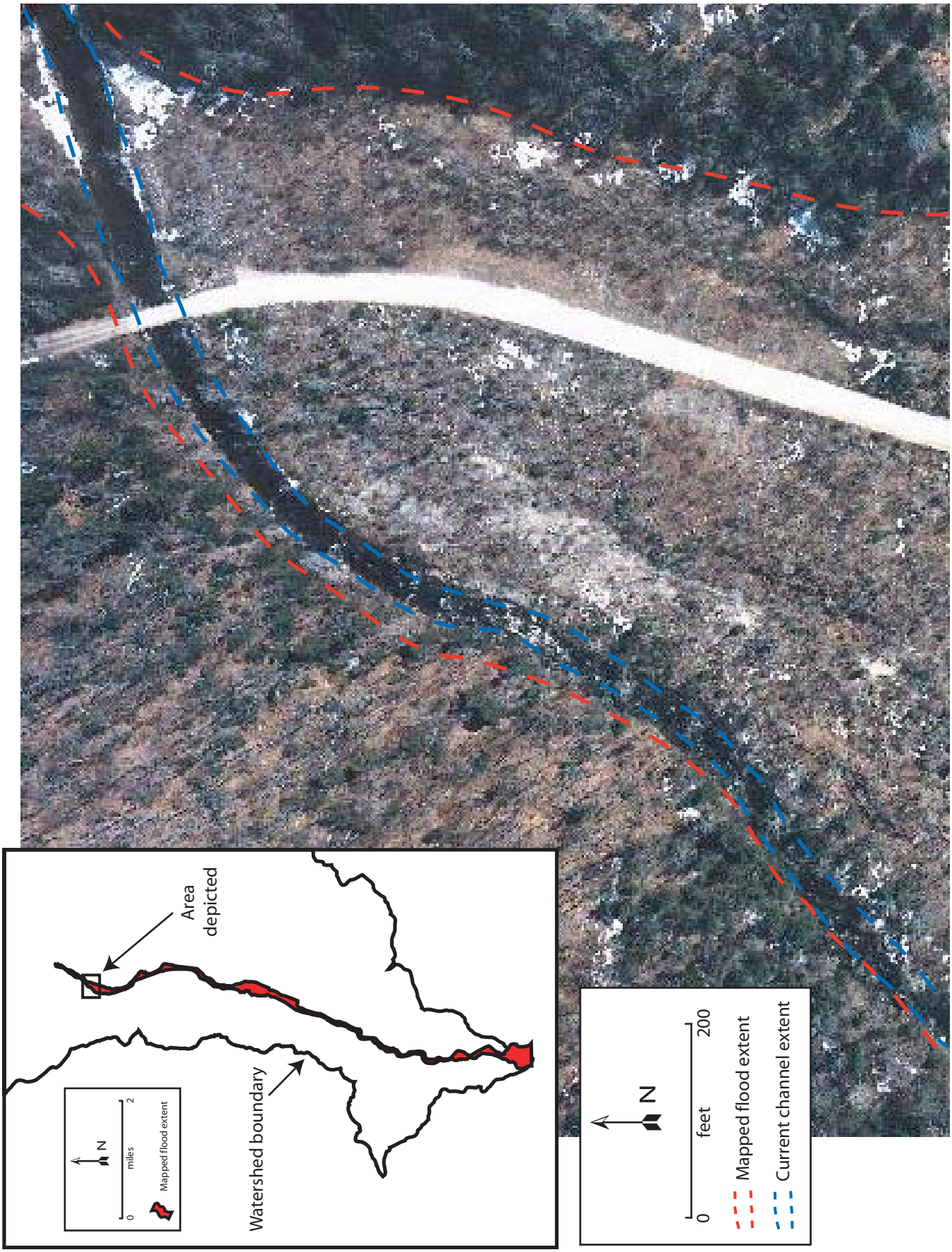


Figure 7: Extent of 1969 flood demarcated by limits of coniferous tree growth (Reach 16).

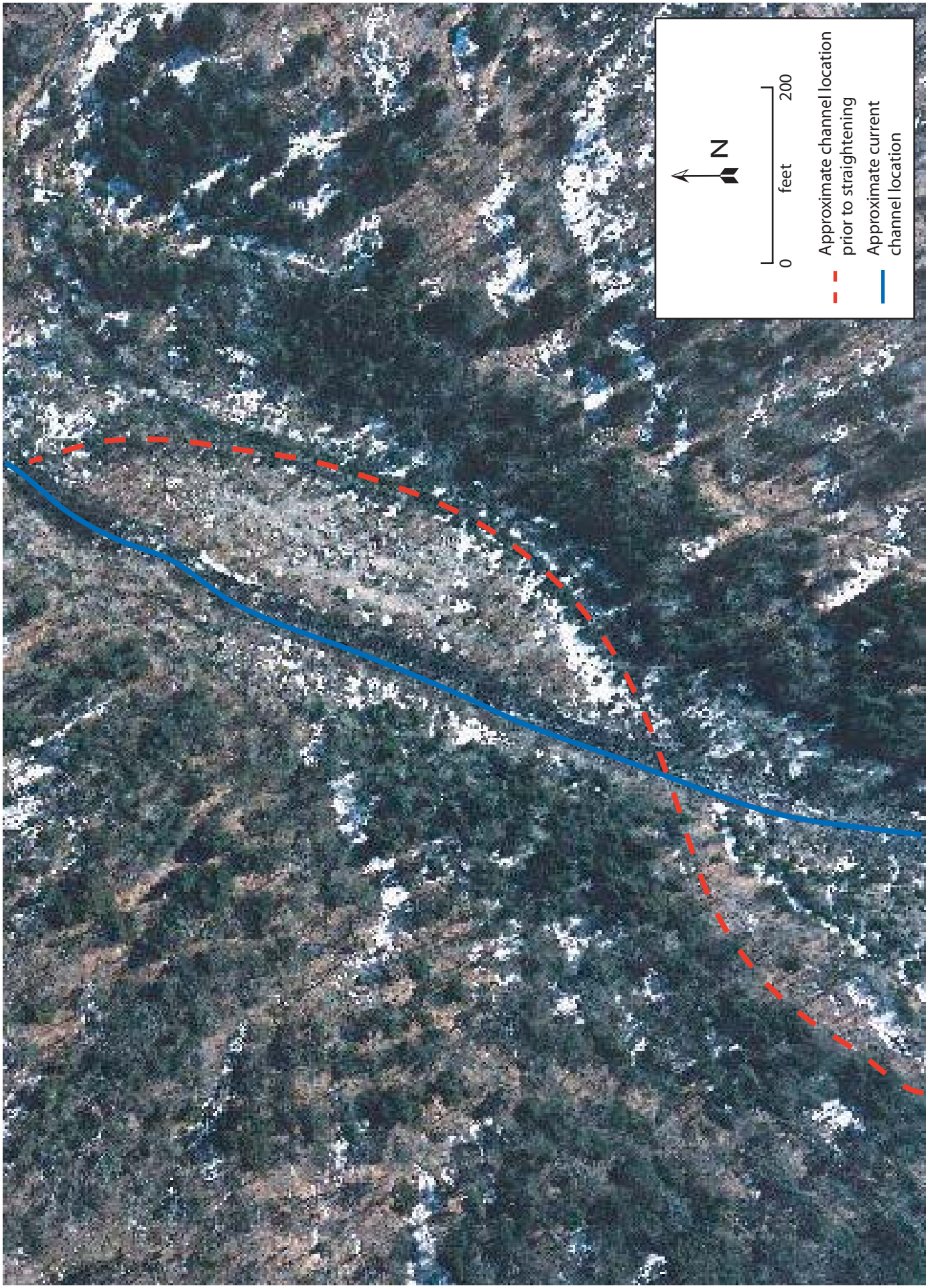


Figure 8: Meanders formed during 1969 flood and subsequently cutoff by channel straightening through boulder bars (Reach 16).

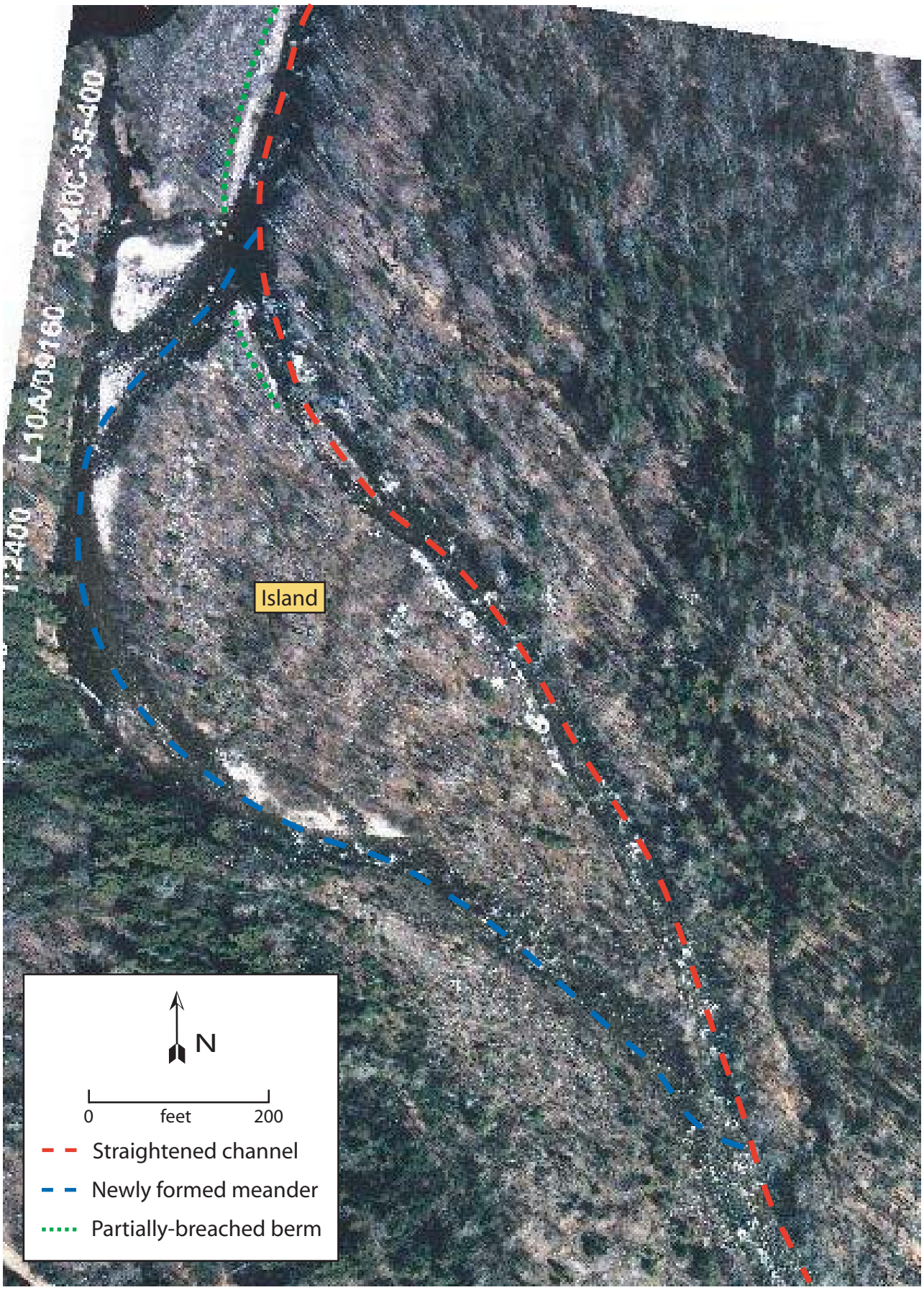


Figure 9: Meander formed along straightened reach (Reach 2).

Figure 10: Berm along low bank of Nash Stream.

Figure 11: High eroding bank of glacial outwash sediment (Reach 7).

a)

b)

Figure 12: Fine sediments brought to surface of boulder bars a) by burrowing ants but b) stripped away by floodwaters inundating the surface (man on left standing on stripped area, man on right standing on fine sediment deposit).

Figure 13: Old log crib dam (Reach 13).

a)

b)

Figure 14: Features behind crib dams include a) gravel bars and channel avulsions in the upper half of the impoundments and b) rooted tree stumps in the lower half.

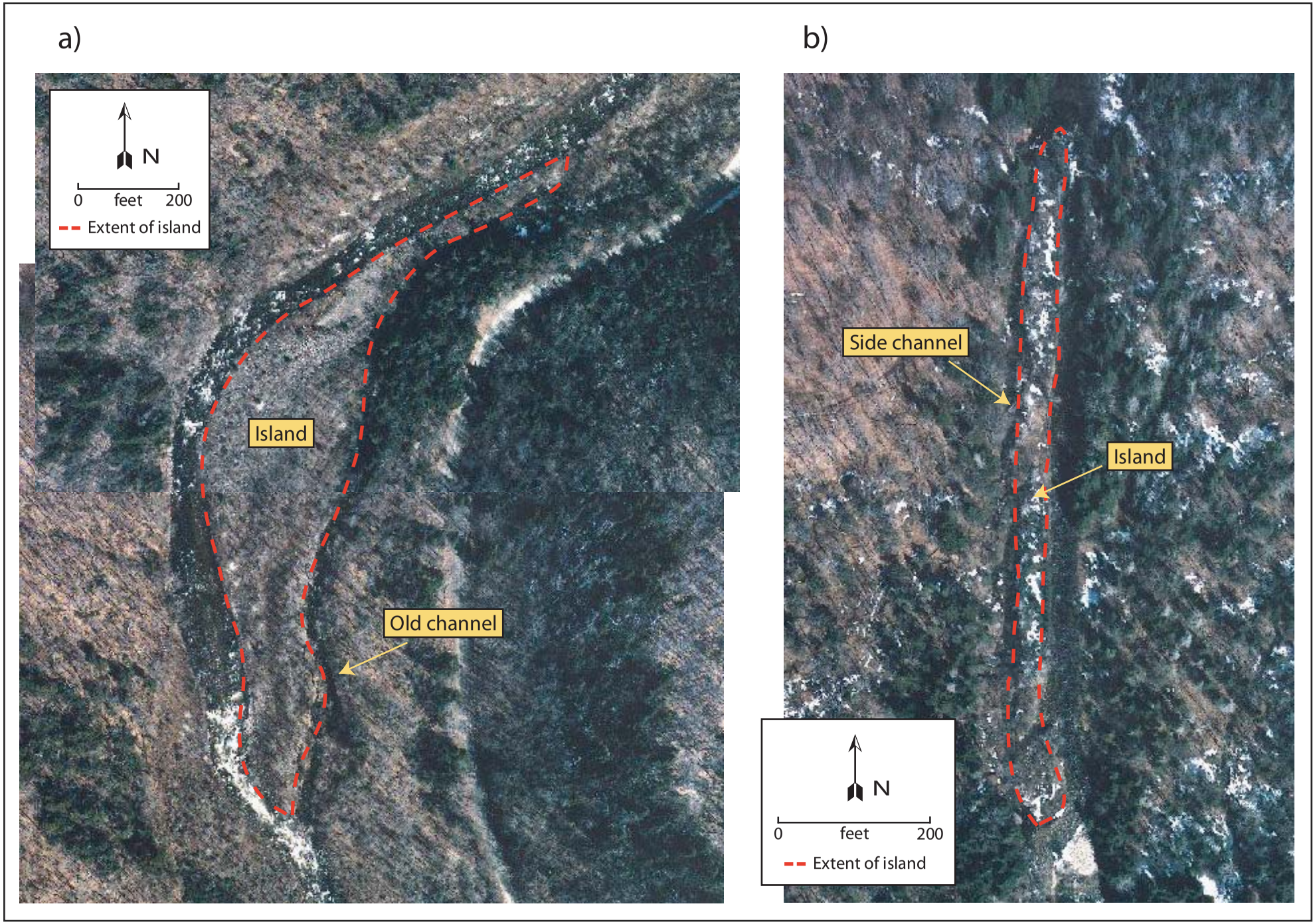


Figure 15: Islands along Nash Stream a) formed by creation of new channels tend to be large and irregularly shaped (Reaches 4 and 5) and b) formed by human construction, perhaps for sluicing logs, tend to be narrow and uniform in shape (Reach 16).

a)

b)

Figure 16: Gravel bars are of several types on Nash Stream, including a) mid-channel bars (Reach 9) and b) point bars (Reach 13).

a)

b)

Figure 17: Meanders reformed by a) break out where berm breached at hard bend connecting two straightened segments (Reach 2, aerial view of location also depicted in Figure 9) and b) flow diversion around point bar (Reach 9).

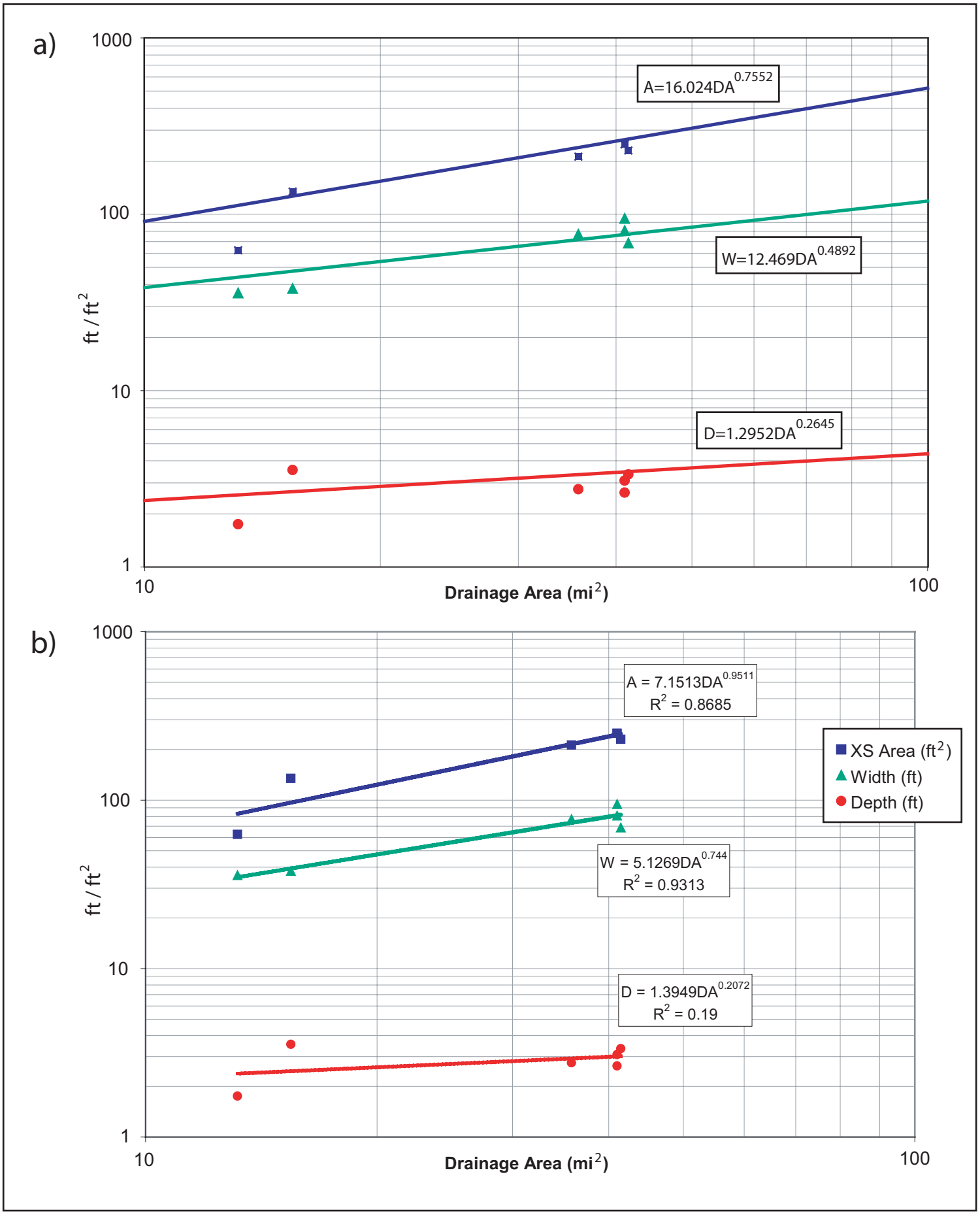


Figure 18: Hydraulic geometry curves for a) New Hampshire with Nash Stream data points shown and b) provisional curve for Nash Stream based on mainstem cross section data.

Reach	Drainage Area (mi^2)	Stream Length (ft)	Distance Upstream (mi)	Channel Gradient (%)	Percent Change	Valley Confinement*	Percent Change	Reason for Break†
17	10.9	828	9.4	2.42	-	9.3	-	CG, VC
16	14.8	5,772	8.3	1.54	-36	12.4	34	CG, VC
15	15.2	2,207	7.9	1.09	-29	9.7	-22	VC
14	15.6	3,212	7.3	0.78	-28	24.2	151	T
13	22.3	1,059	7.1	0.66	-15	10.4	-57	D
12	22.5	1,203	6.8	0.58	-12	8.2	-21	VC
11	24.0	3,582	6.2	0.61	6	18.7	126	T
10	32.9	1,408	5.9	0.50	-19	16.5	-12	VC
9	35.7	7,391	4.5	0.37	-27	13.5	-18	D, CG
8	35.8	1,327	4.2	1.58	333	5.4	-60	T
7	39.2	5,943	3.1	1.46	-7	5.4	-1	T, CG
6	40.3	1,377	2.9	2.32	59	4.8	-10	CG
5	41.1	5,265	1.9	2.28	-2	5.5	15	CG
4	41.1	350	1.8	2.57	13	5.6	1	CG, VC
3	41.4	3,243	1.2	1.88	-27	10.3	84	P
2	43.8	3,217	0.6	1.65	-12	11.9	16	VC
1	44.3	3,000	0.0	0.97	-41	42.2	254	-

*Valley confinement is the ratio of average valley width to reference channel width (from the NH regional curve)
†Reason for reach break: D = former dam site; CG = channel gradient; VC = valley confinement; T = major tributary confluence; P = planform

Table 1. Reach characteristics.

	Maximum Migration (ft)			Maximum Migration Rates (ft/yr)		
Reach	**1955-70**	**1970-86**	**1986-2003**	**1955-70**	**1970-86**	**1986-2003**
17	240	150	50	16	9	3
16	510	90	80	34	6	5
15	120	70	30	8	4	2
14	50	70	60	3	4	4
13	90	90	90	6	6	5
12	50	90	60	3	6	4
11	290	360	80	19	23	5
10	180	110	30	12	7	2
9	370	320	90	25	20	5
8	420	390	50	28	24	3
7	430	320	30	29	20	2
6	320	190	40	21	12	2
5	420	190	40	28	12	2
4	420	360	10	28	23	1
3	290	250	30	19	16	2
2	310	130	60	21	8	4
1	490	80	50	33	5	3
Average	294	192	52	20	12	3

Table 2. Channel migration from historical aerial photographs.

Channel Statistics

	Nash Stream	%	Phillips Brook	%
Stream length (feet)	50,384		15,026	
(miles)	9.54		2.85	
Riffle-pool morphology	45,759	90.8	13,571	90.3
Step-pool morphology	4,625	9.2	1,455	9.7

Depositional Features

	Nash Stream						Phillips Brook			
	LB (ft)	%	RB (ft)	%	Total (ft)	%	LB (ft)	%	RB (ft)	%
Point bars	2,858	5.7	1,937	3.8	4,795	4.8	1,382	9.2	1,301	8.7
Benches	739	1.5	1,433	2.8	2,172	2.2	11,118	74.0	11,461	76.3
Side bars	584	1.2	1,975	3.9	2,559	2.5	0	0.0	0	0.0
Delta bars	257	0.5	154	0.3	411	0.4	0	0.0	0	0.0

	Nash Stream (ft)	%	Phillips Brook (ft)	%
Mid-channel bars	2,658	5.3	1,444	9.6
Islands	12,705	25.2	1,579	10.5
Diagonal bars	1,268	2.5	0	0.0

Bank Stability

	Nash Stream						Phillips Brook			
	LB (ft)	%	RB (ft)	%	Total (ft)	%	LB (ft)	%	RB (ft)	%
Stable	44,565	88.5	44,297	87.9	88,862	88.2	12,629	84.0	13,103	87.2
Eroding	5,819	11.5	6,087	12.1	11,906	11.8	2,198	14.6	1,923	12.8
Armored (Rip-Rap)	281	0.6	263	0.5	544	0.5	199	1.3	0	0.0

Bank Height

	Nash Stream			
	LB (ft)	%	RB (ft)	%
0 to 4 ft	27,160	53.9	21,869	43.4
5 to 9 ft	19,264	38.2	20,136	40.0
10 to 19 ft	3,960	7.9	4,775	9.5
20+ ft	0	0.0	3,604	7.2

					Total	%
Berms	3,703	7.3	1,158	2.3	4,861	4.8

Bank Composition

	Nash Stream					
	LB (ft)	%	RB (ft)	%	Total (ft)	%
Flood-Deposited boulder bars	24,658	48.9	18,042	35.8	42,700	42.4
Alluvial sediments	17,264	34.3	18,185	36.1	35,449	35.2
Non-Alluvial glacial sediments	1,806	3.6	9,553	19.0	11,359	11.3
Impoundment sediments (org.-rich silt)	4,571	9.1	4,566	9.1	9,137	9.1
Road Grade	1,651	3.3	0	0.0	1,651	1.6
Bedrock	434	0.9	38	0.1	472	0.5

Riparian Vegetation Statistics

	Nash Stream					
	LB (ft)	%	RB (ft)	%	Total (ft)	%
Mature Vegetation	8,896	17.7	11,025	21.9	19,921	19.8
Non-mature vegetation	41,488	82.3	39,359	78.1	80,847	80.2

Point Features

Mass failures	13
Rooted tree stumps	6
Old log driving crib dam site	2
Log sluice	4
Bridges	4
Bridge abutments	1
Debris jams	1
Beaver dams	5
Knickpoints	1
Large woody material*	56
Braiding	2
Deep pool	19
Flood chutes	1

*Minimum 6 ft in length and 6 inches in diameter

Table 3. Summary statisitcs of channel features mapping.