

Fluvial Geomorphology and Culvert Assessment of the Meduxnekeag River Aroostook County, Maine

Prepared for

Houlton Band of Maliseet Indians
Littleton, Maine



Meduxnekeag River

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EXECUTIVE SUMMARY

A fluvial geomorphology and culvert assessment were conducted in the Meduxnekeag River watershed in Aroostook County, Maine to identify restoration projects that will assist the Houlton Band of Maliseet Indians fulfill their goal of sustaining tribal cultural practices along the river such as fishing. The fluvial geomorphology assessment identified watershed conditions and human activities influencing river morphology – the shape, sinuosity, and slope of the channel. The river flows through a narrow valley along most of its length (as do the lower tributaries), mostly as a consequence of the geological and glacial history of the region. Due to these natural constraints, the river channel is much straighter than a meandering stream on a wide floodplain. Similarly, the river channel has not experienced major shifts in position during the past 75 yrs. Flood flows concentrated in the narrow valley exert greater shear stress on the channel bed, a condition that leads to the development of a wide shallow channel if no roughness elements (i.e., boulders and logs) are present in the channel. Boulders and logs can reduce flow velocities, increase flow complexity, and encourage sediment deposition that all serve to narrow and deepen the channel.

Historical evidence is unclear as to how much wood and boulder structure was present in the channel prior to European settlement of the region, but considerable amounts were probably removed during extensive logging and agricultural activities over the past two centuries. Reintroduction of this structure is the primary objective of three proposed restoration projects at the: 1) Lowery Bridge to the Covered Bridge site on the Meduxnekeag River, 2) Fish and Game Club site in Monticello upstream of the Route 1 Bridge on the North Branch, and 3) B Stream site upstream of the I-95 Bridge in Houlton. Boulder clusters, isolated logs, and boulder-supported log jams are examples of design measures that will not only improve habitat as isolated elements but can also function together to increase flow complexity, reduce the widths of the severely overwidened reaches, and maximize habitat improvements. All three types of structures proposed occur naturally in the watershed and are associated with excellent habitat features including deep pools for cover and clean gravels segregated from fines for spawning. The restoration proposals represent a passive approach to restoration that will be cheaper, more consistent with natural processes, and more sustainable than more active restoration approaches.

The characterization of culvert impacts and identification of mitigation design measures to improve degraded habitat were the primary objectives of the culvert assessment. The morphology of the channels on either side of the ten culverts assessed reflects the culverts' impact on sediment transport processes. Most culverts are less than half the width of the channel, causing fine sediment deposition upstream and deep scour pools and bank erosion downstream. As culverts are slated for replacement, the new culverts should span the bankfull width of the channel and incorporate floodplain culverts where floodplains are present. However, many of the problematic culverts were only recently replaced. Short-term design measures can be employed to mitigate the habitat impacts at the culverts long before culvert replacement will be possible (Appendix 8). Boulder weirs to reduce undermining of the culvert and log crib walls to prevent bank scouring are examples of design measures that can also enhance physical habitat conditions near the culverts. The results of the fluvial geomorphology and culvert assessment with a focus on both watershed-scale and local problems will be of assistance as the Houlton Band of the Maliseet Indians plan additional projects on the river intended to allow traditional tribal practices to continue long into the future.

1.0 INTRODUCTION

This report describes a fluvial geomorphology and culvert assessment completed by Field Geology Services in the Meduxnekeag River watershed of Aroostook County, Maine (Figure 1). From Meduxnekeag Lake, the Meduxnekeag River flows 23.1 miles to the Canadian border and drains a watershed area of 426 mi² within Maine, including a portion of the North Branch watershed that ultimately joins the mainstem Meduxnekeag in Canada. The total watershed area at the river's confluence with the St. John River in Canada is 516 mi². The assessments reported on here do not include information on the river or surrounding watershed in Canada. A majority of the watershed is well forested but significant agricultural lands occur on the relatively flat uplands bordering the mainstem and the lower ends of major tributaries. Human development along the river is limited, although the river does flow through the city of Houlton as does the lower end of Pierce Brook, a significant tributary.

The assessments were completed for the Houlton Band of Maliseet Indians who have a long cultural tradition of utilizing the river's resources and have tribal lands in the watershed. Tribal culture is largely dependent upon the natural resources found in the waters, floodplains, and riparian zone of the Meduxnekeag River. The river is a critical link in preserving tribal practices, traditions, and history. The tribe's goal in conducting the assessments is to identify and implement restoration opportunities in the Meduxnekeag Watershed that will improve and promote traditional uses of the river such as fishing. A preliminary habitat assessment of the Meduxnekeag River completed by the Maine Inland Fisheries and Wildlife identified a preponderance of wide and shallow channels that lacked high quality pools and large woody debris, conditions associated with warmer summer water temperatures and less channel complexity (Frost, 2002). High sediment loads during runoff events (Schalk and Tornes, 2005) are also of concern, because of their potential to degrade habitat and adversely effect water quality. Even relatively small runoff events can rapidly turn the usually clear water very muddy (Figure 2).

The project reported on here consisted of a watershed-level fluvial geomorphology assessment and a detailed site-specific culvert assessment at ten tributary stream crossings with impaired habitat conditions. The geomorphology assessment had three primary objectives: 1) identify the natural conditions and human land use activities in the watershed that are potentially controlling channel morphology and ongoing fluvial processes; 2) determine how the channel has responded and continues to respond to these watershed conditions; and 3) select and prioritize restoration projects that will eliminate artificial constraints causing adverse channel responses and degraded aquatic habitat. The geomorphology assessment consisted of five work tasks designed to fulfill these objectives: 1) map and aerial photograph interpretation; 2) archival research; 3) mapping of channel features; 4) topographic surveying of channel dimensions; and 5) development of conceptual restoration designs for three priority sites. The results of each work task are described separately in Section 2.0 below.

The results of the geomorphology assessment were in part used to identify the ten stream crossings to be assessed as part of the culvert assessment. The objectives of the culvert assessment were to: 1) conduct a detailed evaluation of ten priority culverts associated with degraded habitat and 2) create mitigation designs for the ten evaluated culverts. The culvert assessment consisted of three work tasks designed to fulfill these objectives: 1) topographic surveying of plan views, longitudinal profiles, and cross sections upstream and downstream of the culverts; 2) measurement of particle sizes (i.e., pebble counts) at the culverts; and 3) identification of design measures that will lead to improved habitat conditions. The results of each work task are described separately in Section 3.0 below.

2.0 FLUVIAL GEOMORPHOLOGY ASSESSMENT

Fluvial geomorphology is a science devoted to understanding how the natural setting and human land use in a watershed determine the shape of the river channel. Fluvial geomorphology assessments seek to determine what physical changes are occurring to a stream channel in response to alterations in watershed conditions and, in turn, how these adjustments are impacting human infrastructure and fish habitat. A river's adjustment to watershed perturbations may take thousands of years, as is the case throughout much of New England in response to deglaciation. In other instances, channel modifications may occur in less than a decade, as is frequently the case with direct human activities in a stream channel. Understanding how these perturbations (i.e., changes), operating at different time scales, alter the width, depth, and planform of a channel is critical for identifying potential problem areas in a river system. Consequently, a geomorphology assessment can identify and prioritize restoration projects that can reduce erosion and flooding while improving aquatic habitat.

2.1 Map and aerial photograph interpretation

2.1a Watershed characterization

The morphology of a river channel is a product of the natural conditions and human activities controlling the water, sediment, and wood inputs in the watershed. At least three characteristics of the Meduxnekeag Watershed increase the time required for runoff to reach the Canadian border and, therefore, reduce, but certainly not eliminate, the chance that extreme floods will inundate the channel and the associated physical habitat. First, the dendritic to rectilinear drainage pattern (Figure 1) means flow follows a longer path down the tributaries before reaching the river's endpoint compared to a watershed with a radial drainage pattern where individual tributaries follow a more direct path to the outlet. In watersheds with a radial drainage pattern, runoff from all of the tributaries can reach the outlet at essentially the same time, leading to higher peak discharges. In a watershed like the Meduxnekeag, flow from various tributaries reach the river at different times, so peak flows are reduced but runoff continues for a longer period

– an important factor for maintaining sufficient flow during the typically dryer summer months. A second characteristic increasing the runoff time to the river's outlet is the presence of Meduxnekeag Lake and other wetlands in the watershed (Figure 1). The lake serves as a buffer between the upper watershed and the river such that large runoff events from the upper basin are stored within the lake (causing a relatively rapid rise in lake level) and drain into the river over a longer time period (causing a slower fall in lake level). Green Pond, a small body of water through which the river flows just downstream of the Mill Brook confluence (Figure 1), has a similar but, given its smaller size, a less significant effect than Meduxnekeag Lake. Runoff from tributary streams is slowed by the presence of extensive wetlands along their length (Figure 3), the result of the glacial topography of the region and greatly enhanced by beaver activity and natural log jams. Finally, the Meduxnekeag Watershed has a total relief of only 1,348 ft between Sam Drew Mountain and the downstream end of the mainstem at the Canadian border. On the North Branch, the relief between Number Nine Mountain and the Canadian border is slightly greater at 1,394 ft. In general, however, the relief is less than 500 ft over most of the watershed (Schalk and Tornes, 2005). Consequently, runoff likely moves through the basin much slower than similar sized watersheds in steeper more mountainous terrain. The USGS stream gauge data are consistent with the expectation that flows are not flashy and extreme peak flood events are less likely to occur in the Meduxnekeag Watershed, because the record peak flows recorded at the Houlton gauge are less than two times the average annual peak (see <http://waterdata.usgs.gov/me/nwis/rt>).

Once runoff from the Meduxnekeag Watershed reaches the river, the narrow valley through which much of the river flows has the potential to amplify river stage and promote rapid sediment deposition; both factors can potentially alter channel morphology and physical habitat dramatically. First, much of the river flows within a very narrow valley with no or very limited floodplain flanking the channel (Figure 4). Confined by the high valley walls, flood flows on the Meduxnekeag River move faster and flow at a greater depth for the same discharge compared to rivers with a wide floodplain. Given the narrow valley, the river impinges directly on the high banks of the valley wall at several locations (Figure 4), encountering both bedrock where deep pools can form and glacial deposits that can supply large amounts of fine sediment to the river in the event of a landslide. Another potential point source of sediments is from tributaries that flow directly into the river without a wide floodplain over which sediments can be stored, resulting in more direct impacts to channel morphology (Figure 5a). The problem can be made worse when land use activities in the tributary watershed are causing channel incision (Figure 5b).

Within the valley, narrower constrictions occur that can have an important morphological impact on the channel due to their effect on the passage of flood flows (Figure 4). Flows are partially impounded behind the constrictions as the flow necks down to pass through the narrower area. This ponding or backwatering upstream of constrictions reduces flow velocities, leads to a reduction in the sediment transport capacity of the flow, and results in the deposition of large gravel bars (Figure 6). While the impacts of constrictions are most noticeable on tributaries such as B Stream, constrictions along the Meduxnekeag mainstem could also be altering physical habitat in

more subtle ways such as enhancing fine sediment deposition that can fill pools and cover spawning gravels.

The constrictions described above serve as grade controls, limiting the extent to which channel adjustments will travel upstream or downstream in response to natural events or human activities. For example a large landslide will typically result in the formation of gravel bars downstream in response to the increased sediment load, but a valley constriction will buffer downstream reaches from the effects of the landslide since most of the excess sediment will be accommodated immediately upstream of the constriction within the backwater zone. Lakes such as Green Pond, the large wetlands found on tributary streams, and dams (essentially artificial valley constrictions) also act as grade controls such that even significant perturbations in the upper watershed, whether natural or human caused, exert little direct influence on channel morphology compared to changes occurring more locally. Consequently, when trying to unravel the causes for channel adjustments that have degraded aquatic habitat in a given reach, focus should be placed on conditions and past events within the zone of influence of that river reach (i.e., the stretch of river and associated watershed between an upstream and downstream grade control).

Human activities can also have a great impact on runoff characteristics and channel morphology. Nearly all rivers and streams in New England continue to adjust to artificial channel straightening, a common practice in the 19th and 20th centuries for improving agricultural lands, reducing flooding, and, perhaps most extensively, for easing the passage of logs downstream during annual log drives. By cutting off meanders and shortening the length of the stream, channel straightening increases the stream gradient. In response to the resulting increased stream power of floods, straightened channels undergo a period of incision and widening to return stream power back to its original pre-straightening level. However, the reconfigured, much wider, channel without meanders is associated with poorer quality habitat compared to a natural unaltered channel. The wide channels, with any sand and gravel bars removed by the incision and pools infilled, ensure summer flows are shallow and warm up more readily. The lack of meanders reduces flow complexity that is needed to carve deeper pools (i.e., create cover habitat) and segregate particles of different sizes (i.e., form clean spawning gravels). The amount of artificial straightening that occurred on the Meduxnekeag River and its tributaries is unclear given the limited space available within the narrow valley for well developed meanders to occur naturally. In other words, the lack of extensive meandering seen on the mainstem today (Figure 4) may be more a consequence of its natural confinement to a narrow valley rather than artificial straightening. Topographic evidence suggests some of the tributaries were straightened where valley confinement is not present (Figure 7). Although valley confinement probably reduced the amount of channel straightening that would have otherwise taken place, other activities associated with straightening, such as the removal of wood and boulders from the channel, probably did occur and would have had similar morphological and habitat impacts. Other human activities in the watershed with an influence on runoff and channel morphology, such as land clearance and dams, are discussed below in Section 2.1b.

2.1b Historical changes

Historical aerial photographs and topographic maps can be an important tool for studying changes in channel morphology and watershed land use. A 1934 topographic map and 1947 aerial photographs of the Meduxnekeag River were visually compared with the 2009 orthophotos to identify changes in land use and channel position (Appendix 1). Land use in the watershed has remained relatively unchanged since 1947 with the upper watersheds forested and the upland areas along the margins of the Meduxnekeag River valley heavily agricultural. Forests cover 79 percent of the watershed, agricultural lands occupy 17 percent, and urban areas and open water covering the remaining 4 percent (Southern Aroostook County Soil and Water Conservation District, 1993). The upper watershed is an active forest, so despite an overall small increase in forest cover at the watershed scale, localized areas have seen a dramatic loss in forest cover due to logging. These decreases in forest cover can degrade habitat in nearby tributaries by increasing peak flows and fine sediment inputs, while elevated summer low flow water temperatures can result from decreasing base flows. However, at the watershed scale, the marginal increases in forest cover in the upper Meduxnekeag Watershed since 1947 have potentially had a positive, albeit small, effect on aquatic habitat. Lower in the watershed, increased development in Houlton occurred north of I-95, an interstate highway constructed after 1947. Also associated with the highway construction are new bridge crossings over tributaries and the mainstem. These changes in land use near Houlton, while noticeable, likely have little effect on the mainstem, because the changes occur over such a small percentage of the total watershed area. Recent development and runoff increases are more likely to have an impact on small tributaries such as occurred with the reconstruction of the Houlton Civic Center (Figure 5). Agricultural lands are prevalent on upland areas at the margins of the narrow Meduxnekeag River valley and lower ends of major tributaries. Runoff from the agricultural fields can increase fine sediment inputs to the mainstem, especially where the lower tributaries have a poor riparian buffer or lack other features (e.g., wetlands) that enhance sediment storage. Because of the potential for tributaries to buffer the river against upland land use changes, human activities occurring directly in the river channel are more likely to engender channel adjustments and changes to channel morphology.

The most striking change on the Meduxnekeag mainstem since 1947 is the removal of the large dam on the river in Houlton, once a prominent feature in downtown (Figure 8). Significant changes in channel position have not occurred on the mainstem since 1934, not necessarily surprising given the narrow valley through which the river flows. Minor changes on the mainstem may have occurred, but are difficult to discern given the resolution of the historical images. Similarly, the small size of the tributaries makes identifying changes difficult, especially where riparian trees obscure the channel. Large-scale changes on the tributaries would be discernable, so the absence of such changes indicates the tributary channels have experienced only minor, if any, channel migration since 1934.

2.2 Archival research

Archival documents and previous reports can provide information on past floods, other watershed conditions, and historical uses of a river that may still be impacting river morphology. The Meduxnekeag Watershed has a long history of logging and agriculture, including several related businesses powered by dams on the river. In 1886, Houlton had two cheese factories, two or more starch factories, a canning factory, a bark-extract facility, a woollen-mill, four lumber-mills, three flour-mills, one tannery, two iron-foundries and machine shops, two printing offices, and a sash, blind and door factory (Pioneer, 1881). These businesses were in part powered by dams known as the Cary, Page and Madigan, Ham, Logan, Mansur, Cresses, and Houlton water-powers (Pioneer, 1881). A sawmill and starch factory in Monticello by 1886 suggest one or more dams were also present on the North Branch by the late 19th century (Varney, 1886). Most dams, including on the mainstem in Houlton, no longer exist. Many smaller dams were certainly present in the watershed at one time. The evidence for these forgotten structures includes large logs protruding from the bank (Figure 9a) or banks composed of fine-grained impoundment sediments deposited behind dams no longer visible (Figure 9b; see Section 2.3 below).

The dams had a direct impact on fish as Pioneer (1861) describes how salmon struggled to pass over the obstructions and how the fish would “run against the water-wheels while the mills were in operation, which would kill them instantly” (p. 34). Salmon were abundant in the river near Houlton until shut out by dams around 1832 (Kendall, 1935). Continuing effects of the dams on fish, now that most of the dams are no longer standing, are less direct. The dam on the mainstem in Houlton created a long narrow impoundment as seen on the 1934 topographic map (Appendix 1). The high banks on either side of the river prevented vast areas from being inundated and may have kept flow moving through the impoundment. Silt and clay deposited in the impoundments (Figure 9b) may supply fine sediment to the river channel that can degrade spawning habitat and water quality (Figure 2).

Aside from dams, other direct activities in the river channel and floodplain were limited owing to the narrow valley. However, land use on the steep slopes along the valley margins is likely to have a more direct impact on the river where the valley is narrow. The slopes were probably less forested historically than they are today (Figure 10), so sediment inputs directly from the valley sides have likely decreased over time. Although dramatic additions to the landscape, new bridges across the narrow valley are able to span almost the entire channel, thus minimizing the potential morphological and habitat impacts (Figure 11).

Soil maps for the watershed are available at <http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>. Floodplain soils, such as the Winooski silt loam, comprise a small percentage of the area and are restricted to the bottom of the narrow valleys flanking the Meduxnekeag River and lower tributaries. The soils in the upland areas along the narrow Meduxnekeag River valley are largely formed on glacial tills (e.g., Caribou gravelly loam, Monarda and Burnham silt loams) and sandier glacial outwash, kames, and eskers (e.g., Colton

gravelly sandy loam and Macias gravelly loam). Bedrock is less than 30 inches below the surface in many upland areas and results in stony soils such as the Mapleton shaly silt loam, the most dominant upland soil along the valley margins. Nearly all of the soils, even those with shallow bedrock, are classified as highly erodible or potentially highly erodible (U.S. Department of Agriculture, 1994) and, thus, provide a ready and plentiful source of fine sediment for the river.

2.3 Mapping of channel features

Several channel features were mapped continuously along the Meduxnekeag River channel and ten of its tributaries in order to: 1) identify locations of channel instability and sensitivity; 2) characterize physical habitat conditions; and 3) document the impacts of past 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 sediments, impoundment sediments, bedrock); 4) grade controls (e.g., dams, waterfalls); 5) bar types (e.g., point bars, mid-channel bars); 6) channel reach morphology (e.g., pool-riffle, step-pool); 7) dominant substrate size (e.g., boulder, cobble, gravel); and 8) habitat features (e.g., log jams, deep pools). Where the floodplain was particularly narrow, both the height of the bank on the river and the height of the valley wall on the backside of the floodplain were recorded and referred to as the low and high bank height, respectively.

The mapping was completed with two individuals from the Water Resources Program of the Houlton Band of Maliseet Indians. While walking or floating downstream, the mappers, each equipped with a Trimble GeoXt GPS unit, recorded the location of point features (e.g., grade controls, habitat features) and the start and end points of line features (e.g., bank stability, bank height). For example, to record a section of eroding bank, a point would be recorded and appropriately coded at the upstream end of erosion and another point at the downstream end. One mapper recorded all of the features on the left bank while another focused on the right bank. Responsibility for recording features within the channel (e.g., bar types, grade controls) was split between the mappers. Since the mappers did not remain precisely along the center of the channel while mapping, the GPS data for each mapped attribute were later cut to the stream centerline in ArcGIS using the National Hydrography Dataset theme (1:5000 source scale). In this manner, the length of the mapped bank and channel features could be more accurately calculated.

A total of 59.8 miles of stream length were mapped on the mainstem and portions of ten tributaries (Table 1). When the character of one or more features were not discernible or recordable due to water depth, access, or other reasons (e.g., lack of satellite coverage), those particular features were not mapped along that length of stream. Consequently, the total mapped length of some features is less than others, but more than 90 percent coverage was achieved for most features. The distribution of the mapped features can be viewed with ArcGIS using the shapefiles created for each feature

(Appendix 2). Based on an analysis of the GIS shapefiles, a statistical summary of the data shows the percentage of stream length along which certain conditions are found (e.g., percentage of eroding banks) (Table 2). The statistical analysis was completed for the entire mapped length, but the GIS shapefiles could be used to analyze the mainstem or tributaries individually.

The results of the mapping process reveal a stable channel network characterized by a prevalence of bedrock in and along the stream channels. Where bedrock spans the width of the active channel, creating a grade control, the rock's resistance to erosion controls the channel bed elevation, providing vertical stability to the stream. Bedrock is also found along 6.2 percent of the banks, where it provides lateral stability and limits bank erosion and channel migration. While bedrock appears to play an important role throughout the watershed, its influence on channel morphology is particularly apparent on B Stream, where 31.0 percent of the channel is floored by rock and 8.6 percent of the banks are ledge outcrops.

The amount of bedrock on the bed and banks of the channel would be expected to reduce the incidence of bank erosion. However, 20 percent of the banks are eroding, a figure in line with other mapped rivers in New England where substantially less bedrock is encountered (Field et al., 2001; Field, 2004; Field, 2006; NEE, 2005). The higher than expected rate of erosion might be related to the preponderance of bedrock lining the channel bottom. Unable to scour the stream bottom where bedrock floors the channel, flows will preferentially erode the banks. Although some large active mass failures are present on the North Branch, the bank erosion is not severe in most locations with historical aerial photographs showing little evidence of long-term channel migration and erosion (see Section 2.1b above).

The mapping of channel features also revealed a significant lack of physical habitat features in the Meduxnekeag Watershed. Large wood was found at only 151 locations along the 59.8 stream miles mapped. While this number may seem large and some mapped locations may represent multiple, not single, logs, the density of wood represented by this figure is less than 3 pieces (or concentrations of pieces) per mile. Most of the wood is found in limited areas of the upper tributaries. In contrast, no wood was mapped along the mainstem downstream of the Mill Brook confluence, a distance of 16.2 miles. The low densities of wood in the Meduxnekeag Watershed compares poorly with recent studies from unaltered watersheds in the northeastern United States that document 175 to 225 pieces of large wood per mile (McKinley et al., undated). The near absence of wood in the Meduxnekeag River and its tributaries has important biological implications, because streams with more wood in the channel generally have higher fish populations (Flebbe, 1999), a greater abundance and richness of macroinvertebrates (Bond et al., 2006), and more complex physical habitat (Benke and Wallace, 2003). The lack of deep pools in the Meduxnekeag Watershed, mapped in only 96 locations (Table 2), is probably directly linked to the limited occurrences of wood and large boulders in the channel. (Boulder locations were not mapped but their density is considered low). Despite a heavily forested watershed (Southern Aroostook County Soil and Water Conservation District, 1993), natural recruitment of wood into the Meduxnekeag River

system will occur slowly and only after the forests are allowed to mature to a point where trees are dying off and falling into the channel.

The legacy of the long history of dams on the mainstem and its tributaries is reflected in the impoundment sediments seen along the banks (Figure 9b). While these deposits are only mapped along 0.9 percent of the banks, this figure probably significantly under represents the actual extent of these deposits in the study area. The fine, sometimes laminated, sediments are easily confused with floodplain sediments that are well represented in the mapping. Linking the distribution of impoundment sediments with known historic dam sites is also difficult and suggests the presence of numerous unrecorded dams (Figure 9a), perhaps temporary splash dams used in log driving. Long continuous exposures of impoundment sediments in some areas, often containing large logs to small pieces of wood in the basal layers, formed in the long impoundments formed behind dams built in the narrow valleys of the mainstem and lower tributaries. The impoundment sediments exposed in the banks are a ready source of fine sediments that may contribute to the rapid discoloration of flow during runoff events (Figure 2).

2.4 Topographic surveying of channel dimensions

The purpose of the topographic surveys and an associated substrate particle size analysis was three fold: 1) quantify several morphological parameters at sites representative of conditions elsewhere; 2) characterize physical habitat conditions; and 3) provide the basis for developing conceptual restoration designs (see Section 2.5 below). The detailed surveys were completed with a Sokkia Set 5 electronic total station on six reaches of varying length referred to as geomorphic assessment sites (Figure 12). Two areas were surveyed on the mainstem, two on the North Branch, one on B Stream, and one on the South Branch with the survey results for each presented in Appendix 3. The sites either represent areas where restoration might occur, high quality habitat elements are present, or human activities control channel morphology (Table 3). Channel cross sections were used to establish the bankfull channel width, mean and maximum depth, and width:depth ratio (Table 3). Channel gradient and sinuosity were measured as part of a longitudinal profile at each survey site. Substrate particle size data were also collected at each survey site (Appendix 4) using standard pebble count procedures (Wolman, 1954). The data from the longitudinal profiles and substrate particle size analysis can be used during the final restoration design phase (beyond the scope of this project) to calculate bankfull shear stress and sediment entrainment thresholds, essential values for determining stream sensitivity, guiding restoration design, and sizing in-stream structures.

Boulders and log jams, where present, as well as bedrock can create flow complexity in the channel (Figure 13) that can improve water quality and physical habitat. Often, deep pools form and particle size segregation occurs in association with these structural elements (Figure 14). Log jams and boulder-supported log jams were surveyed in detail at the geomorphic assessment sites on South Branch and B Stream to characterize the size and configuration of these structures and their associated pools

(Appendix 3). Bedrock outcrops on the banks or that extend partially across the channel (Figure 13a) are also frequently associated with deep pools and flow complexity as at the Canadian Border Site on the North Branch (Appendix 3). The detailed information gleaned from natural boulder and log-jam obstacles can be replicated at restoration sites to create high quality cover habitat (i.e., pools) and spawning gravels (i.e., segregated particle sizes) (see Section 2.5 below). Generally, deep pools form at the lateral margins and downstream end of log jams while a trail of cleaner gravel accumulates as a crescent shaped mound at the downstream end of the pools. This configuration is ideal spawning habitat, as some of the flow exiting the pool is forced downward into the cleaner gravel, helping to aerate eggs and remove accumulating fines and waste from the spawning beds.

In contrast the geomorphic assessment sites selected as prospective restoration reaches do not have boulders, log jams, or other physical structure to create flow complexity and other habitat features. The width:depth ratios of the Covered Bridge site on the mainstem and the Fish and Game Club site on the North Branch are greater than 30 with width:depth ratios greater than 20 typically associated with poor habitat (Rosgen, 1996). With increasing width:depth ratios, flow for a given discharge becomes shallower and slower moving as flow is spread across a wider channel (Figure 15). During the low flow summer months, the shallow flows can lead to elevated water temperatures that can become stressful, or even lethal, for trout, especially where no riparian buffer is present to shade the stream. The pool-riffle morphology that typically develops in meandering channels with a low width:depth ratio is absent from the overwidened plane bed channels at the Covered Bridge and Fish and Game Club sites as documented by the lack of complexity in the bed topography on the longitudinal profiles (Appendix 3). Without boulders and logs present in the channel, the overwidened reaches have no structure around which to scour pools, so the temperature stress in the summertime is further complicated by the lack of deep-water refuge for fish.

The low sinuosity at the Covered Bridge site and the Fish and Game Club site leads to a homogeneous flow pattern with no variation in flow velocity across the channel (Figure 15; Table 3; Appendix 3). On meandering channels, flow velocities are higher on the outside bend and slower on the inside. This variation in flow velocities leads to a segregation of particle sizes with sediments becoming progressively finer towards the inside of the bend. In straight overwidened channels, substrate particle size is typically homogeneous across the channel with sands mixed in with cobbles. While the finer sediments are typically carried away at the surface leaving an armor of clean cobbles on the channel bed, the finer particles are present just beneath the surface and flows in the Meduxnekeag Watershed are quickly clouded if the substrate is disturbed by high flows (Figure 2) or, locally, if the surface armor is kicked away with a boot. Fines in the substrate degrade the quality of spawning gravels, because the pore space between individual pebbles becomes filled and hyporheic flow passing through the gravel is inhibited. The absence of structure, sinuosity, and the flow complexity they create are, therefore, directly related to the lack of spawning habitat at the Covered Bridge and Fish and Game Club sites. These two sites are not unique reaches in the watershed, but were chosen because they are characteristic of long stretches of the mainstem and North Branch.

Better habitat conditions are present at the Canadian Border site on the North Branch and the B Stream site despite width:depth ratios over 20 (Table 3). The Canadian Border site likely suffers from high summer water temperatures, but the presence of bedrock leads to some pool formation and cooler water refuge (Appendix 3). Deposition of gravel bars at the site further increases complexity by creating multiple flow paths (Appendix 3). Although multiple flow paths might enhance warming of the water during the summer, the slower moving water in side channels provide juvenile rearing habitat separated from the faster moving main channel occupied by adults. While the B Stream site does not have multiple flow paths and other complexity within the envisioned restoration reach, the riparian vegetation along this much narrower tributary provides some shading to minimize temperature increases. Finally, excellent natural habitat structures (i.e., log jams and boulders) are present on B Stream immediately upstream and downstream of the prospective restoration site (Appendix 3).

The Houlton site has a lower width:depth ratio than most sites as a result of human constraints, lack of a floodplain, and potentially in response to the removal of the dam on the mainstem. The high banks along the channel are armored with concrete and large rock (Figure 16), preventing lateral channel adjustments. Minor incision has likely occurred upstream since removal of the dam with impoundment sediments exposed along the banks. Through Houlton, the valley is particularly narrow with artificial fill perhaps constricting further the naturally narrow valley that has limited to no floodplain. Consequently, flood flows are confined to the channel, producing greater shear stress on the channel bottom. The lack of a pool-riffle morphology (Appendix 3) and coarser substrate compared to elsewhere (Appendix 4) is consistent with these conditions.

2.5 Conceptual restoration designs

Conceptual restoration designs were developed for three of the geomorphic assessment sites where the habitat is impaired along straight overwidened reaches: Covered Bridge site, Canadian Border site, and B Stream site (Appendix 5). The extent of the proposed Covered Bridge restoration site extends upstream to the Lowery Bridge, much further upstream than the area surveyed during the geomorphic assessment (Appendix 3). While meandering channels with pool-riffle morphology are typically considered ideal trout habitat, constructing meanders along the low sinuosity channels at the three sites would not be a sustainable restoration design approach. An idealized channel form cannot be imposed on the ground if the processes in the surrounding watershed do not support that form. While the expected absence of flow flashiness and severe peak flows in the watershed (see Section 2.1a above) is consistent with the long-term development of a meandering channel pattern, the narrow valley through which the river flows inhibits meander development. In many areas, the Meduxnekeag River is not free to develop a self-formed channel on an alluvial floodplain, but rather its movement and channel pattern is constrained by bedrock (Table 2 and Appendix 2). Even where a narrow floodplain exists, the confinement of flood flows within the valley walls increases the stream power acting in the channel, another factor inhibiting meander growth.

While creating meanders or encouraging their development is not a sustainable restoration approach, other restoration techniques can be used to replicate habitat conditions that likely existed prior to European settlement of the watershed. A considerable amount of wood and boulders were likely removed from the channel in the 19th and 20th centuries as part of logging operations and drainage/flood control projects. The removal of such structure from the channel leads to additional losses in habitat as the increased flow velocities wash out depositional features (i.e., spawning habitat) and infill pools (i.e., cover habitat). Considerable natural recruitment of new wood (from falling riparian trees) and boulders (from erosion of glacial deposits) into the channel will happen only very slowly, perhaps over several hundred years. What small amounts of wood do enter the channel today are easily transported downstream by flood flows confined to the narrow valley with no structure in the channel to hold the wood in place. Restoration efforts should attempt to restore the wood and boulder structure in the channel, so natural recruitment processes can occur to sustain the created habitat.

Log jam and boulder structures observed on the Meduxnekeag River can be replicated to improve habitat conditions at the restoration sites (Figure 13). The detailed surveys of log jam and boulder structures provide insight on how to best position and construct the structures (Appendix 3). Natural structures decay and move over time, but are replaced by the introduction of new boulders and wood from the channel margins. An equilibrium condition is eventually reached that sustains the habitat over time when the rate of wood recruitment is sufficient to form log jams as quickly as they fall apart. Presently, the Meduxnekeag River system is far removed from an equilibrium condition as little natural wood is available. Consequently, the proposed restoration structures (Appendix 5) will need to be properly anchored to remain intact for the several decades needed before a large number of trees in the riparian zone mature, die, and begin falling into the river naturally.

Three types of structures will be used to restore fish habitat along the restoration reaches: isolated logs, boulder clusters, and boulder-supported log jams. Design typicals for each structure are based on natural structures observed in the watershed and elsewhere in the region, but are modified for restoration purposes to increase stability and maximize habitat formation (Appendix 5). Structures at the restoration sites will be engineered to remain intact during large floods by partially burying the boulders and logs in the channel bed or banks. The anchored structures will be designed to remain in the channel for at least the several decades needed for natural recruitment to begin forming habitat features similar to the engineered structures. Riparian buffer planting projects such as the one completed on the Houlton Band of Maliseet Indians tribal lands (Figure 16) ensure that small stretches of the river may serve as a source of trees that will eventually fall into the channel. Reestablishment of the riparian buffer elsewhere will be critical for sustaining habitat improvements throughout the watershed. Boulders added to the channel do not decay (i.e., weather) as fast as wood and once placed in the channel are essentially permanent features, if large enough to resist transport. The boulder clusters and boulder-supported log jams will, therefore, help retain naturally recruited wood in the channel for centuries to come. While natural log jams occur in the watershed

(Figure 13), engineered log jams are not incorporated into the conceptual restoration designs because of the greater costs and time associated with their construction; however, their use could be incorporated into future restoration efforts.

The placement and spacing of the engineered structures are shown on the conceptual restoration plan views for each restoration site (Appendix 5). Boulder-supported log jams are placed on the channel margins, mimicking the position of natural structures where a large key log is trapped between a boulder and the bank before recruiting smaller pieces (Figure 13d). In addition to the pools formed around the structures, a series of boulder-supported log jams along the channel margins of the restoration sites could potentially buildup sediment between them and serve to narrow the overwidened channels. A narrowing of the channel would increase low flow velocities and depths and thereby reduce summer water temperatures. While a series of log or boulder vanes extending from the bank may similarly help trap sediment along the margins and narrow the channel, their use are not recommended here as they are not naturally occurring and, consequently, would impact the natural appearance of the restoration efforts.

Naturally occurring boulders in the Meduxnekeag River and its tributaries generally occur singly. While individual boulders are capable of scouring a pool around their margins (Figure 14a), the boulder-cluster design proposed for the restoration sites consists of boulder pairs with a small gap left between them (Appendix 5), so the concentrated flow increases the power to scour a pool downstream. The boulder-cluster design incorporates partially buried logs to simultaneously support the boulders against movement and provide cover over the downstream pool. Boulder clusters are typically placed in the thalweg (i.e., deepest part) of the channel where a greater proportion of the flow passes through the gap in the boulders. On the overwidened restoration reaches, no well defined thalweg exists. Consequently, the proposed clusters are alternately placed in the center and near the margins of the channel with the purpose of ultimately creating a more sinuous thalweg between the pools formed by the clusters. This will lead to greater flow complexity across the channel compared to what would exist with a straighter thalweg.

Isolated logs occur in the Meduxnekeag River and its tributaries. When a rootwad is attached to a log in a river, the log is typically oriented with the rootwad on the upstream end and a pool formed at the upstream face of and wrapping around the rootwad. A “shadow” zone of reduced flow velocity downstream of the rootwad promotes deposition of finer sediment, sometimes pebbles suitable for brook trout (*Salvelinus fontinalis*) spawning. Natural logs can become buried at their downstream ends and remain stationary even during large floods. The isolated log design proposed for the restoration sites replicates these conditions by orienting the rootwad upstream and burying most of the log in a backfilled trench excavated at the downstream end. Like boulder clusters, isolated logs can be placed in various positions in the channel to encourage the development of flow complexity. The spacing between isolated logs and boulder clusters should be great enough to avoid having two structures negatively interact with each other. For example, a boulder cluster should not be placed in the “shadow”

zone downstream of an isolated log, because less flow would be concentrated between the boulders.

The presence of smallmouth bass (*Micropterus dolomieu*) on the mainstem (Frost, 2002) has been considered in developing the proposed restoration plan for the Covered Bridge site. The habitat needs of small mouth bass (Edwards et al., 1983) and brook trout (Raleigh, 1982) are similar, so the proposed structures, although intended to improve brook trout habitat, will also prove attractive to small mouth bass. One significant difference in habitat preferences between smallmouth bass and brook trout is the water temperatures they prefer with brook trout favoring cooler waters. Consequently, smallmouth bass are likely to outcompete brook trout for cover habitat during the critical warm summer months. Smallmouth bass are less likely to occupy cover habitat in cooler water temperatures, so a higher density of structures is proposed at the mouth of cold water tributaries (e.g., Big Brook and Suiter Brook) or known areas of spring seeps (e.g., Lowery Bridge). Conversely, a lower density of structures is proposed between these point sources of cold water. While smallmouth bass will likely occupy the cover habitat around the proposed structures for most of the year, brook trout might have greater access to the cover at cooler times of year, such as during fall spawning, when they are moving between tributaries and the mainstem. Constructing structures throughout the site, even widely spaced, will help increase the movement of brook trout between tributaries and prevent separate populations from becoming isolated through time. Similarly, the proposed restoration on B Stream will fill in a gap of poor habitat between two areas where natural boulder structures and log jams already exist, thus promoting greater movement of brook trout in the stream.

The three proposed restoration projects (Appendix 5) are consistent with ongoing natural processes and will speed up by several decades, if not centuries, the development of pools and other habitat features. The trend towards a reforestation of riparian areas either naturally (Figure 10) or through purposeful plantings (Figure 16) will ensure long-term recruitment of wood to the channel. Boulders may not return naturally to the channel for millennia as many of those that once existed may have been relicts of deglaciation, although a few are likely to be recruited through erosion of glacial deposits. The rapid change in conditions that occur at any restoration site, no matter how well intentioned, always has the potential to cause adverse responses elsewhere. Although negative channel adjustments are unlikely to occur with the relatively passive approaches proposed for the three restoration sites, the presence of grade controls throughout the watershed (i.e., valley constrictions, bedrock channel) will prevent inadvertent problems from migrating far beyond the limits of the project areas.

3.0 CULVERT ASSESSMENT

Poorly functioning culverts can impede the movement of fish throughout a river system. Culverts with a width much less than the width of the channel can upset sediment transport processes along the stream and thus create instabilities that degrade aquatic habitat both upstream and downstream. During floods where flow completely

fills the channel, a narrow culvert can have a damming effect with floodwaters impounded upstream of the culvert while flow passes through the culvert slowly. The drop in velocity in the impounded area upstream results in sediment deposition with mud sometimes covering natural gravel bottoms. On low gradient channels, the deposition can extend hundreds of feet upstream, especially where the constriction is severe. Downstream, the now sediment-deficient flow exits the constricted culvert moving faster and is said to be “hungry” for sediment, a hunger satiated through erosion of the bed and banks. Typically, a deep scour pool forms downstream that can undermine the pipe and leave it perched above the water surface. The big pool can be an attraction for numerous organisms that later become trapped in an overcrowded pool during low flow periods when accessing pools elsewhere becomes difficult (John Magee, NH Fish and Game, personal communication, 2009). Also problematic is the severe drop formed at the downstream end of the culvert, because under severe conditions the perched culvert can become a barrier to fish movement.

No culverts are present on the mainstem of the Meduxnekeag River, but dozens of culverts are present on tributaries throughout the watershed. A preliminary study of stream crossings on the larger tributaries conducted by the Houlton Band of Maliseet Indians in partnership with the Organization for Watershed Living and Trout Unlimited identified several culverts that were potentially impacting aquatic organism passage and habitat. The culverts were identified by tributary and then numbered from the downstream end such that the downstream most crossing on Pearce Brook was labeled Pearce Brook 1, the next culvert upstream Pearce Brook 2, and so forth. Ten of the culverts identified in the preliminary study were selected for the more detailed culvert assessment described below (Figure 17 and Table 4). The ten culverts were selected based on two primary factors: 1) the severity of impacts to aquatic organism passage and habitat and 2) the amount of upstream habitat that would become available if passage issues were addressed at the culvert. As a result of this second factor, most of the culverts are lower in the watershed with more stream length available upstream.

3.1 Topographic surveying

Each assessed culvert was surveyed in sufficient detail to create a topographic map, longitudinal profile, and cross sections of the culverts and areas upstream and downstream (Appendix 6). Moose Brook 1 and Moose Brook 2 are in close proximity, so a single survey incorporated both culverts; a single survey was also completed of Pearce Brook 2 and the adjacent Pearce Brook 3. The surveys were conducted to 1) characterize morphological conditions near the culverts, 2) identify potential impacts associated with the culverts, and 3) provide the basis for developing conceptual mitigation designs to improve habitat conditions (see Section 3.3 below).

The topographic maps reflect survey notes recording impacts related to the culverts such as bank erosion and deep scour pools downstream of the culvert (Appendix 6). The depth of the scour pool and the constriction ratio (i.e., ratio of culvert width to bankfull width) are two important variables for identifying the impacts of the culverts on

channel morphology (Table 4). The deepest scour pool occurs at Smith Brook 1 where the constriction ratio of 0.39 is high, but not as severe of a constriction as at Moose Brook 1 where the second deepest scour pool is found. In contrast, Brown Brook 2 where the constriction is the least severe has the shallowest scour pool. An equally shallow pool is associated with Suiter Brook 1 with one of the highest constriction ratios, indicating that the severity of the constriction is not the only factor controlling pool depth. Bither Brook 3 was recently replaced by the Maine Department of Transportation using new culvert design guidelines and was chosen as a culvert assessment site to provide a contrast with the older culverts. While Bither Brook 3 does have a lower constriction ratio than most of the other sites, the culvert opening is still only half of the channel width and may explain why a boulder weir built downstream for habitat purposes was outflanked and no longer functions properly (Appendix 6). The culvert is also now slightly perched. Where measured, the culvert slopes are similar to the gradient of the stream channels upstream and downstream, so slope changes are not further compounding channel adjustments occurring in response to the culvert constrictions.

3.2 Measurement of particle sizes

Particle sizes were measured upstream and downstream of each culvert using the Wolman (1954) pebble count method. Particle size downstream is larger than upstream at eight of the ten sites, similar at one site, and finer at Moose Brook 2 (Table 4 and Appendix 7). The particle size data reflect the strong influence the culverts exert on flow velocities and sediment transport with low velocities in the impounded area upstream of the culverts resulting in the deposition of fine sediments. The lone anomaly in the particle size trend might be due to the close proximity of Moose Brook 1 and Moose Brook 2. The impoundment behind Moose Brook 1 is confined to a narrow valley and therefore might extend far enough upstream to influence particle size at the downstream end of Moose Brook 2.

3.3 Identification of design measures

Most of the assessed culverts are constricting the channel and should ultimately be replaced with bottomless arch culverts that fully span the channel width and whose gradients match the natural channel slope. Where a floodplain is present, the installation of floodplain culverts should also be considered. However, the culverts cross major roadways in most instances and their replacement will occur only in conjunction with the agencies or municipalities responsible for them. Ongoing channel adjustments at the culverts demonstrate the need for replacement, but other, more realistic, mitigation measures can be taken to improve impaired habitat in the short term. The morphological and habitat impacts of the culverts can be partially mitigated without replacement of the culverts. The proposed culvert design measures focus on these shorter-term mitigation efforts (Appendix 8). Each site is briefly described below with recommendations to improve aquatic habitat and culvert stability. Ground photographs of the culvert assessment sites help visualize conditions at the site (Appendix 9).

3.3a Suiter Brook 1

The Suiter Brook 1 culvert significantly constricts the channel. On tribal lands, the culvert might be a good candidate as a demonstration project for culvert replacements with bottomless arch culverts spanning the channel width. However, the culvert was only recently replaced. Suiter Brook has a channel width of less than 20 ft, small enough that shrubby vegetation along the banks provides a canopy over the entire channel (Appendix 9). The dense vegetation and root mass in the bank may inhibit bank erosion and lead to the relatively low width:depth ratio (Table 4). The narrow channel precludes installing significant habitat measures but some small isolated logs placed at the downstream end of the culvert (Appendix 8) will baffle higher velocity flows exiting the highly constricted culvert, providing refuge for fish.

3.3b Smith Brook 1

Despite the presence of a double culvert, the constriction at Smith Brook 1 is significant enough to form a deep scour pool downstream and cause erosion of the higher bank flanking the pool (Appendix 9). Upstream of the culvert is a marsh that extends upstream beyond the influence of the culvert, so the culvert is not entirely responsible for the low velocity conditions observed. To protect the bank from further scour, a near vertical log crib wall can be constructed to avoid sloping the bank back and provide rootwads for cover over the pool (Appendix 8). A boulder weir is proposed at the downstream exit of the culvert to prevent perching of the culvert and ease fish passage through the culvert. Partially buried logs, which will also provide cover in the pool, can support the boulders. Additional cover elements can be placed in and around the pool such as isolated boulders and logs.

3.3c Pearce Brook 2 and Pearce Brook 3

Given their close proximity, Pearce Brook 2 and Pearce Brook 3 were assessed together. Both are older culverts with considerable fill above them. The upstream and downstream ends of the assessed area are within well confined channels but the area between the two culverts flows through an area with a narrow floodplain. A number of concrete structures of unknown purpose are built on this floodplain and into the channel. The mitigation measures address these structures and provide for cover elements to enhance habitat around the culverts. The narrow confined channel downstream of Pearce Brook 2 will be treated with marginal isolated logs to reduce scour at the toe of the steep high banks while also providing some refuge for fish from high velocity flows.

3.3d Pearce Brook 4

The Pearce Brook 4 culvert passes under Green Street in Houlton. The culvert is on the Maine Department of Transportation's priority replacement list, so new culvert designs should plan for a channel spanning bottomless culvert to eliminate the severe constriction. Flood flows can overtop the low bridge and banks, so morphological effects are less severe. Particle size coarsening downstream is significant, but the scour pool depth is less than average for the ten sites (Table 4). Marginal isolated logs are proposed to stabilize an eroding bank upstream of the culvert. The erosion may be unrelated to the culvert, but the logs will provide cover habitat and high velocity refuge near the culvert.

3.3e Brown Brook 2

Brown Brook is a small tributary to Pearce Brook. Brown Brook 2 is the least constricted of the ten culverts assessed with only a shallow scour pool formed as a result (Table 4). The sharp bend immediately upstream of the culvert poses a more serious problem (Appendix 6 and Appendix 9). In addition to bank scour that has been protected against with riprap, the superelevation of floodwaters around the sharp bend increases the risk of the culvert being overtopped and flow passing over the roadway. If further bank scour at the sharp bend outflanks or undermines the riprap then the road could wash out around the culvert. The culvert was only recently replaced but the hard bend at the approach might result in long term-maintenance issue. To reduce the chance of further upstream bank erosion isolated logs are proposed along the riprapped outside bend. The culvert may have been built slightly perched, a condition that can be remedied with the proposed boulder weir at the outlet built to the level of the culvert bottom. A second weir will be built downstream to maintain pool depth downstream of the culvert and to prevent incision on this steep stream from undermining the culvert.

3.3f Brown Brook 3

Brown Brook 3 is a long double pipe culvert running at an angle across Route 1. The fill above the culvert is so thin that frost heaving has caused a portion of the roadway to settle around the pipes, leaving the road undulating over the humps of the culverts. The low road and banks also allow floodwaters to overtop the road with some scour occurring around the culvert at the downstream end as flow returns to the channel (Appendix 9). Mitigation options on this narrow channel are limited but isolated logs are proposed at the downstream end to reduce scour and provide cover habitat.

3.3g Moose Brook 1 and Moose Brook 2

Given their close proximity, Moose Brook 1 and Moose Brook 2 were assessed together. Both are older culverts with considerable fill above them. High banks confine the channel upstream of Moose Brook 1, but the outlet empties out at the confluence with the Meduxnekeag River (Appendix 9) where flow becomes spilt across the small delta at the mouth of Moose Brook (Appendix 6). The scour hole downstream is very deep, owing to the severe constriction at the culvert (Table 4). The double culvert under the railroad tracks at Moose Brook 2 is not nearly as constrictive. Access to the confined valley upstream of Moose Brook 1 is difficult, so the proposed mitigation design is limited to downstream where the morphological impacts are greatest. A boulder weir is proposed at the outlet of the culvert to reduce the impact of the perching that has developed. Two more weirs downstream will concentrate flow into one branch rather than having flow spread out over the small delta. Isolated logs and boulders are incorporated into the design as additional cover in the scour pool.

3.3h Bither Brook 3

Bither Brook 3 was recently replaced by the Maine Department of Transportation. Habitat mitigation measures installed with the culvert have been outflanked and are no longer fully functioning. The flow is wide and shallow as it exits the culvert, so boulder clusters and isolated logs are proposed at the outlet to increase pool depth and cover habitat (Appendix 8). A weir is also proposed to help concentrate flow into a single area. The culvert is slightly perched (Appendix 9), so a second boulder weir could be constructed at the outlet to improve fish passage, but is not shown on the conceptual habitat mitigation design (Appendix 8).

4.0 CONCLUSIONS

The fluvial geomorphology assessment results demonstrate that the Meduxnekeag River system is not currently undergoing any major adjustments in form. No major changes in channel position have occurred in 75 yrs and severe erosion is limited to very short reaches. The lack of excess sediment that would be generated by active channel adjustments means very few depositional features occur along the river. The most significant impact to channel morphology has resulted from the removal of boulders and wood from the channel over the past two centuries. The current lack boulder and wood structure in the channel has led to overwidened channels with few pools or flow complexity. The overwidened channels are in equilibrium with the presently high energy channel devoid of roughness elements. The lack of bars and other depositional features means low flows spread out across the entire width of the channel, leading to warmer summer water temperatures.

The three proposed restoration projects (Appendix 5) are designed to reintroduce wood and boulder structures to the channel and allow the channel to adjust in response to the installed structures. Such a passive approach to restoration is less expensive and more sustainable than a more active approach of reconstructing a narrower channel to the width that is ultimately expected. Long-term riparian buffer management is needed to ensure trees will be recruited into the channel through time and replace the constructed habitat features as they decay over several decades. Maintaining the extensive wetlands in the upper watershed will also be important, so increases in peak flows do not threaten the stability of the installed structures.

The characterization of culvert impacts and identification of mitigation design measures to improve degraded habitat were the primary objectives of the culvert assessment. The morphology of the channels on either side of the ten culverts assessed reflects the culverts' impact on sediment transport processes. Most culverts are less than half the width of the channel, causing fine sediment deposition upstream and deep scour pools and bank erosion downstream. As culverts are slated for replacement, the new culverts should span the bankfull width of the channel and incorporate floodplain culverts where floodplains are present. However, many of the problematic culverts were only recently replaced. Short-term design measures can be employed to mitigate the habitat impacts at the culverts long before culvert replacement will be possible (Appendix 8). Boulder weirs to reduce undermining of the culvert and log crib walls to prevent bank scouring are examples of design measures that can also enhance physical habitat conditions near the culverts. The results of the fluvial geomorphology and culvert assessment with a focus on both watershed-scale and local problems will be of assistance as the Houlton Band of the Maliseet Indians plan additional projects on the river intended to allow traditional tribal practices to continue long into the future.

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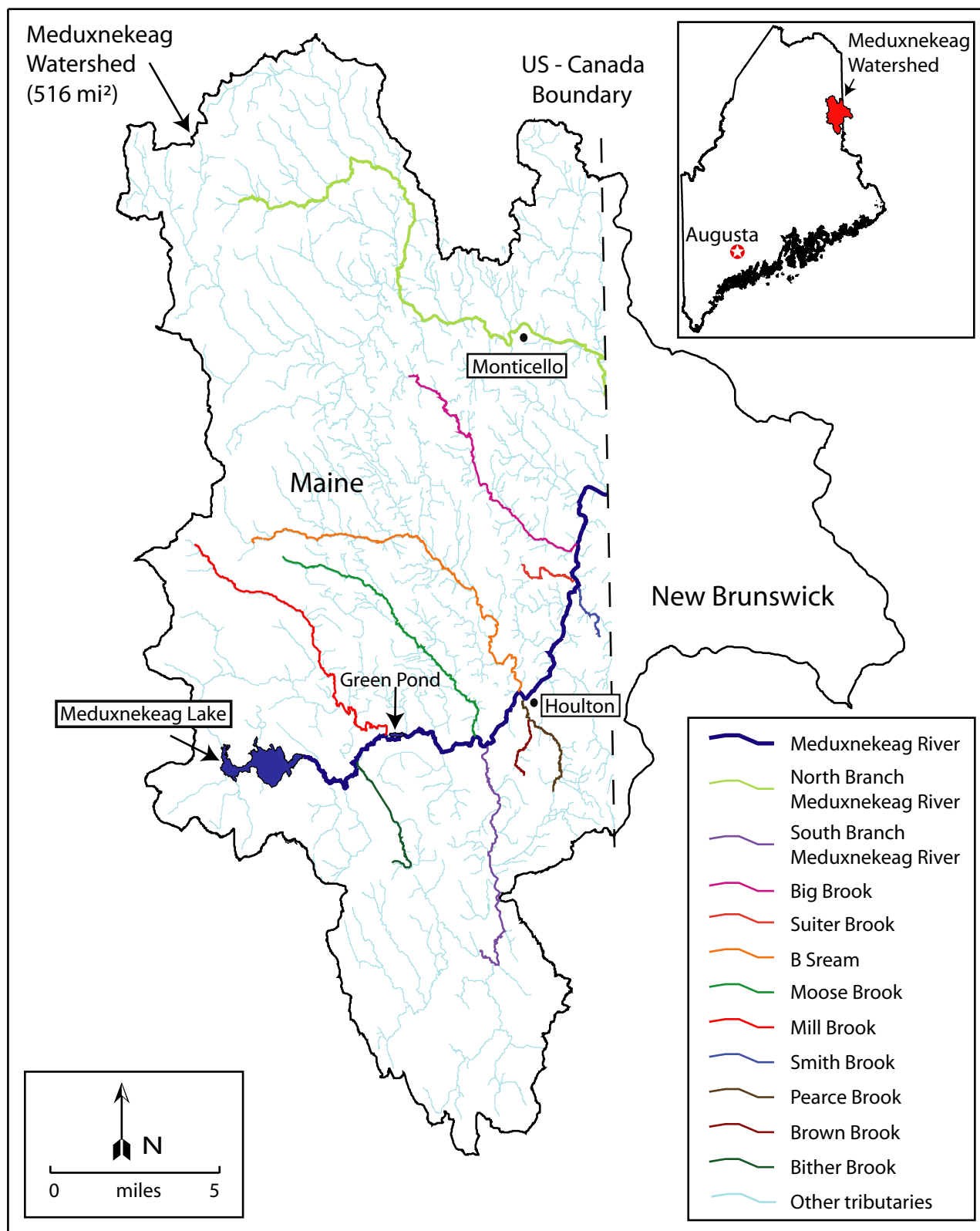


Figure 1. Watershed map of Meduxnekeag River in Maine showing major tributaries.



Figure 2. The Meduxnekeag River flows very muddy during runoff events.



Figure 3. Extensive wetlands are a common feature on many of the tributaries to the Meduxnekeag River such as Pearce Brook.

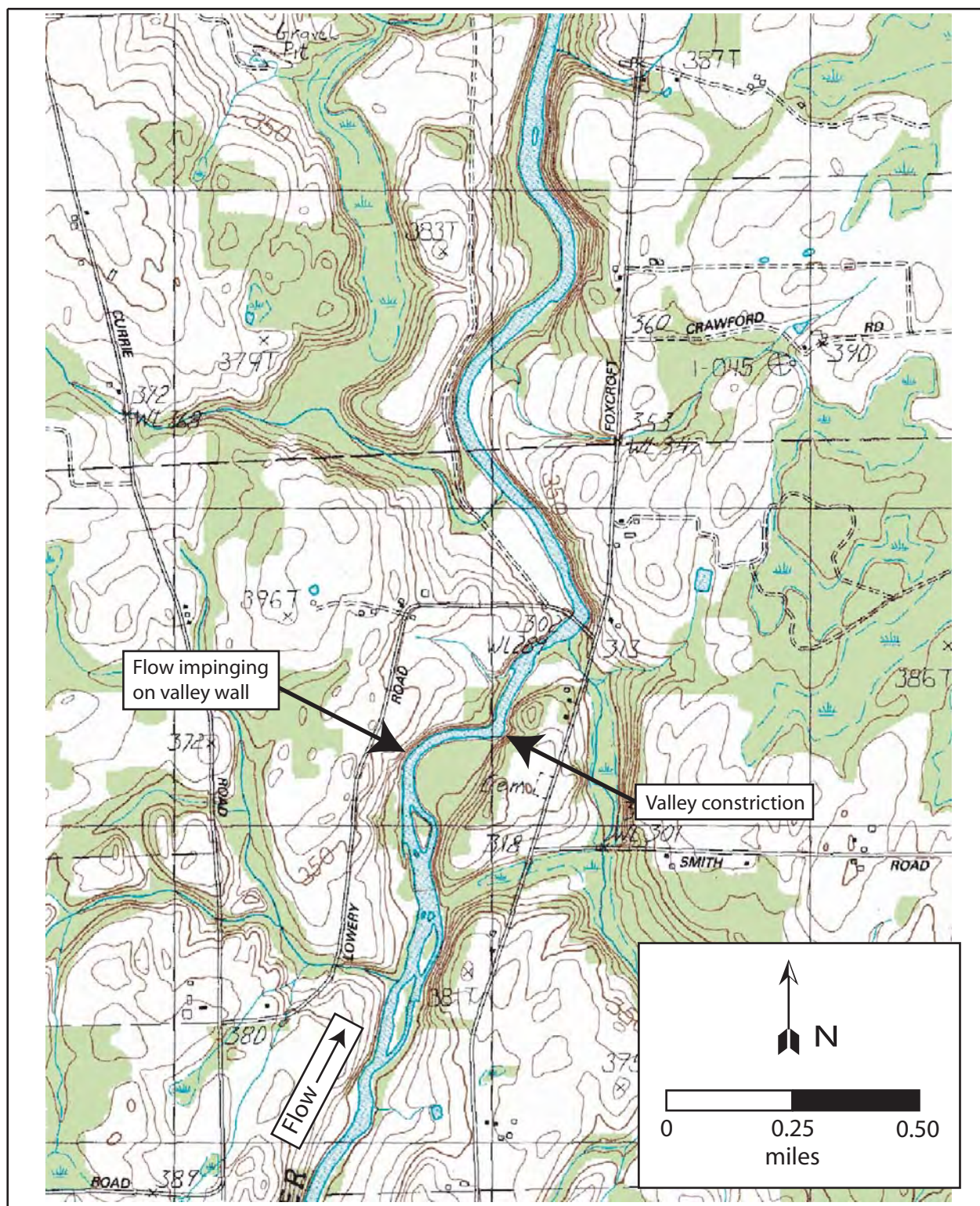


Figure 4. Topographic map of the Meduxnekeag River downstream of Houlton showing narrow valley through which the river flows. The river sometimes encounters the valley walls and valley constrictions.

a)



b)



Figure 5. a) Sediment deposition directly into the Meduxnekeag River at the mouth of an unnamed tributary is b) enhanced by channel incision upstream caused by the concentration of flow after rebuilding of the Houlton Civic Center.

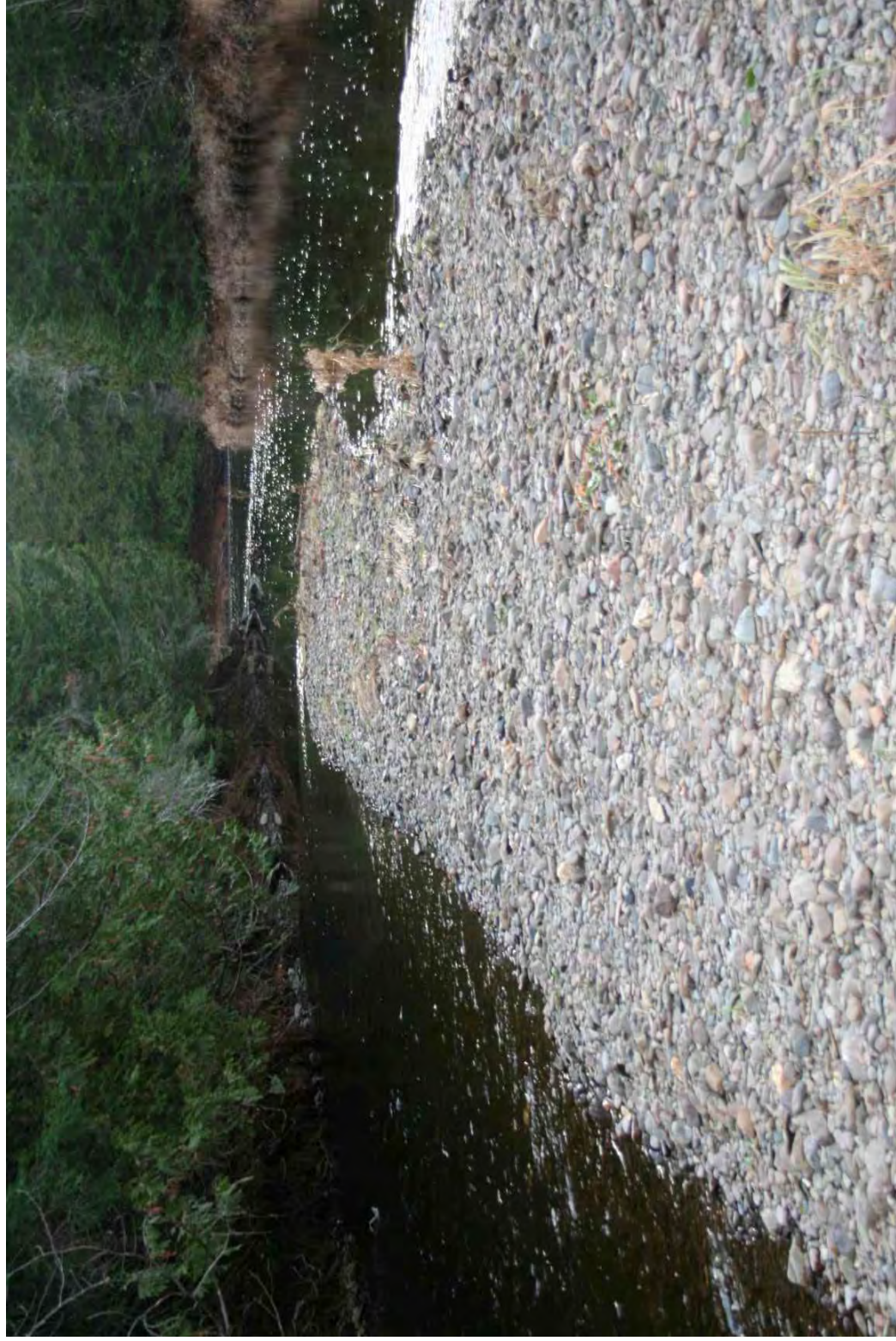


Figure 6. Gravel bar on B Stream deposited upstream of a valley constriction.



Figure 7. Artificial straightening probably occurred on lower Mill Brook where a straight channel is present along the valley margins despite an unconfined valley across which the channel could meander. Note presence of old meanders abandoned during the straightening.



Figure 8. Dam across the Meduxnekeag River in Houlton. Photo date unknown. From Sleeper, 1994.

a)



b)



Figure 9. Evidence for old dams no longer existing can be seen as a) large logs protruding from the bank and oriented normal to flow and b) fine-grained impoundment sediments often containing abundant logs and wood fragments.

a)



b)



Figure 10. Photos highlighting change in land use 0.5 miles downstream of the old dam site in Houlton in a) upstream view circa 1890 showing agricultural land use on left bank (right of photo) and b) 2003 aerial photo showing deciduous tree growth in approximately the same location (outlined in blue box).

a)



b)



Figure 11. a) Historical photograph circa 1890 of the Meduxnekeag River downstream of Cooks Brook contrasts dramatically with b) a recent photograph of the same area showing I-95 bridge crossing that spans almost the entire channel.

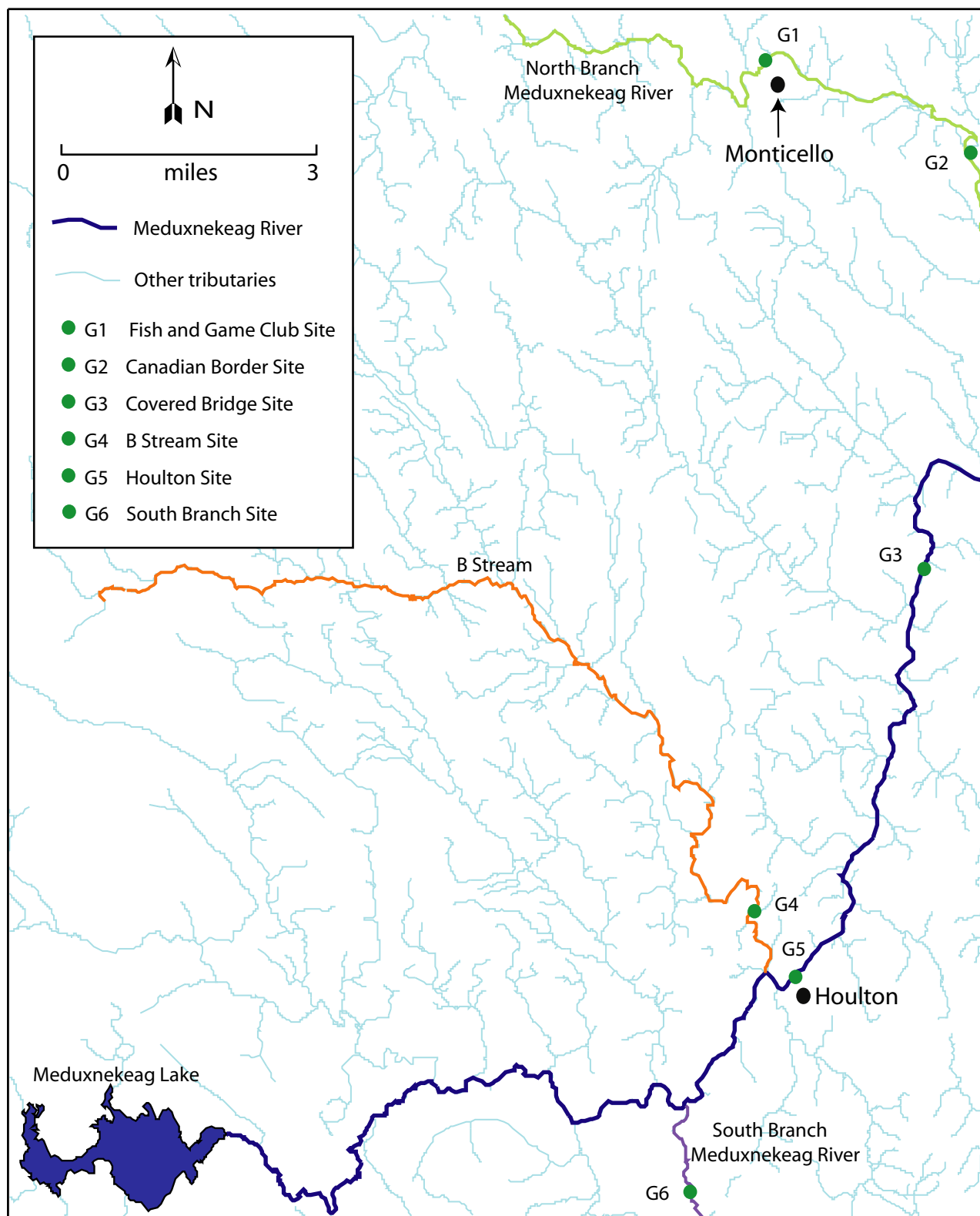


Figure 12. Location of the geomorphic assessment sites.



Figure 13. Flow complexity created by a) bedrock, b) isolated boulder, c) log jam, and d) boulder-supported log jam.

a)



b)



Figure 14. a) Deep pool formed around boulder and b) sand and gravel deposited upstream of log jam



Figure 15. High width:depth ratio channel at the Fish and Game Club site is shallow and slow moving at low flow.



Figure 16. Riparian buffer planting projects will one day provide a supply of trees that will fall into the channel and increase flow complexity and habitat.

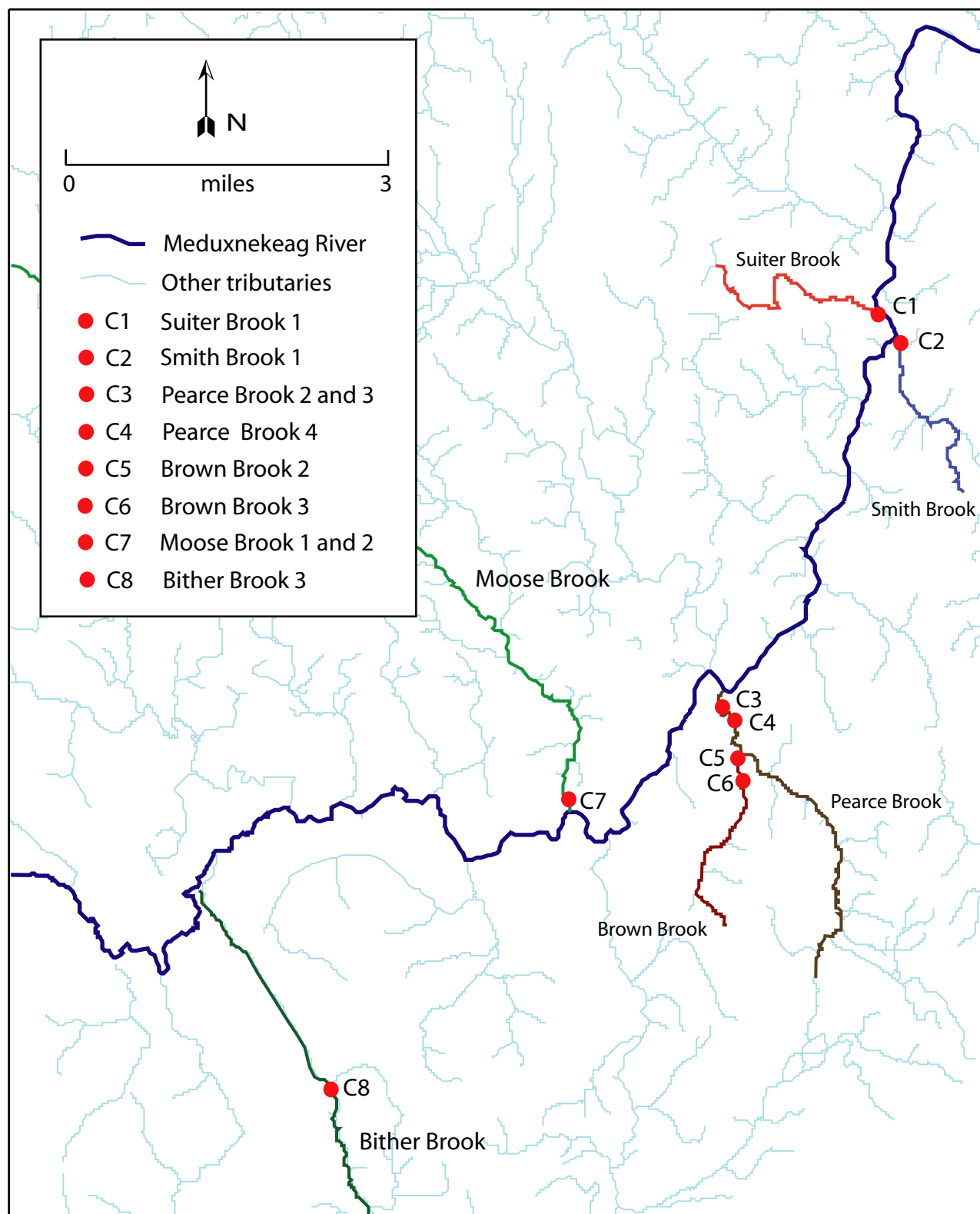


Figure 17. Location of the culvert assessment sites.

Name	Miles mapped
Meduxnekeag mainstem	21.8
North Branch Meduxnekeag	12.0
B Stream	9.4
South Branch Meduxnekeag	4.3
Pearce Brook	3.4
Moose Brook	2.2
Mill Brook	2.0
Cook Brook	1.8
Smith Brook	1.1
Big Brook	0.9
Jimmy Brook	0.9
Total	59.8

Table 1. Length of channel features mapped along the Meduxnekeag River and ten tributaries.

Drainage Area (U.S. portion)	425.5 sq. miles					
Stream length (feet)	315,807					
(miles)	59.8					
Morphology	Length	%				
Marsh	336	0.1				
Cascade	1,409	0.5				
Dune-Ripple	113	0.0				
Plane-Bed	47,151	16.2				
Pool-Riffle	238,942	82.2				
Step-Pool	2,746	0.9				
Substrate	Length	%				
Boulder	24,249	8.4				
Cobble	182,373	62.9				
Gravel	64,182	22.1				
Sand	10,684	3.7				
Silt/Clay	8,455	2.9				
Depositional Features	LB	%	RB	%	Total	%
Side bars	11,109	3.5	6,908	2.2	18,017	5.7
	Length	%				
Mid-channel bars	12,539	4.0				
Islands	8,066	2.6				
Mud bars	221	0.1				
Point bars	14,278	4.5				
Delta bars	1,121	0.4				
Low Bank Height	LB	%	RB	%	Total	%
0 to 2 ft	36,428	12.8	15,009	4.9	51,437	8.7
2 to 4 ft	148,465	52.0	143,976	47.0	292,441	49.4
4 to 6 ft	41,809	14.7	63,808	20.8	105,617	17.9
6 to 10 ft	18,373	6.4	26,965	8.8	45,338	7.7
10 to 15 ft	15,446	5.4	23,183	7.6	38,629	6.5
15 to 20 ft	9,265	3.2	8,278	2.7	17,543	3.0
20 to 30 ft	7,439	2.6	16,367	5.3	23,806	4.0
30+ ft	8,042	2.8	8,689	2.8	16,731	2.8
High Bank Height	LB	%	RB	%	Total	%
4 to 6 ft	11,198	17.6	55,540	26.0	66,738	24.0
6 to 10 ft	12,243	19.2	39,995	18.7	52,238	18.8
10 to 15 ft	11,361	17.8	46,701	21.8	58,062	20.9
15 to 20 ft	9,701	15.2	21,877	10.2	31,578	11.4
20 to 30 ft	9,652	15.2	27,009	12.6	36,661	13.2
30+ ft	9,545	15.0	22,761	10.6	32,306	11.6

Table 2. Summary statistics for mapped channel features.

Bank Composition	LB	%	RB	%	Total	%
Artificial Fill	1,125	0.4	402	0.1	1,527	0.2
Floodplain	185,633	73.7	204,560	69.3	390,193	61.8
Non-Alluvial glacial sediments	49,459	19.6	60,863	20.6	110,322	17.5
Impoundment sediments	5,271	2.1	625	0.2	5,896	0.9
Bedrock	10,417	4.1	28,790	9.8	39,207	6.2
Bank Stability	LB	%	RB	%	Total	%
Stable	256,865	87.0	210,656	70.4	467,521	78.6
Eroding	12,244	4.1	58,915	19.7	71,159	12.0
Moderately Eroding	22,103	7.5	27,846	9.3	49,949	8.4
Armored (Riprap)	4,178	1.4	1,969	0.7	6,147	1.0
Bedrock control	Length	%				
Grade controls	39,590	12.5				
Bedrock in channel	29,347	9.3				
Total bedrock	68,937	21.8				
Point Features						
Grade control locations	106					
Bedrock in channel locations	113					
Woody material locations	151					
Deep pool	96					
Bridges	25					
Beaver dams	24					
Dam	1					

Table 2 (continued). Summary statistics for mapped channel features.

Site	Assessment Purpose	Slope	Bankfull Width (ft)	Max Depth(ft)	Mean Depth(ft)	W/D Ratio	Sinuosity	D-50 Particle Size (mm)
Fish and Game Site	Restoration	0.001	88.2	3.9	1.8	31.7	1.0	45
Canadian Border Site	Restoration	0.003	103.5	2.7	2.1	67.8	1.0	32
Covered Bridge Site	Restoration	0.001	139.8	2.7	2.0	70.3	1.1	22
Houlton Site	Human impacts	0.002	110.2	6.3	3.8	25.4	1.0	90
B Stream Site	Restoration and habitat features	0.005	72.4	2.5	2.1	38.2	1.0	22
South Branch Site	Habitat features	0.009	63.4	3.9	2.2	21.7	1.1	2

Notes:

- W/D ratio = width to depth ratio; bankfull width / mean bankfull depth
- D-50 particle size represents the median particle size
- Sinuosity = channel length / valley length

Table 3. Morphological characteristics of the geomorphic assessment sites.



Site	XS	Slope	Culvert Slope	Bankfull Width (ft)	Max Depth(ft)	W/D Ratio	Culvert Width (ft)	Confinement Ratio	Pool Depth (ft)	D-50 Particle Size (mm)
Suiter Brook 1	US	0.001	0.011	18.0	2.4	11.3	6.0	0.33		2
Suiter Brook 1	DS	0.019		12.6	2.3	8.0			1.2	16
Smith Brook 1	US	0.005	0.010	30.2	2.4	19.4	11.9	0.39		6
Smith Brook 1	DS	0.009		35.3	4.0	14.7			6.4	11
Pearce Brook 2	US	0.008	insufficient	26.7	2.7	13.9	9.0	0.34		45
Pearce Brook 2	DS	0.010	data	33.1	2.8	14.4			2.3	32
Pearce Brook 3	US	0.001	insufficient	34.4	5.6	8.1	9.0	0.26		4
Pearce Brook 3	DS	0.008	data	26.7	2.7	13.9			2.7	45
Pearce Brook 4	US		0.010	23.0	2.5	13.7	10.0	0.43		22
Pearce Brook 4	DS	0.010		26.9	2.6	15.2			2.0	45
Brown Brook 2	US	0.009	0.014	14.6	1.8	10.9	9.0	0.62		2
Browns Brook 2	DS	0.018		20.1	2.6	8.9			1.2	22
Brown Brook 3	US	0.013	0.009	16.5	1.8	17.5	7.0	0.42		2
Brown Brook 3	DS	0.005		15.6	1.5	14.3			1.4	4
Moose Brook 1	US	0.002	insufficient	44.2	2.8	19.7	7.8	0.18		6
Moose Brook 1	DS	0.011	data	36.7	4.4	11.4			3.6	32
Moose Brook 2	US	0.014	insufficient	53.1	3.9	19.0	21.3	0.40		45
Moose Brook 2	DS	0.002	data	44.2	2.8	19.7			2.1	6
Bither Brook 3	US	0.009	0.010	Marsh			7.6	0.50		2
Bither Brook 3	DS			15.3	2.4	9.6			1.9	8

Notes:

- XS = location in reach
- US = upstream of culvert
- DS = downstream of culvert
- W/D ratio = width to depth ratio; bankfull width / mean bankfull depth
- Confinement ratio = culvert width / bankfull width
- Pool depth measured at low flow. Pool depth will vary with flow conditions.
- D-50 particle size represents the median particle size

Table 4 . Morphological characteristics of the culvert assessment sites.



Appendix 1

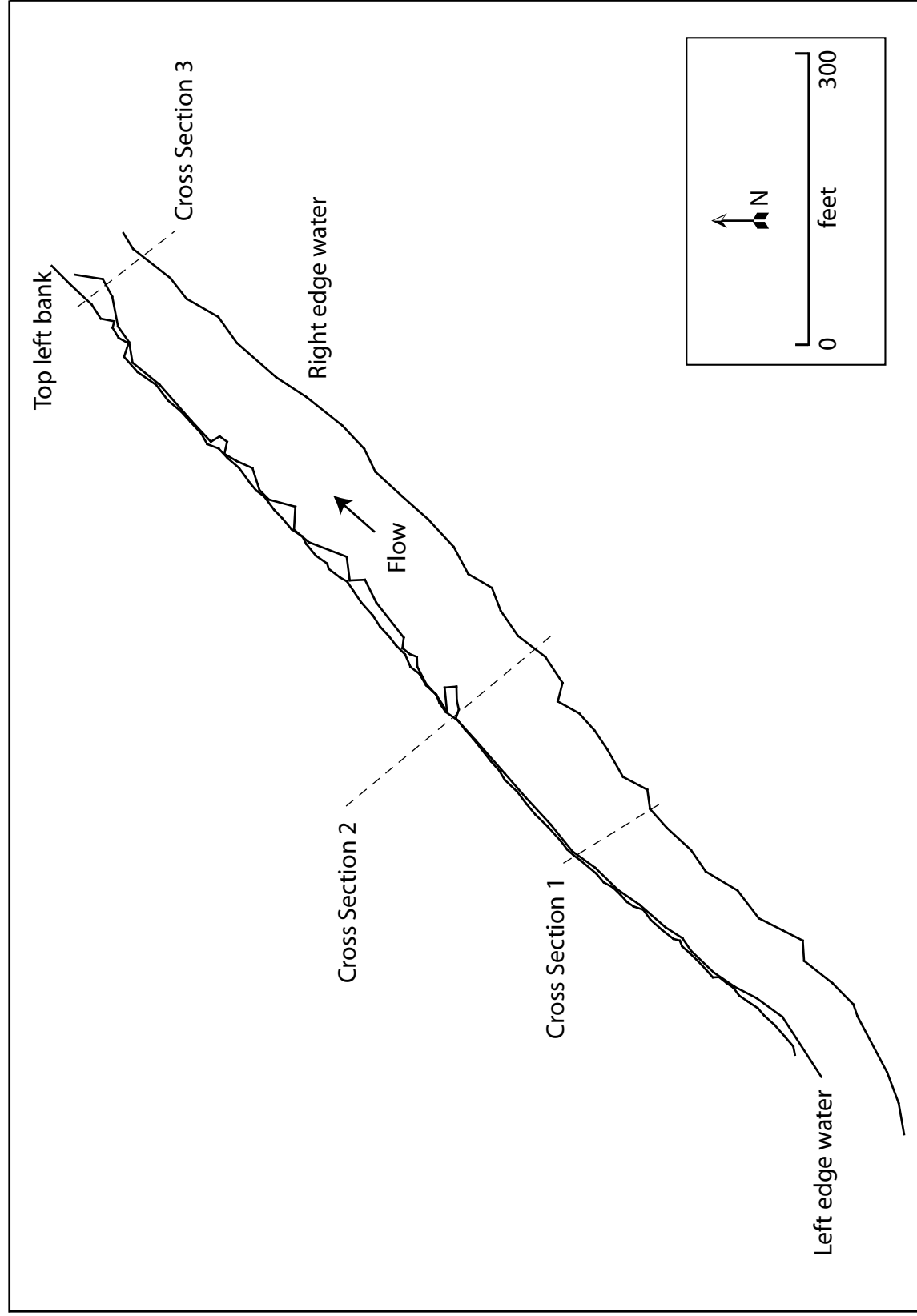
Historical Topographic Maps and Aerial Photographs
(Refer to enclosed CD.)

Appendix 2

GIS Shapefiles of Channel Features Mapping
(Refer to enclosed CD.)

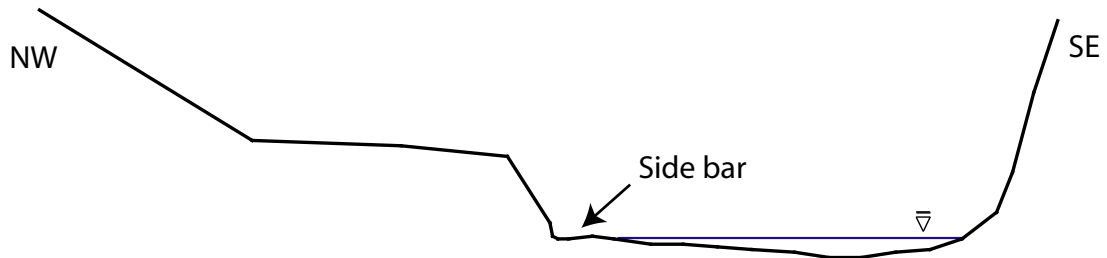
Appendix 3

Topographic Survey Data for the Geomorphic Assessment Sites
(Refer to CD for additional data.)



Appendix 3. Topographic survey data planview for the Fish and Game Club Geomorphic Assessment Site.

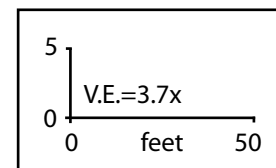
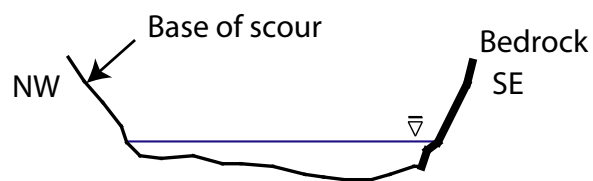
Cross Section 1 : Downstream view



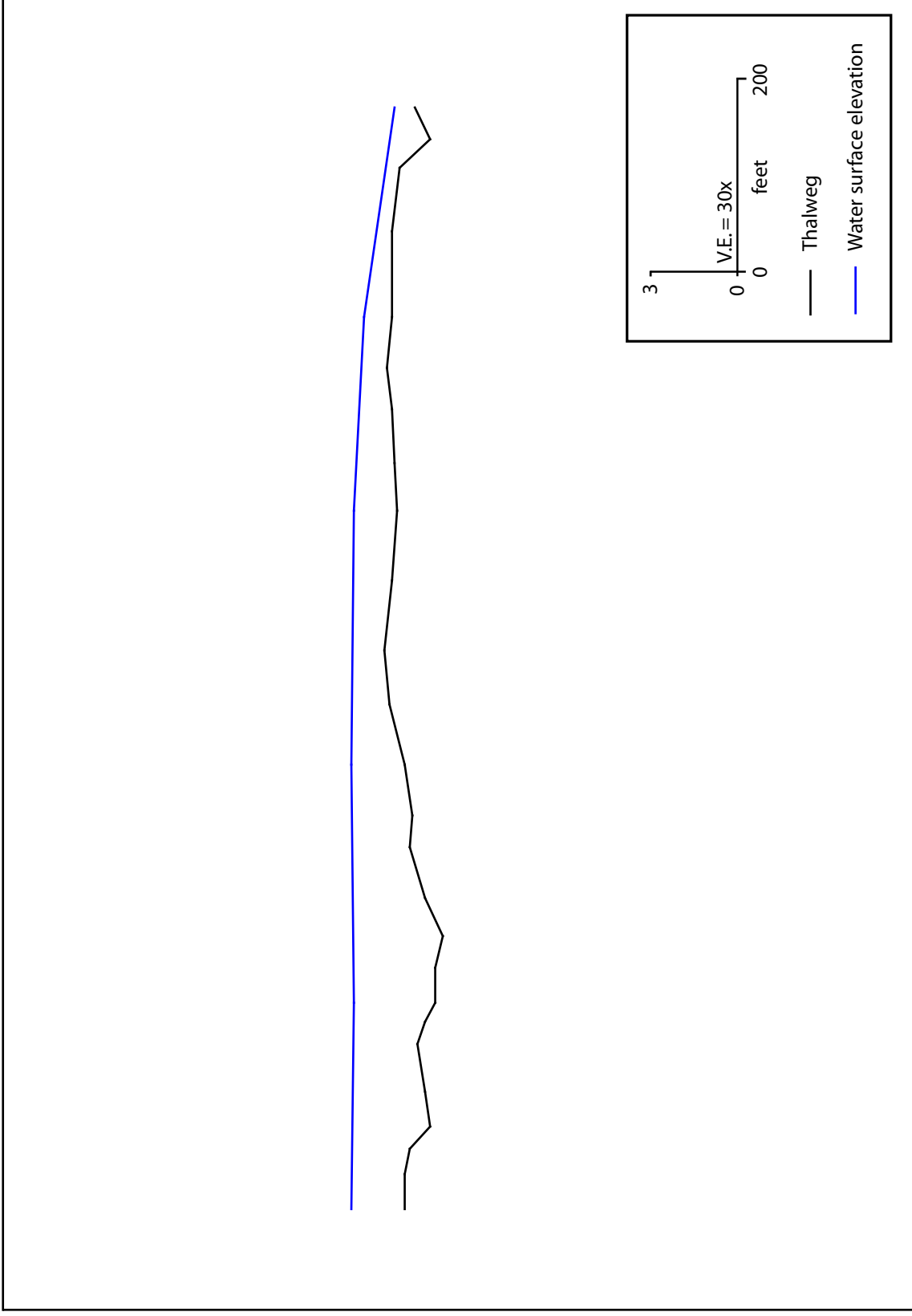
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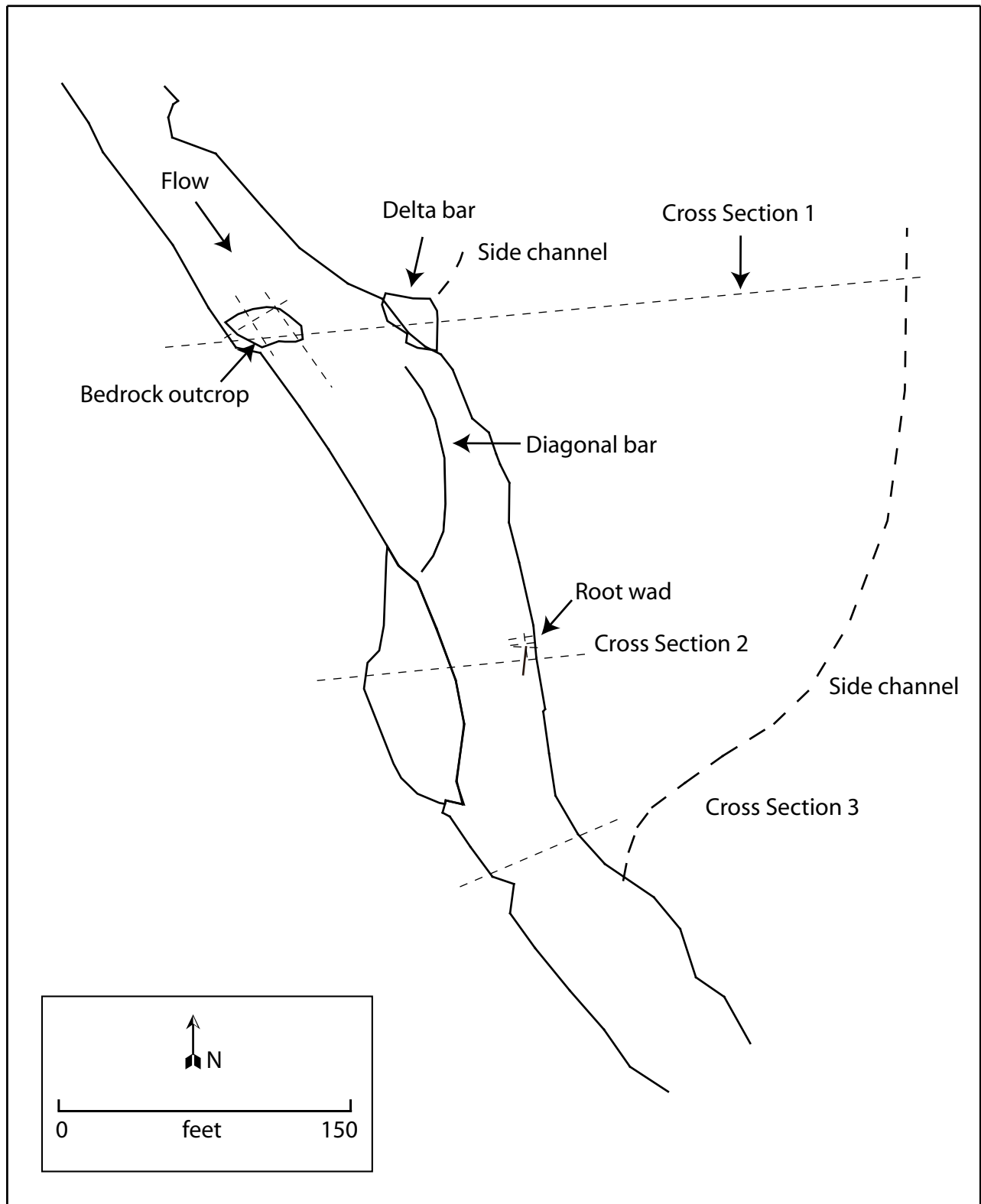
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Appendix 3. Topographic survey data cross sections for the Fish and Game Club Geomorphic Assessment Site.

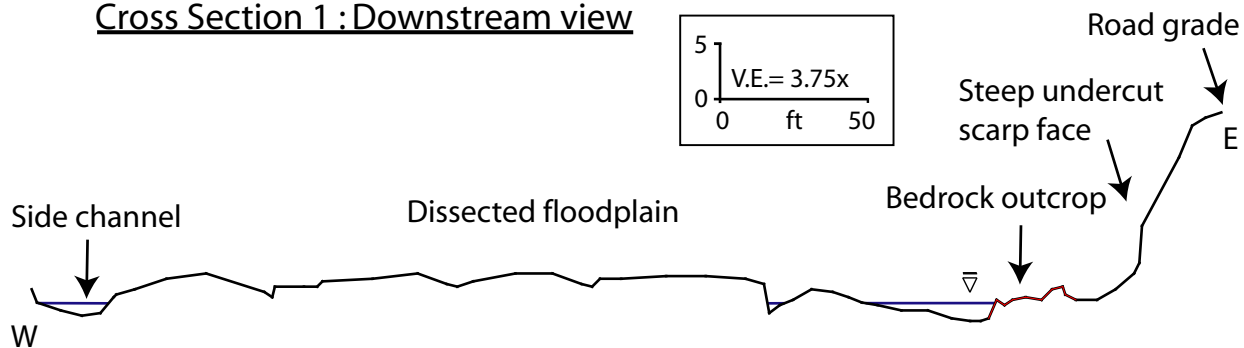


Appendix 3. Topographic survey data longitudinal profile for the Fish and Game Club Geomorphic Assessment Site.

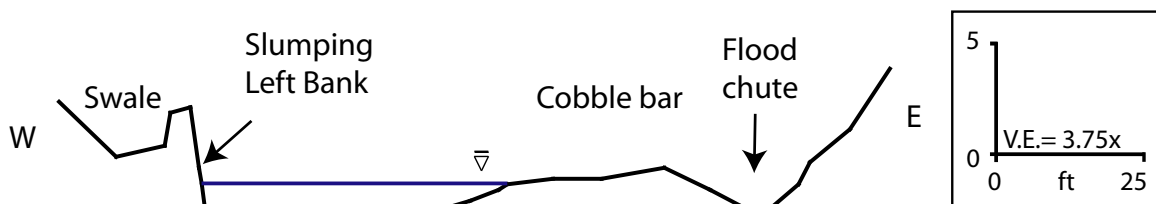


Appendix 3. Topographic survey data planview for the Canadian Border Geomorphic Assessment Site.

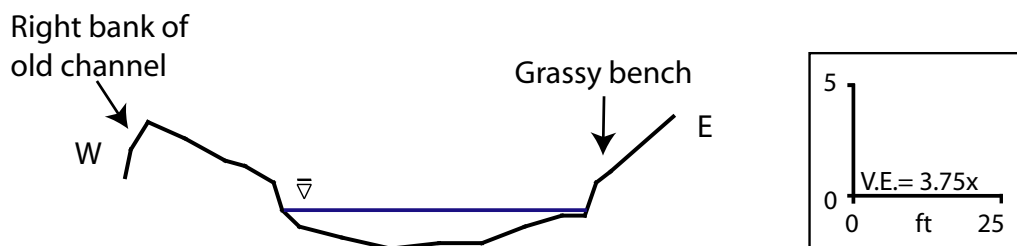
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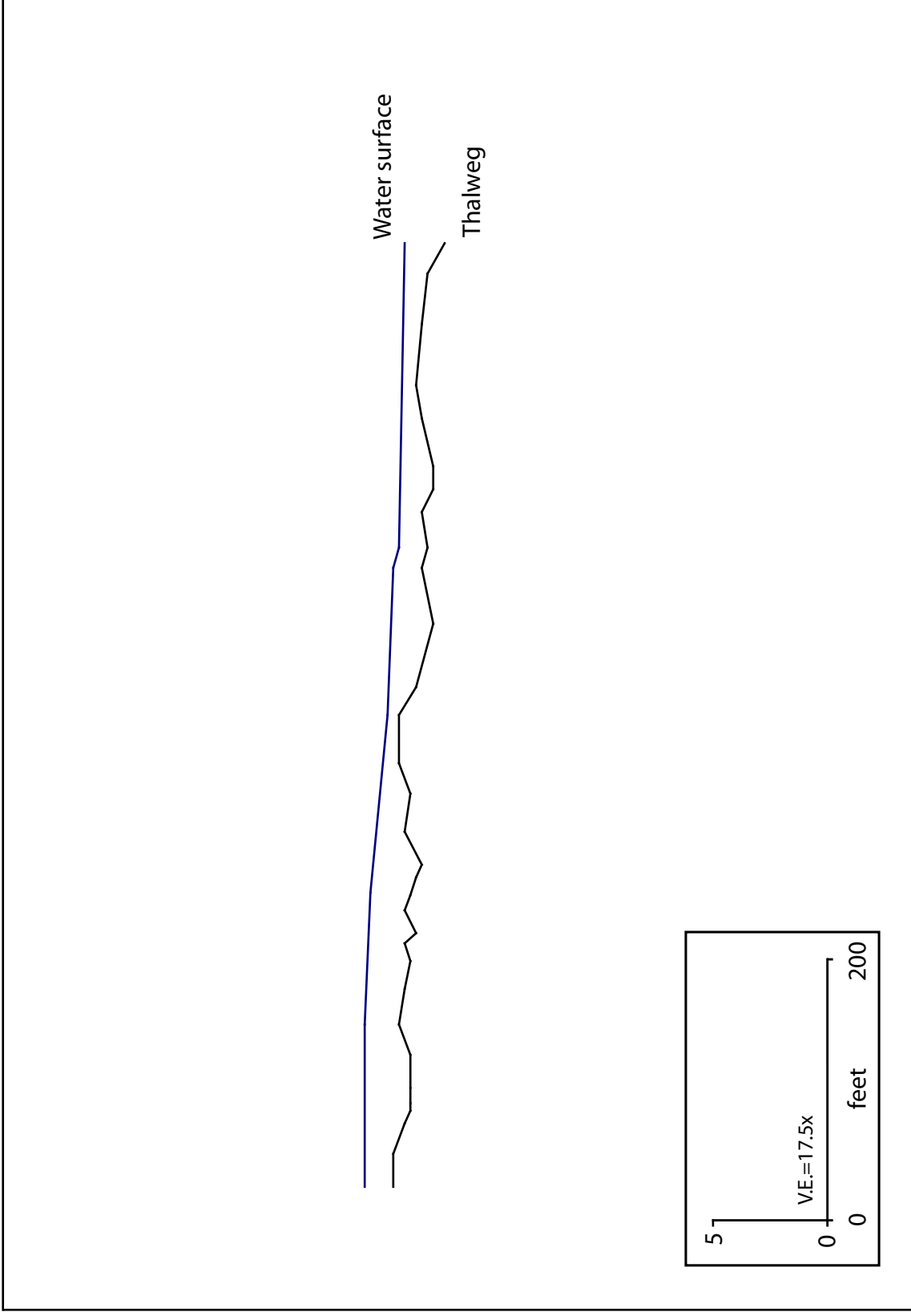
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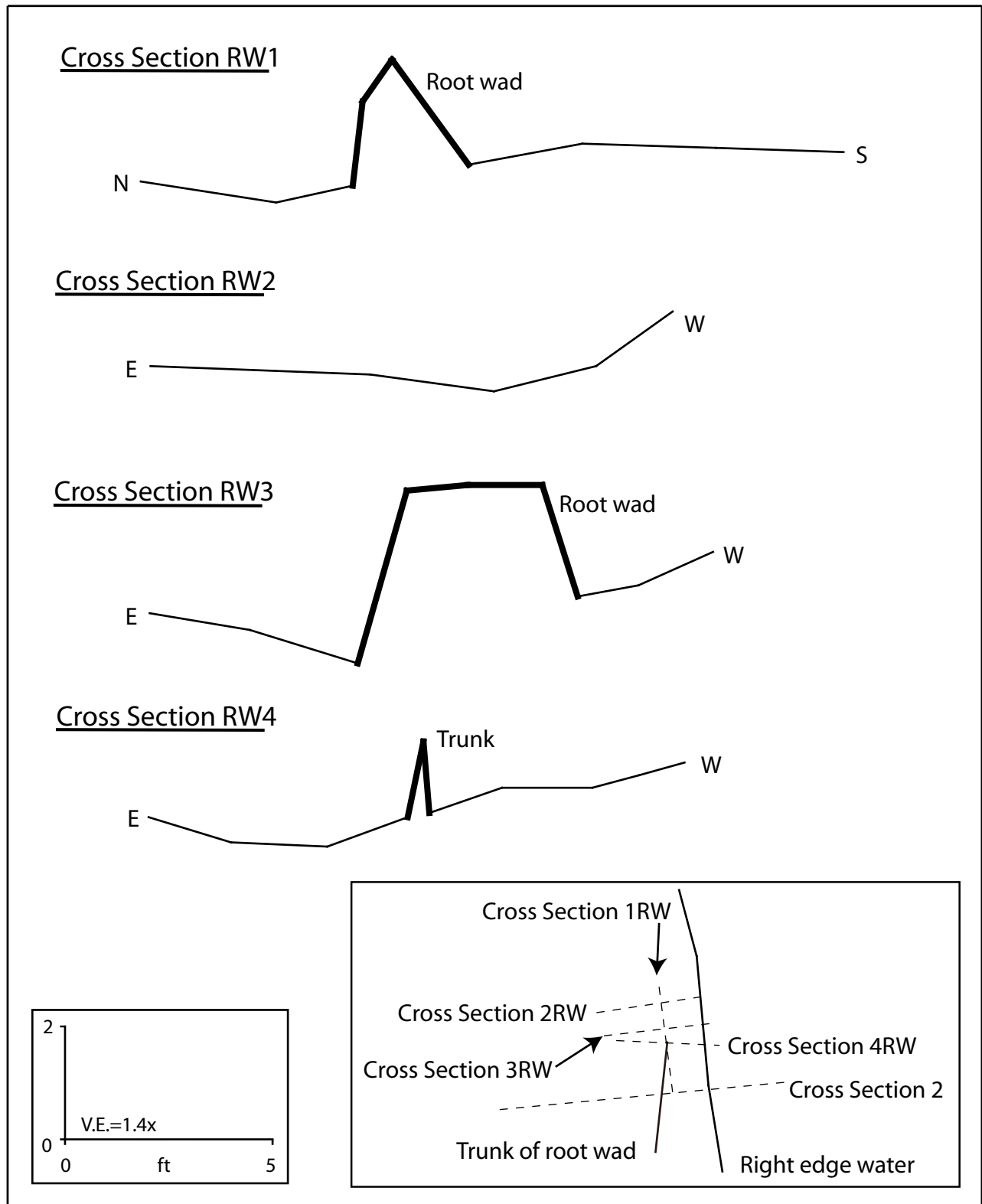
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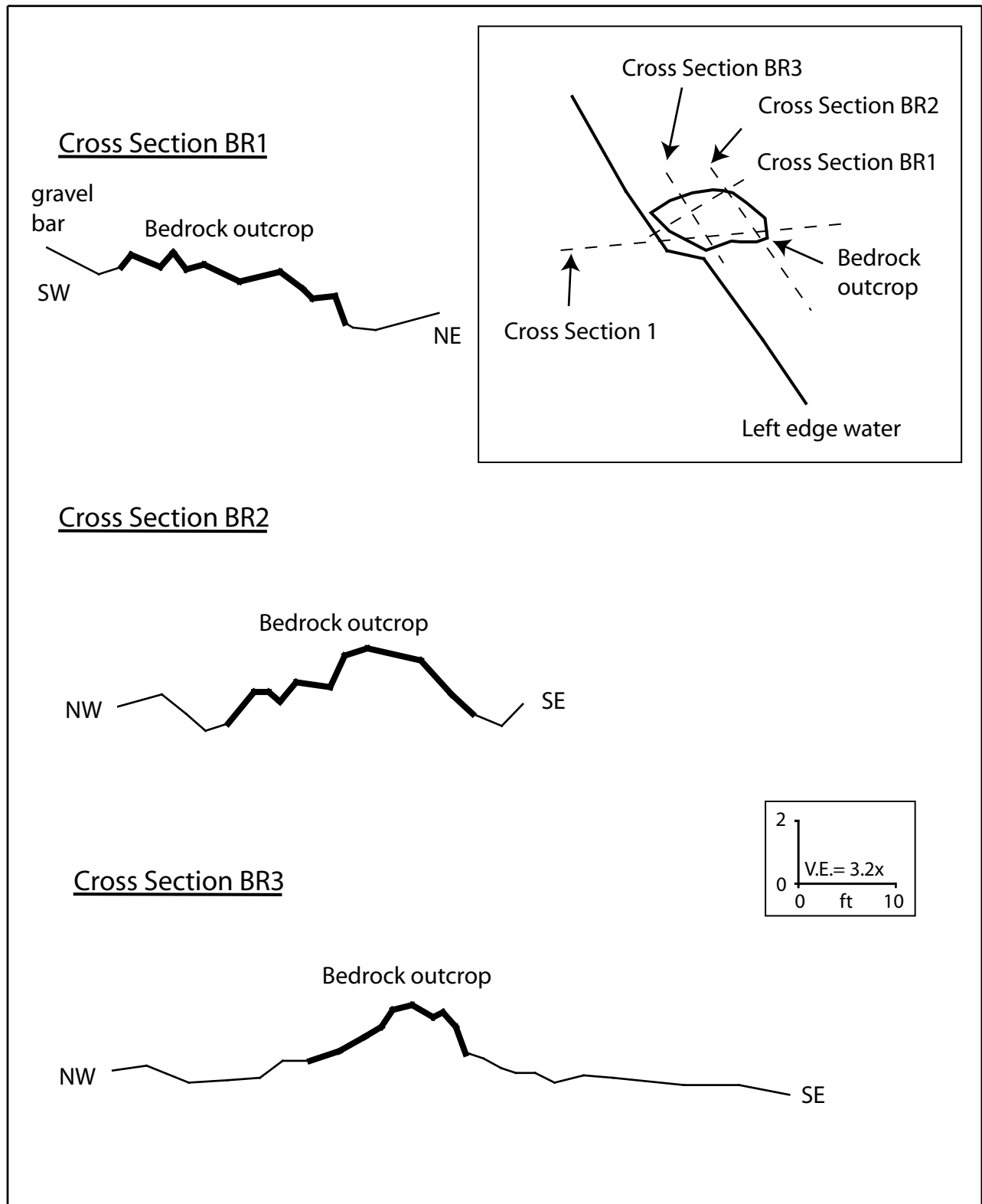
Appendix 3. Topographic survey data cross sections for the Canadian Border Geomorphic Assessment Site.



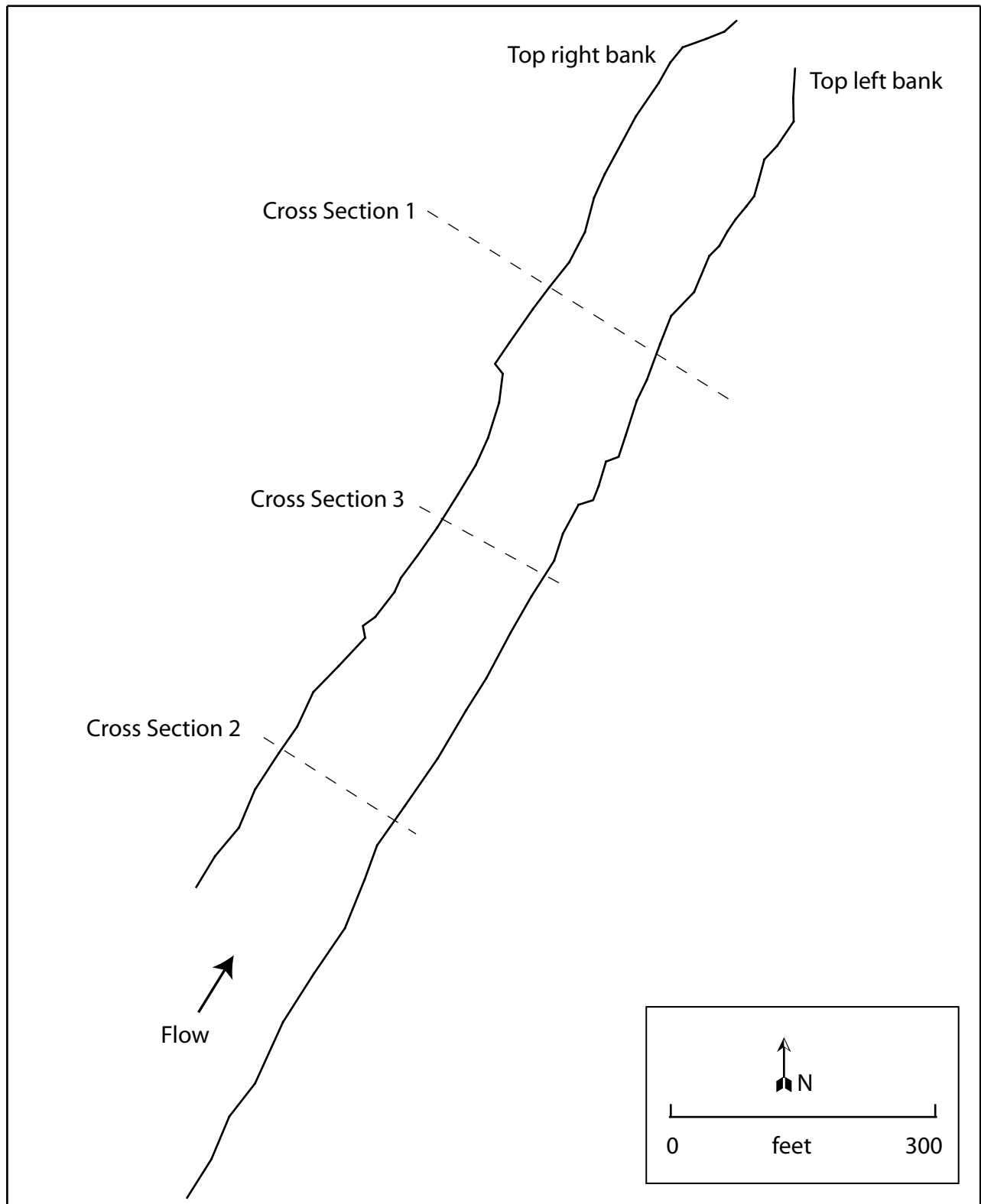
Appendix 3. Topographic survey data longitudinal profile for the Canadian Border Geomorphic Assessment Site.



Appendix 3. Topographic survey data cross sections for the Canadian Border Geomorphic Assessment Site root wad detail.

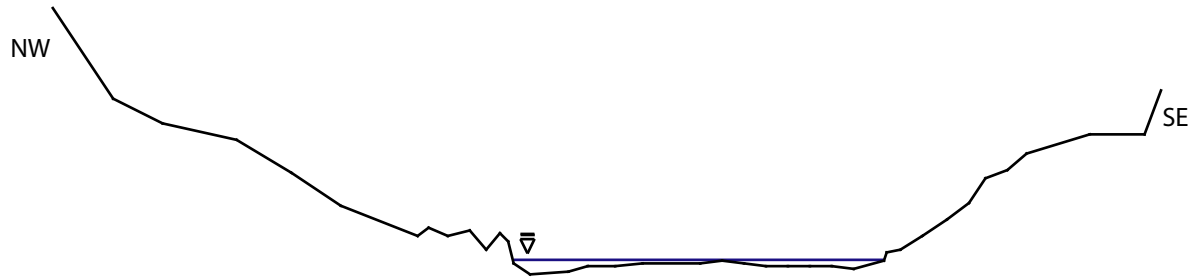


Appendix 3. Topographic survey data cross sections for the Canadian Border Geomorphic Assessment Site bedrock outcrop detail.



Appendix 3. Topographic survey data planview for the Covered Bridge Geomorphic Assessment Site.

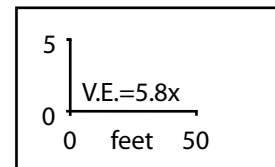
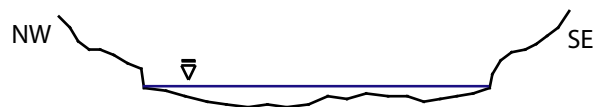
Cross Section 1 : Downstream view



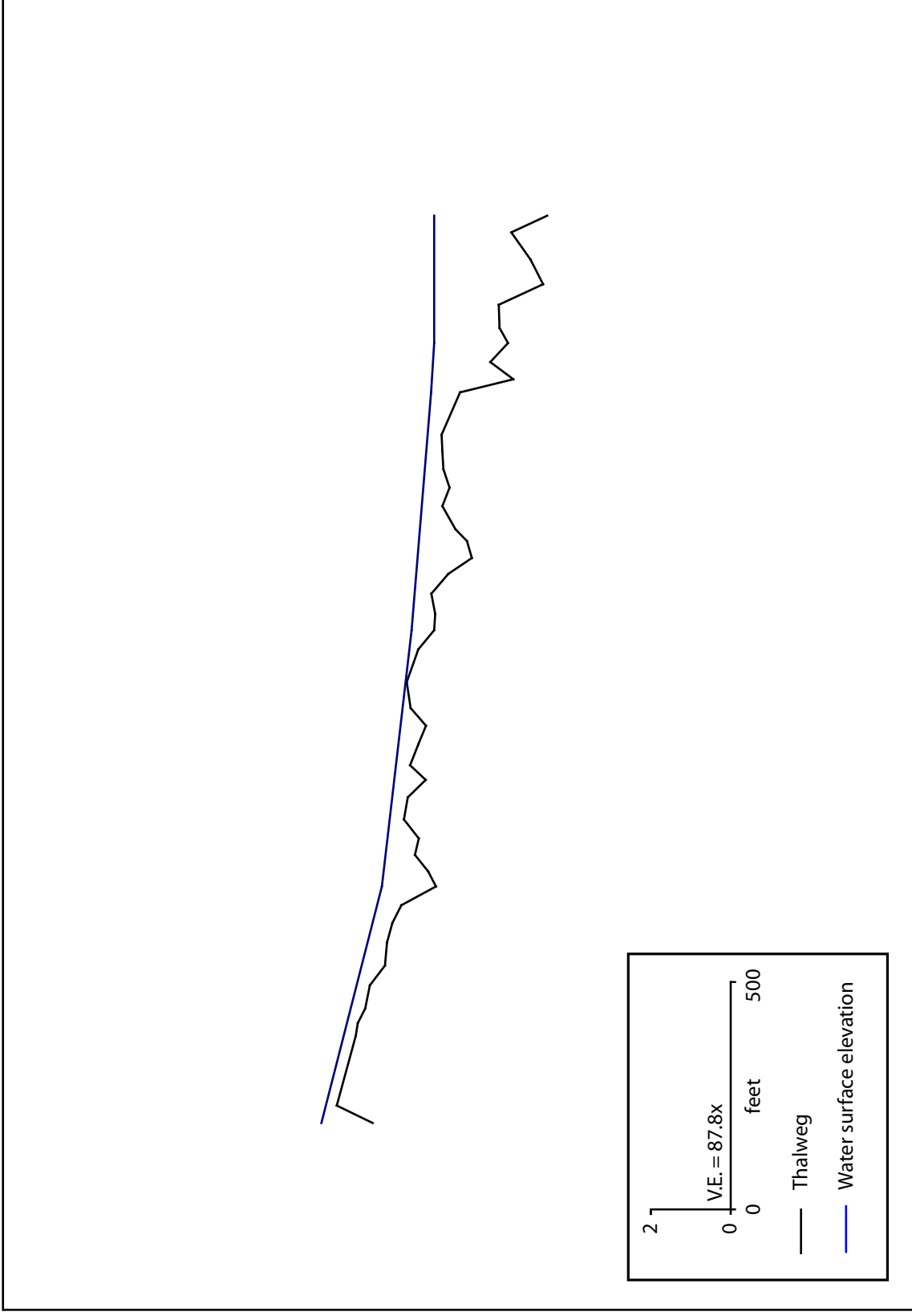
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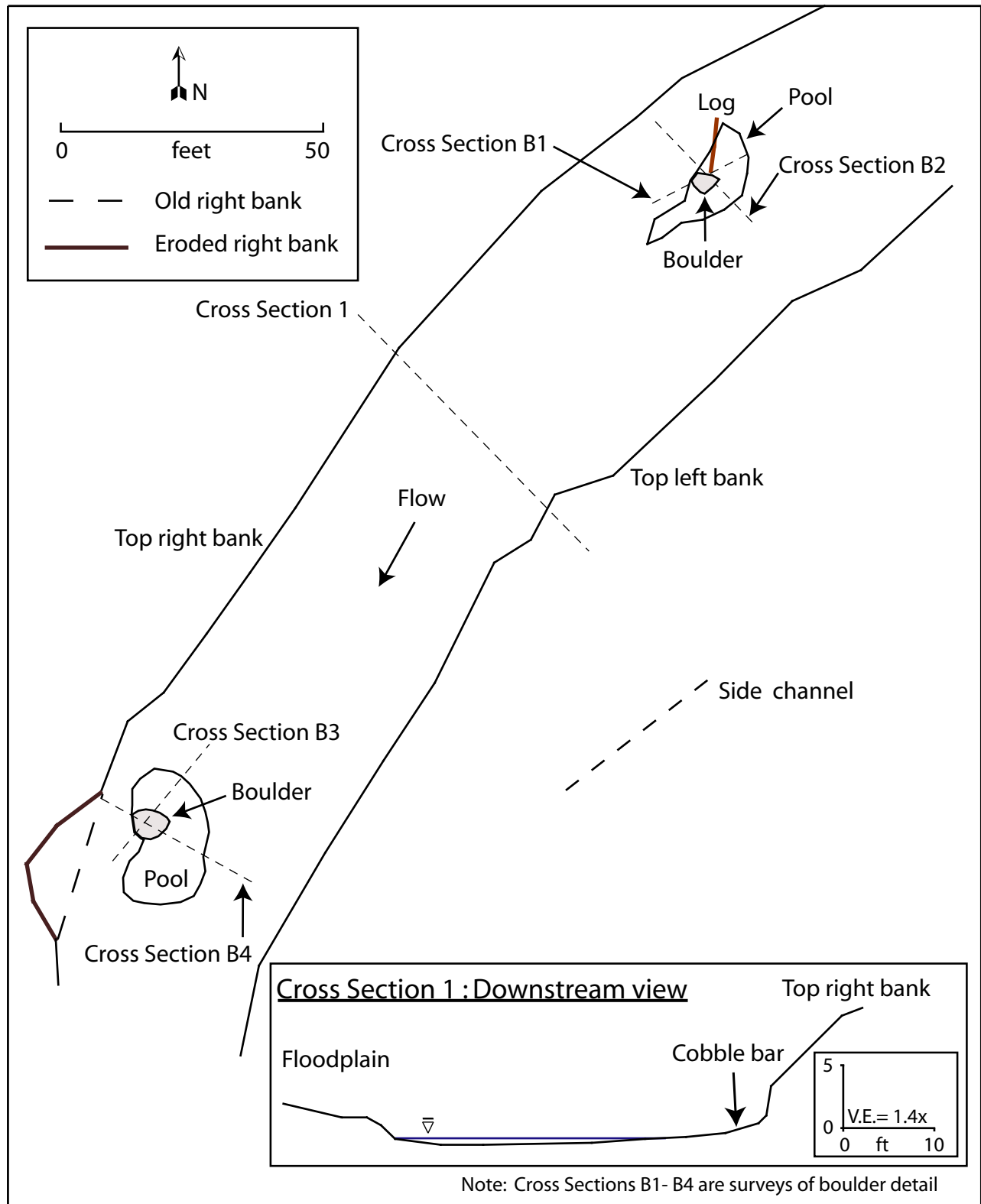
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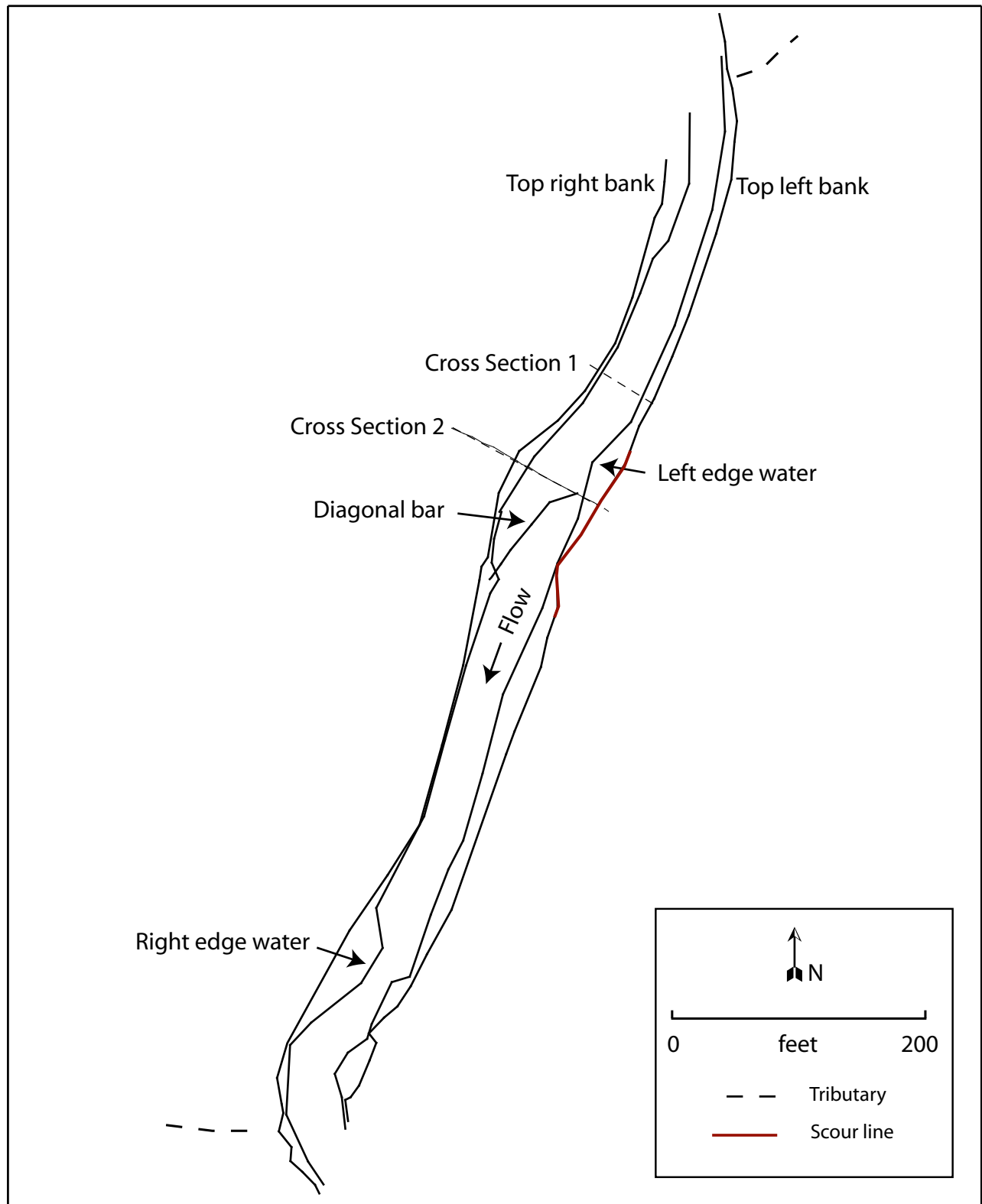
Appendix 3. Topographic survey data cross sections for the Covered Bridge Geomorphic Assessment Site.



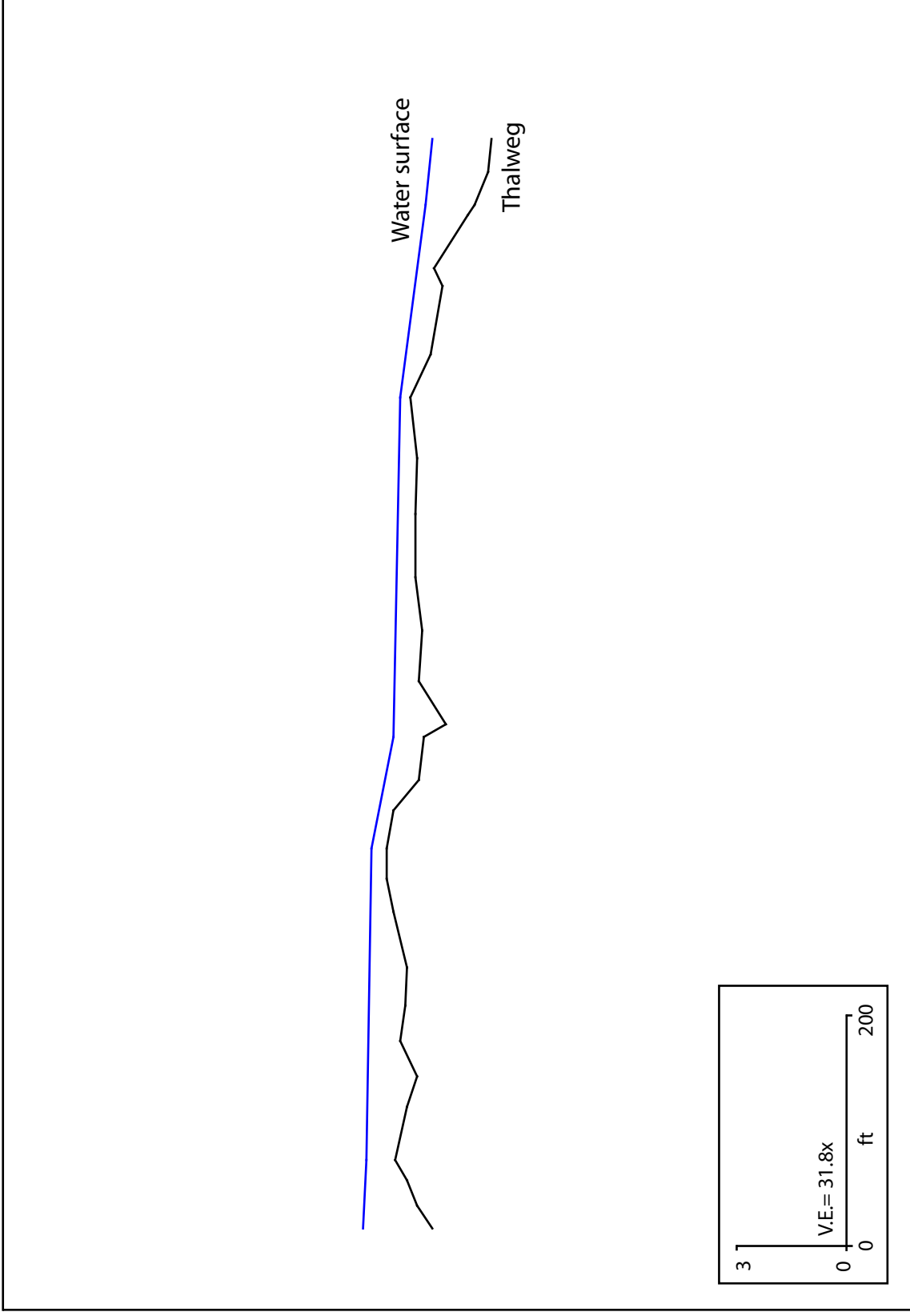
Appendix 3. Topographic survey data longitudinal profile for the Covered Bridge Geomorphic Assessment Site.



Appendix 3. Topographic survey data planview for B Stream Geomorphic Assessment Site boulder detail.

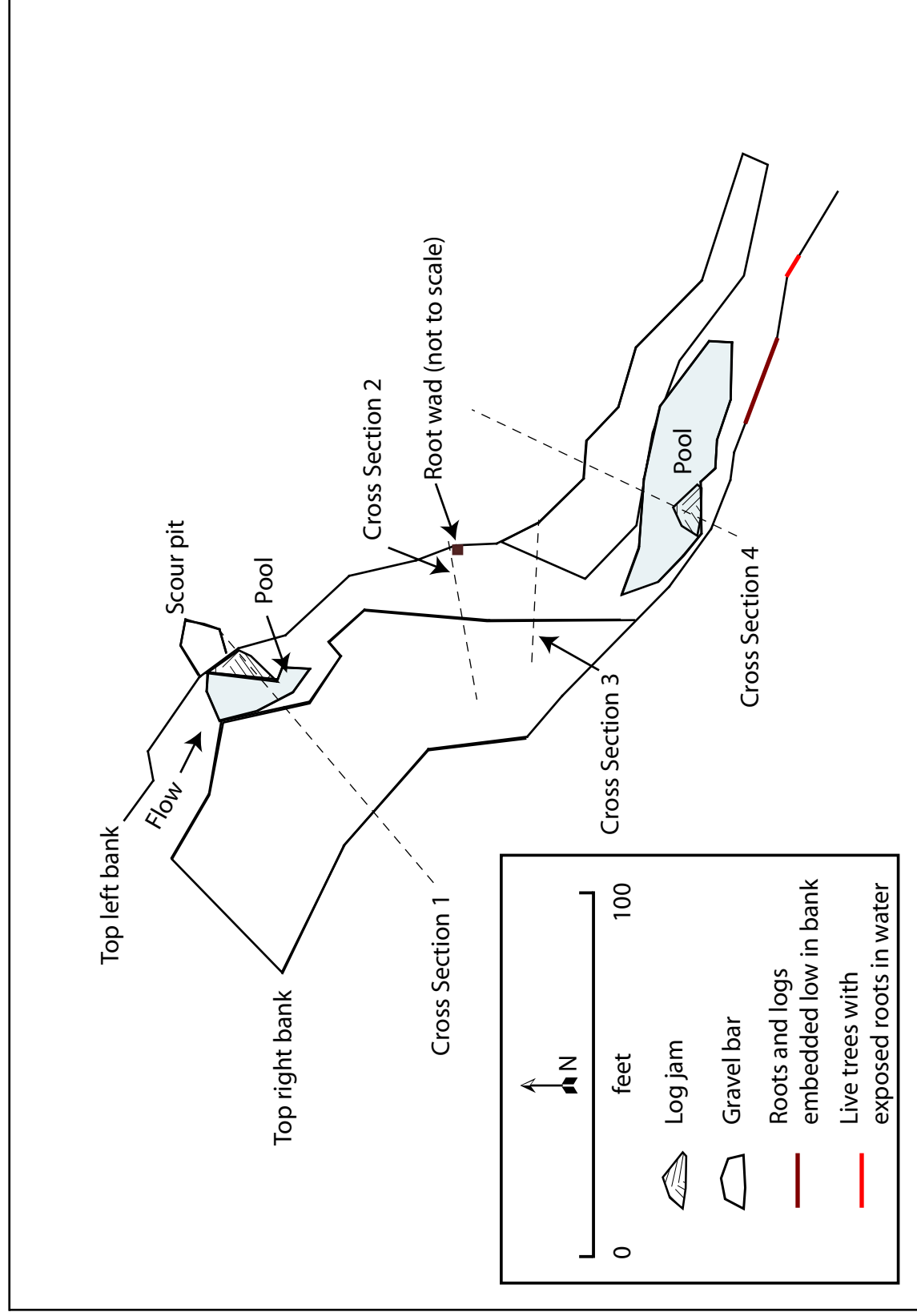


Appendix 3. Topographic survey data planview for B Stream Geomorphic Assessment Site.



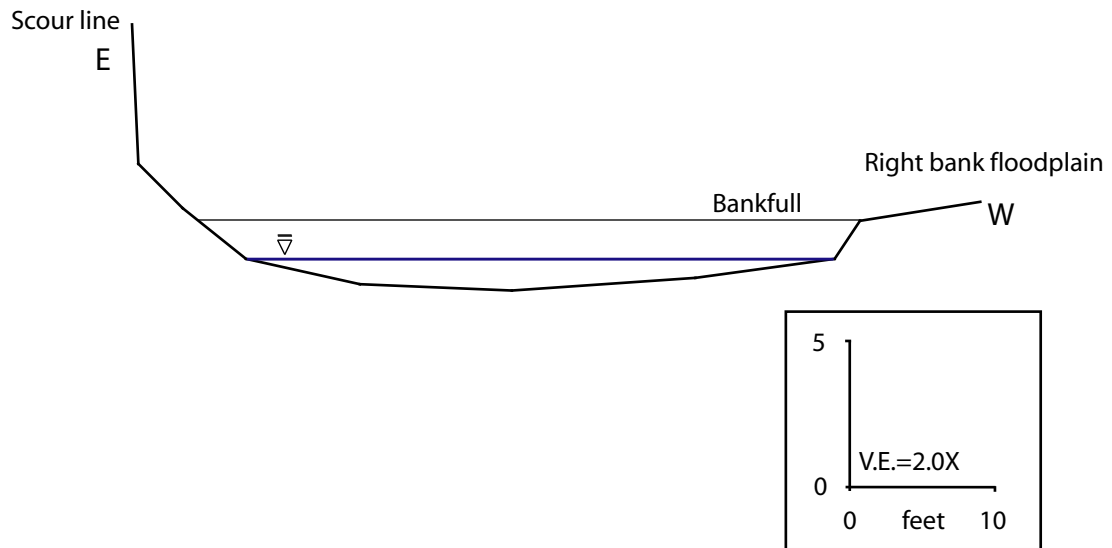
Appendix 3. Topographic survey data longitudinal profile for B Stream Geomorphic Assessment Site.



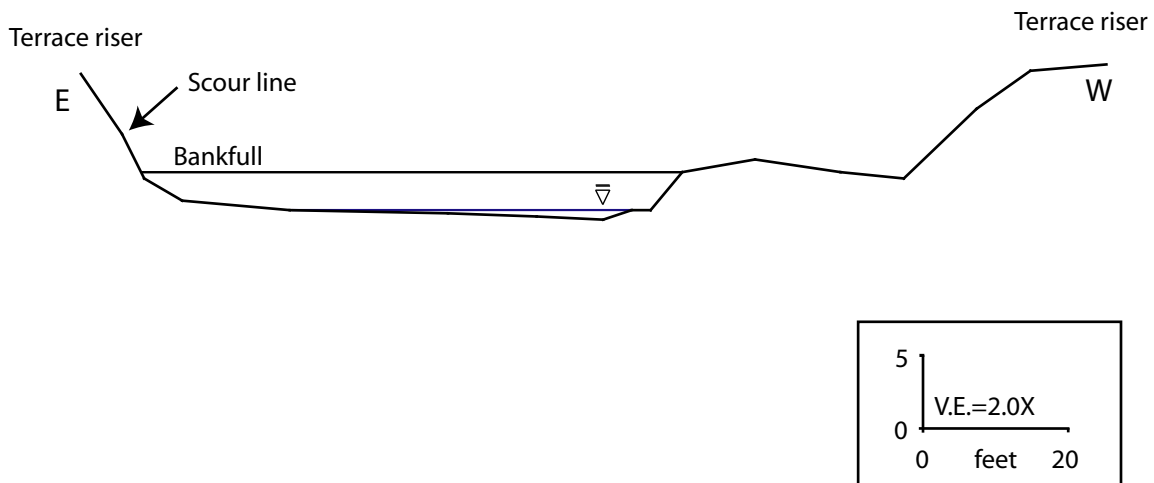


Appendix 3. Topographic survey data planview for B Stream Geomorphic Assessment Site log jam detail.

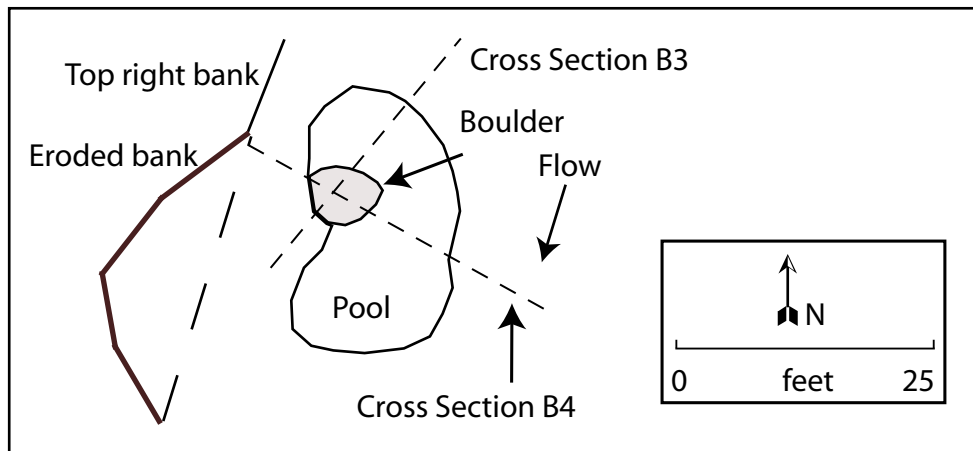
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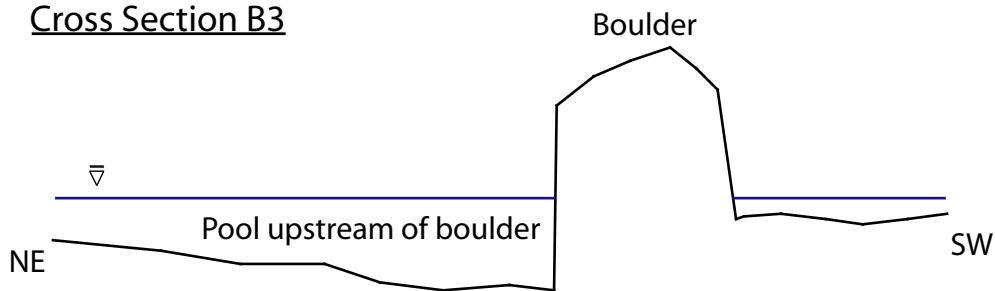
Cross Section 2 : Downstream view



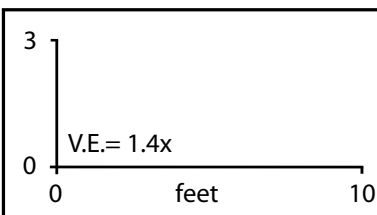
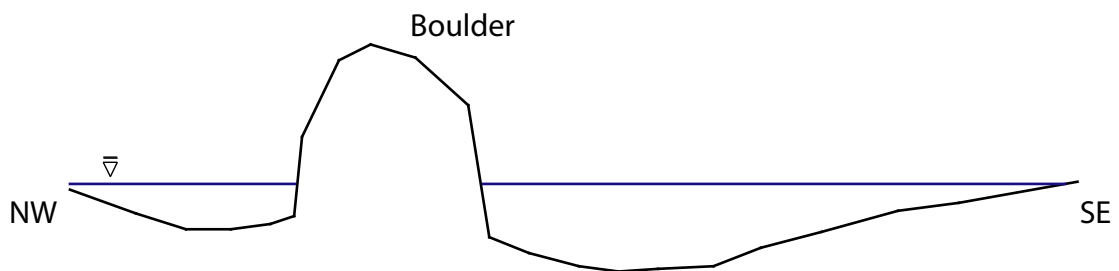
Appendix 3. Topographic survey data cross sections for B Stream Geomorphic Assessment Site.



Cross Section B3

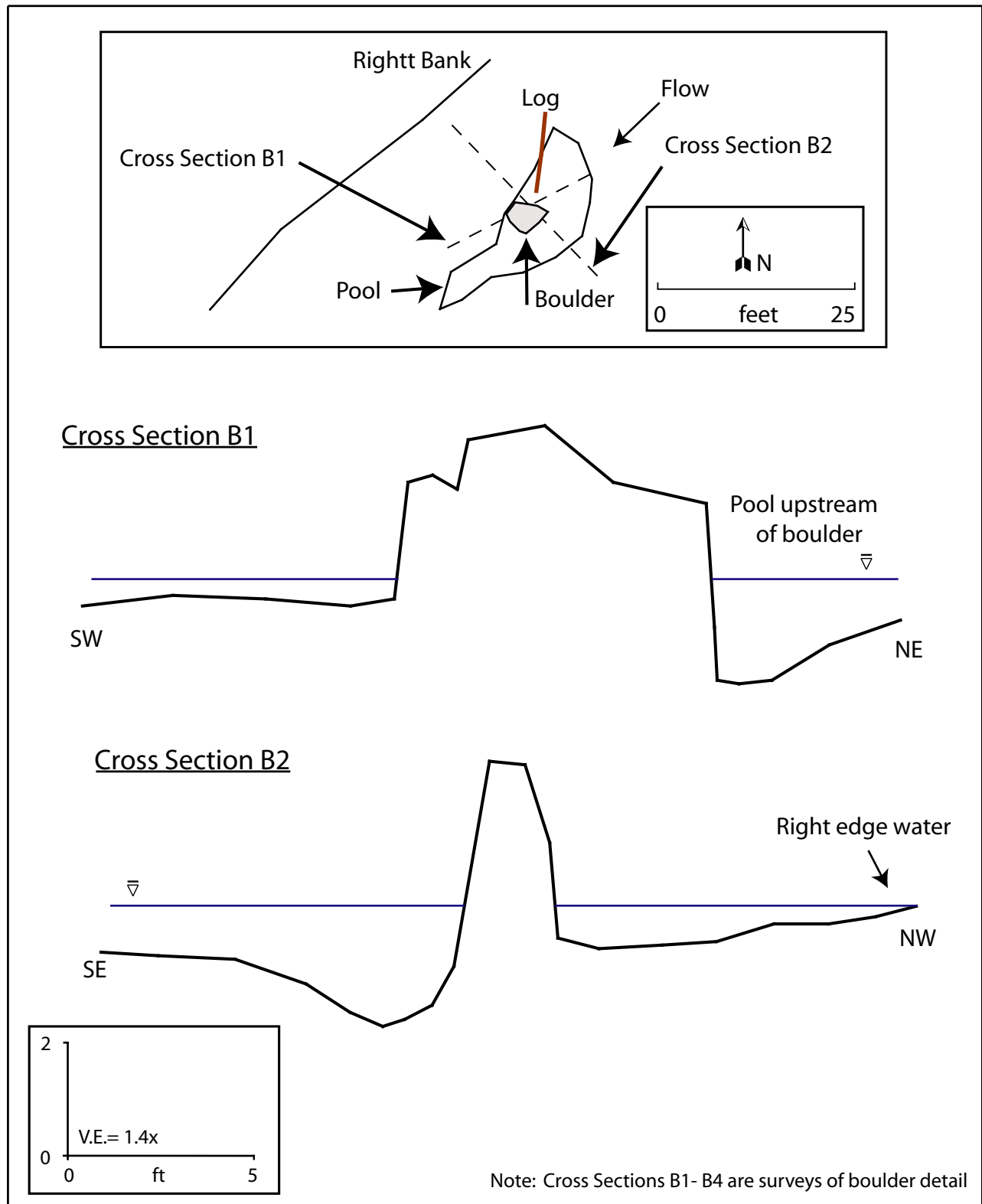


Cross Section B4



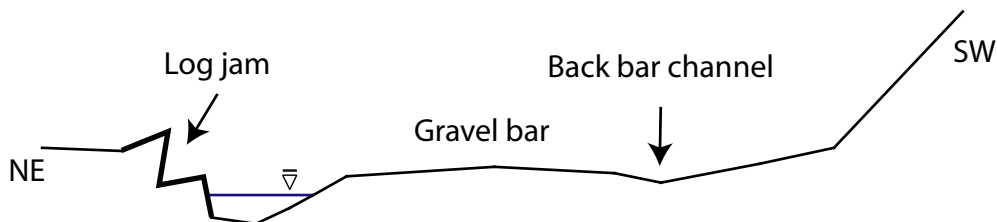
Note: Cross Sections B1- B4 are surveys of boulder detail

Appendix 3. Topographic survey data cross sections for B Stream Geomorphic Assessment Site boulder detail.

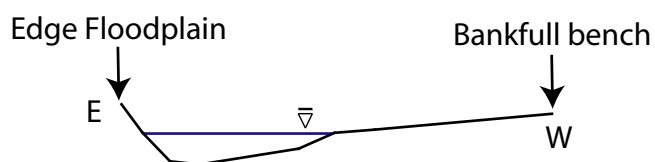


Appendix 3. Topographic survey data cross sections for B Stream Geomorphic Assessment Site boulder detail.

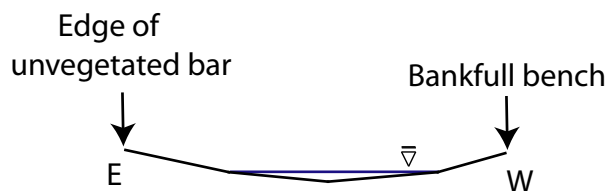
Cross Section 1 : Downstream view



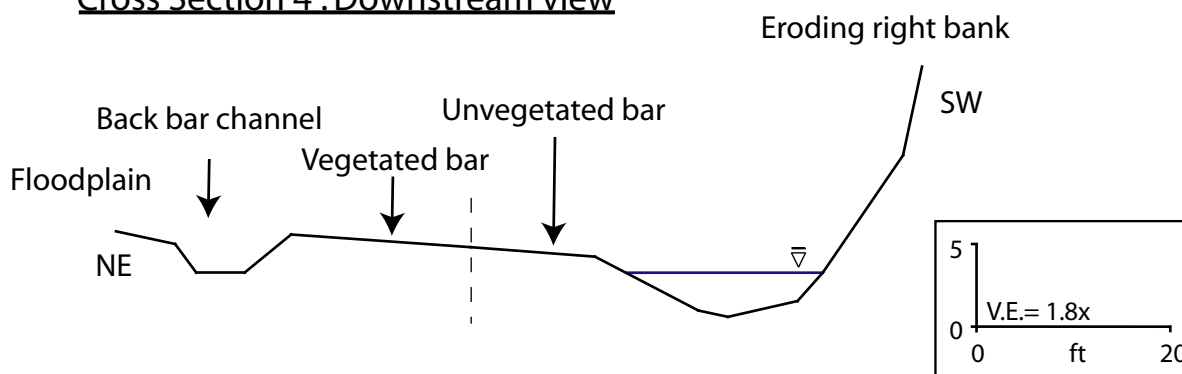
Cross Section 2 : Downstream view



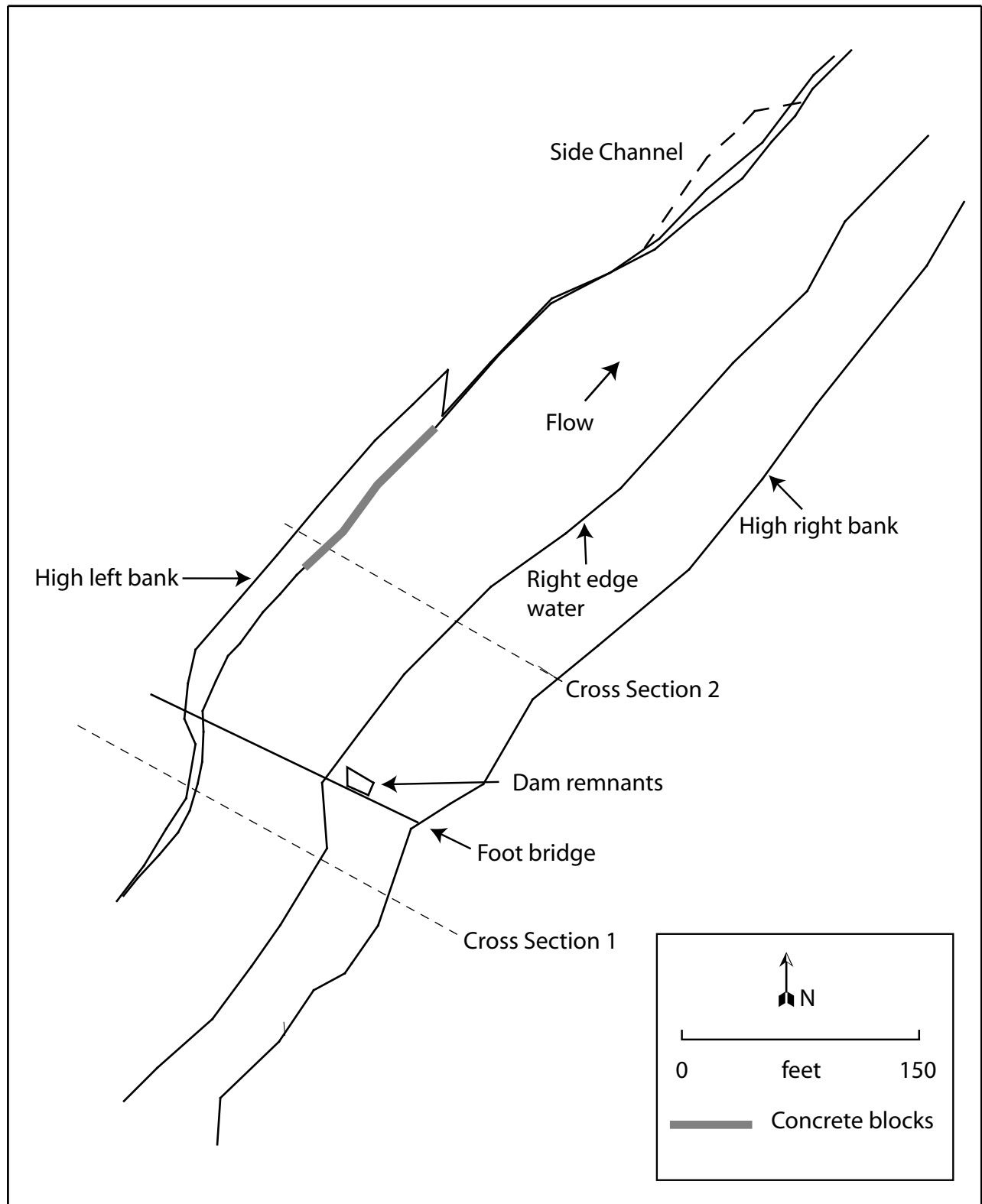
Cross Section 3 : Downstream view



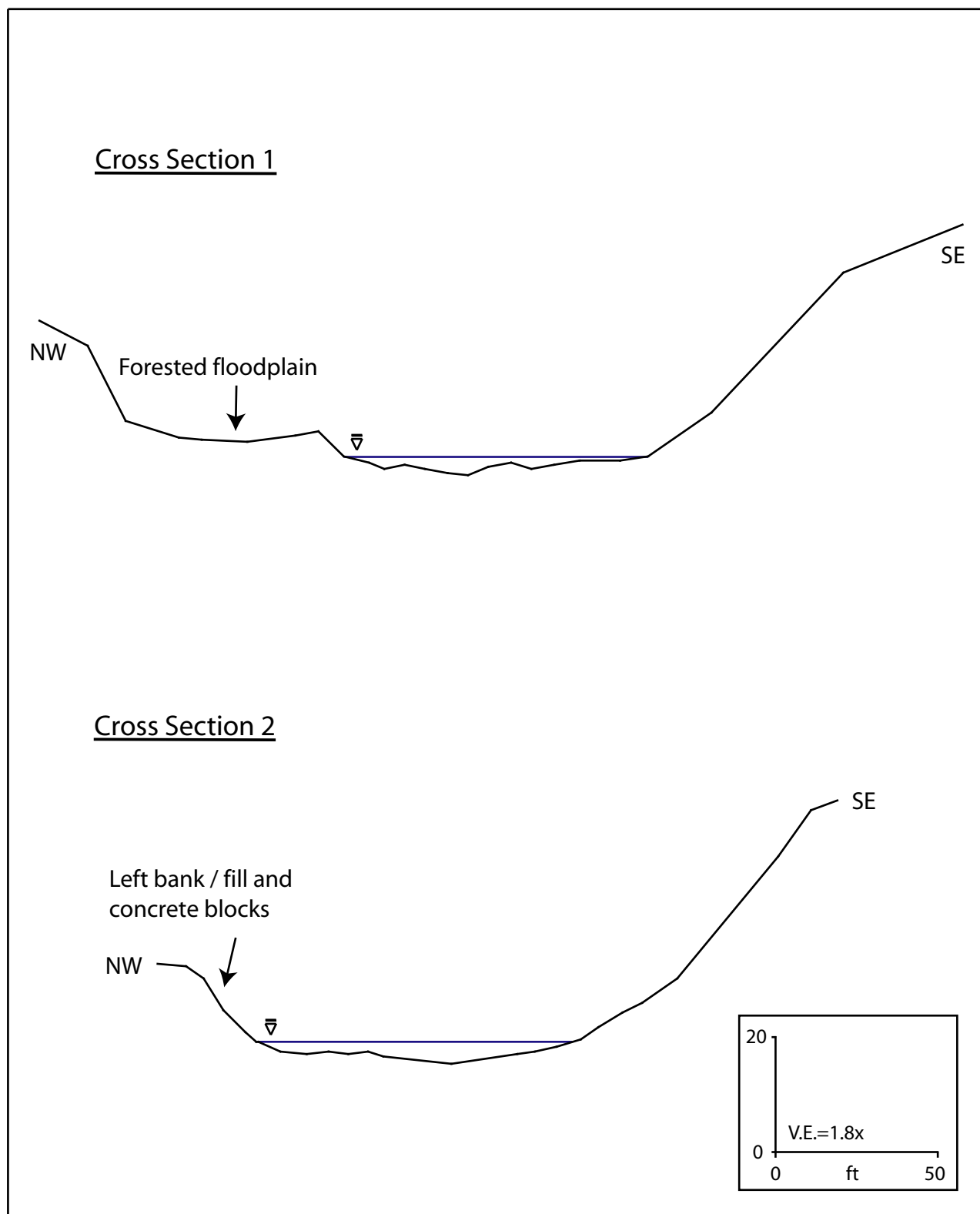
Cross Section 4 : Downstream view



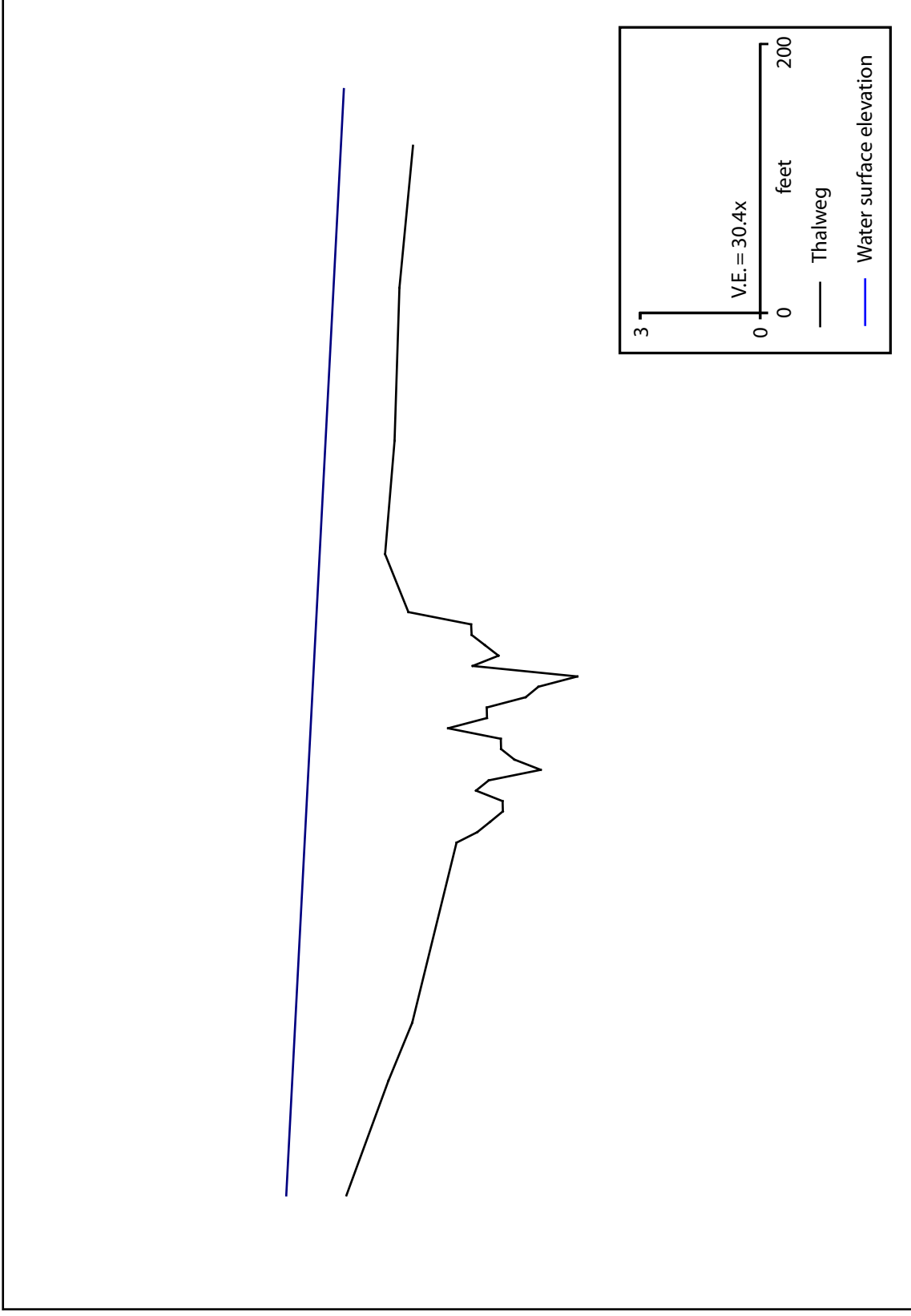
Appendix 3. Topographic survey data cross sections for B Stream Geomorphic Assessment Site log jam detail.



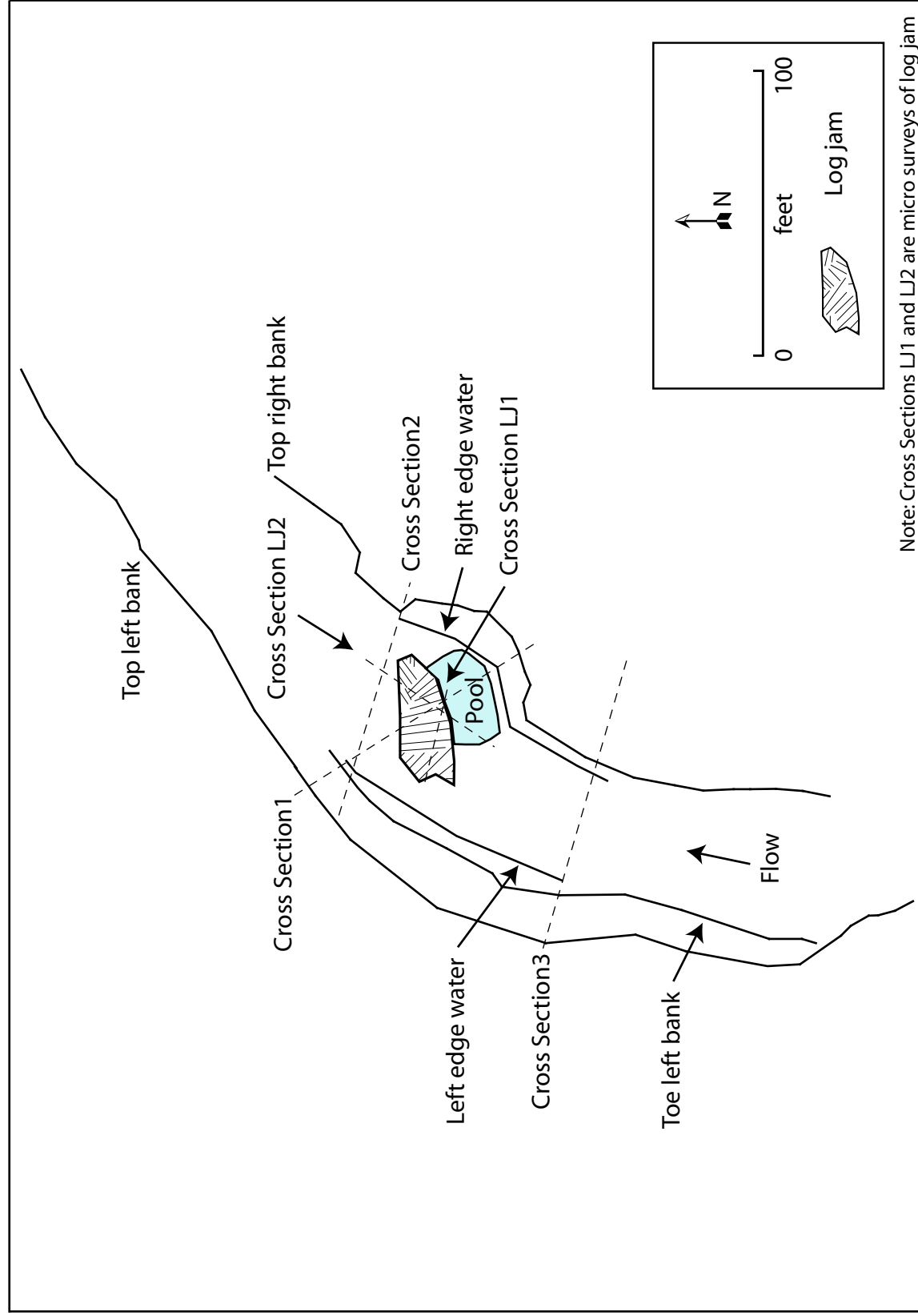
Appendix 3. Topographic survey data planview for the Houlton Geomorphic Assessment Site.



Appendix 3. Topographic survey data cross sections for the Houlton Geomorphic Assessment Site.

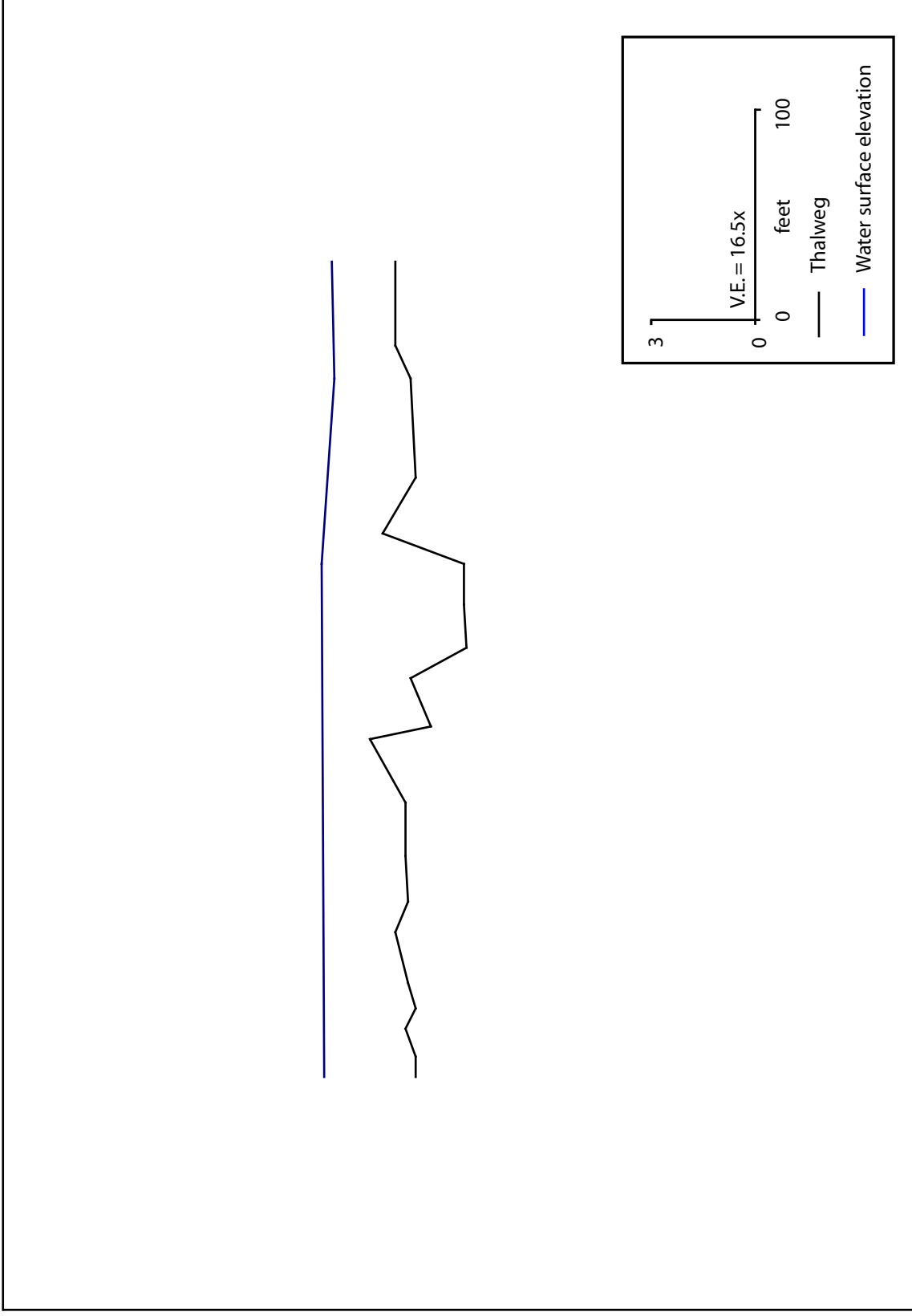


Appendix 3. Topographic survey data longitudinal profile for the Houlton Geomorphologic Assessment Site.



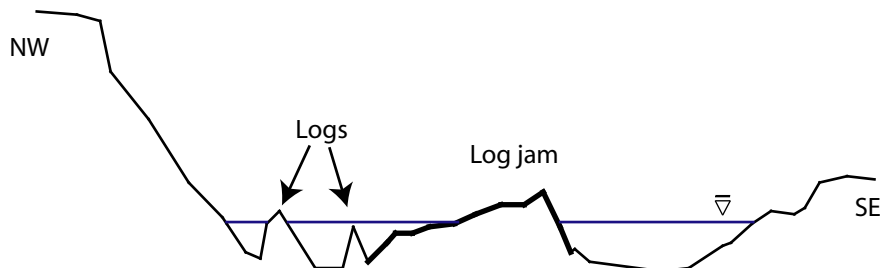
Note: Cross Sections LJ1 and LJ2 are micro surveys of log jam

Appendix 3. Topographic survey data planview for the South Branch Geomorphic Assessment Site.

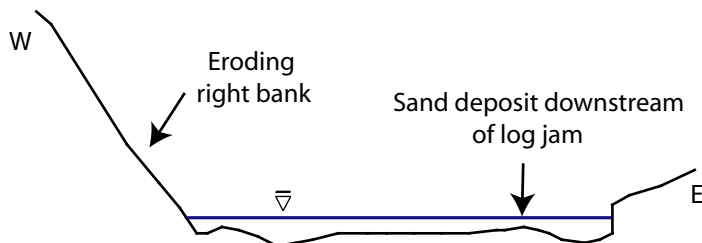


Appendix 3. Topographic survey data longitudinal profile for the South Branch Geomorphic Assessment Site.

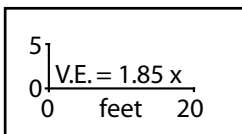
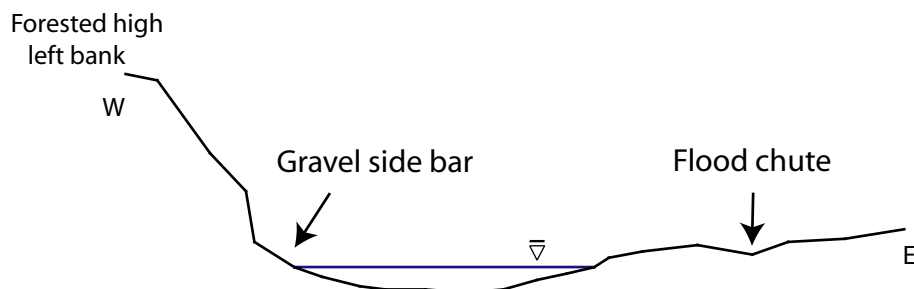
Cross Section 1: Downstream view



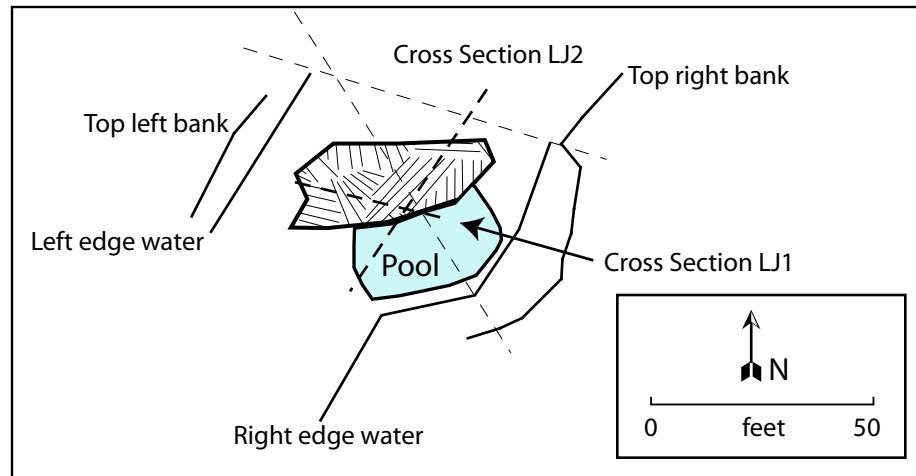
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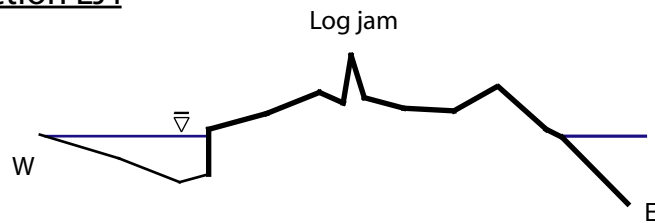
Cross Section 3: Downstream view



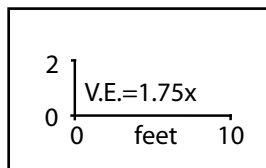
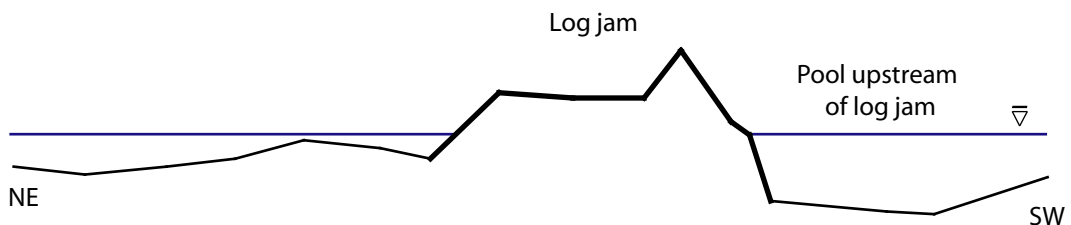
Appendix 3. Topographic survey data cross sections for the South Branch Geomorphic Assessment Site.



Cross Section LJ1



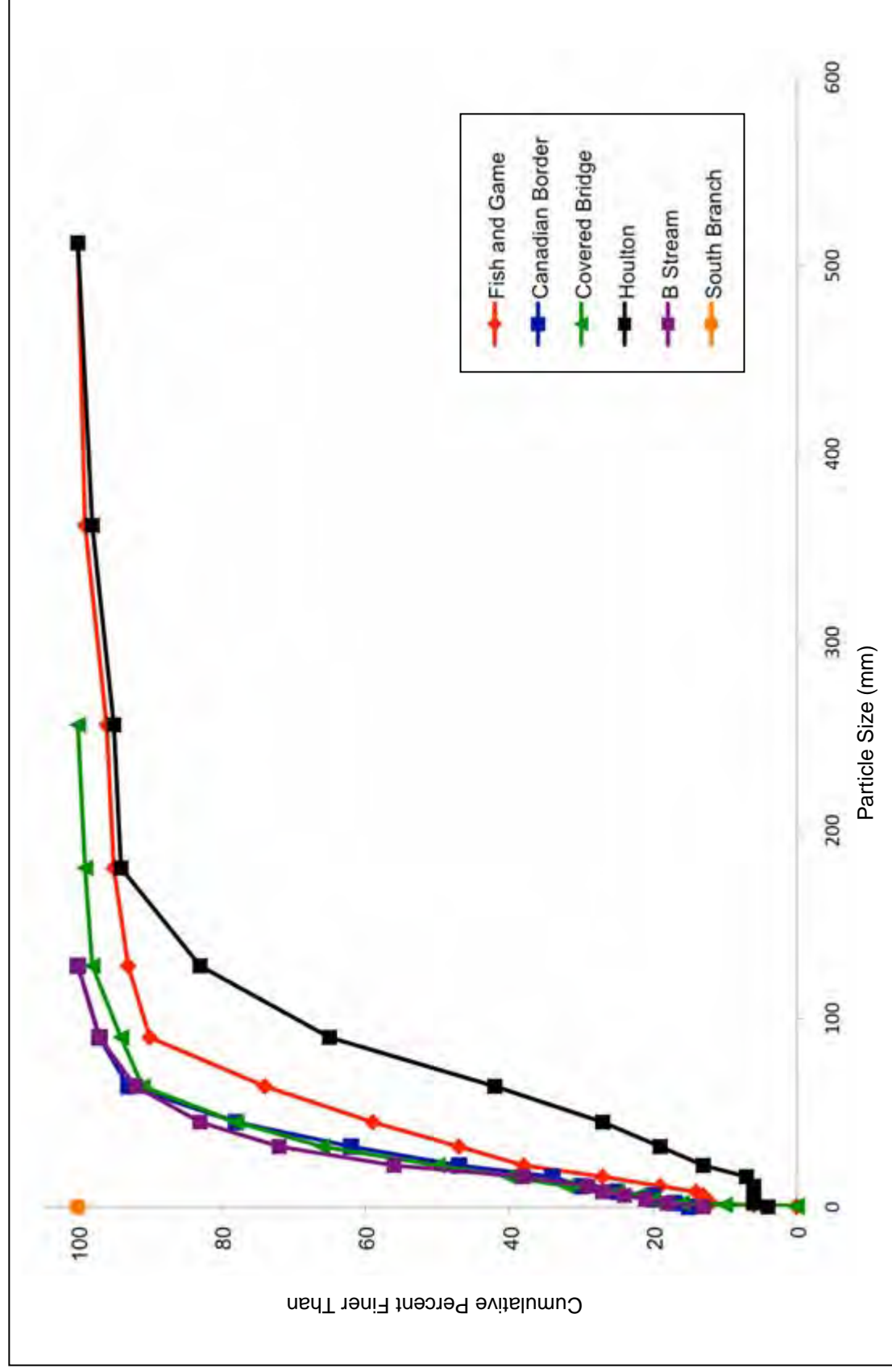
Cross Section LJ2



Appendix 3. Topographic survey data cross sections for the South Branch Geomorphic Assessment Site log jam detail.

Appendix 4

Substrate Particle Size Data for the Geomorphic Assessment Site
(Refer to CD for additional data.)



Appendix 4. Cumulative histograms of the substrate particle size data for the geomorphic assessment sites.

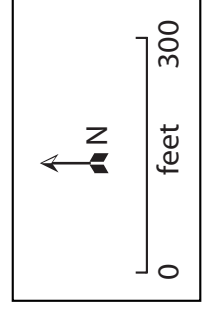
Appendix 5

Conceptual Restoration Designs for Three Geomorphic Assessment Sites



Appendix 5. Conceptual restoration design planview for the Fish and Game Club Geomorphic Assessment Site.

Note: Structures not to scale

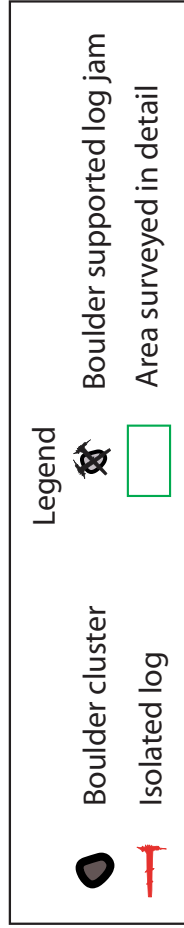
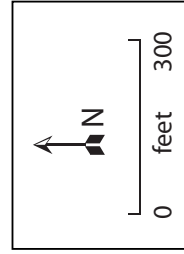


Legend	
	Boulder cluster
	Isolated log
	Boulder supported log jam
	Area surveyed in detail



Appendix 5. Conceptual restoration design planview for the Covered Bridge Geomorphic Assessment Site (1 of 7).

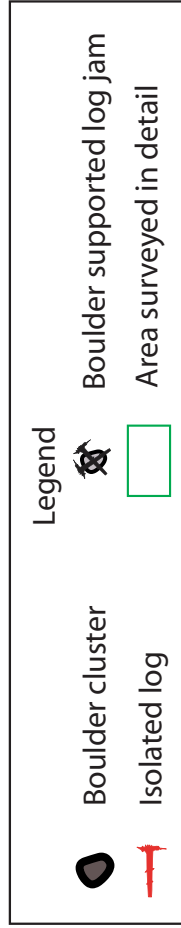
Note: Structures not to scale





Appendix 5. Conceptual restoration design planview for the Covered Bridge Geomorphic Assessment Site (2 of 7).

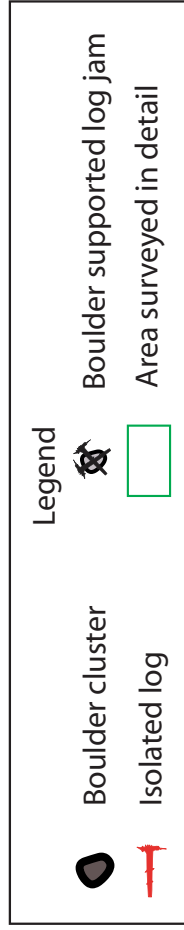
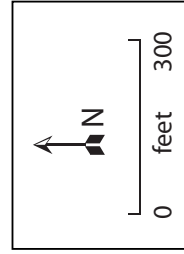
Note: Structures not to scale





Appendix 5. Conceptual restoration design planview for the Covered Bridge Geomorphic Assessment Site (3 of 7).

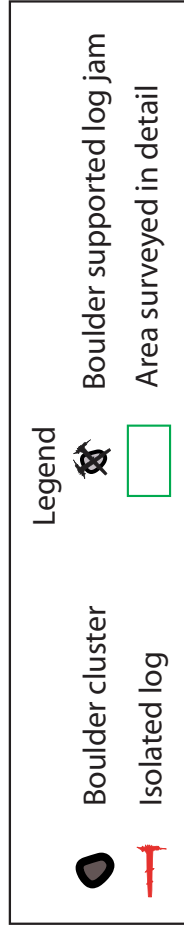
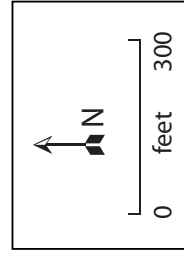
Note: Structures not to scale





Appendix 5. Conceptual restoration design planview for the Covered Bridge Geomorphic Assessment Site (4 of 7).

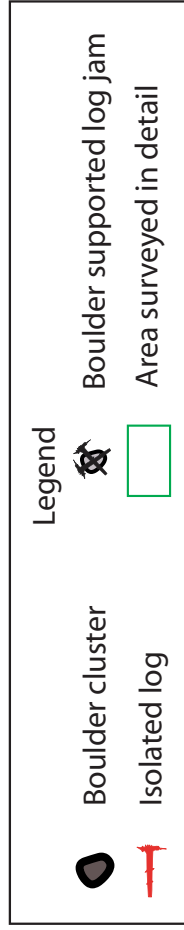
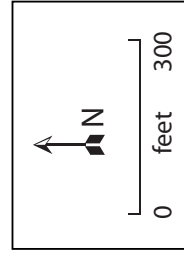
Note: Structures not to scale

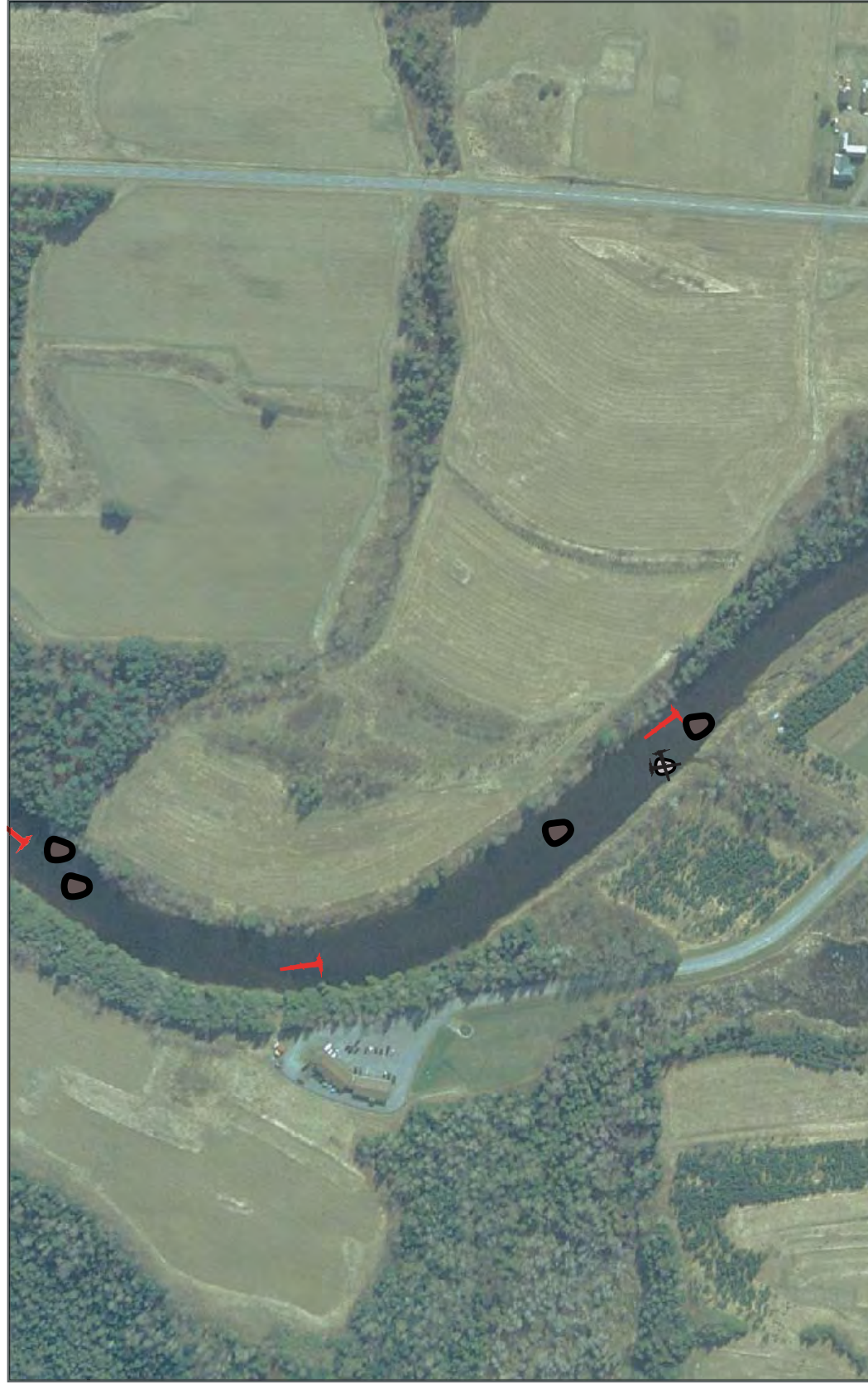




Appendix 5. Conceptual restoration design planview for the Covered Bridge Geomorphic Assessment Site (5 of 7).

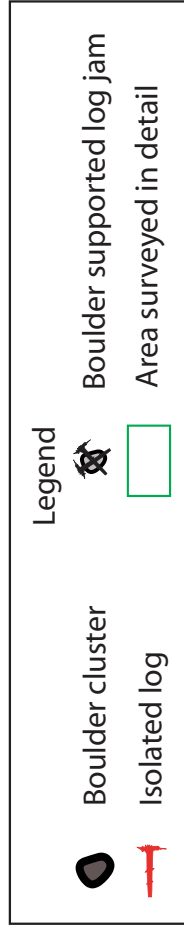
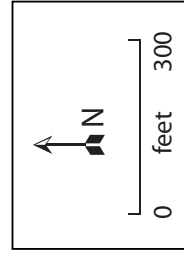
Note: Structures not to scale





Appendix 5. Conceptual restoration design planview for the Covered Bridge Geomorphic Assessment Site (6 of 7).

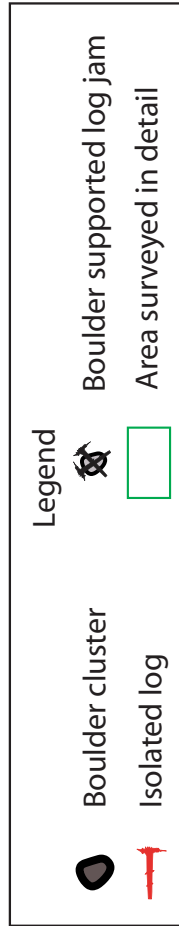
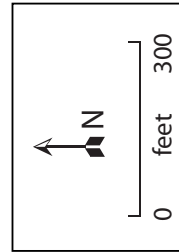
Note: Structures not to scale





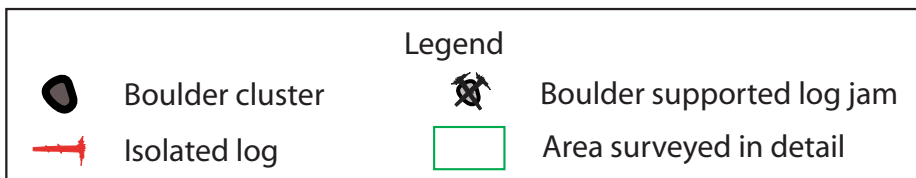
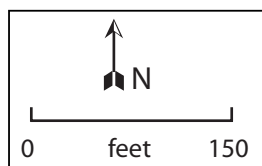
Appendix 5. Conceptual restoration design planview for the Covered Bridge Geomorphic Assessment Site (7 of 7).

Note: Structures not to scale

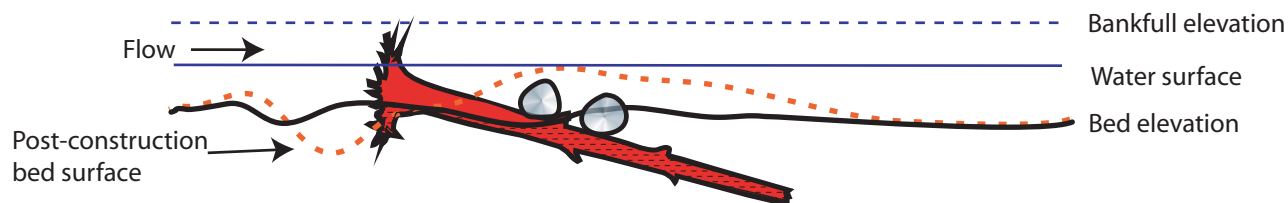




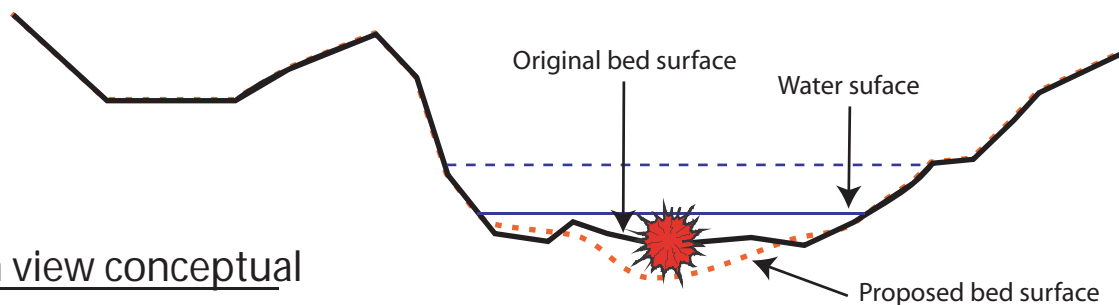
Appendix 5. Conceptual restoration design planview for the B Stream Geomorphic Assessment Site.



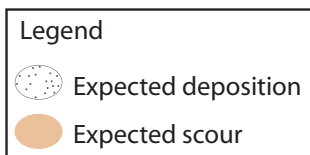
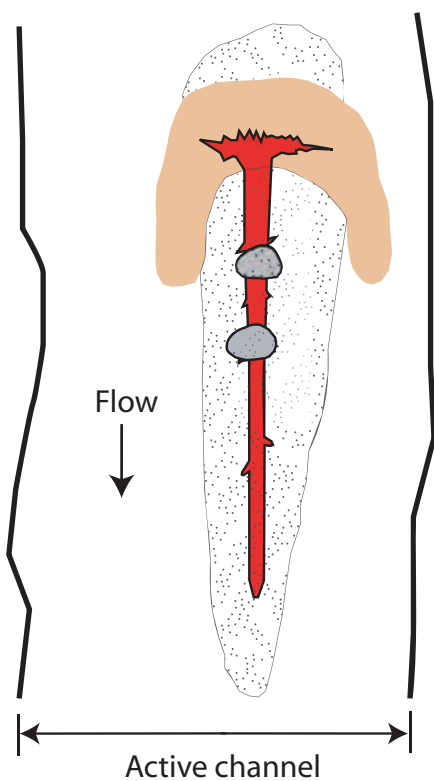
Longitudinal view conceptual



Side view conceptual



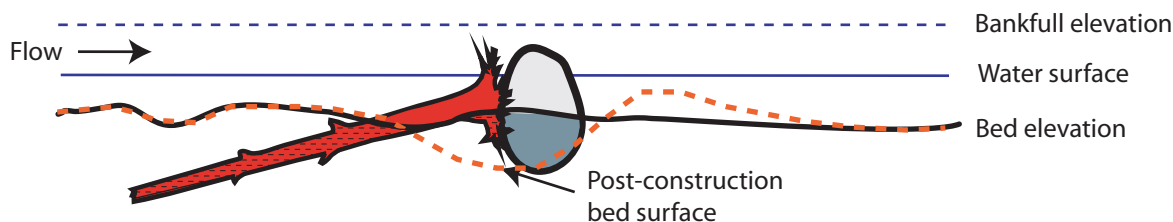
Plan view conceptual



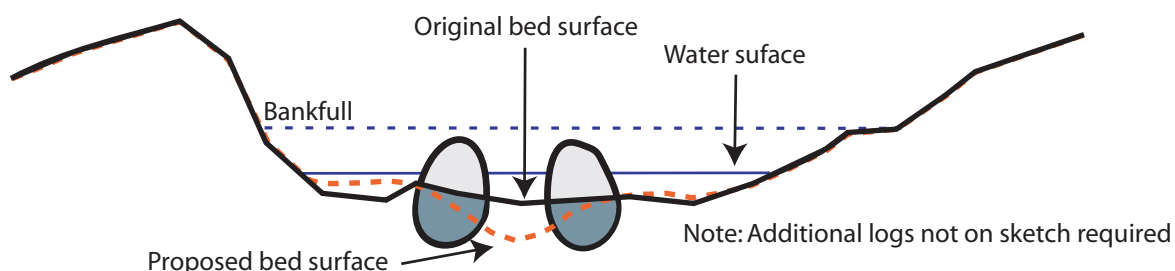
Treatment: Isolated logs

The isolated logs are a treatment where individual logs are added and naturally anchored within the low flow channel. The root wad of each log is faced upstream and remains above the channel bed while most of the attached log (at least 15 ft long) is placed in a trench excavated into the channel bed. The log is anchored when the trench is backfilled over the log with a couple of boulders added for extra stability. The isolated log treatment provides additional roughness and alters the flow velocities to create distinct zones of scour and deposition with pools generally forming upstream of the root wad face and sand/gravel bars downstream along the length of the buried portion of the log.

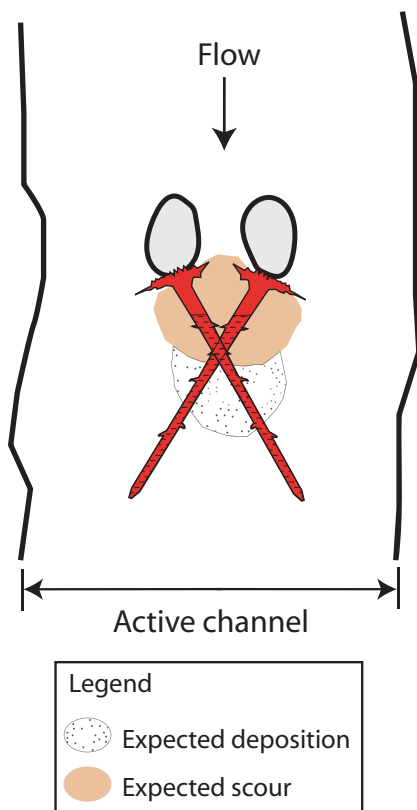
Longitudinal view conceptual



Side view conceptual



Plan view conceptual

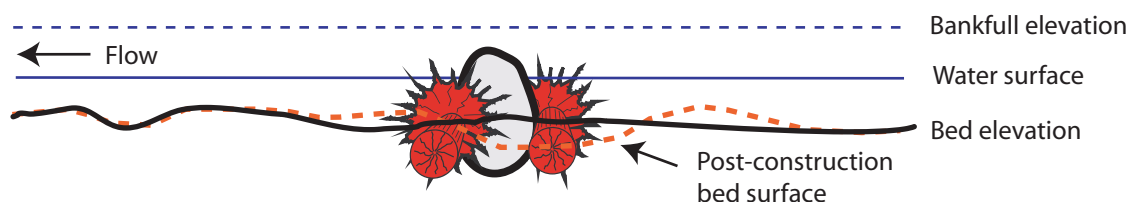


Treatment: Boulder clusters

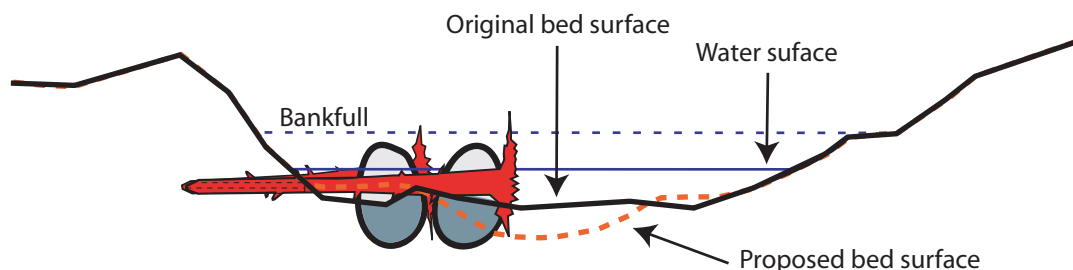
Boulder clusters are groups of large rocks placed within the low flow channel with irregular spacing and configurations. This treatment mimics natural clusters, defined as discrete, organized groupings of particles that sit above the average elevation of the surrounding bed surface. Boulder clusters are typically built as pairs of boulders with a small gap between them where water becomes concentrated in order to help maintain pools created downstream of the boulders. Large boulders are used with more than half of the boulder buried below the bed to prevent movement during large flow events. One or two logs, installed as in the isolated log treatment, are incorporated into the boulder clusters to provide cover over the pool and additional stability to the boulders when the root wads are placed against the downstream face of the boulders.

Note: Drawings are not to scale

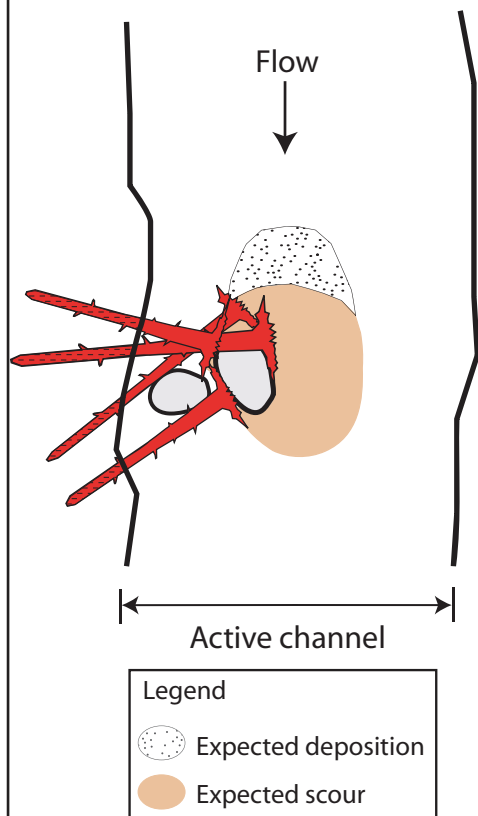
Longitudinal view conceptual



Side view conceptual



Plan view conceptual

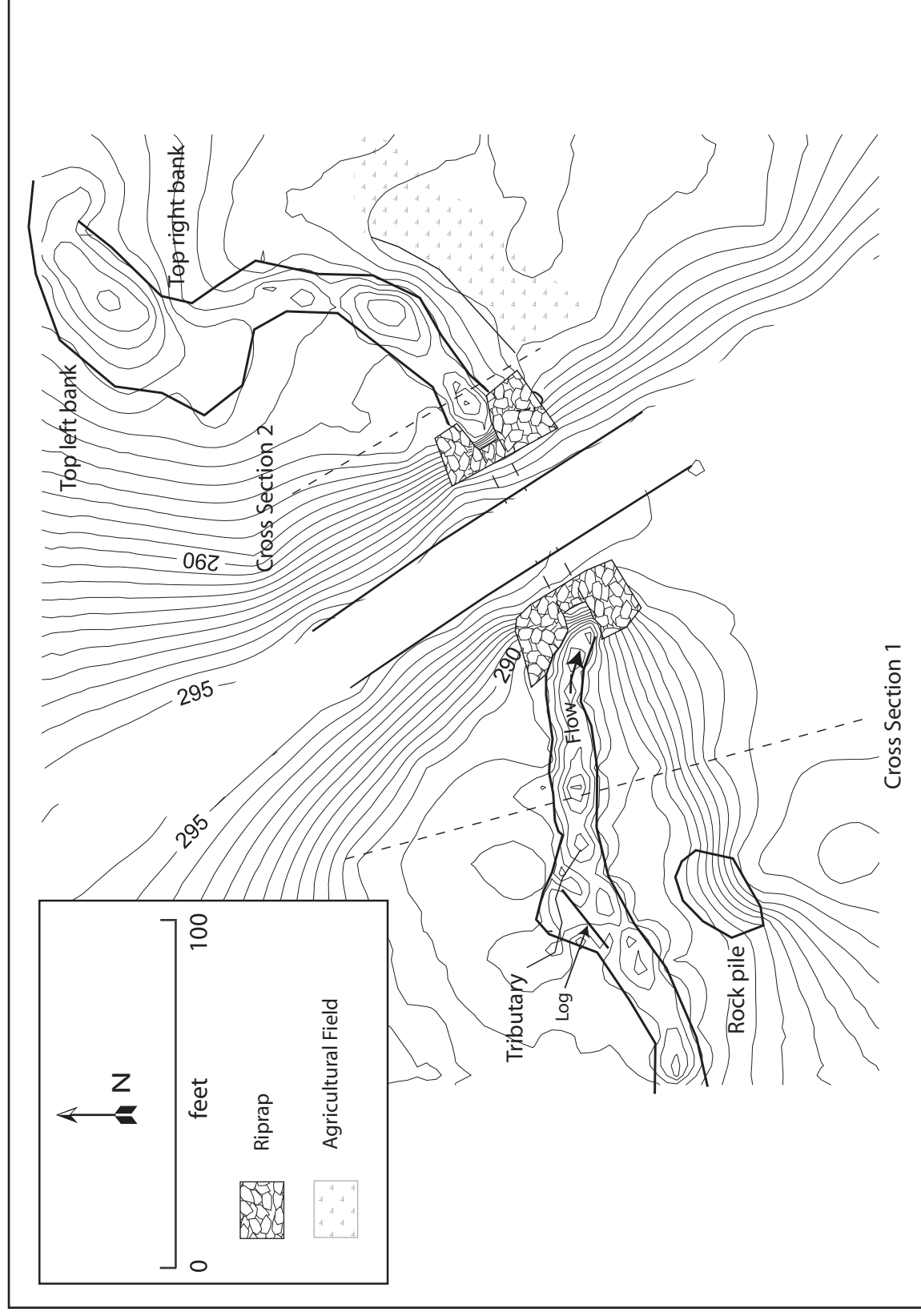


Treatment: Boulder-supported log jam

Boulder-supported log jams are a treatment that mimic natural features observed in the Meduxnekeag Watershed where large boulders near the margin of the channel trap logs between the boulder and the banks. Constructed boulder-supported log jams will utilize large boulders to support an anchor log placed against the upstream face of the boulders and partially buried in the bank. Extra support can be added by cabling the log to eye-bolts drilled into the boulders. The root wad of the anchor log will face the center of the channel. Additional logs could be intertwined between the boulder, anchor log, and bank, although the natural recruitment of logs floating in from upstream might also occur. The boulder-supported log jam treatment will create a pool that wraps around the boulder towards the center of the channel.

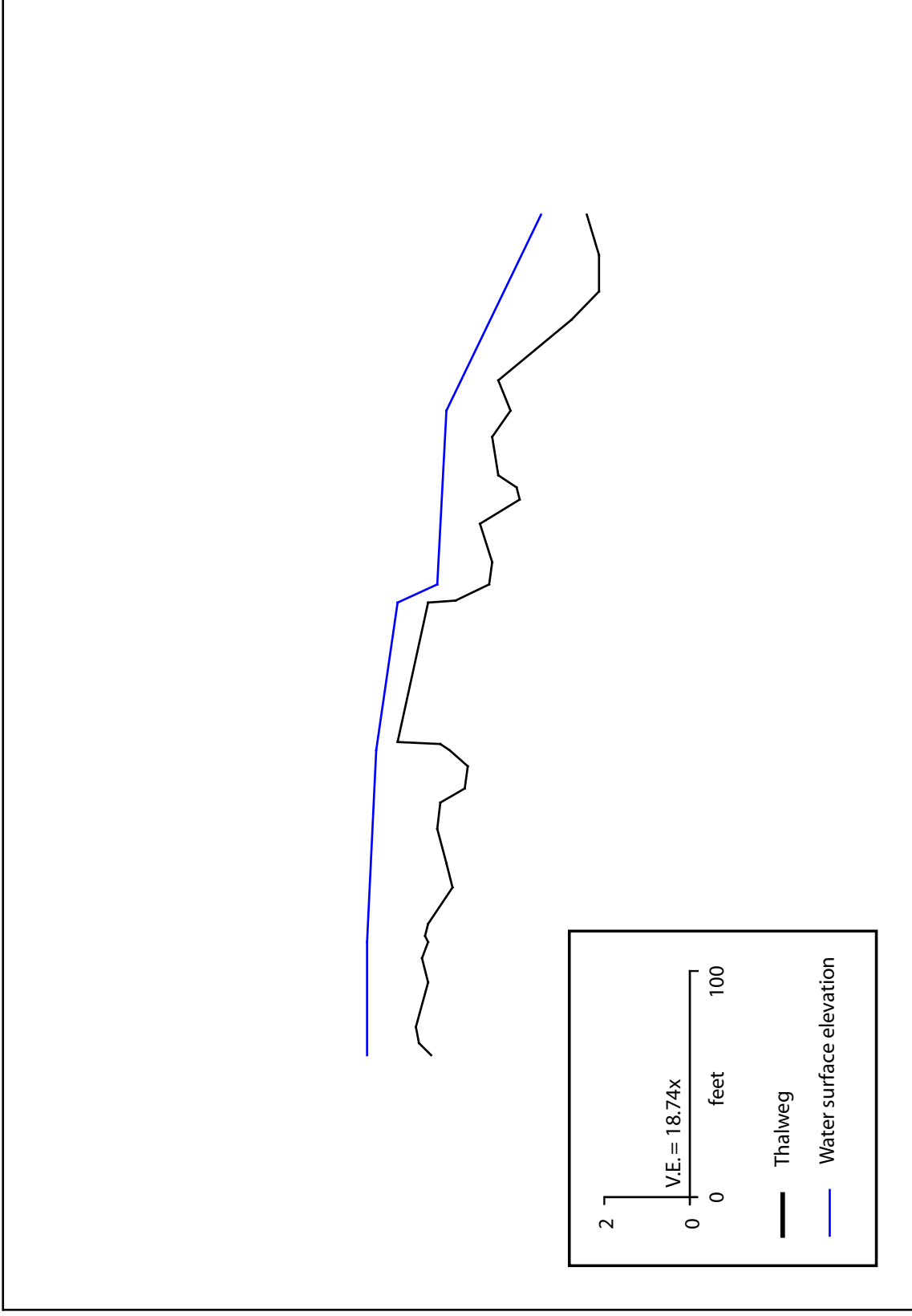
Appendix 6

Topographic Survey Data for the Culvert Assessment Sites
(Refer to CD for additional data.)

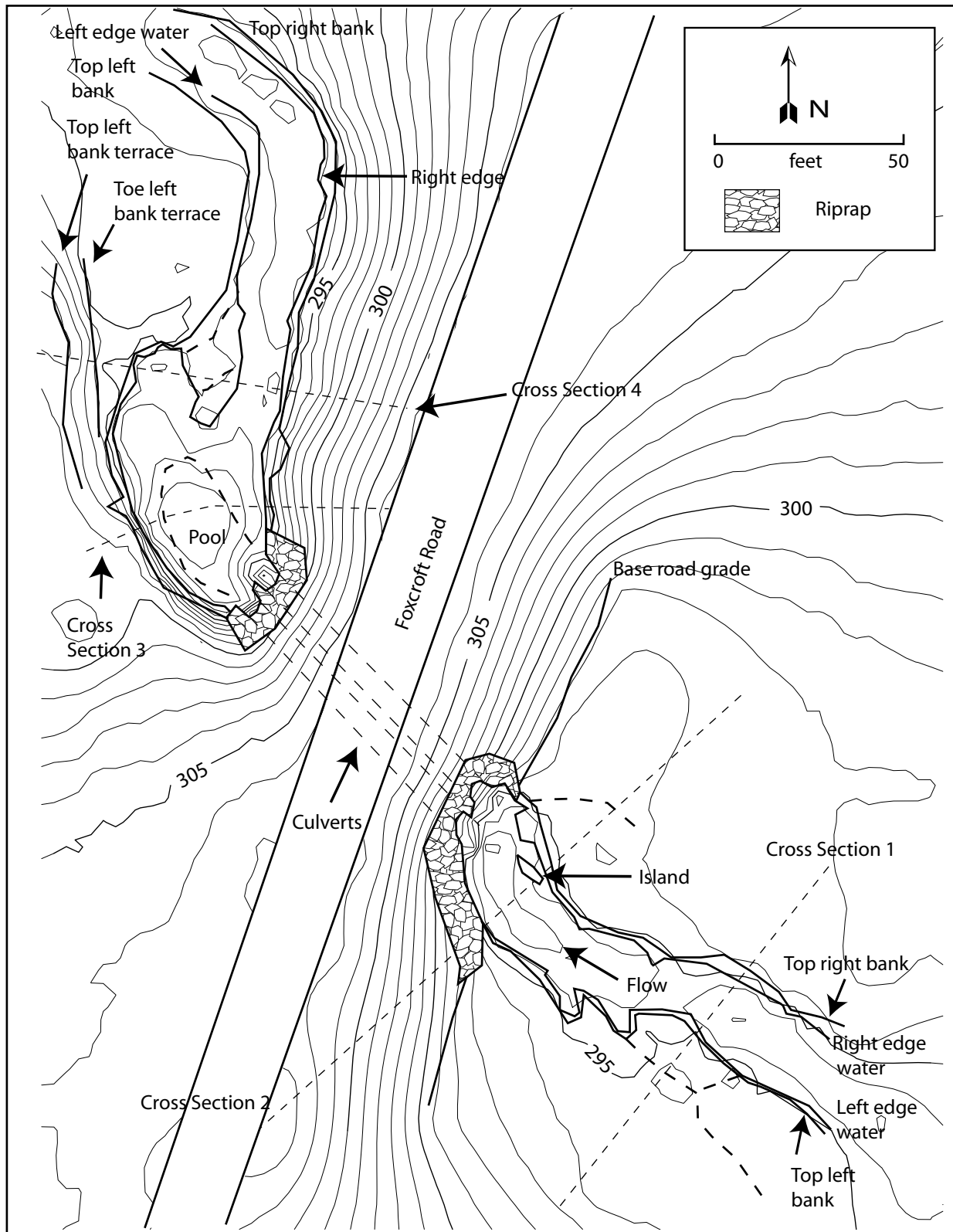


Appendix 6. Topographic survey data planview for Suiter Brook 1 Culvert Assessment Site.



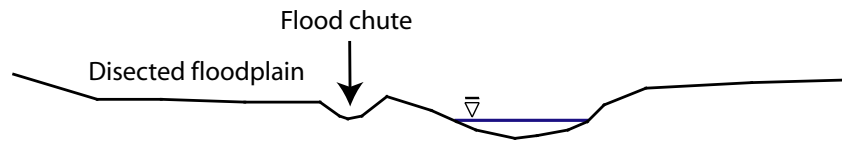


Appendix 6. Topographic survey data longitudinal profile for Suiter Brook 1 Culvert Assessment Site.

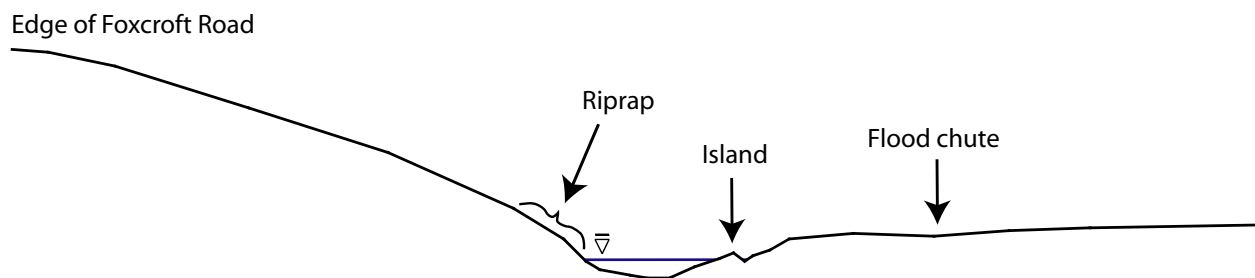


Appendix 6. Topographic survey data planview for Smith Brook 1 Culvert Assessment Site.

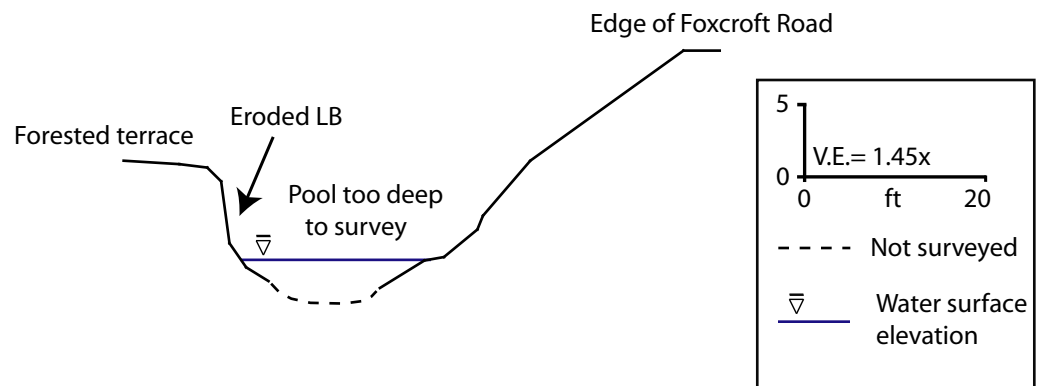
Cross Section 1 : Downstream view



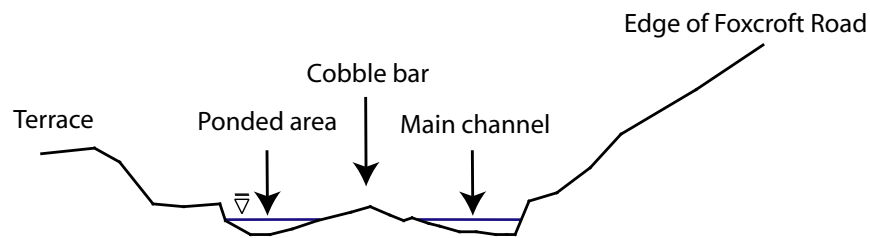
Cross Section 2 : Downstream view



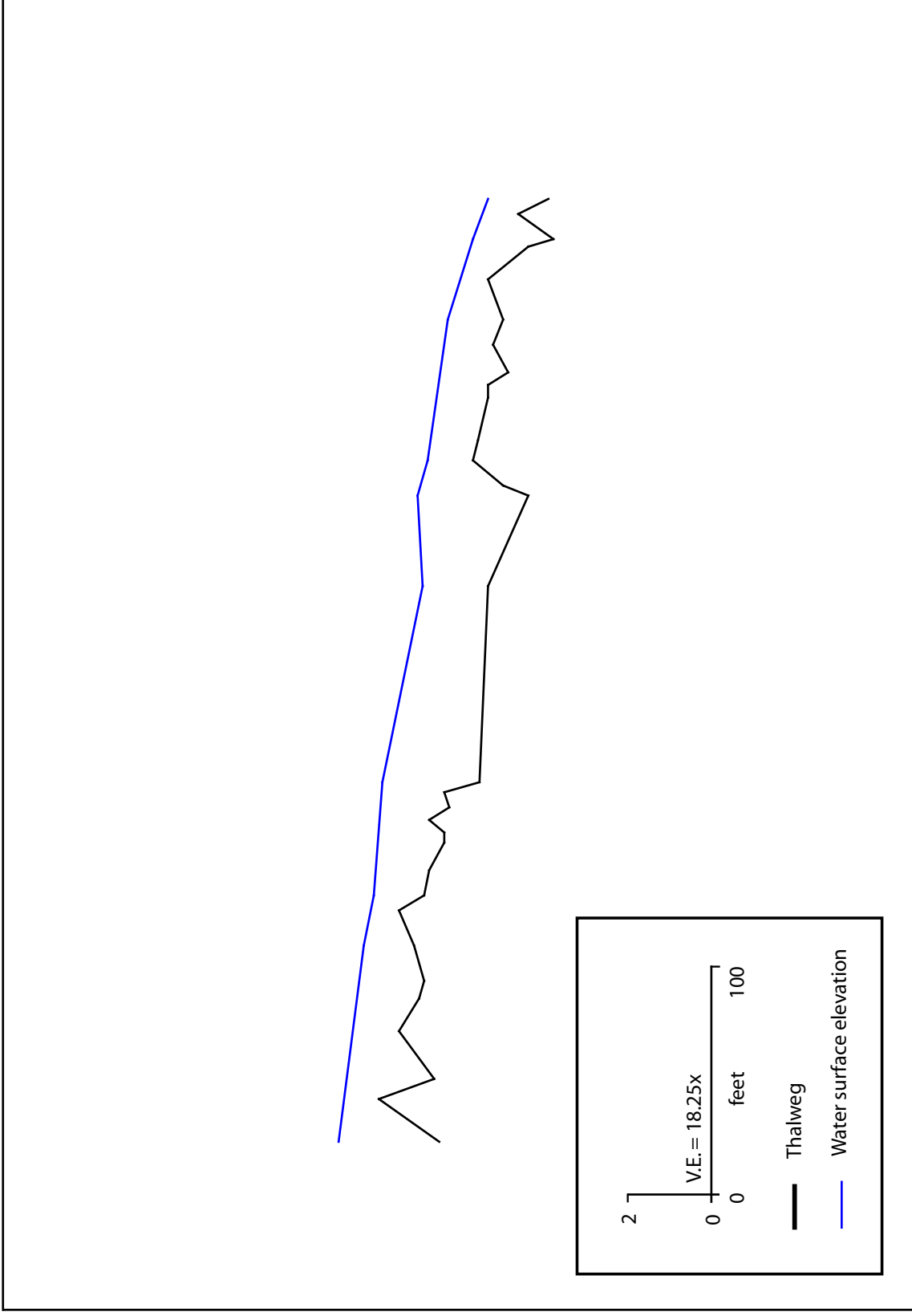
Cross Section 3 : Downstream view



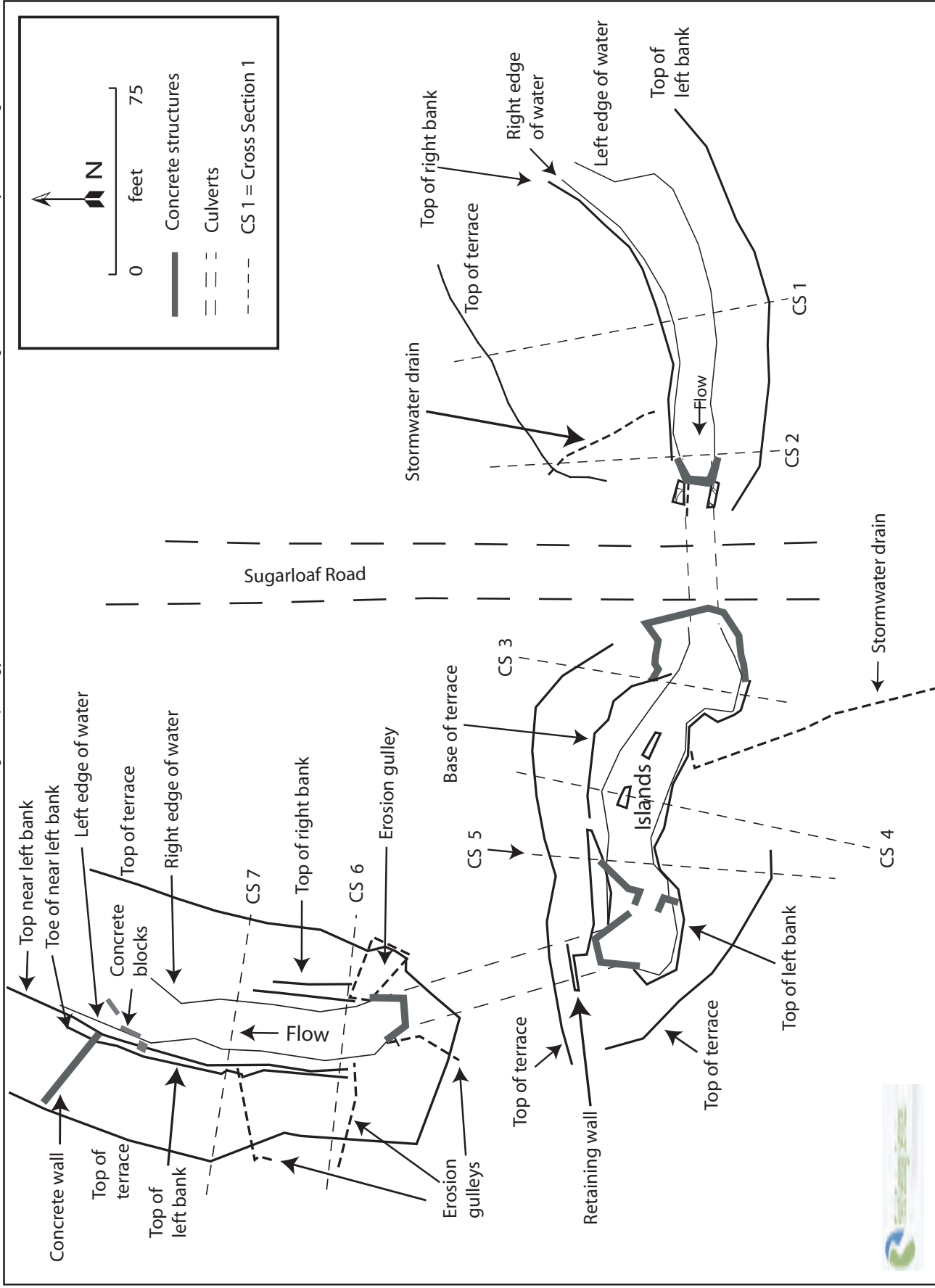
Cross Section 3 : Downstream view



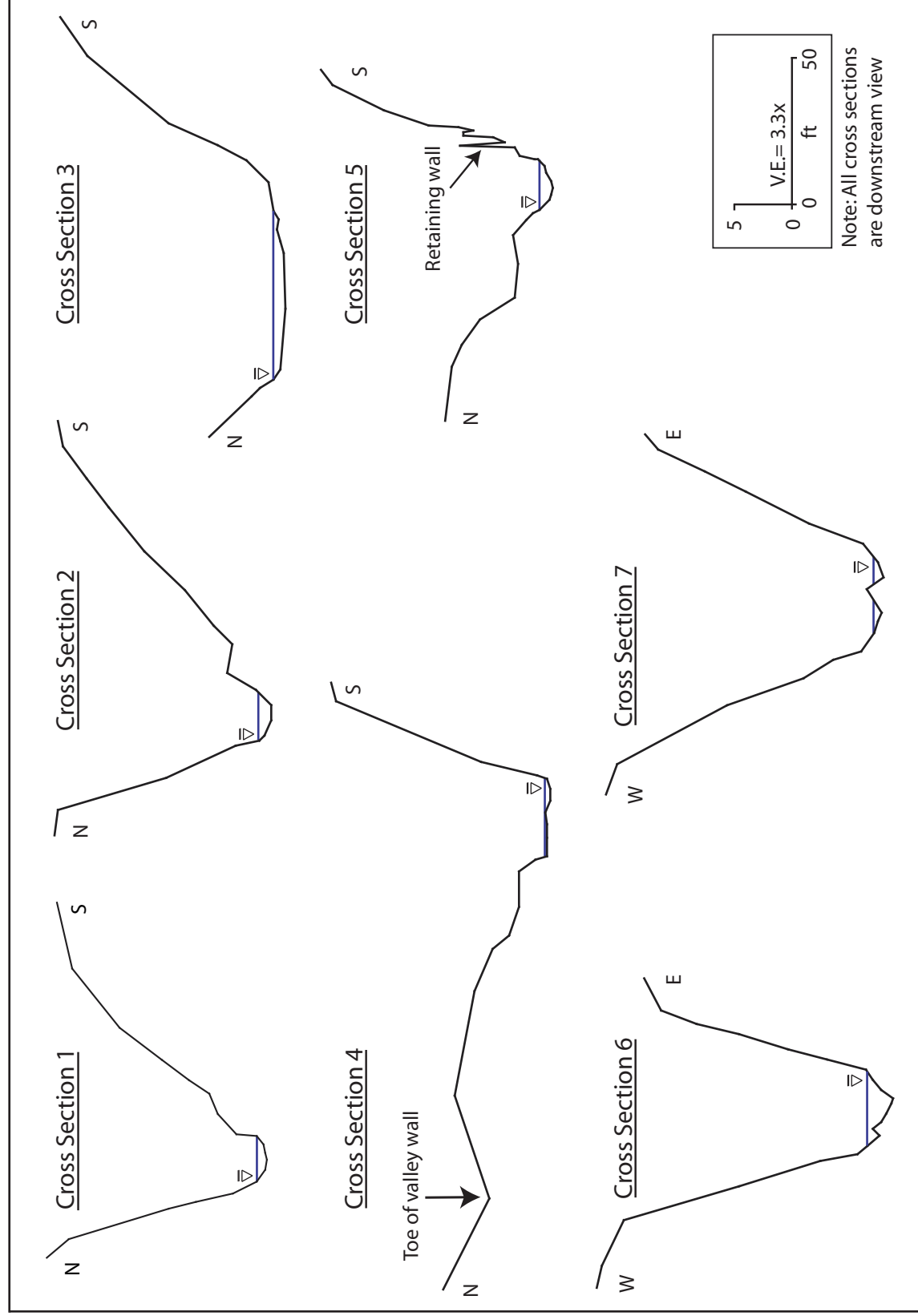
Appendix 6. Topographic survey data cross section for Smith Brook 1 Culvert Assessment Site.



Appendix 6. Topographic survey data longitudinal profile for Smith Brook 1 Culvert Assessment Site.

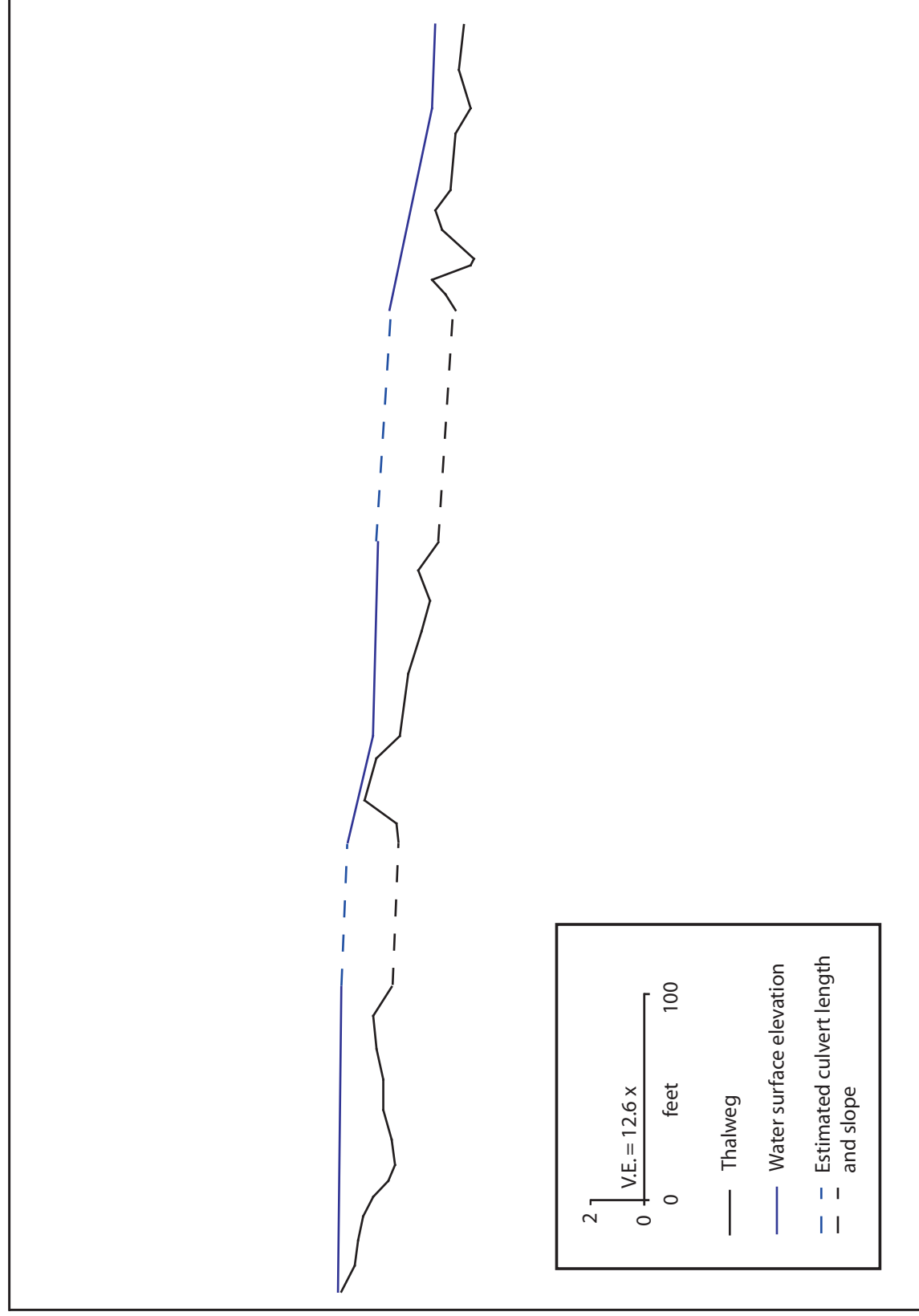


Appendix 6. Topographic survey data planview for Pearce Brook 2 and 3 Culvert Assessment Site.



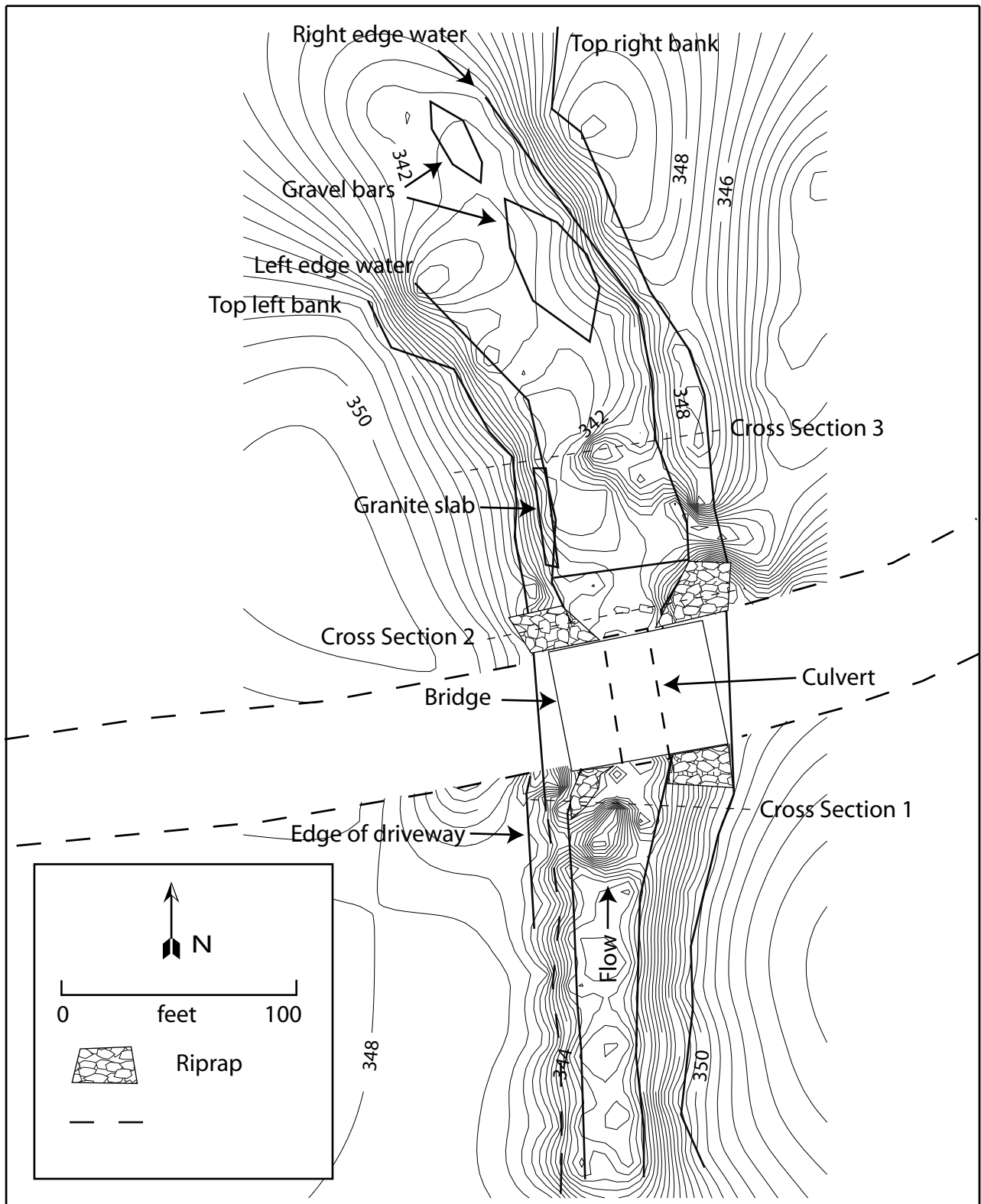
Appendix 6. Topographic survey data cross sections for Pearce Brook 2 and 3 Culvert Assessment Site.





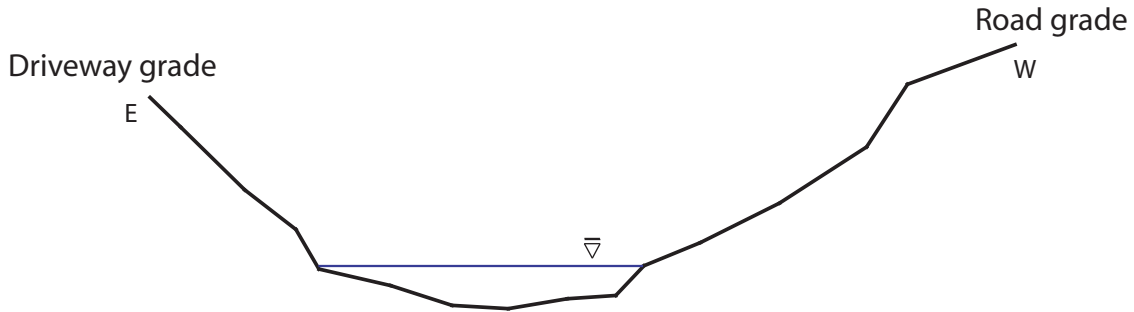
Appendix 6. Topographic survey data longitudinal profile for Pearce Brook 2 and 3 Culvert Assessment Site.



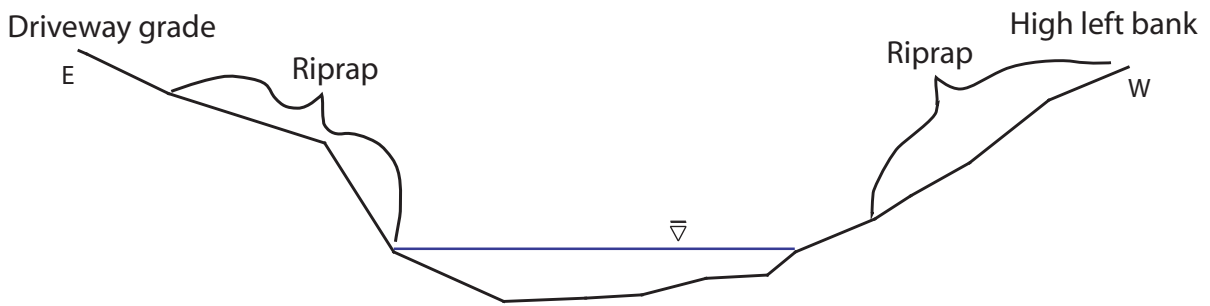


Appendix 6. Topographic survey data planview for Pearce Brook 4 Culvert Assessment Site.

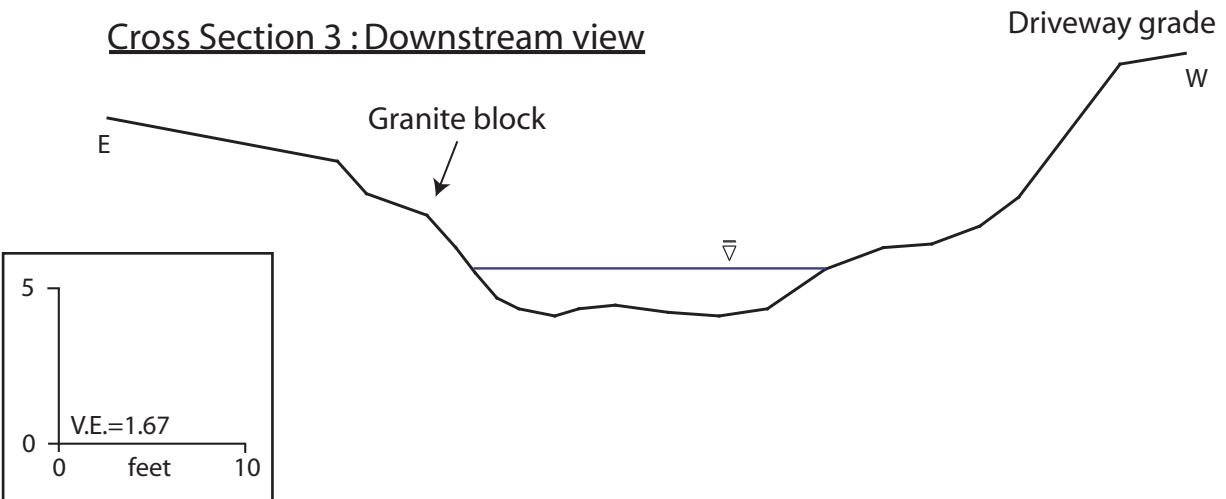
Cross Section 1 : Downstream view



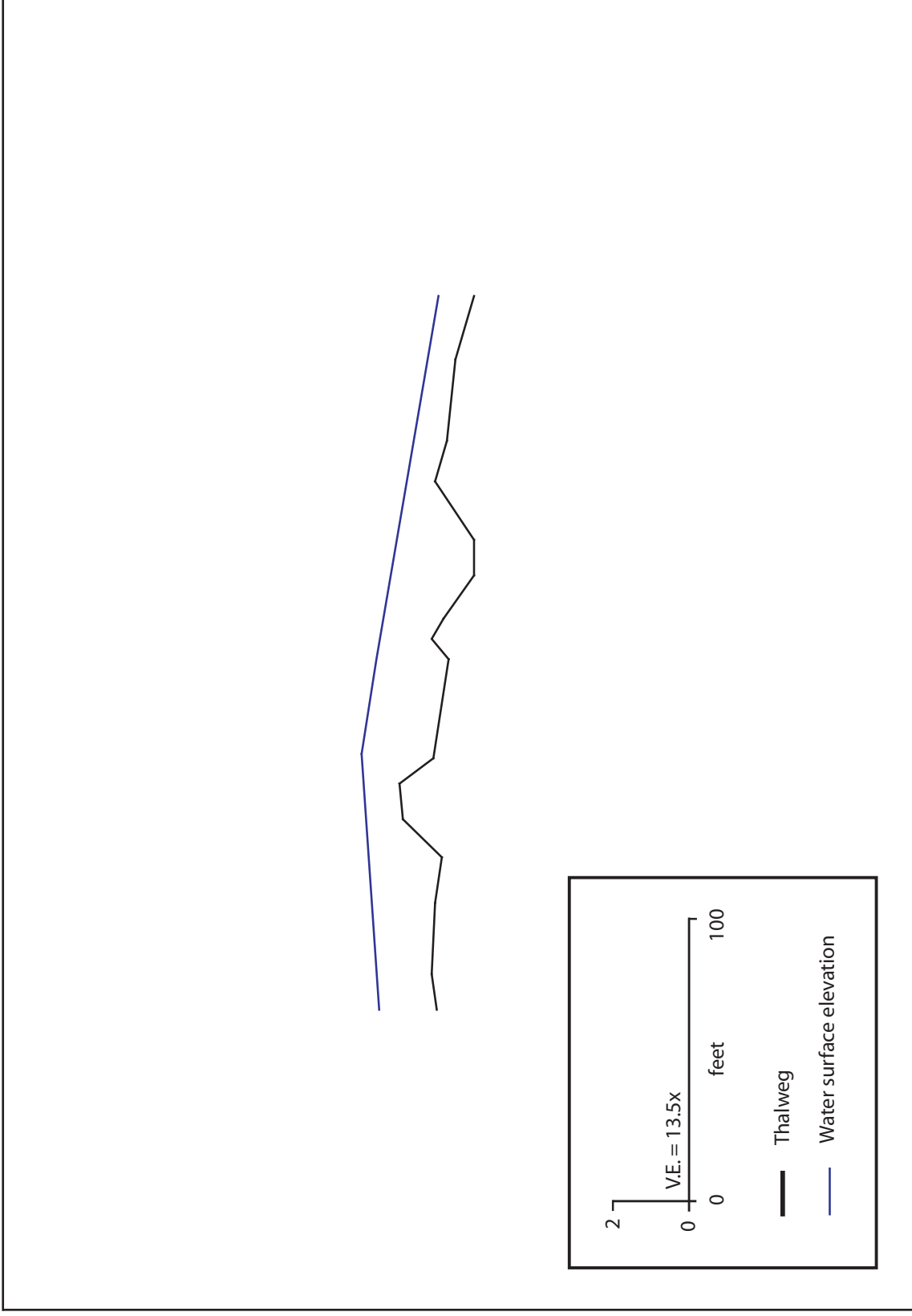
Cross Section 2 : Downstream view



Cross Section 3 : Downstream view

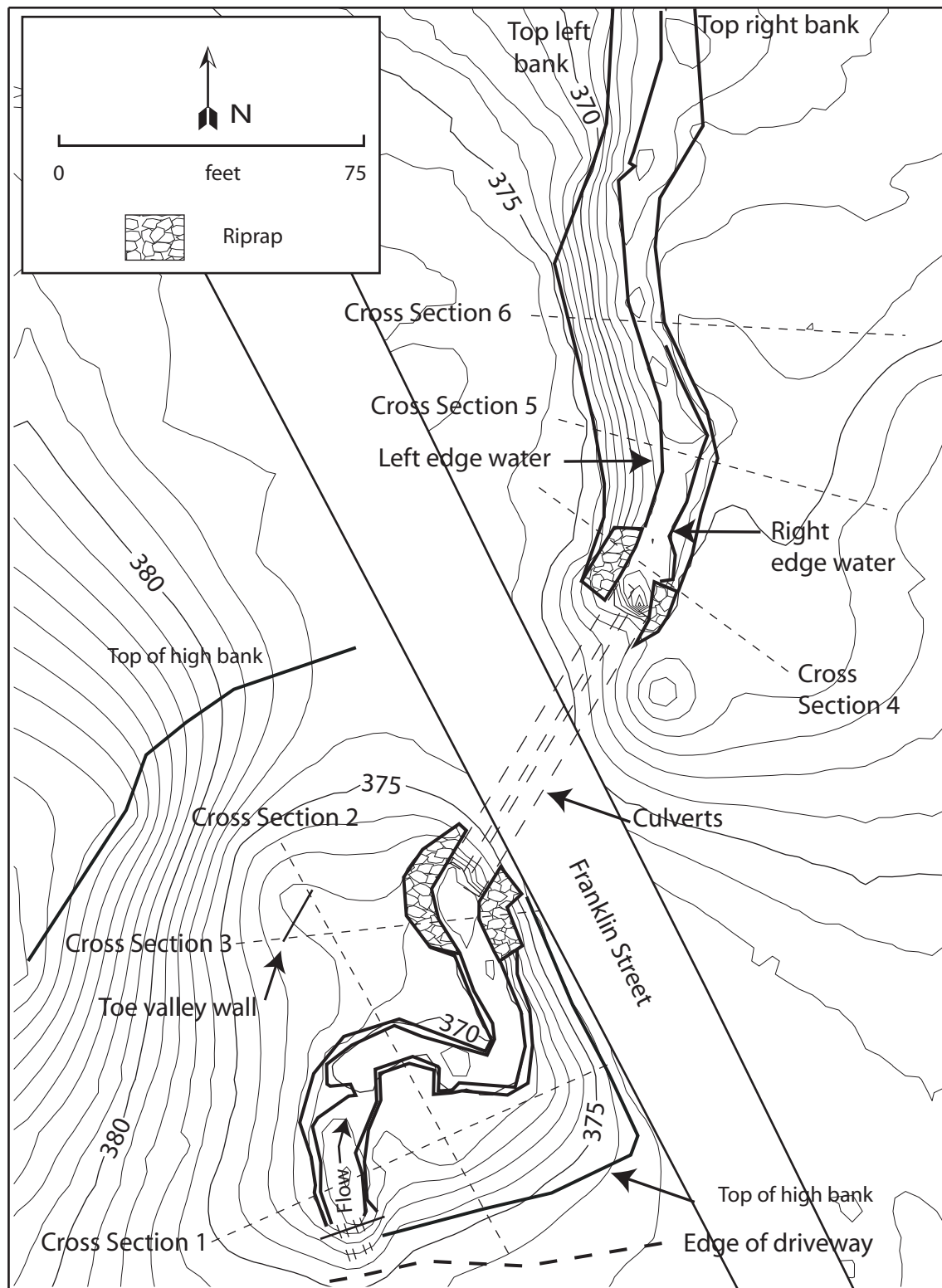


Appendix 6. Topographic survey data cross sections for Pearce Brook 4 Culvert Assessment Site.

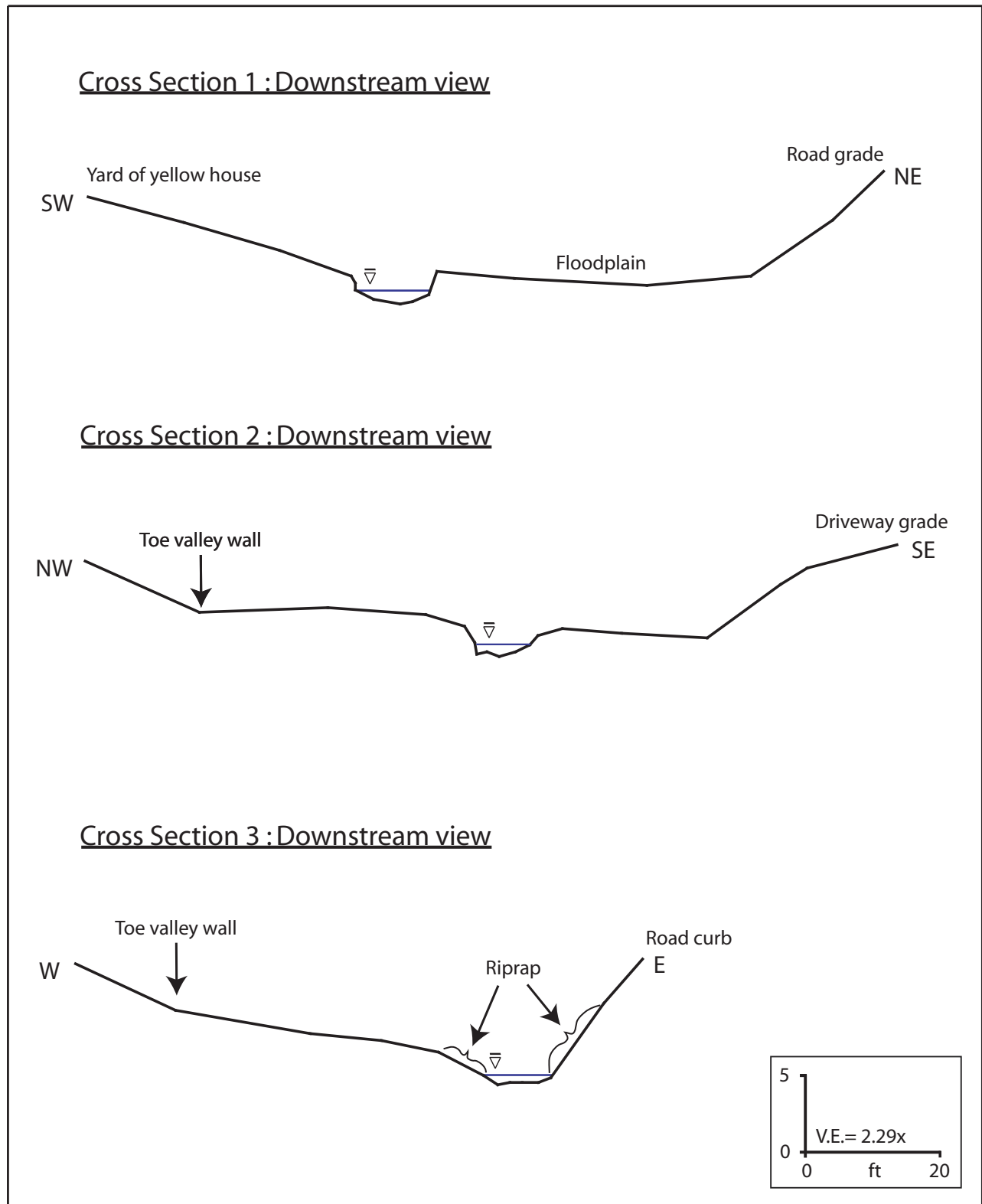


Appendix 6. Topographic survey data longitudinal profile for Pearce Brook 4 Culvert Assessment Site.

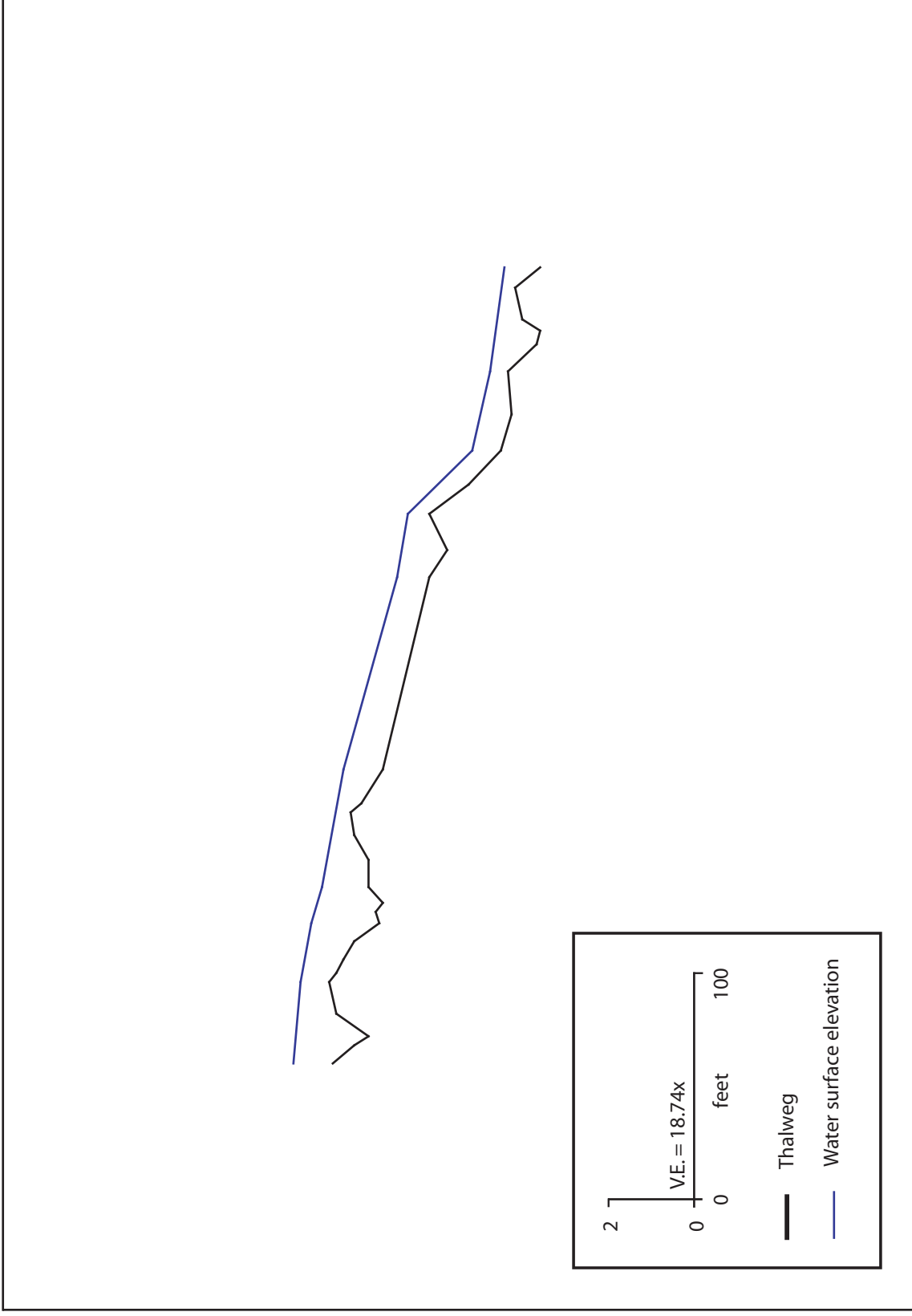




Appendix 6. Topographic survey data planview for Brown Brook 2 Culvert Assessment Site.

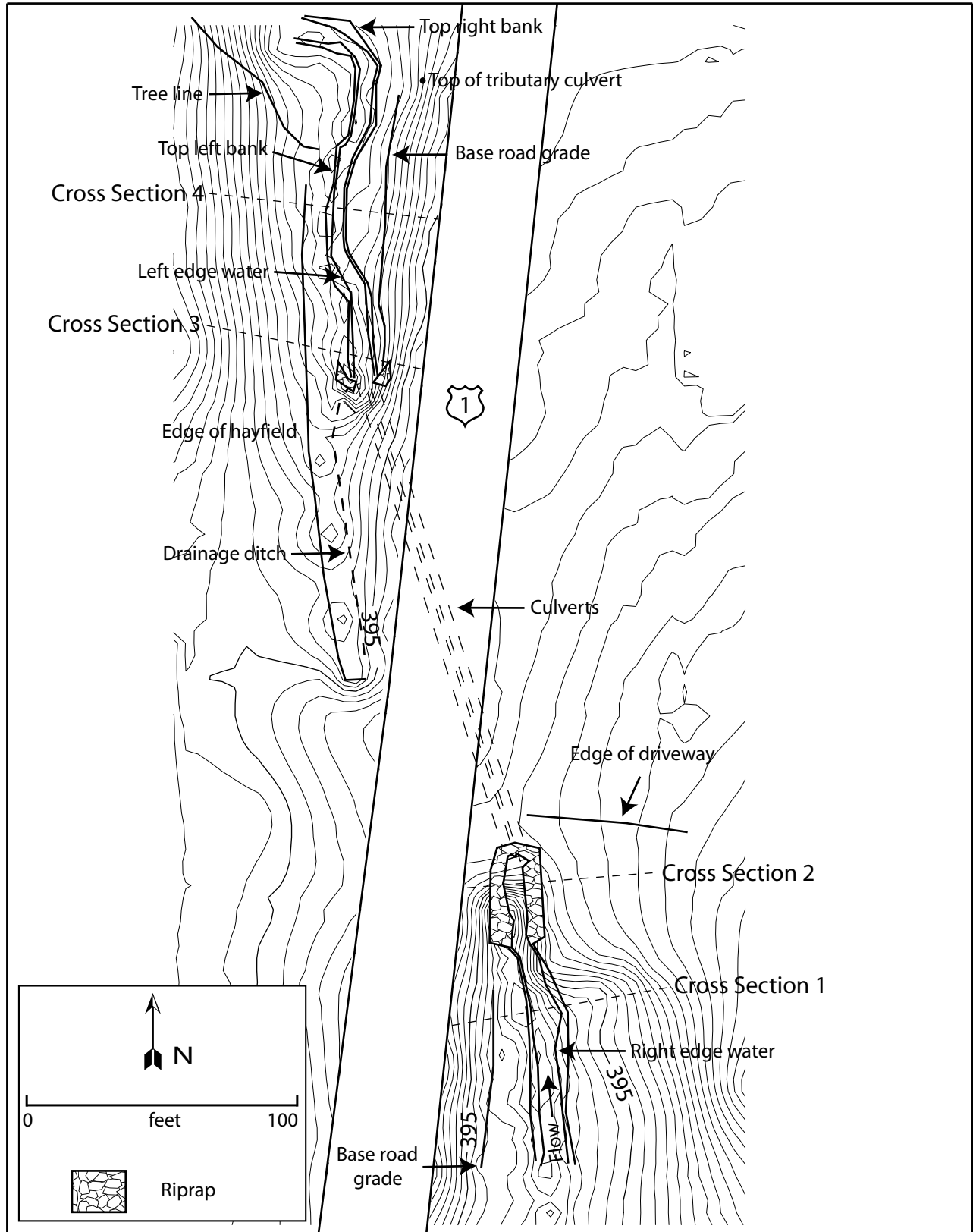


Appendix 6. Topographic survey data cross sections for Brown Brook 2 Culvert Assessment Site.



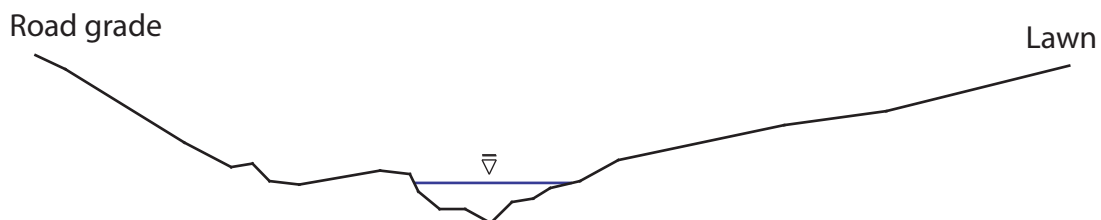
Appendix 6. Topographic survey data longitudinal profile for Brown Brook 2 Culvert Assessment Site.



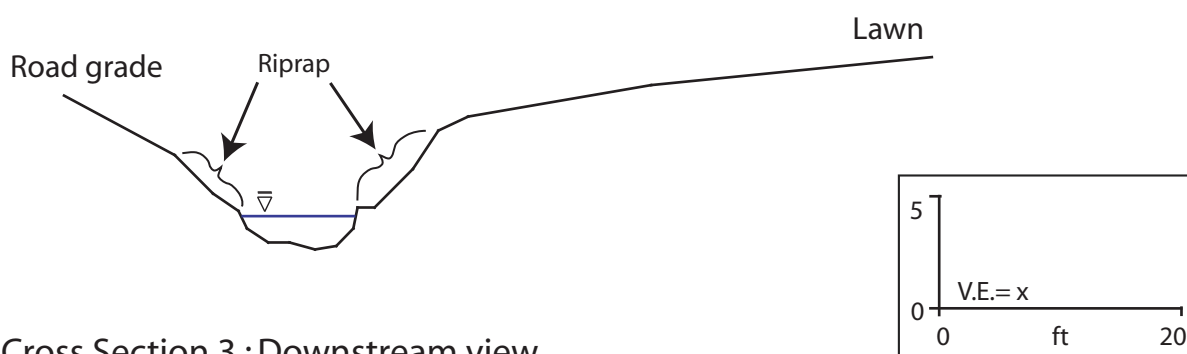


Appendix 6. Topographic survey data planview for Brown Brook 3 Culvert Assessment Site.

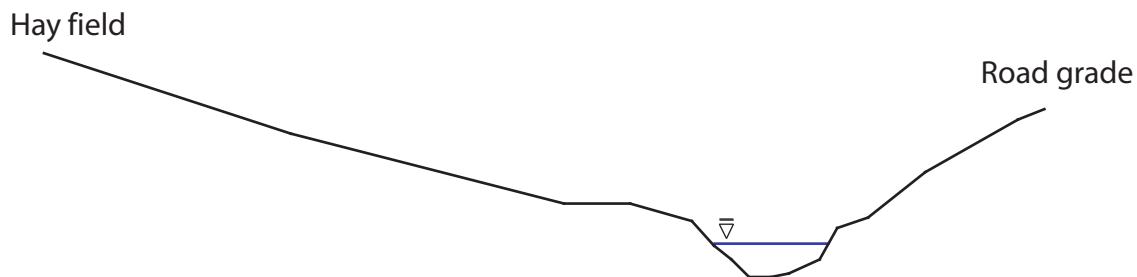
Cross Section 1 : Downstream view



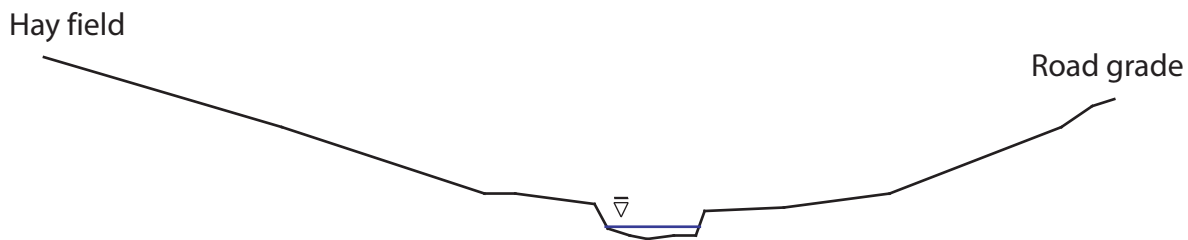
Cross Section 2 : Downstream view



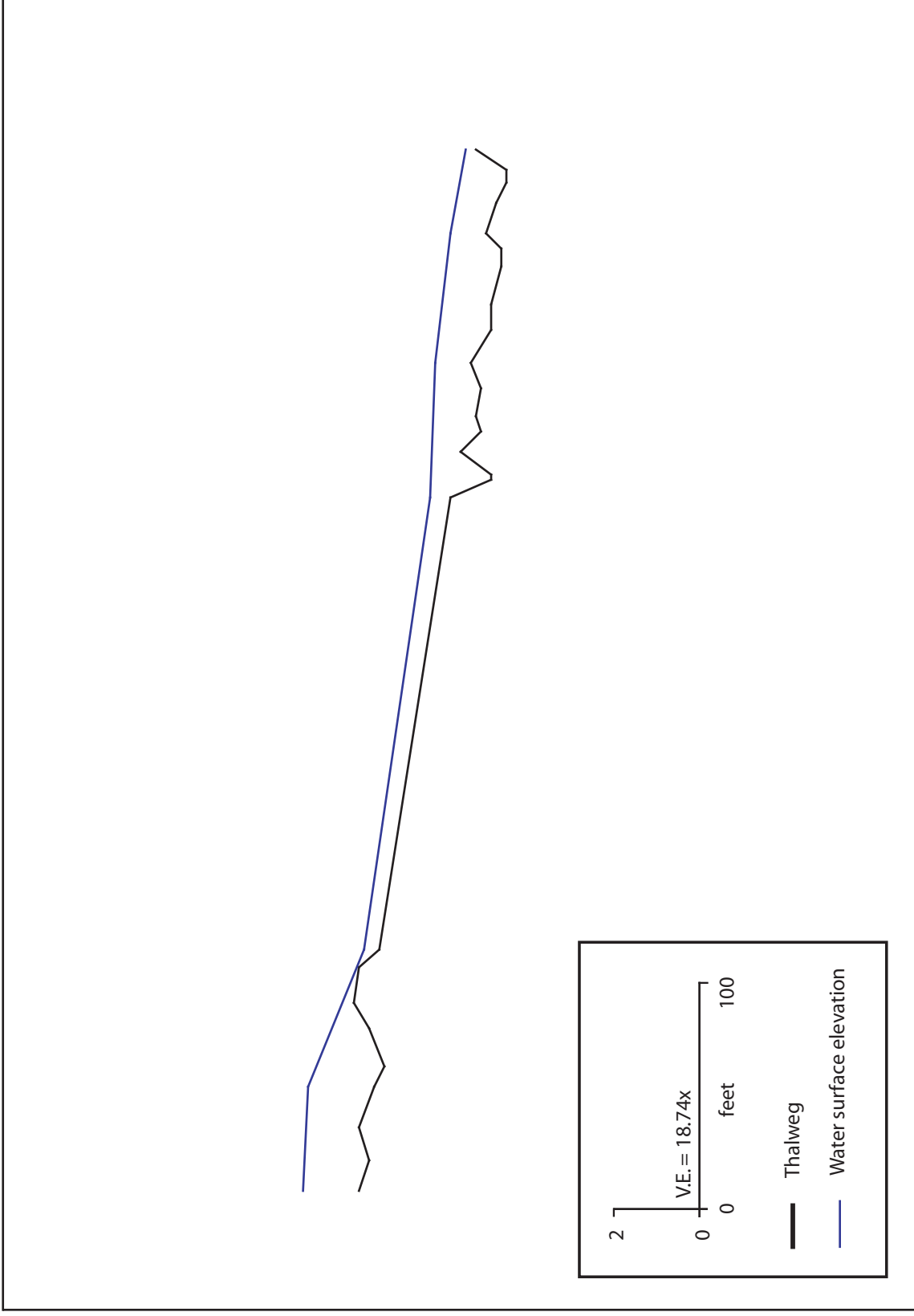
Cross Section 3 : Downstream view



Cross Section 4 : Downstream view

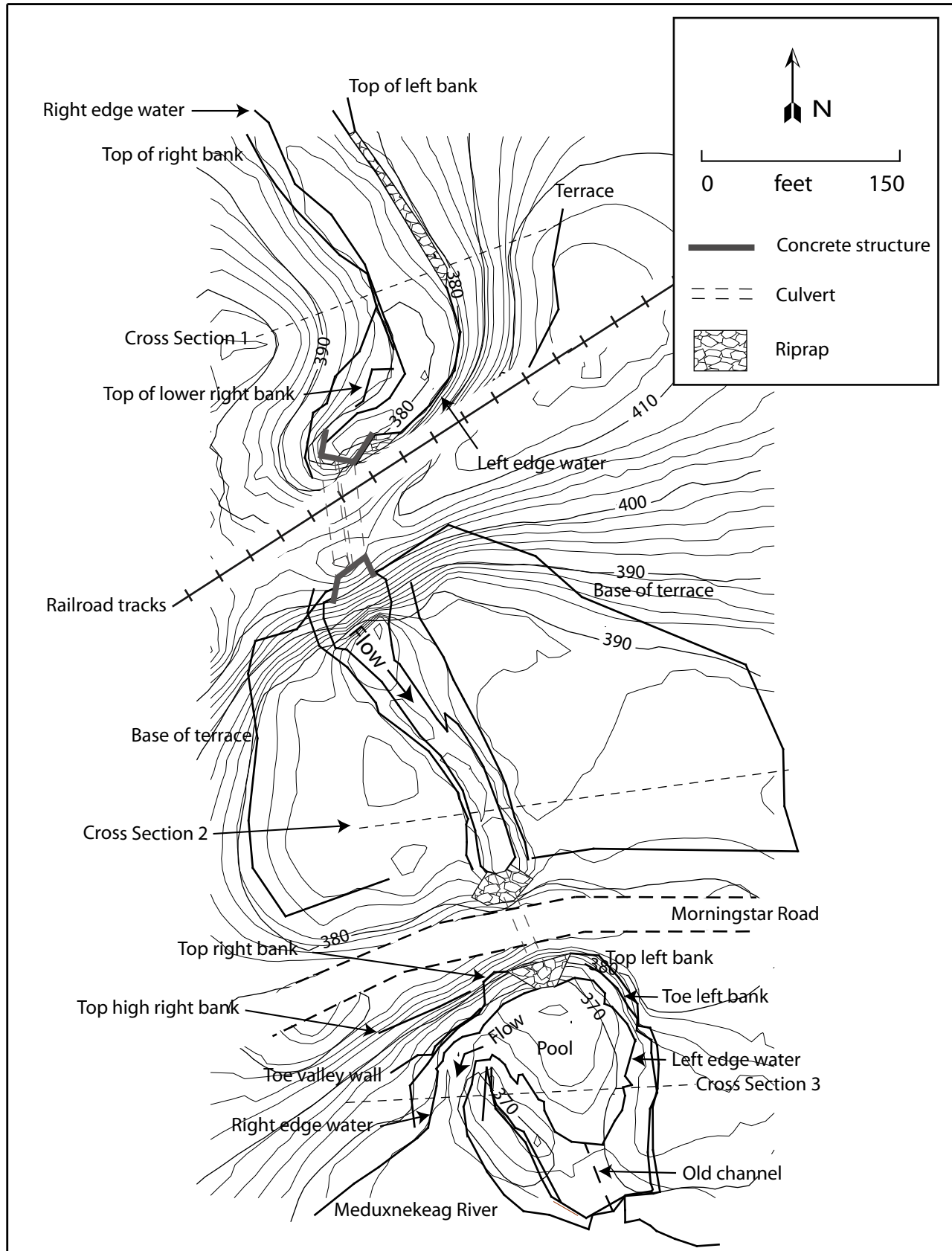


Appendix 6. Topographic survey data cross sections for Brown Brook 3 Culvert Assessment Site.



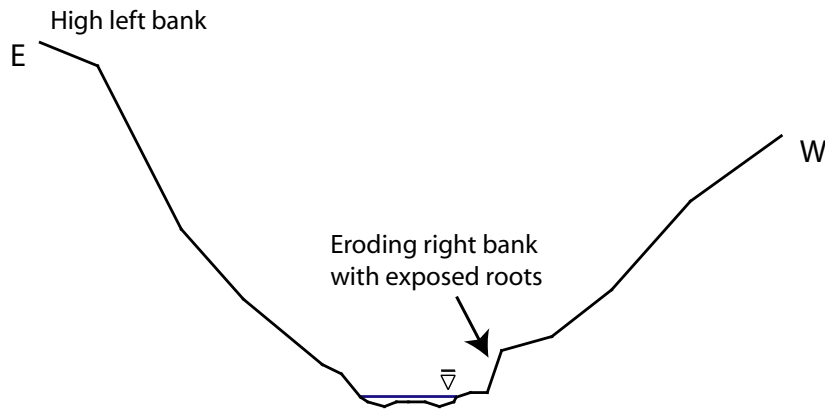
Appendix 6. Topographic survey data longitudinal profile for Brown Brook 3 Culvert Assessment Site.



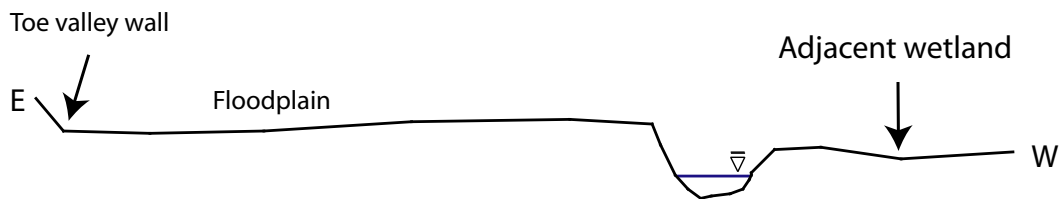


Appendix 6. Topographic survey data planview for Moose Brook 1 and 2 Culvert Assessment Site.

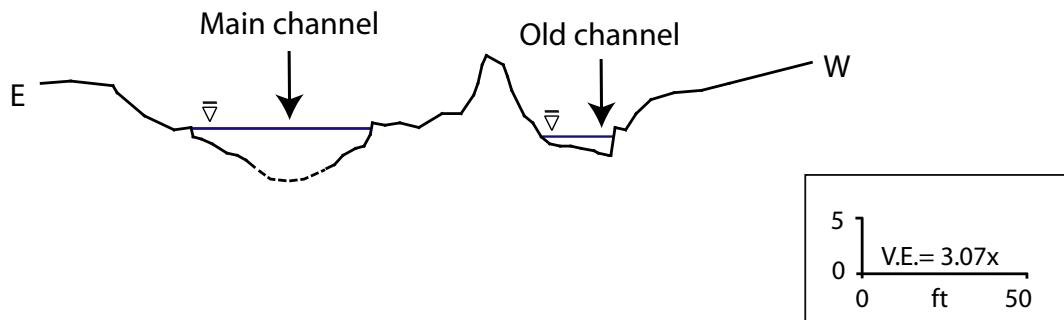
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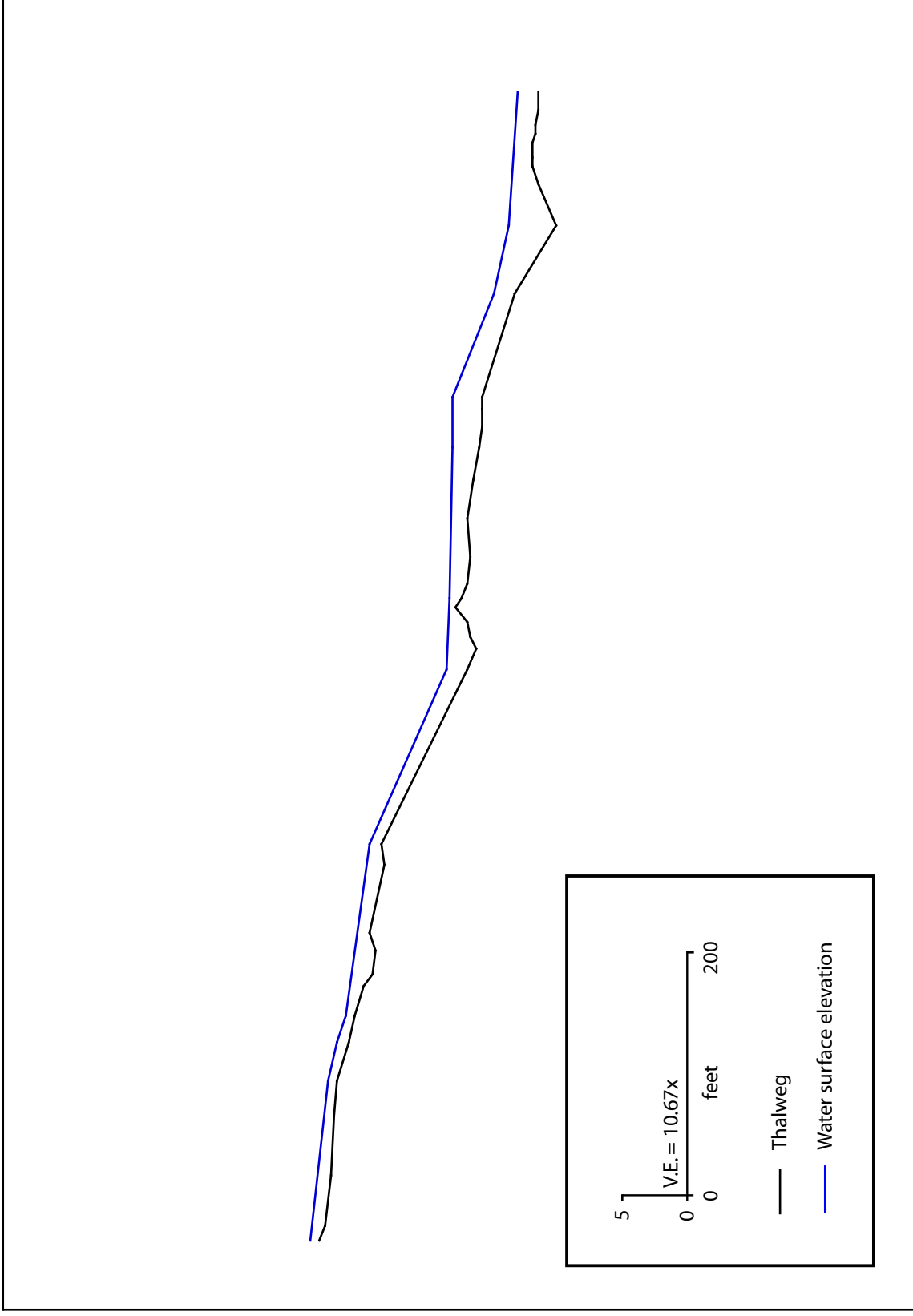
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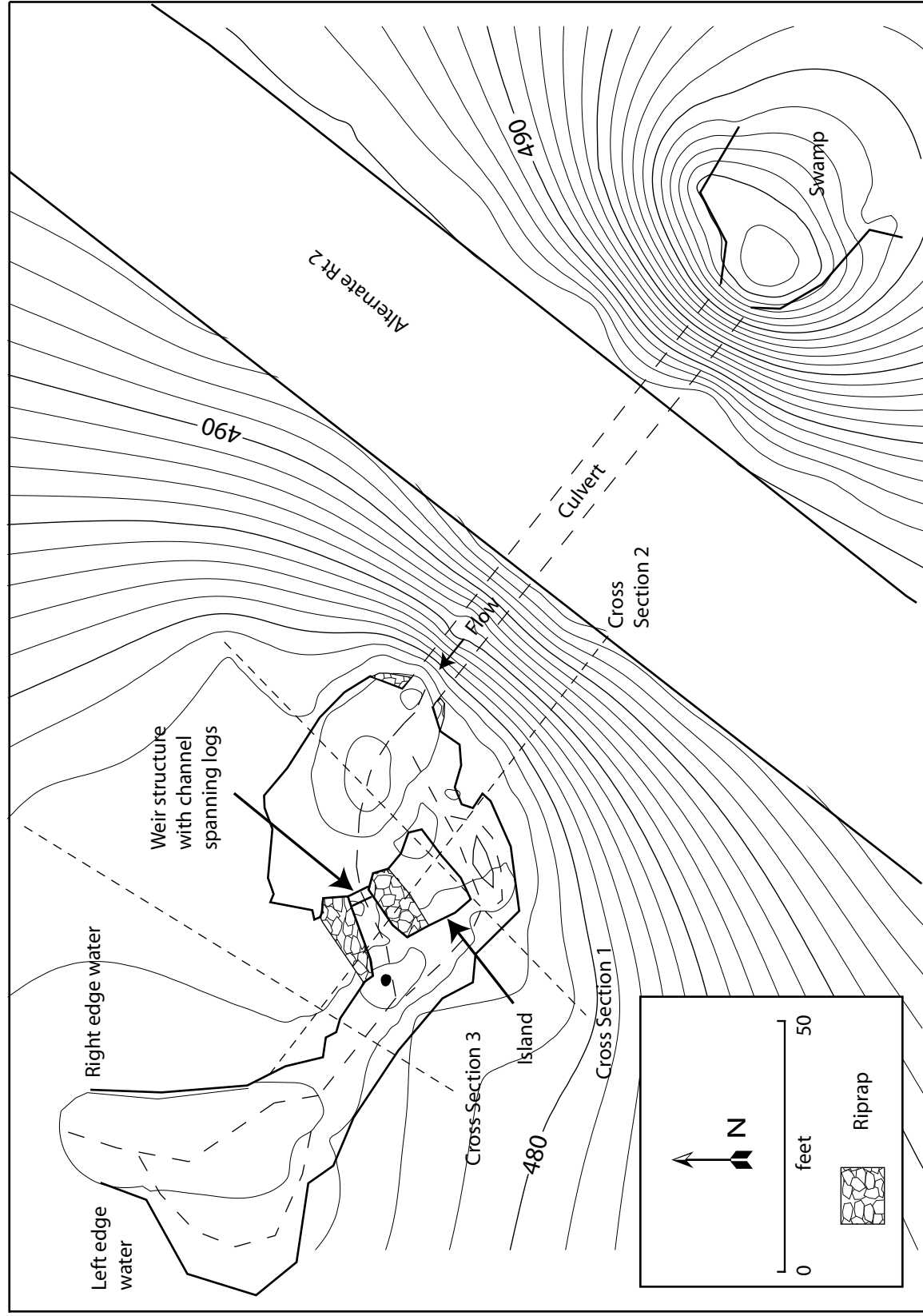
Cross Section 3 :Downstream view



Appendix 6. Topographic survey data cross sections for Moose Brook 1 and 2 Culvert Assessment Site.

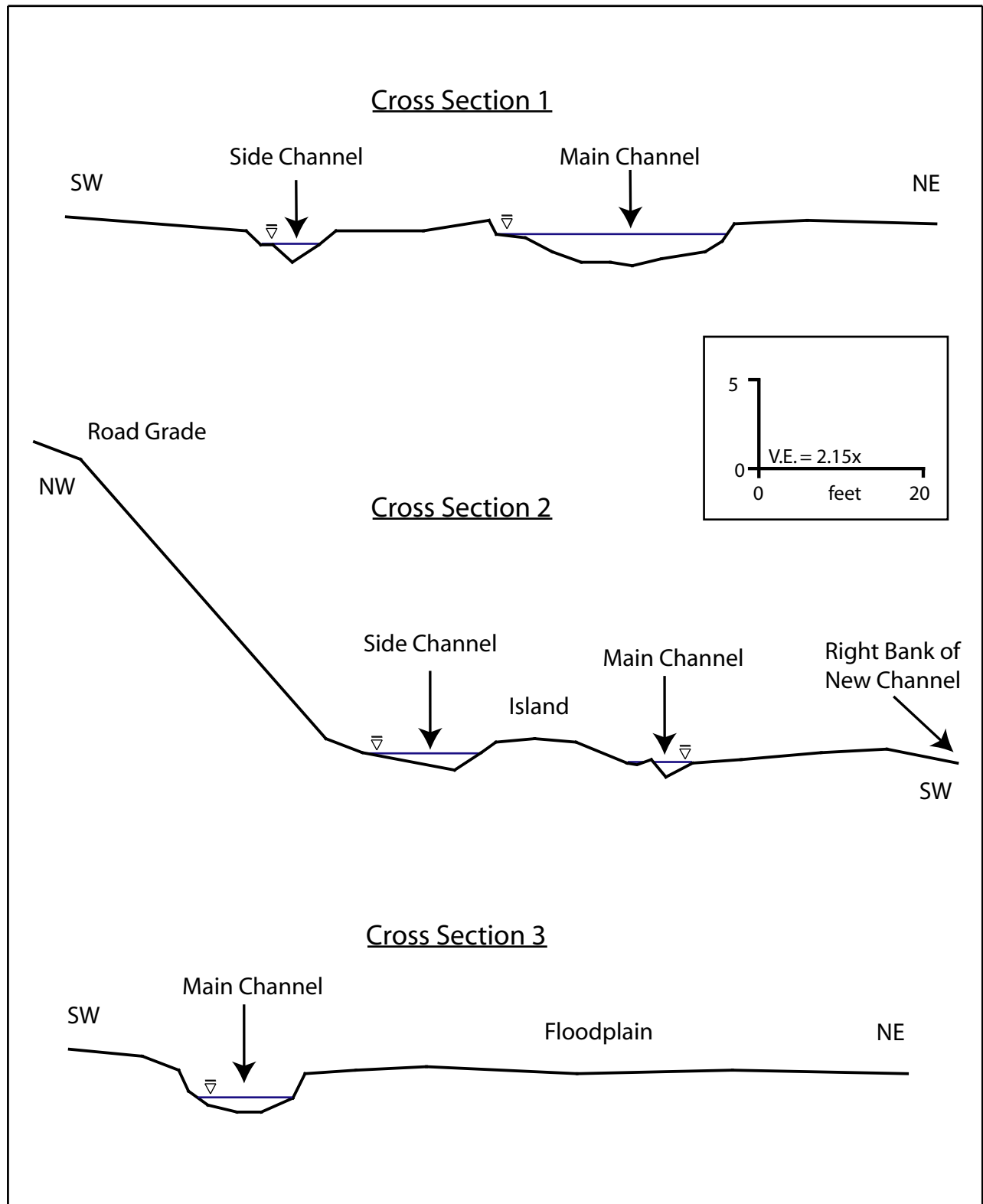


Appendix 6. Topographic survey data longitudinal profile for Moose Brook 1 and 2 Culvert Assessment Site.

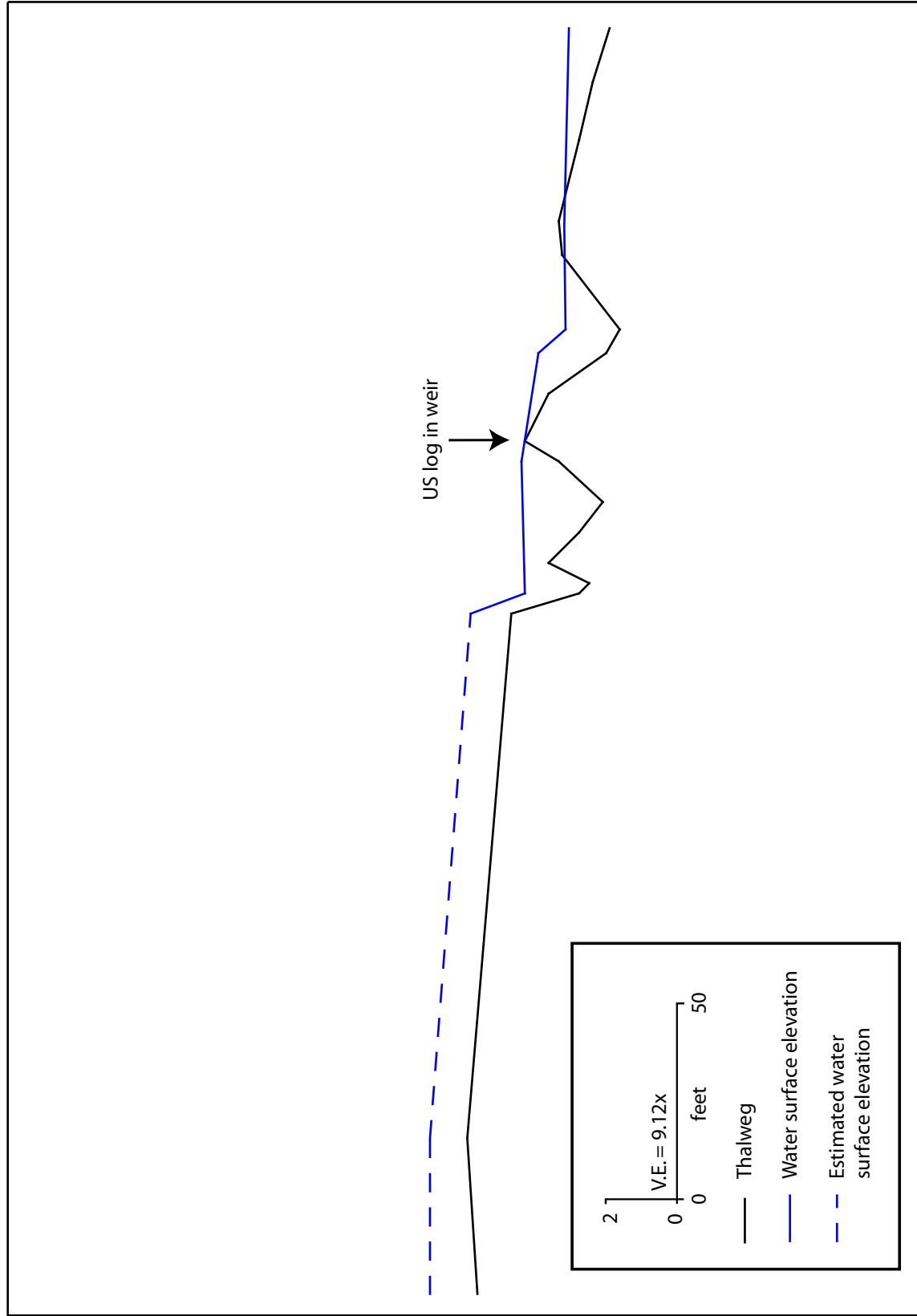


Appendix 6. Topographic survey data planview for Bither Brook 3 Culvert Assessment Site.





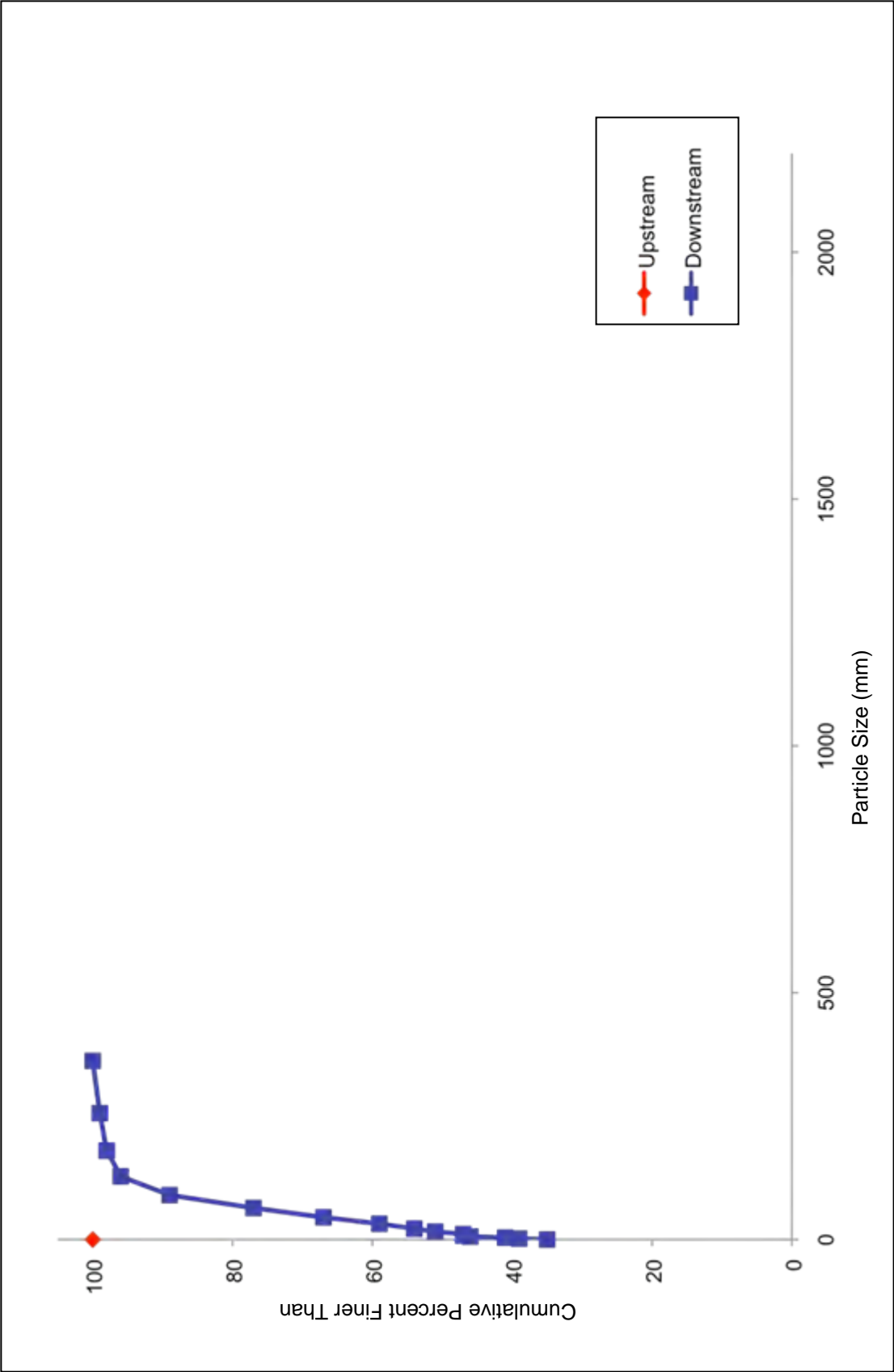
Appendix 6. Topographic survey data cross sections for Bither Brook 3 Culvert Assessment Site.



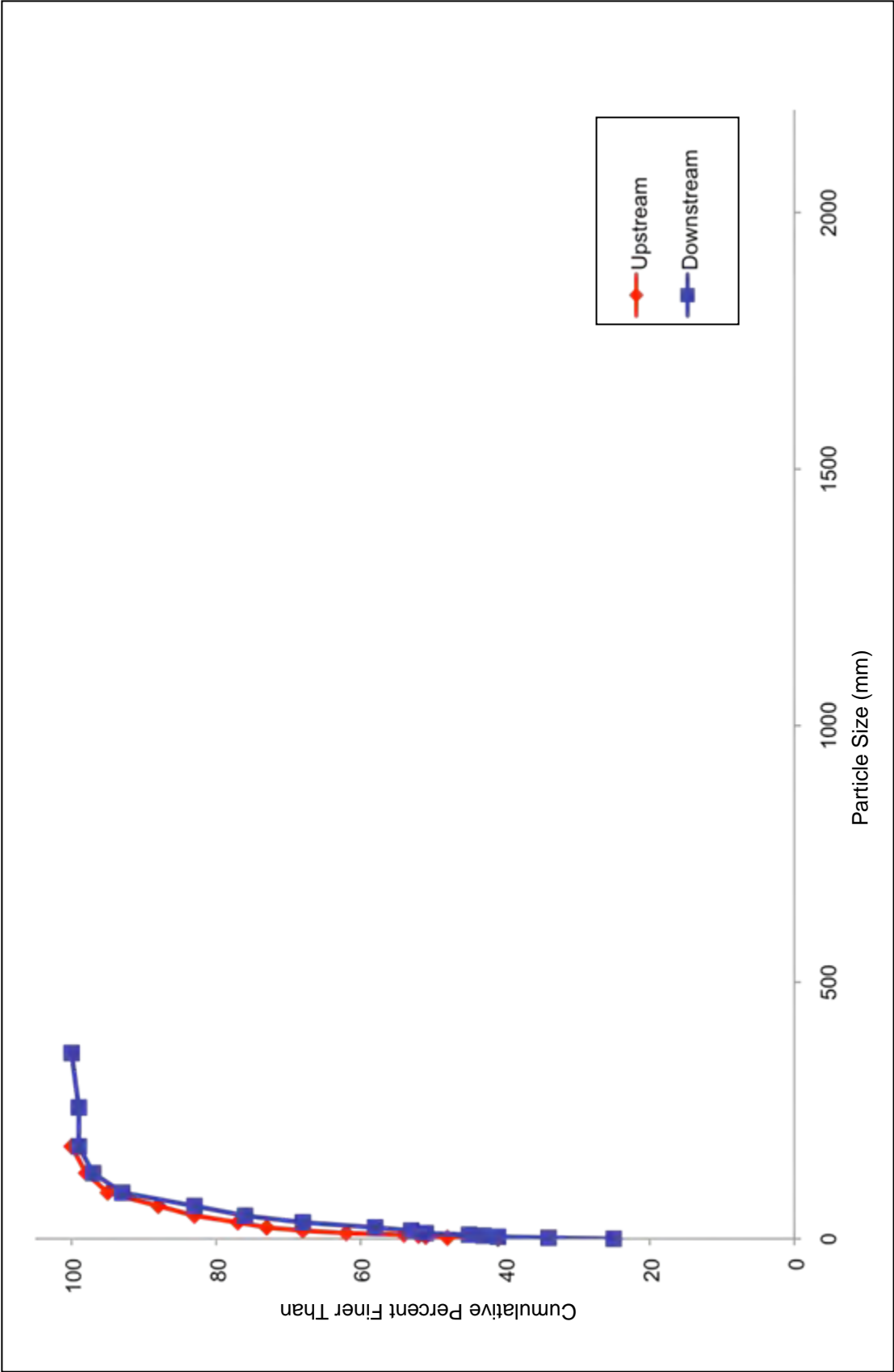
Appendix 6. Topographic survey data longitudinal profile for Bither Brook 3 Culvert Assessment Site.

Appendix 7

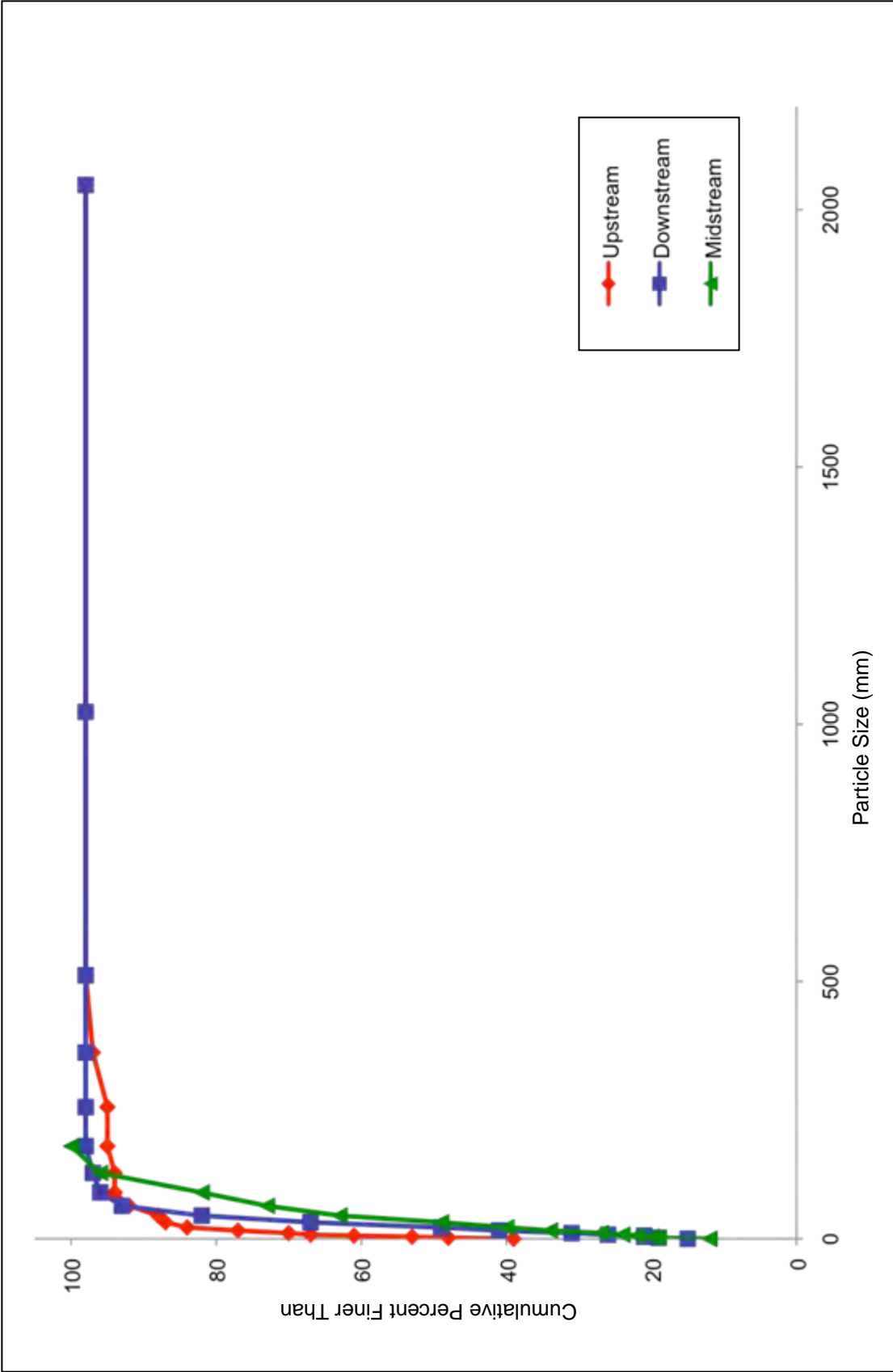
Substrate Particle Size Data for the Culvert Assessment Sites
(Refer to CD for additional data.)



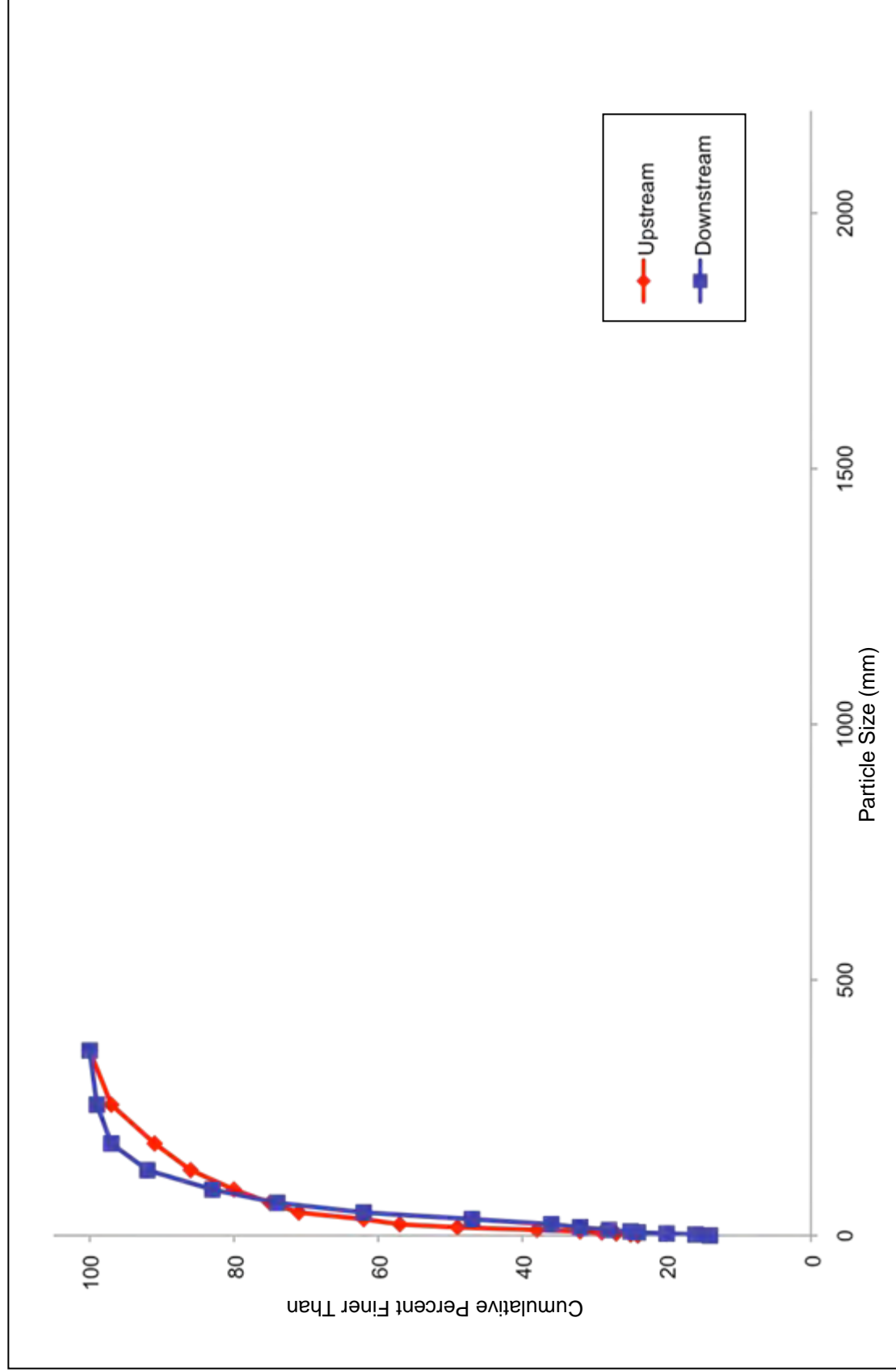
Appendix 7. Cumulative histograms of the substrate particle size data for the Suiter Brook culvert assessment site.



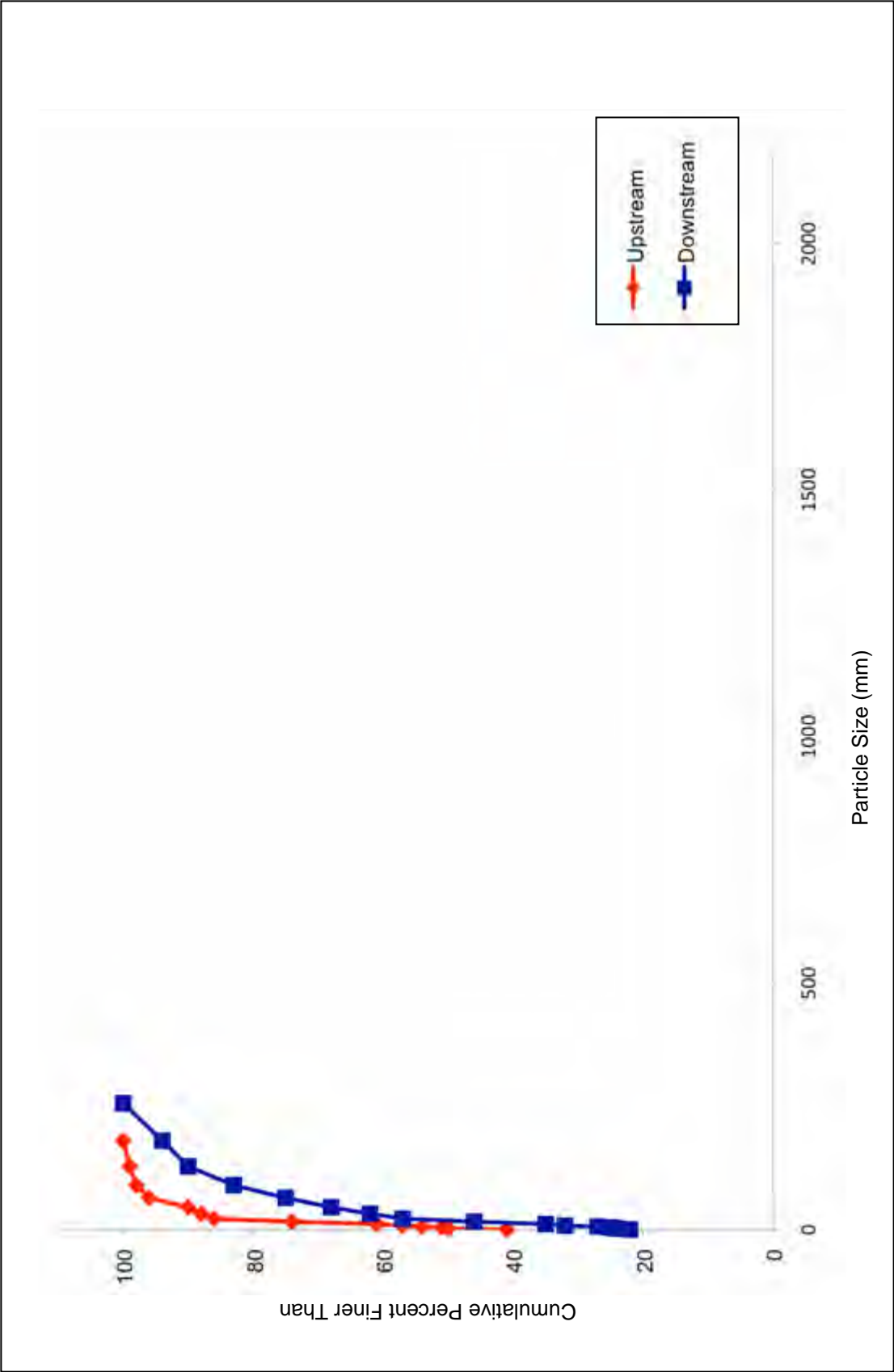
Appendix 7. Cumulative histograms of the substrate particle size data for the Smith Brook culvert assessment site.



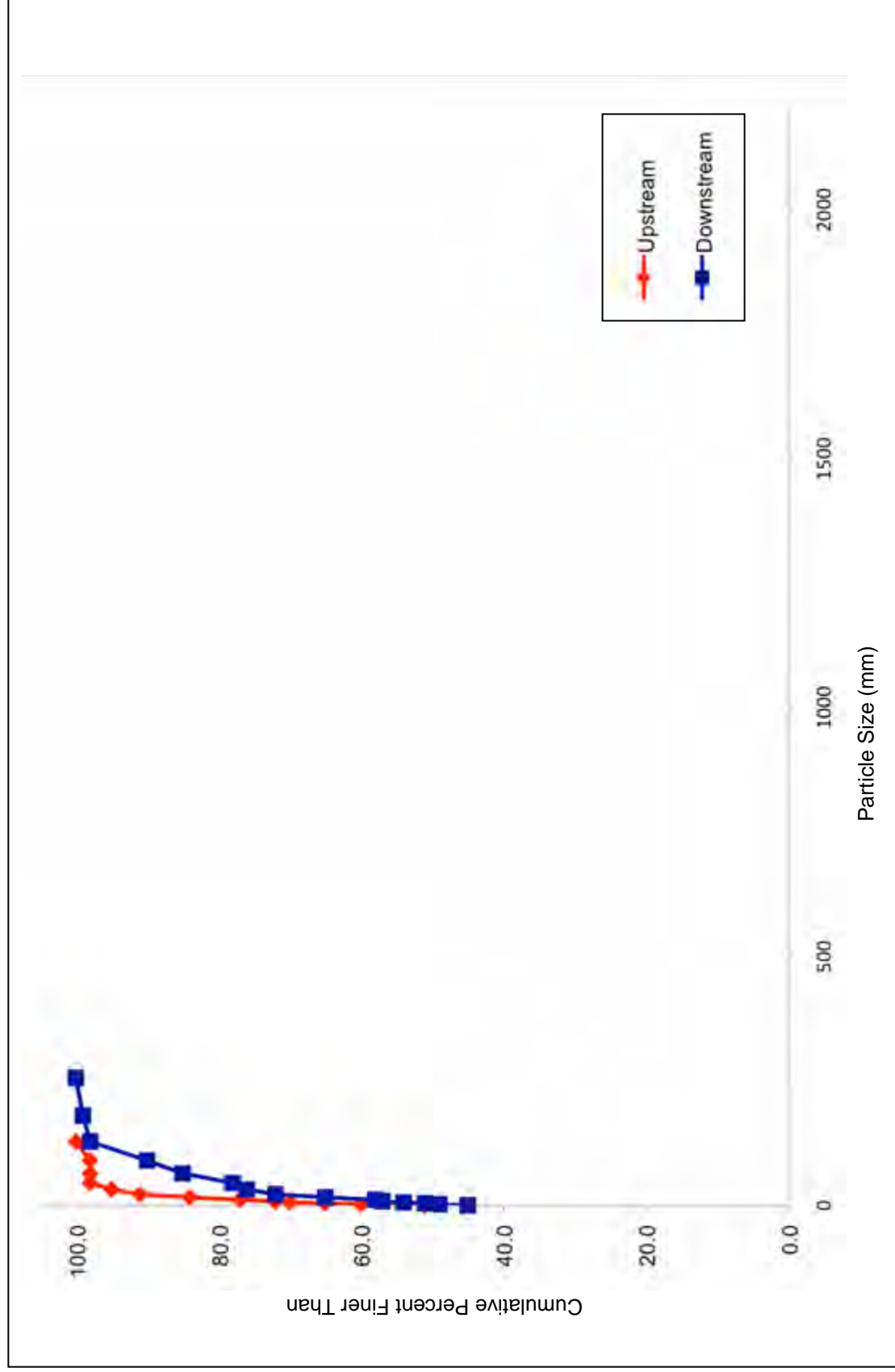
Appendix 7. Cumulative histograms of the substrate particle size data for the Pearce Brook culverts 2 and 3 assessment sites.



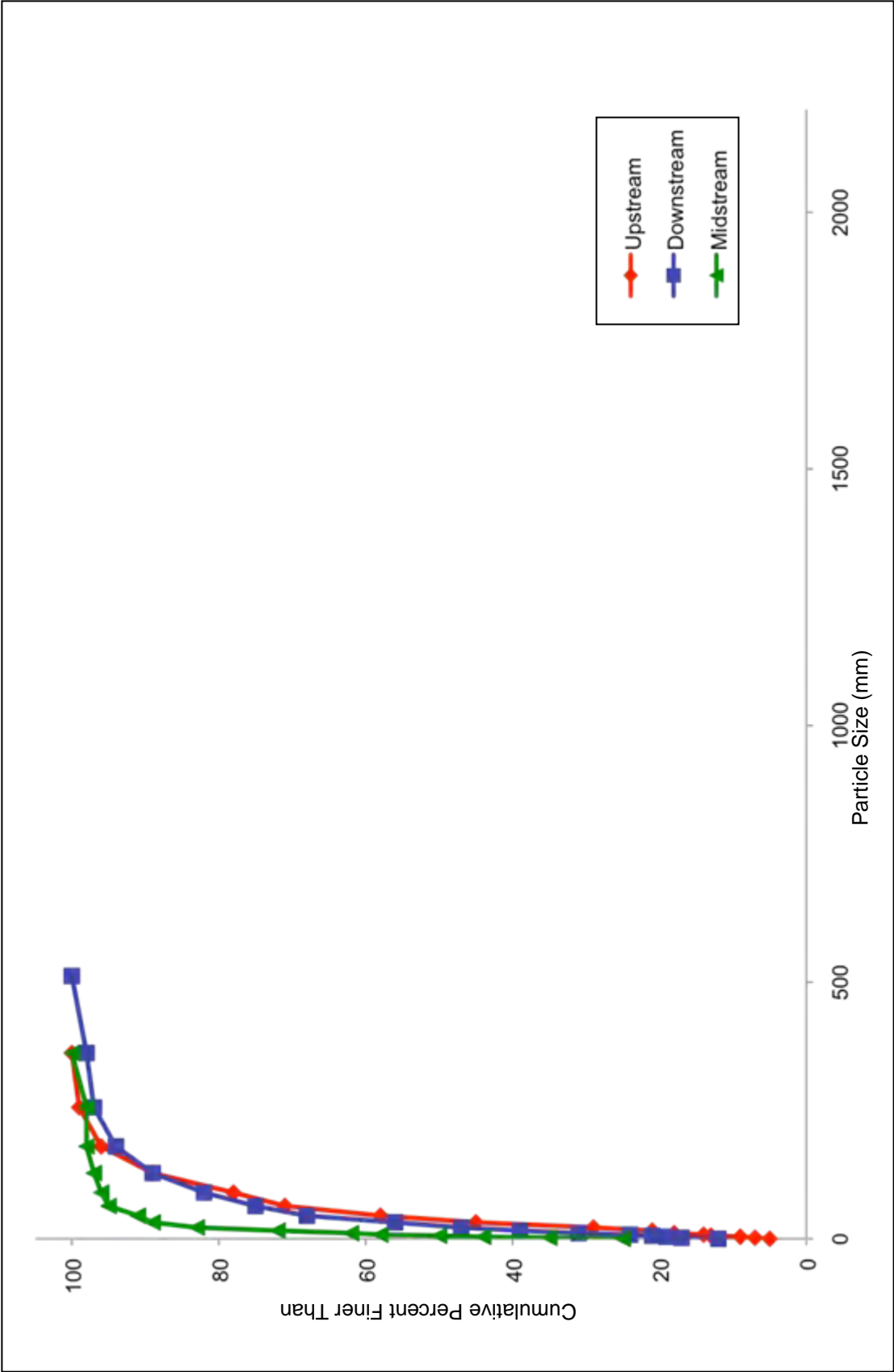
Appendix 7. Cumulative histograms of the substrate particle size data for the Pearce Brook culvert 4 assessment site.



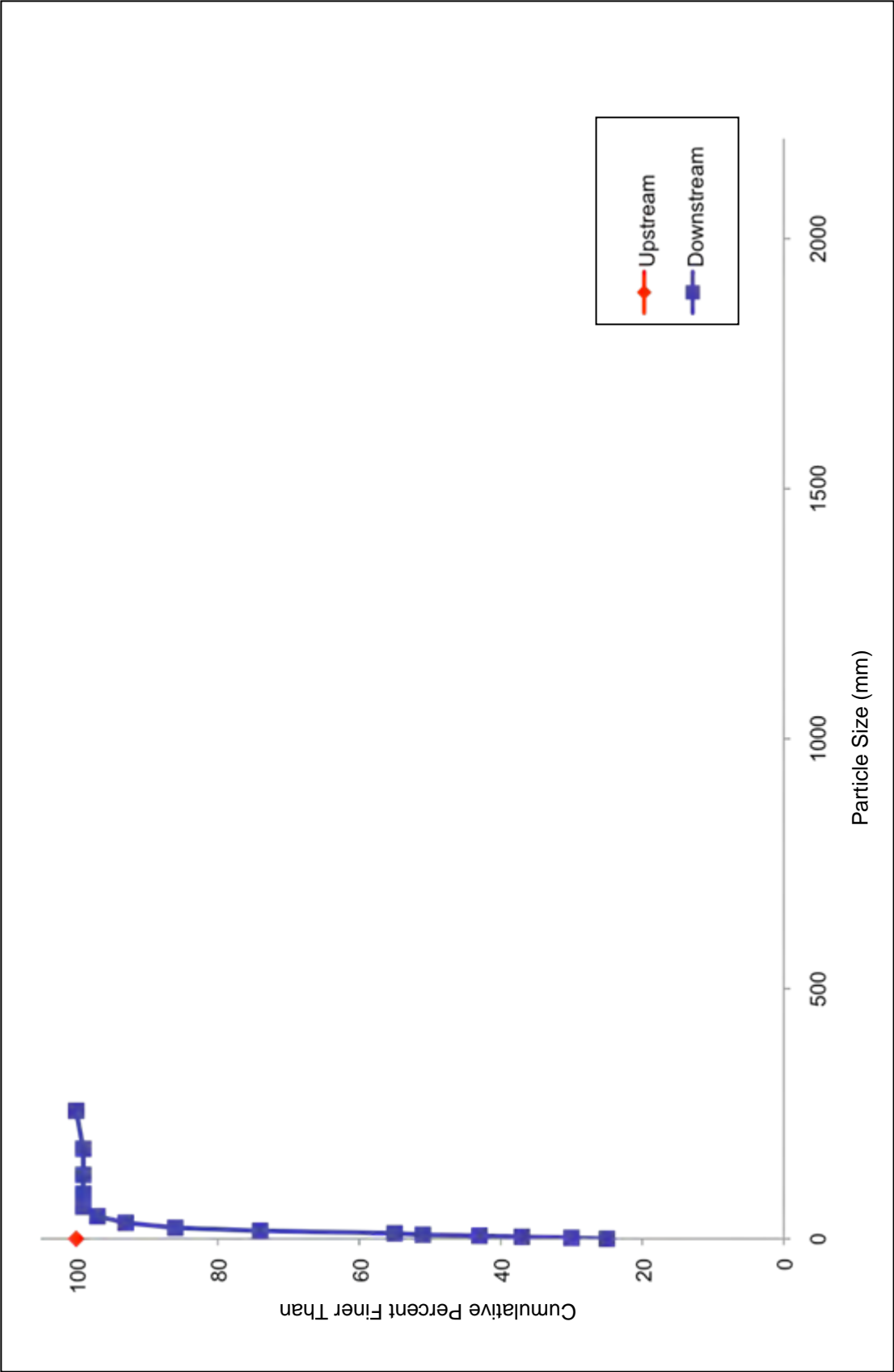
Appendix 7. Cumulative histograms of the substrate particle size data for the Brown Brook culvert 2 assessment site.



Appendix 7. Cumulative histograms of the substrate particle size data for the Brown Brook culvert 3 assessment site.



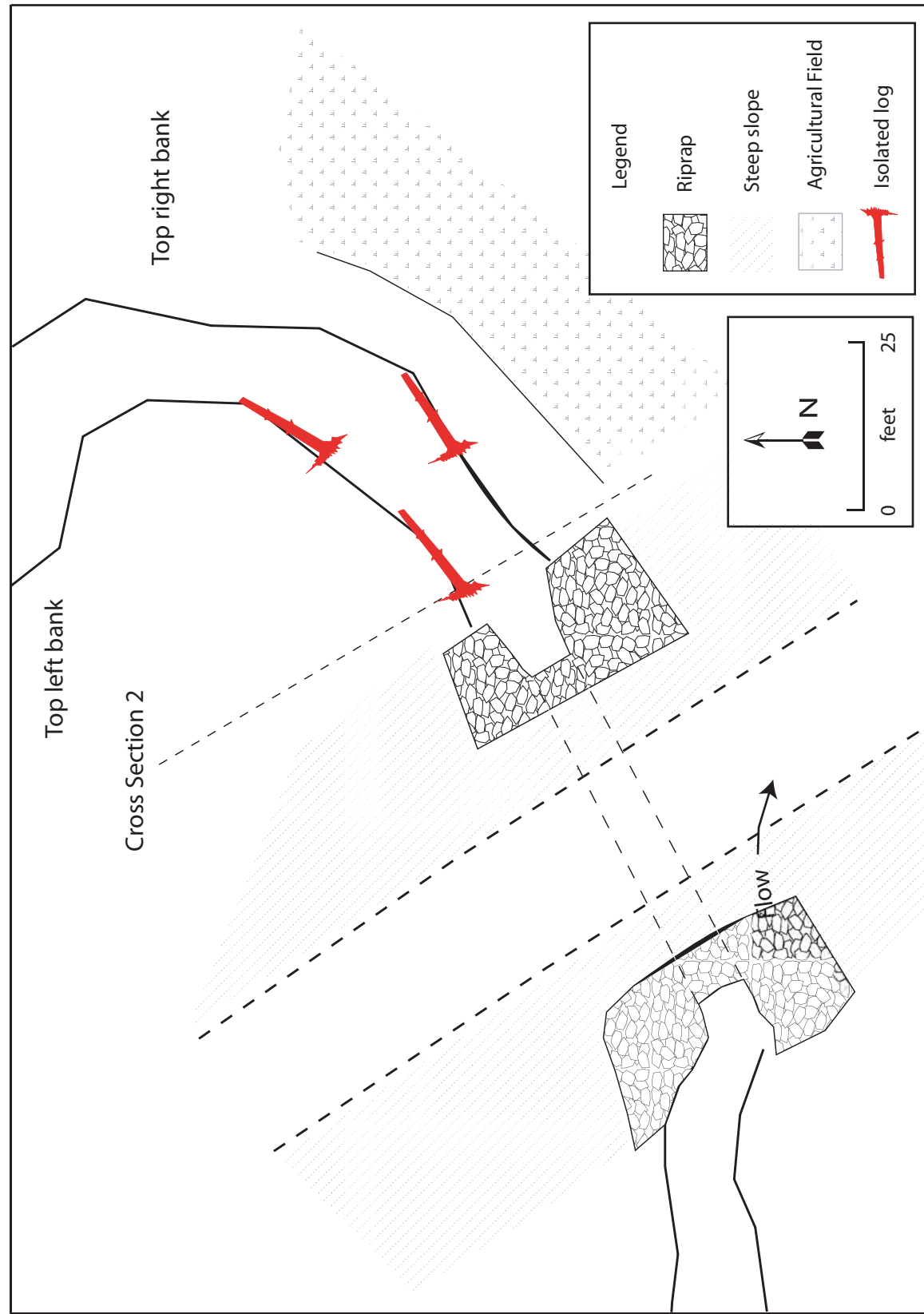
Appendix 7. Cumulative histograms of the substrate particle size data for the Moose Brook culverts 1 and 2 assessment sites.



Appendix 7. Cumulative histograms of the substrate particle size data for the Bither Brook culvert assessment site.

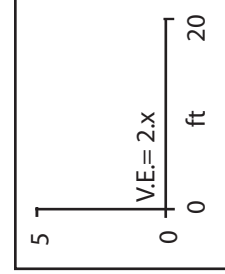
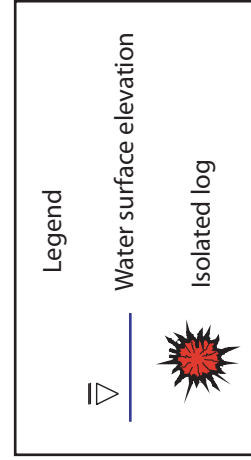
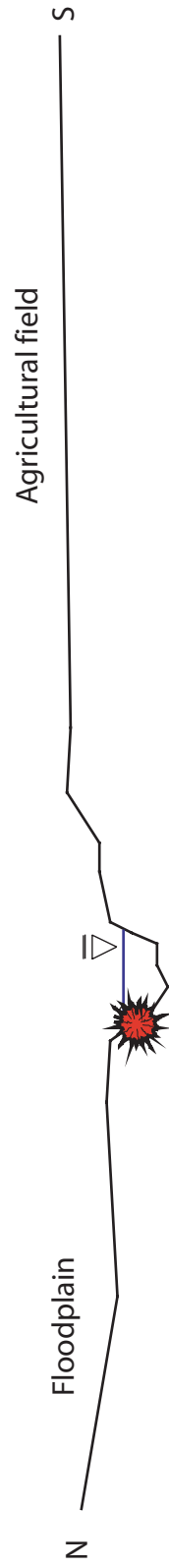
Appendix 8

Conceptual Habitat Mitigation Designs for the Culvert Assessment Sites

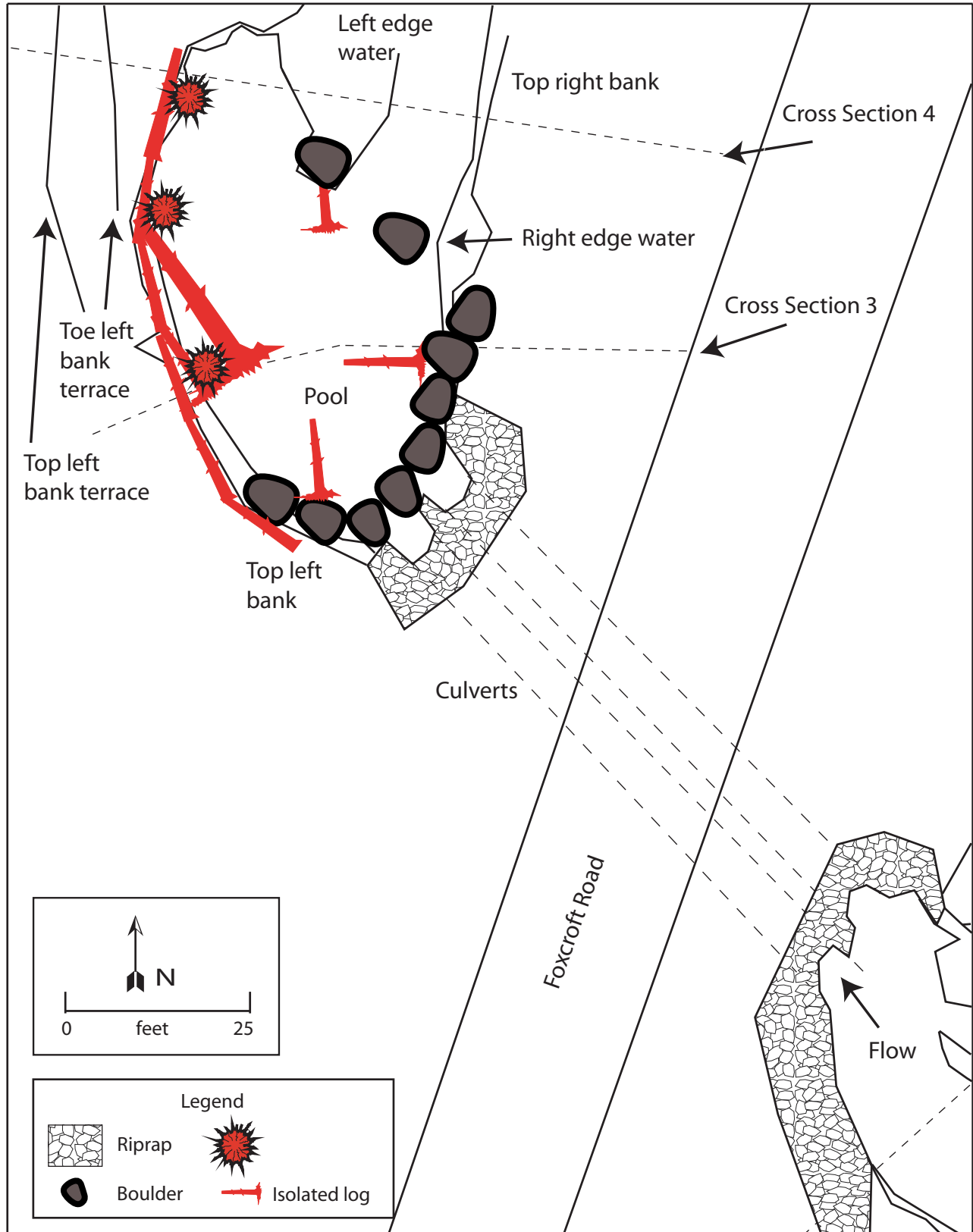


Appendix 8. Conceptual habitat mitigation design plan view for Suiter Brook culvert.

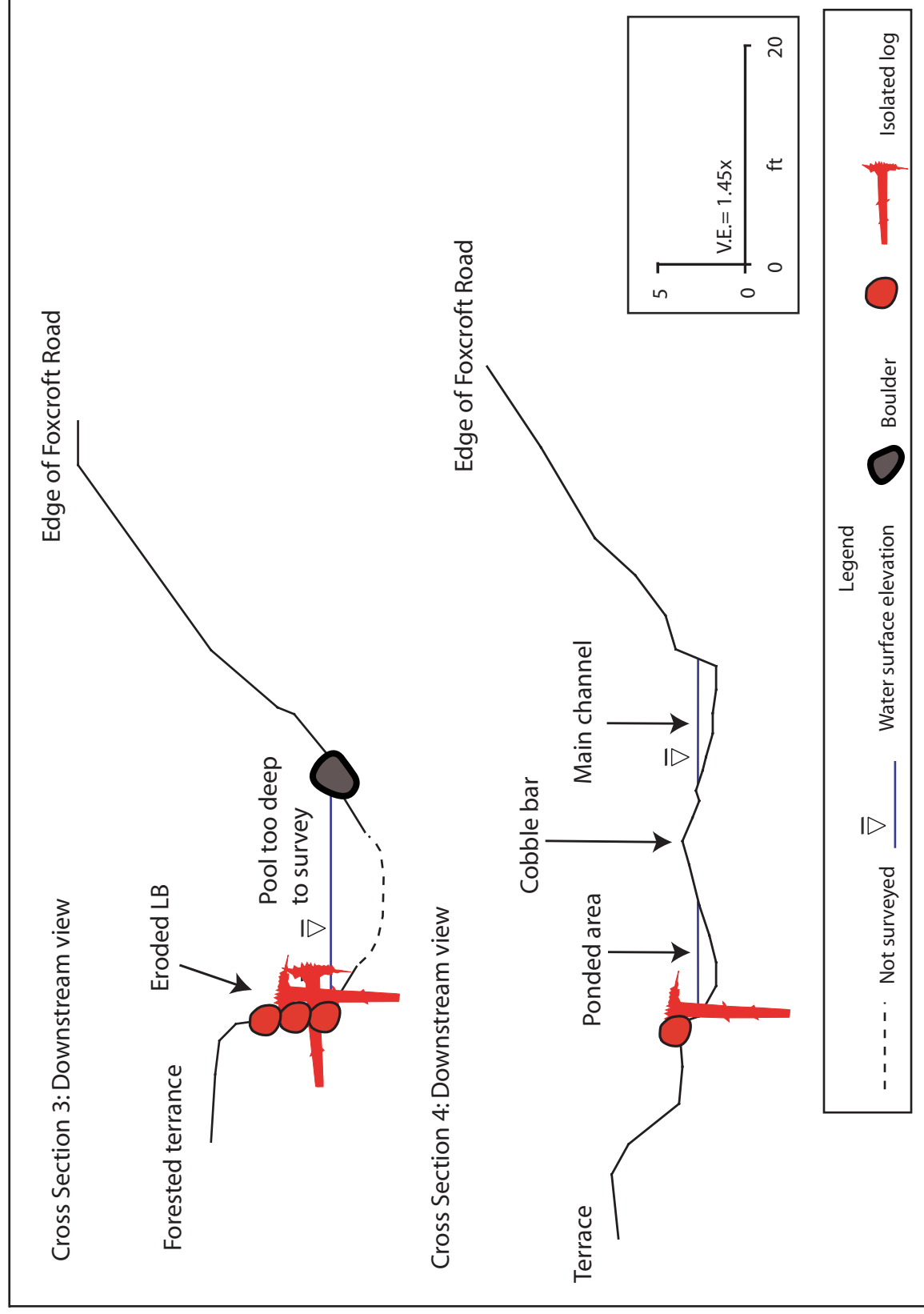
Cross Section 2 : Downstream view



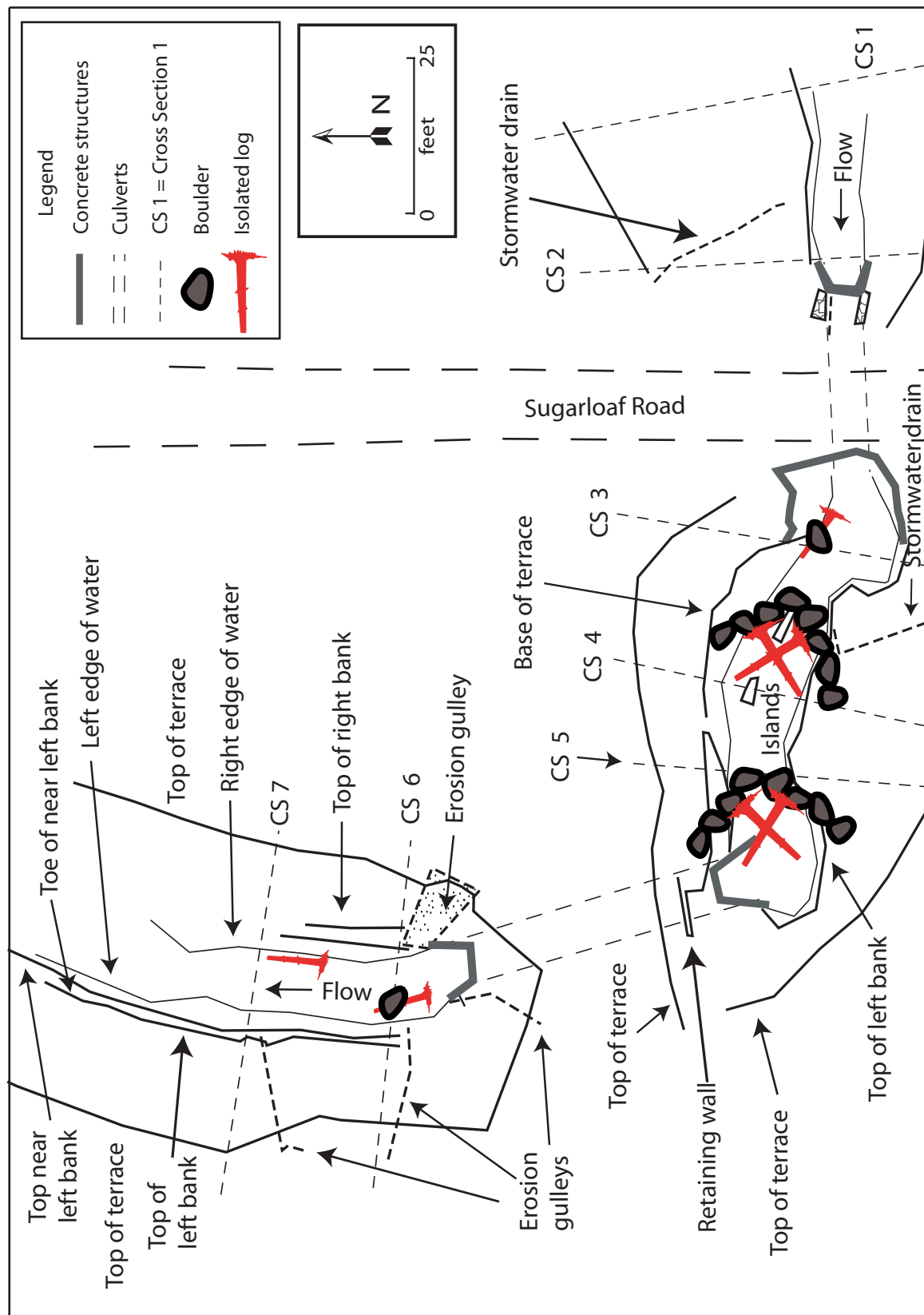
Appendix 8. Conceptual habitat mitigation design cross section for Suiter Brook culvert.



Appendix 8. Conceptual habitat mitigation design plan view for Smith Brook culvert.

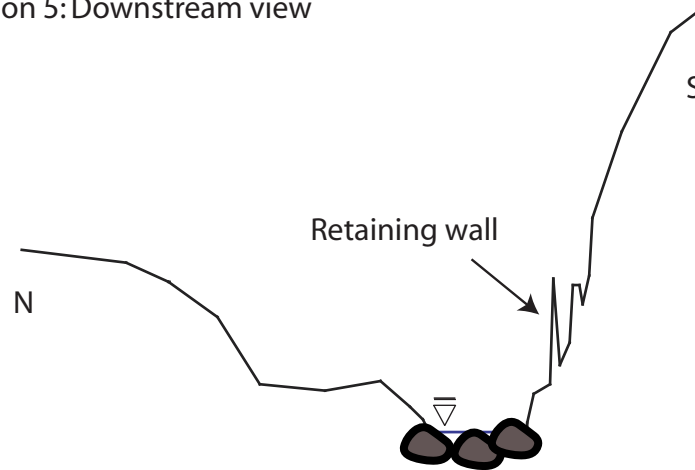


Appendix 8. Conceptual habitat mitigation design cross sections for Smith Brook culvert.

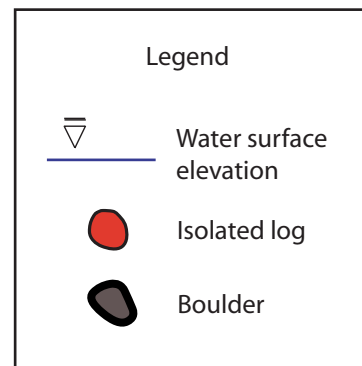
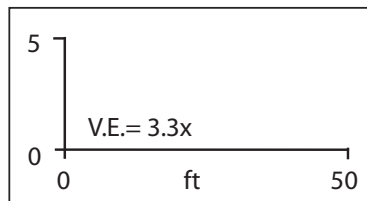
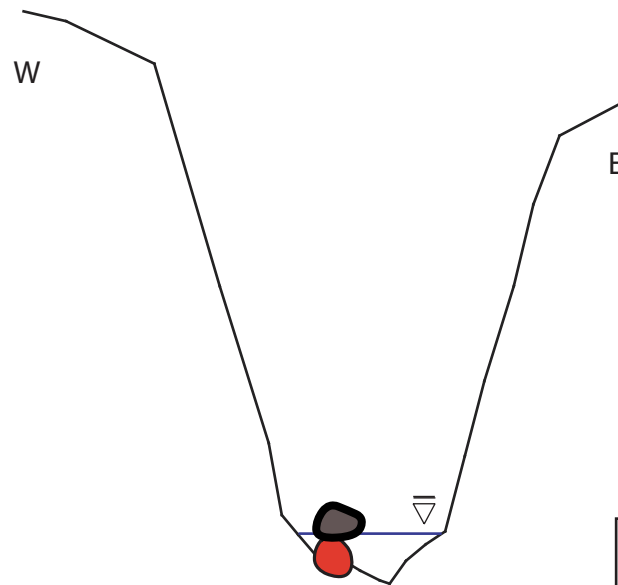


Appendix 8. Conceptual habitat mitigation design plan view for Pearce Brook Culvert.

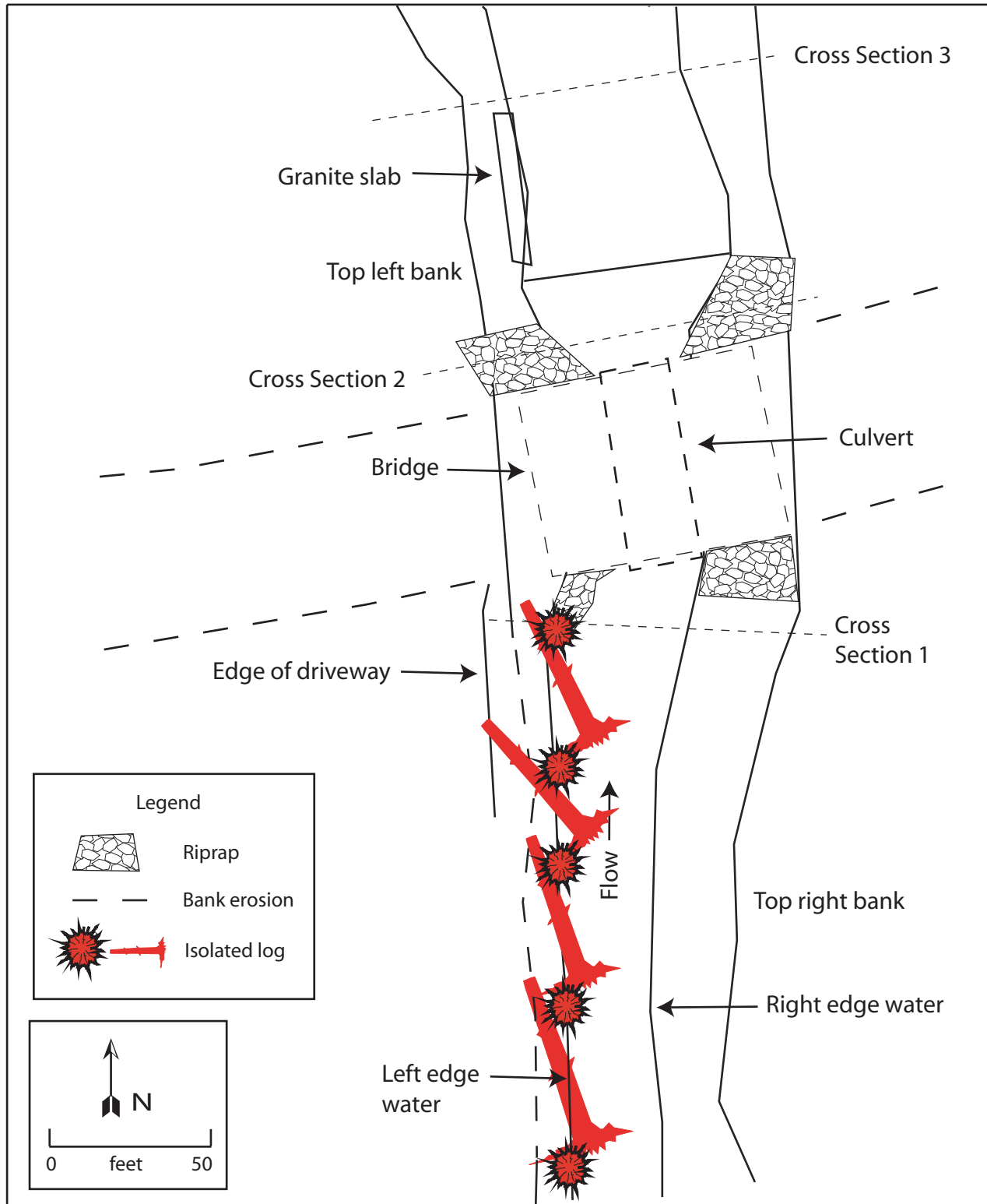
Cross Section 5: Downstream view



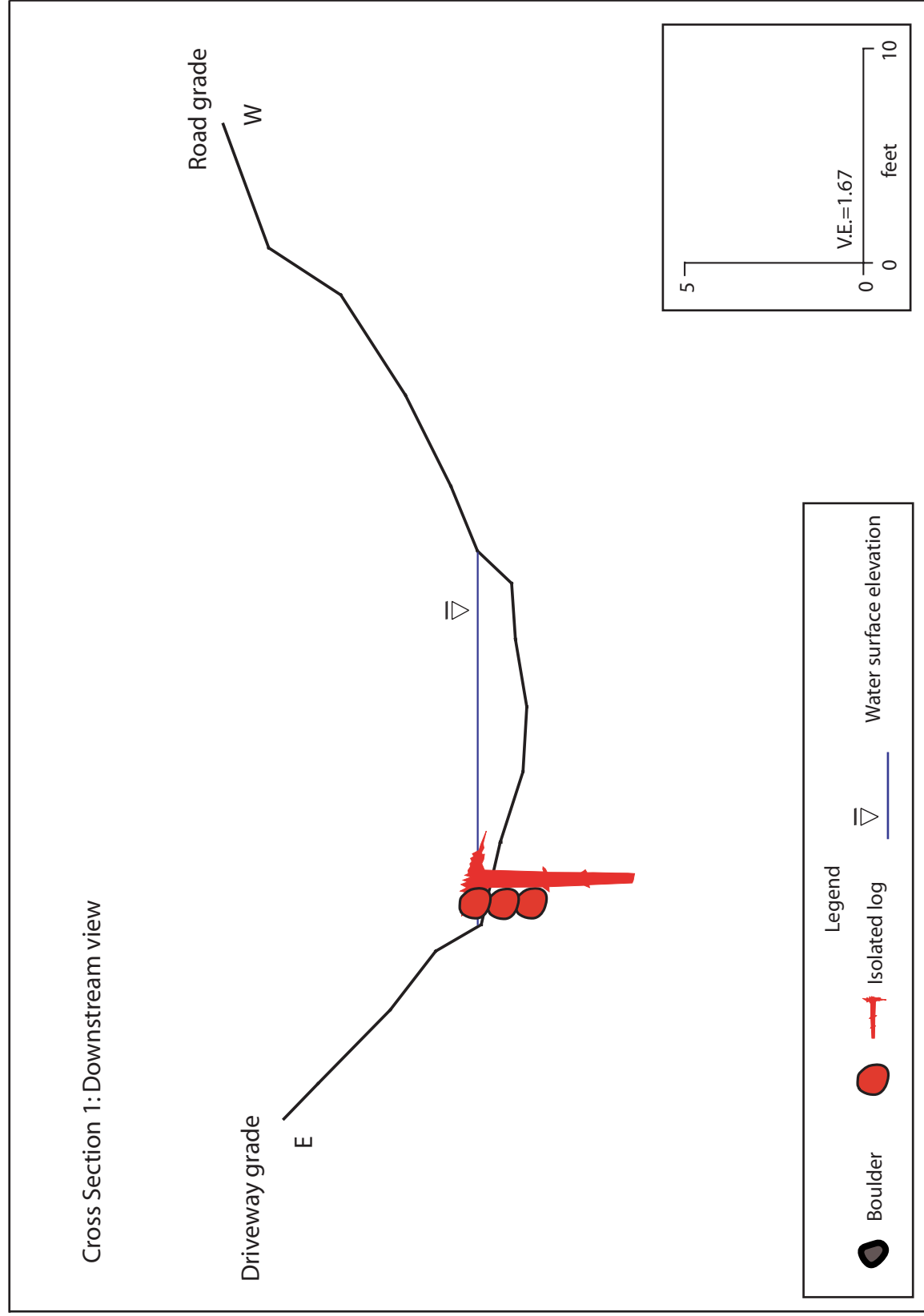
Cross Section 6: Downstream view



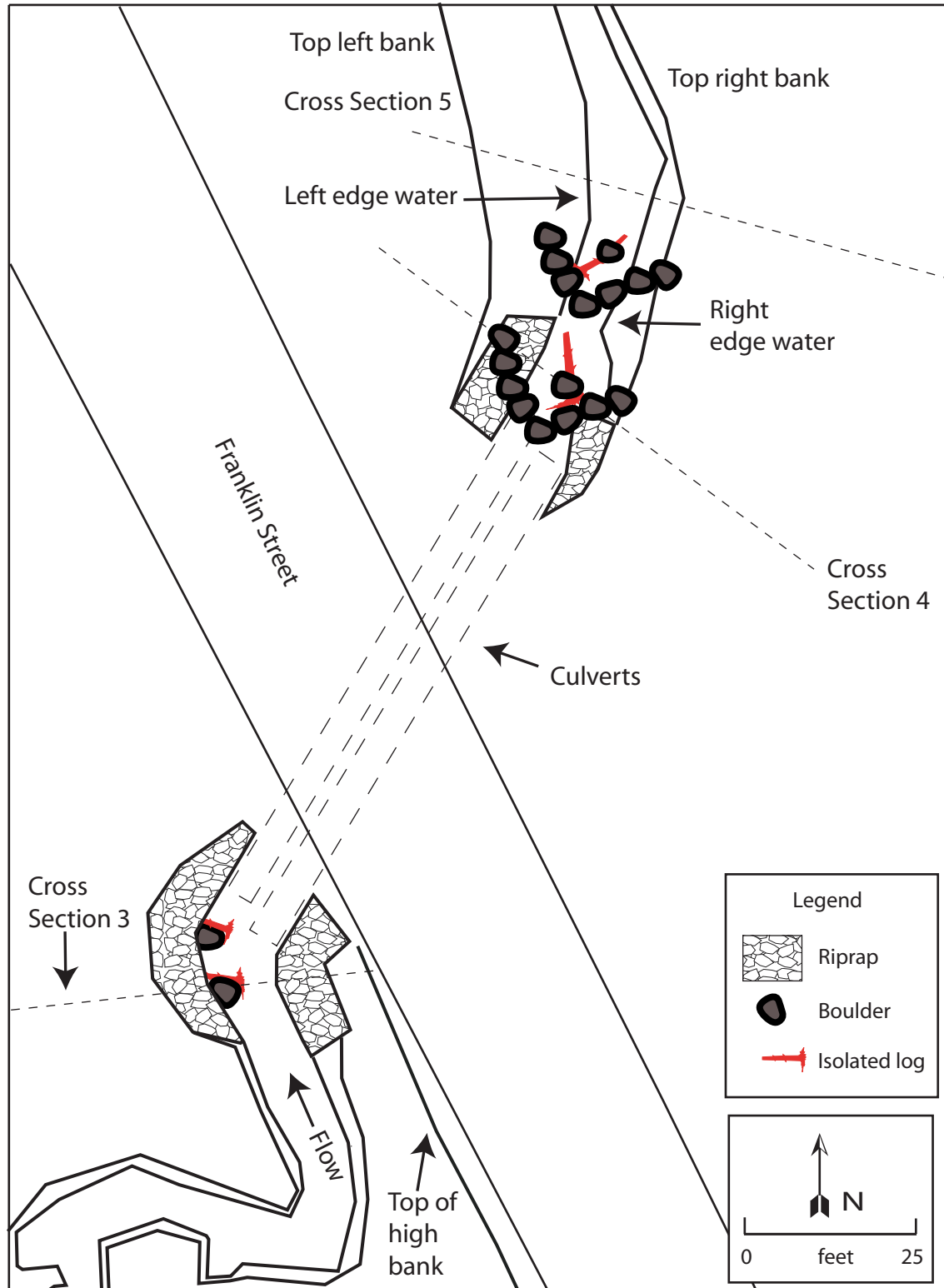
Appendix 8. Conceptual habitat mitigation design cross sections for Pearce Brook culvert.



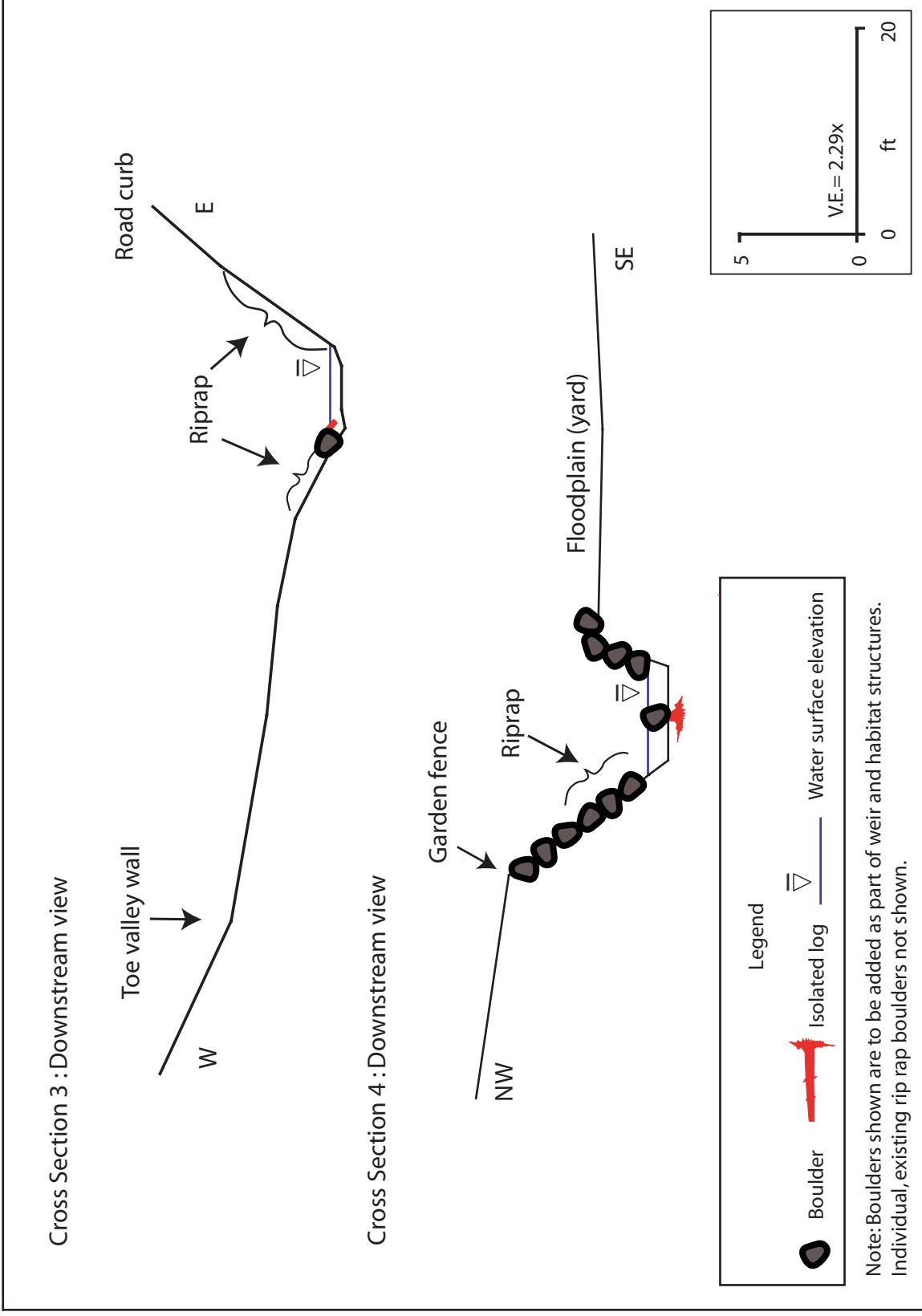
Appendix 8. Conceptual habitat mitigation design plan view for Green Street culvert.



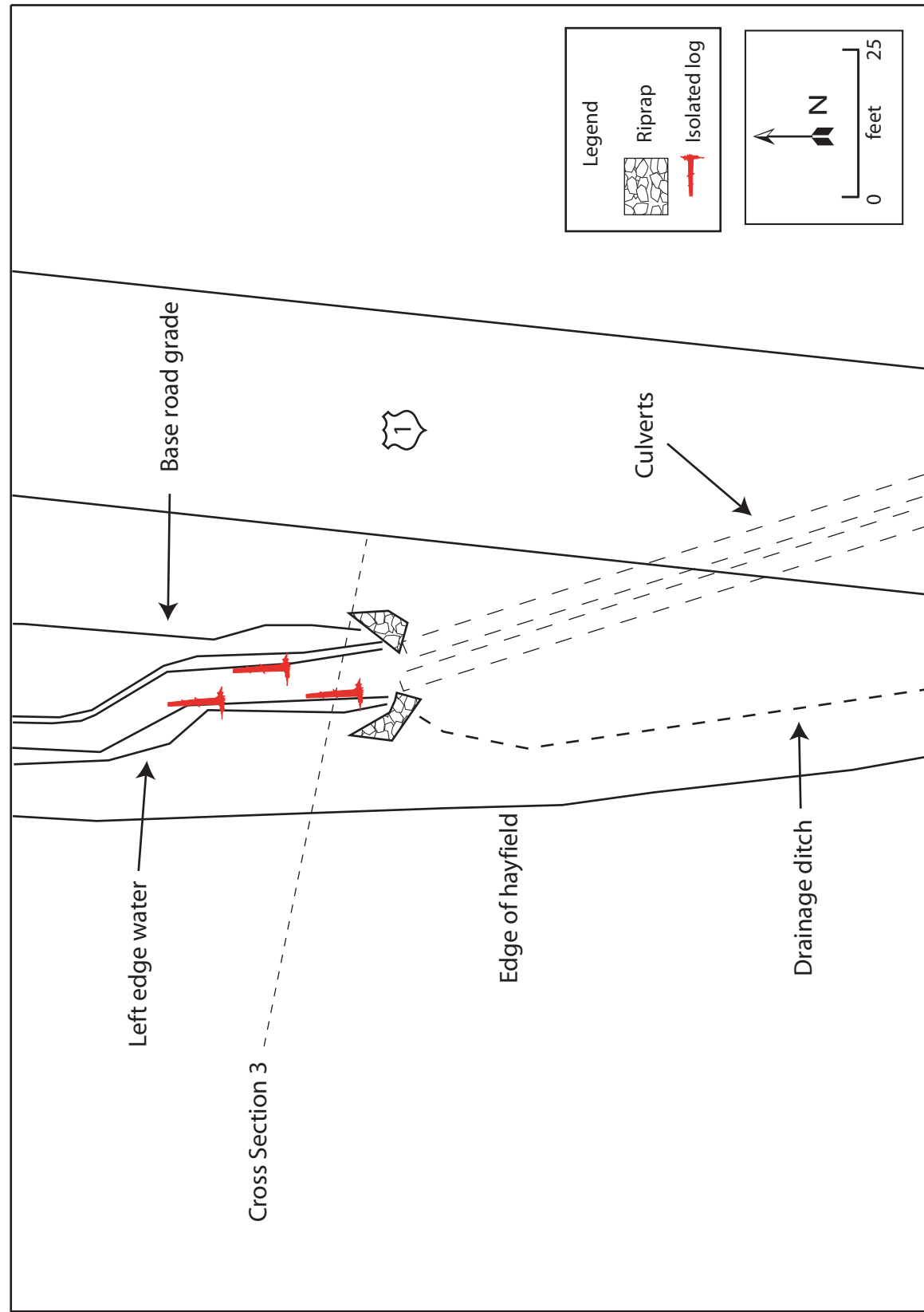
Appendix 8. Conceptual habitat mitigation design cross section for Green Street culvert.



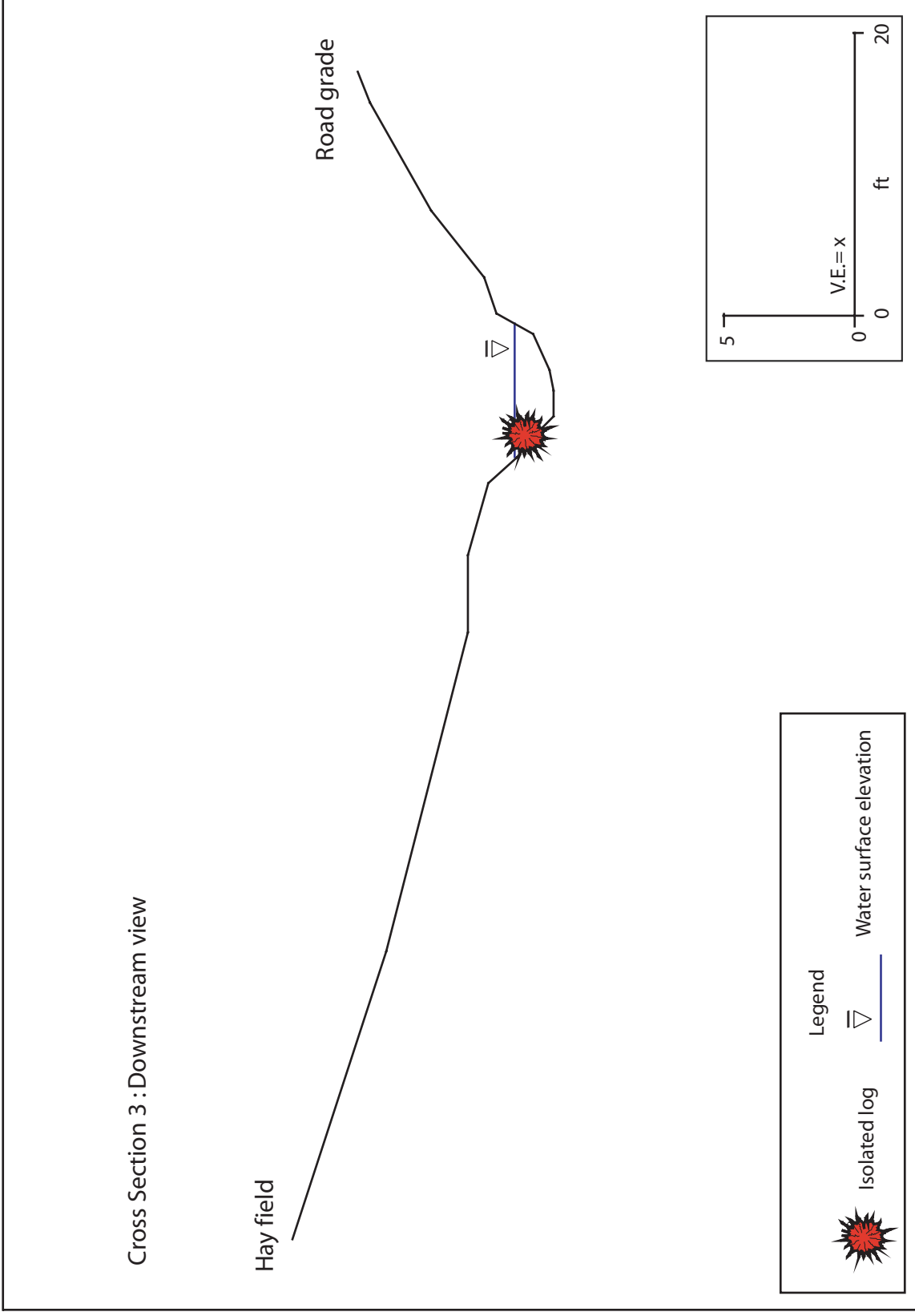
Appendix 8. Conceptual habitat mitigation design plan view for Brown Brook culvert 2.



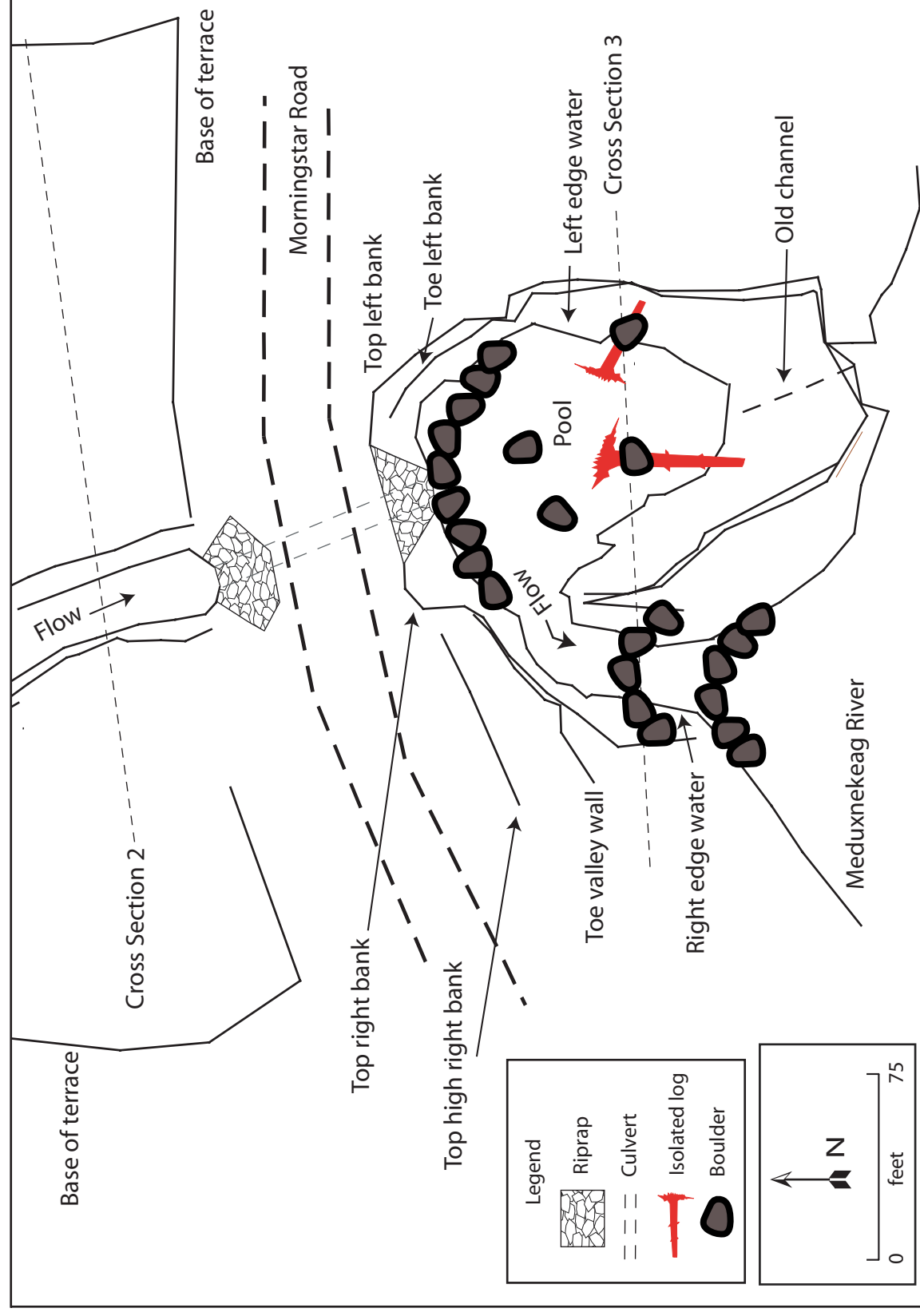
Appendix 8. Conceptual habitat mitigation design cross sections for Brown Brook culvert 2.



Appendix 8. Conceptual habitat mitigation design plan view for Brown Brook culvert 3.

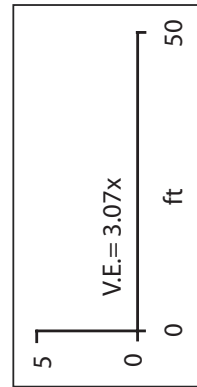
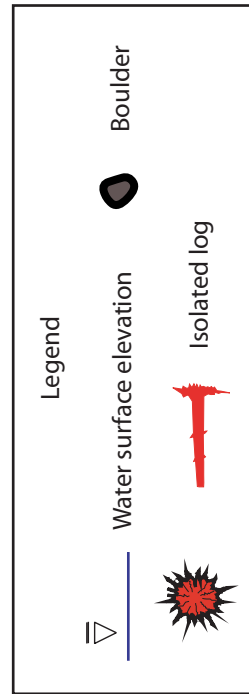
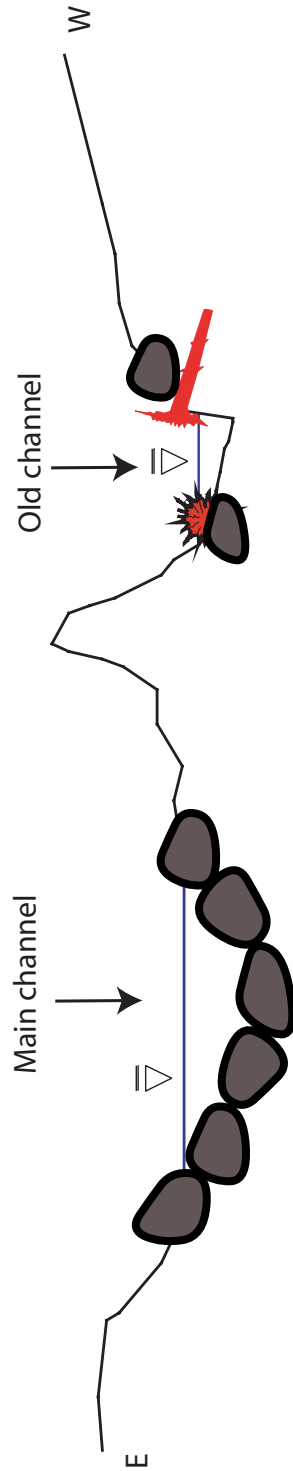


Appendix 8. Conceptual habitat mitigation design cross section for Brown Brook culvert 3.

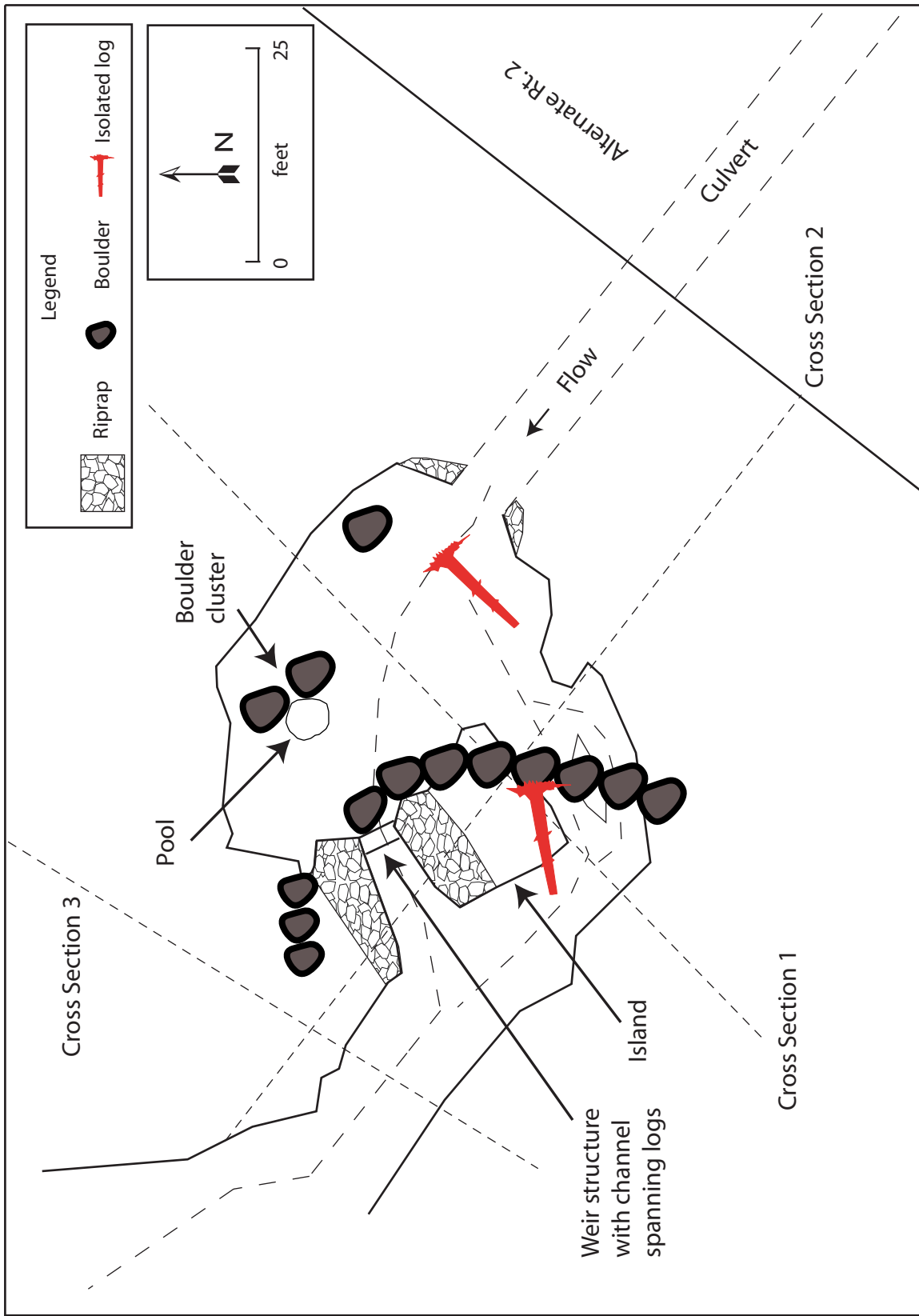


Appendix 8. Conceptual habitat mitigation design plan view for Moose Brook culvert.

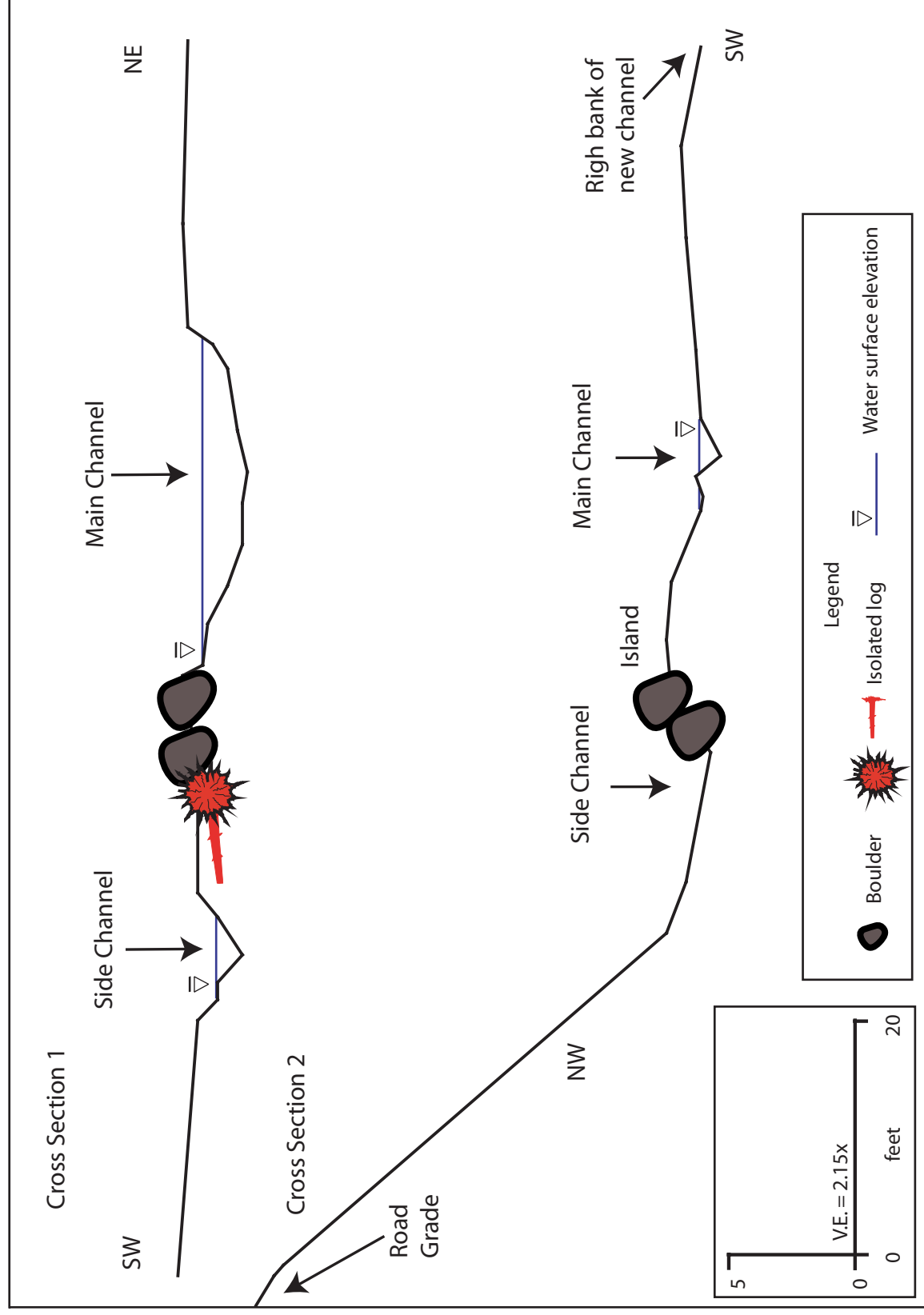
Cross Section 3 : Downstream view



Appendix 8. Conceptual habitat mitigation design cross section for Moose Brook culvert.



Appendix 8. Conceptual habitat mitigation design plan view for Bither Brook culvert.



Appendix 8. Conceptual habitat mitigation design cross sections for Bither Brook culvert.

Appendix 9

Ground Photographs of the Culvert Assessment Sites



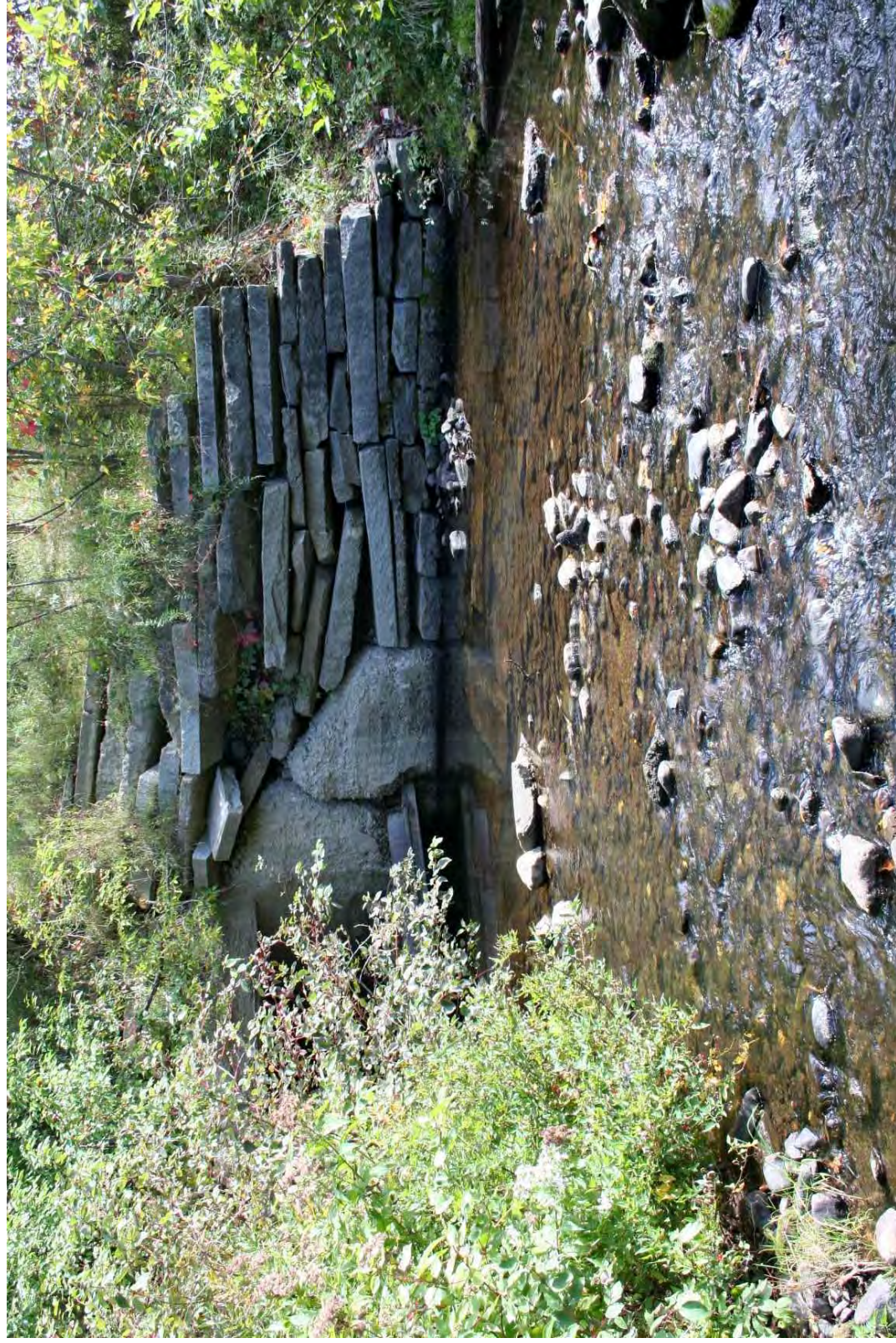
Appendix 9. Ground photograph of Suiter Brook 1.



Appendix 9. Ground photograph of Smith Brook.



Appendix 9. Ground photograph of Pearce Brook 2.



Appendix 9. Ground photograph of Pearce Brook 3.



Appendix 9. Ground photograph of Pearce Brook 4.



Appendix 9. Ground photograph of Brown Brook 2.



Appendix 9. Ground photograph of Brown Brook 3.



Appendix 9. Ground photograph of Moose Brook 1.



Appendix 9. Ground photograph of Moose Brook 2.



Appendix 9. Ground photograph of Bither Brook.