GEOMORPHIC EFFECTS AND HABITAT IMPACTS OF LARGE WOOD AT RESTORATION SITES IN NEW ENGLAND

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Large wood (used interchangeably with the term "instream wood"), which refers to trees, logs and other wood within a channel, is beneficial to river ecosystems and is being used more frequently as a component of river restoration projects. The process of large wood becoming stable within a river channel, inducing floodplain formation, and eventually providing large wood back to the system is known as the 'floodplain large-wood cycle' hypothesis (Collins et al., 2012). In a stream restoration context, this process can be viewed as an indicator of a self-sustaining cycle.

The 'floodplain large-wood cycle' hypothesis was formulated in the Pacific Northwest. To investigate this process in other regions, I used the Merrimack Village Dam (MVD) study site in southern New Hampshire. The study site provided a location where instream wood was recruited to the river from an adjacent terrace as a consequence of erosion associated with a dam removal. Assessment of wood in this scenario was used to evaluate the 'floodplain large-wood cycle' (Collins et al., 2012), and to compare MVD to "passive" large wood restoration and deliberate, and potentially engineered, large wood restoration sites throughout New England.

To assess multiple sites, I identified metrics to evaluate the effectiveness of large wood to promote ecological and geomorphic complexity within channels. The metrics were quantified at the MVD site and several other sites in New England with natural or

placed large wood. I also collected additional data at the MVD site using methods implemented during previous studies, including cross section surveys and repeat photographs (Collins et al., 2017; Pearson et al., 2011).

The study assessed habitat and geomorphic effects of large wood within river systems in the northeastern U.S. and provided information to evaluate the use of large wood during river restoration. Overall, only 33%, 33%, and 20% of surveyed sites are consistent with hypotheses formulated regarding significant differences in depth variability, velocity variability, and median velocity between test and reference reaches, respectively. With evidence for and against each hypothesis at both passive and active sites, large wood structures did not cause the geomorphic and hydraulic changes I expected to see. The availability of sand in a channel and the stream slope influencing sediment transport seem to be important factors in determining whether or not large wood has the ability to impact the geomorphic and hydraulic characteristics of a channel. At the MVD site, where sand is available, up to 0.90 m of sediment deposition is seen on top of the surface eroded by a March 2010 flood, surrounding recruited trees. Evaluation of historical aerial imagery further indicates that evidence of the 'floodplain large-wood cycle' hypothesis is present at the MVD06 cross section on the Souhegan River in New Hampshire.

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1. Introduction

The role of large wood in river systems has been increasingly studied within the field of fluvial geomorphology. Instream wood affects flow patterns and sediment storage, which creates channel and floodplain complexity, and in turn provides diverse habitats for aquatic and riparian species (Abbe and Montgomery, 1996; Wohl and Scott, 2017). For aquatic species such as salmon, instream wood provides protection from predators, as well as temperature and nutrient benefits. In many natural systems large wood recruitment to rivers can be a self-sustaining cycle known as the 'floodplain large-wood cycle' (Collins et al., 2012). In this cycle, when large wood recruited from floodplains becomes stable, meaning the wood resists re-entrainment by the river (Collins et al., 2012), a logjam can accumulate enough sediment around it over time to form an instream island that can provide habitat and support vegetation growth, and may eventually be integrated into an adjacent floodplain (Figure 1). Trees that grow on the new landform can eventually supply more large wood to the river corridor, via river migration and bank erosion, leading to a recurring cycle. Once instream wood was recognized as an essential component of many fluvial systems, restoration practitioners began deliberately incorporating logjams into engineered channel sections to inhibit or induce bank erosion, create channel pattern diversity, and foster productive ecological and biological functions (Abbe and Brooks, 2013).

Many times, river restoration is done in response to anthropogenic influences, and aims to return the river to a more natural state. The practice of river restoration relates to the modification of river corridors and inputs such as water and sediment (Wohl et al., 2015). Some common goals of river restoration include bank stabilization, fish passage,

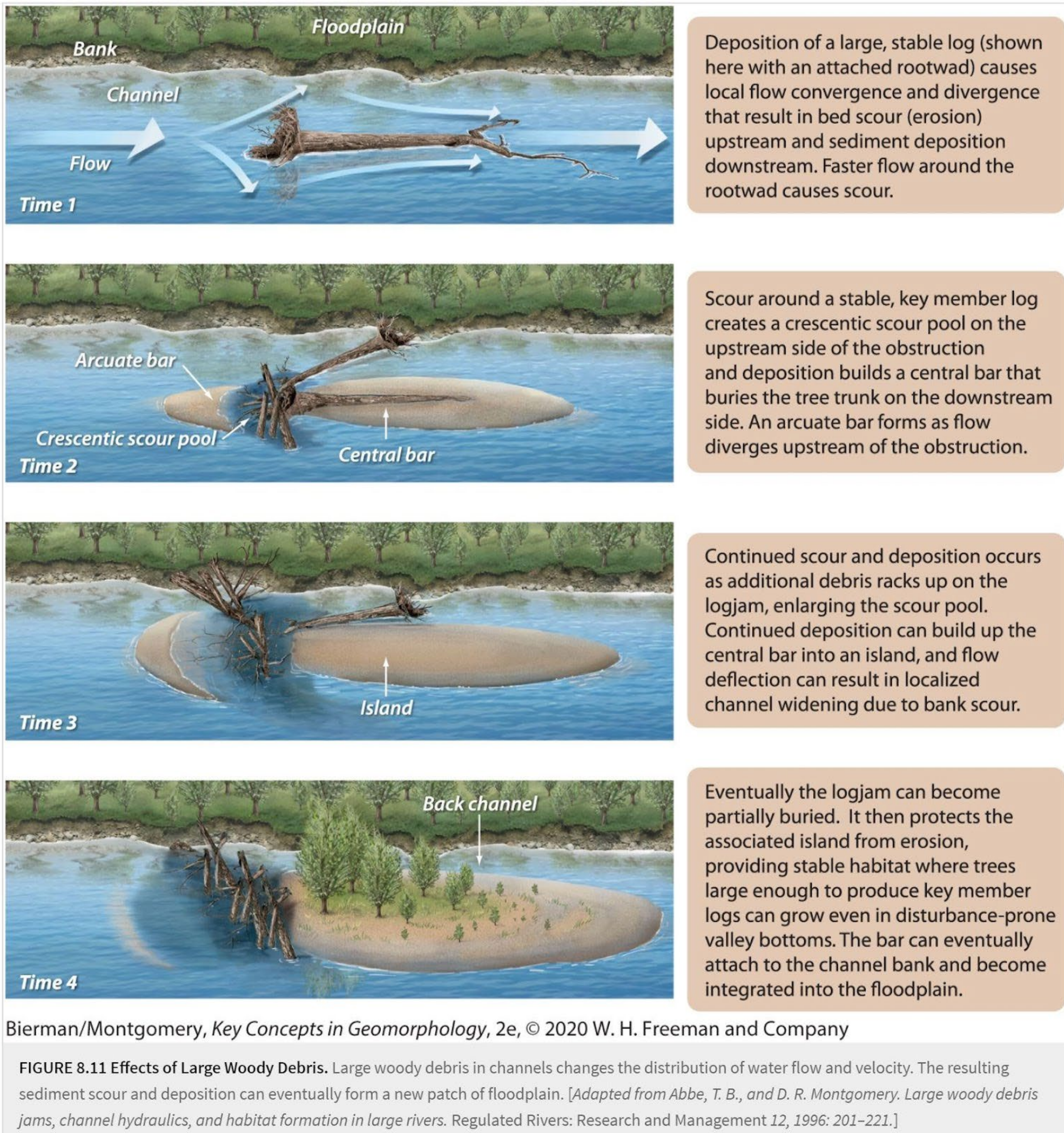


Figure 1. The process of large wood enabling floodplain formation (from Bierman and Montgomery, 2020).

barrier removal, and instream habitat improvement (Wohl et al., 2015). More recently, restorations have shifted toward a process-based approach, such as floodplain reconnection, rather than focusing efforts on channel form (Beechie et al., 2010).

Most previous studies about large wood in river systems focus on biomes of the Pacific Northwest and Intermountain West Regions of the United States (e.g., Washington, Oregon, and Colorado; Swanson et al., 1976; Collins and Montgomery, 2002; Wohl and Beckman, 2014; Wohl et al., 2018). With large wood increasingly being used in New England, it is important to investigate whether or not placing wood loads within channels for restoration purposes is achieving the objectives of restoration practitioners. Persistent concerns with restoration practice already exist, including the difficulty in quantifying the success or failure of some restoration objectives (Wohl et al., 2015). Research that has been done on large wood is hindered by the lack of commonly applied metrics to enable straightforward comparisons between studies (Wohl et al., 2010). For restoration projects employing large wood, it is critical to identify the restoration objectives associated with the large wood and choose metrics that can be used to assess the effectiveness of the wood for achieving those objectives. Metrics should be clear and quantifiable and be applicable at the necessary scale.

To focus on the implications of instream wood for river restoration and the role that wood can play in establishing a floodplain, I used the site of a previous dam removal as a case study (Figure 2). In 2008, the Merrimack Village Dam (MVD) was removed from the Souhegan River in southern New Hampshire (Collins et al., 2017; Pearson et al., 2011). Conditions at the site while the dam was in place promoted growth of white pine trees along the edge of the impoundment. As the river responded to dam removal,

Figure 2. An aerial photograph of the Merrimack Village Dam study site location (Google Earth, 2019). The red star is adjacent to a location on the Souhegan River where instream wood has gathered. The Souhegan river flows from southwest to northeast into the Merrimack River. The Merrimack River is shown along the eastern edge of the photograph, flowing from north to south.

impoundment banks eroded, causing several trees to lose stability and topple into the channel. The MVD site presented a scenario where several pieces of large wood act together to influence river morphology.

The MVD site also provided a unique opportunity to compare incidental, or "passive", restoration of large wood at a restoration site to one or more sites where large wood has been deliberately placed within river corridors. In order to assess the wood performance at the MVD site and compare it with other sites, I developed a set of metrics suitable for evaluating the effectiveness of wood for achieving associated restoration objectives.

1.1. Objectives

The objective of my study is to evaluate the geomorphic and habitat impacts of large wood in river systems comparing intentionally placed wood with wood that was passively derived. I used the MVD site, as well as other sites containing instream wood, to evaluate the following questions:

- Has the instream wood at the MVD site created a fluvial landform that is consistent with the 'floodplain large-wood cycle' hypothesis (Collins et al., 2012)?
- Do metrics used to evaluate the effectiveness of intentionally placed wood for achieving restoration project goals show variability at active and passive restoration sites between impacted (i.e., test) areas and adjacent control areas? Do active and passive sites vary in their effectiveness?

1.2. Literature Review and Hypotheses

I reviewed scientific literature (e.g., Abbe and Brooks, 2013; Armstrong et al., 2003; Scott et al., 2019; Wilkins and Snyder, 2011; Wohl et al., 2010) and manuals (e.g., USBR & ERDC, 2016) to compile a large set of metrics that can potentially be used to evaluate the effectiveness of large wood in passive and active restorations (Appendix A). I then collaborated with salmon biologists and restoration practitioners who implemented the active restorations to understand their restoration goals and objectives, and mutually identify appropriate fish habitat effectiveness measures. The metrics we agreed upon were then quantified at field sites throughout New England (Table 1). From the metrics, I generated a series of hypotheses that were evaluated (Table 2):

- H1) There is evidence of the 'floodplain large-wood cycle' hypothesis at MVD cross section MVD06.
- H2) When compared to river reaches without large wood (reference reach), reaches with large wood (test reach) have:
    - H2a) more variable water depths
    - H2b) more variable velocities
    - H2c) lower velocities
    - H2d) more variable sediment grain sizes
    - H2e) greater cover ratios

As large wood becomes stable within the channel, flow deflection and scour create pools beneficial to fish in some areas around the wood and enable the deposition of sediment in other areas (H2a; Abbe and Montgomery, 2003). I hypothesized that (H2b, H2c) water velocities would be more variable in river reaches containing large wood, with velocities higher where flow was deflected around wood, and lower downstream of wood inhibiting flow. As a result of flow diversion, scour would occur upstream of rootwads, large wood, and logjams that extended down to the riverbed, and where water was deflected beneath wood. Additionally, (H2d) I expected a greater variety of grain sizes would occur in reaches with large wood. Coarser sediments would be present directly upstream and to the sides of large wood structures that deflect flow. Areas downstream of wood should have lower amounts of shear stress, resulting in finer grained sediments and elevated sediment bars. As a consequence of scour and bar formation, (H2a) reaches containing large wood would have greater water depth variability than those without wood.

Cover and shade provided by submerged structures, turbulent water surfaces, vegetation and undercut banks are important components for ideal Atlantic salmon habitat as they provide protection from predators and help to maintain cooler water temperatures (Nislow et al., 1999). I hypothesized that (H2e) reaches containing large wood would provide more cover.

Table 1. Modes of quantifying ecogeomorphic metrics for evaluating large wood effectiveness.

Metric	Measurement	Mode
Large wood piece	Diameter	Tape
	Root wad dimensions	Tape
	Length	sUAS
	Orientation	sUAS
Logjam	Dimensions	sUAS
	Wood load per channel reach	sUAS
Scour	Number of pools	Field count
	Residual pool depth	Elevation survey (auto level)
Sediment	Dominant grain sizes	Visual estimate
	Deposition height, measured below or above the water surface	Elevation survey (auto level)
Cover	Ratio of reach water surface covered and reach width	sUAS
Velocity	Cross sections	Flow meter
	Flow deflection	Visual observations
Channel geometry	Bankfull depth	Elevation survey (auto level)
	Bankfull width	Tape
	Channel slope	lidar
	Drainage area	USGS StreamStats

Table 2. Methods for testing hypotheses for the 'floodplain large-wood cycle' and specific ecogeomorphic metrics.

Metric	Hypothesis	Test Method
'Floodplain Large-Wood Cycle' Hypothesis	Evidence of the hypothesis at MVD cross section MVD06 (H1)	• Deposition quantification from repeat surveys • Determination of timeline of events via sUAS imagery, historical aerial imagery, and repeat photography at photo points
Scour/ Channel geometry	Greater water depth variability in test reaches (H2a)	• Rank-sum (RS) and Fligner-Killeen (FK) tests for comparing test reach vs. reference reach data
Water velocity	More variable (H2b), and lower (H2c) in test reaches	• RS and FK tests comparing test reach vs. reference reach data
Sediment	Larger variety of grain sizes in test reaches (H2d)	• Organize visual estimates into categories and create plots to display substrate results against channel geometry • Qualitatively identify any associations
Cover	More cover provided in test reaches (H2e)	• Use sUAS aerial photographs to calculate cover at each cross section • Qualitatively identify any associations

2. Methods

2.1. MVD Repeat Channel Surveys

I repeated data collection methods used in previous surveys of the MVD study site (Collins et al., 2017; Pearson et al., 2011). Techniques for the surveys of the channel cross sections and repeat photographs were described by Pearson et al. (2011). A total station with a built-in global positioning system (GPS) unit (mm-scale relative accuracy) was used along with a reflecting prism on a telescoping pole to complete the surveys. Total stations have the ability to determine x, y, and z coordinates, also referred to as latitude, longitude, and elevation, of survey points chosen during field measurements. The survey component included repeating the same cross sections used in prior surveys at this study area (Figure 3; Pearson et al., 2011). Survey points were taken approximately every 2 m unless significant changes in slope, geomorphology, or substrate necessitated more frequent sampling. For points within the river, water depth was measured with the prism pole.

During previous surveys at the MVD site, ground level photographs were taken on both sides of the river at each cross section looking upstream, downstream, and across the river (Pearson et al., 2011). I used the same method and photo point locations for the surveys. Comparing photographs to those from earlier field work provided beneficial information about how the river corridor has changed over time. A particular focus was evaluating when large wood fell into the channel and how areas around the wood have evolved over time. Images showing sediment deposition and vegetation growth through the years were compared to the progression expected during the 'floodplain large-wood cycle' hypothesis. Establishment of vegetation on sediment accumulation around large

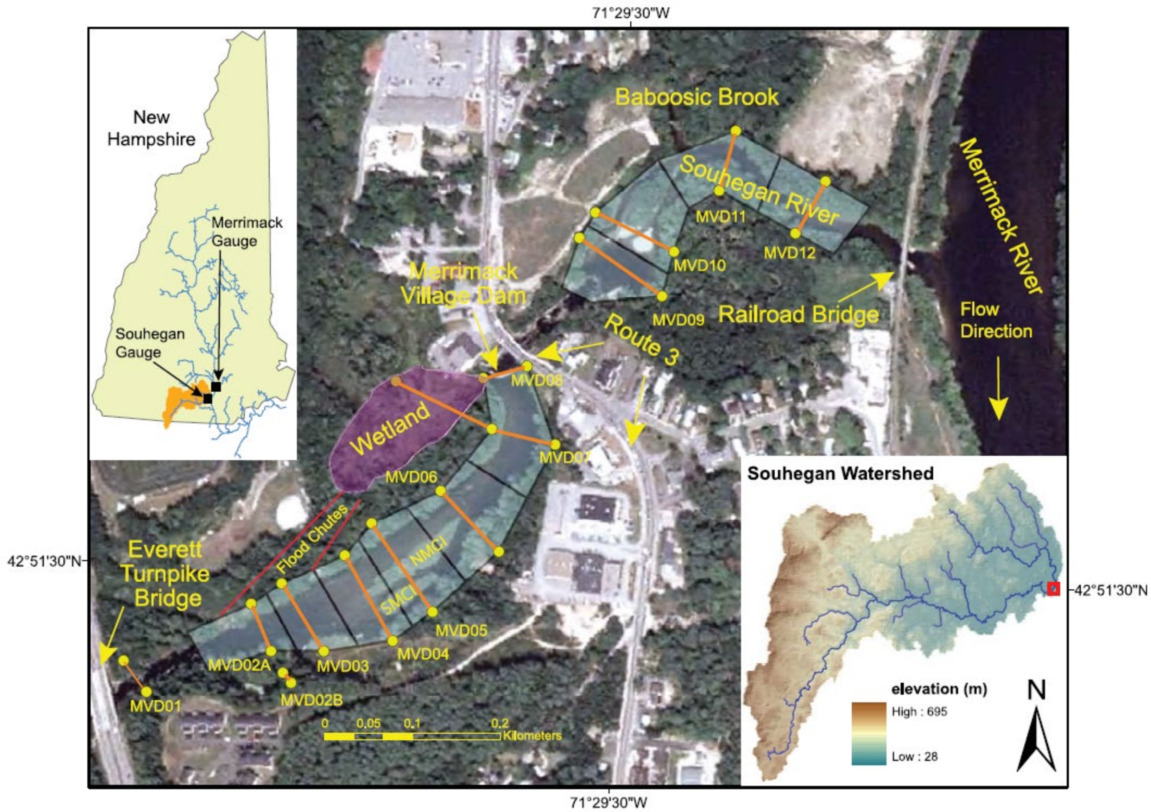


Figure 3. MVD study site location and survey cross sections shown with an aerial photograph (2003; from Pearson et al., 2011). Cross sections were installed during the summer of 2007. Insets display watershed and gauge station locations within New Hampshire (top left) and elevations within the watershed (datum: NAVD 88) where the site is boxed in red (bottom right). Cross sections are shown as orange lines, with yellow pins. Souhegan River flow direction is from MVD01 to MVD12. Translucent blue areas outlined in black represent areas associated with each cross section. The off-channel wetland (purple) is displayed along with the flood chute outlined in red. NMCI and SMCI represent the north and south midchannel islands.

wood indicates that the wood has successfully provided protection to the developing floodplain (Abbe and Montgomery, 2003).

2.2. Measuring Geomorphic and Habitat Impacts of Large Wood

Field work was done during the summer of 2021 to evaluate the ecogeomorphic metrics (Table 1) that provide insight on processes resulting from the presence of large wood within river systems. The same set of metrics were quantified at the MVD study site where large wood is present within the channel and at all other sites throughout New England (Figure 4; Table 3). Each site included a reference reach (no active restoration or large wood present) and a test reach (actively placed or passively recruited large wood present).

To specifically evaluate locations where restoration goals involve Atlantic salmon habitats, I surveyed ten sites within the upper Narraguagus River watershed in Maine. I collaborated with a team at the University of Maine investigating macroinvertebrate response at the same sites to obtain complementary data to further understand biophysical linkages. Test reaches included either post-assisted log structures (PALS) or griphoist (GH) trees (Figure 5). PALS are several pieces of large wood secured in the channel by posts driven into the bed and twine. GH sites are those where trees were pulled into the river from a nearby bank.

Two restoration sites within Nash Stream in New Hampshire were also evaluated. There, restoration efforts positioned large wood so that part of the engineered logjams (ELJs) rested on the adjacent floodplain, while the other portion of the jams extended into the channel (Figure 6).

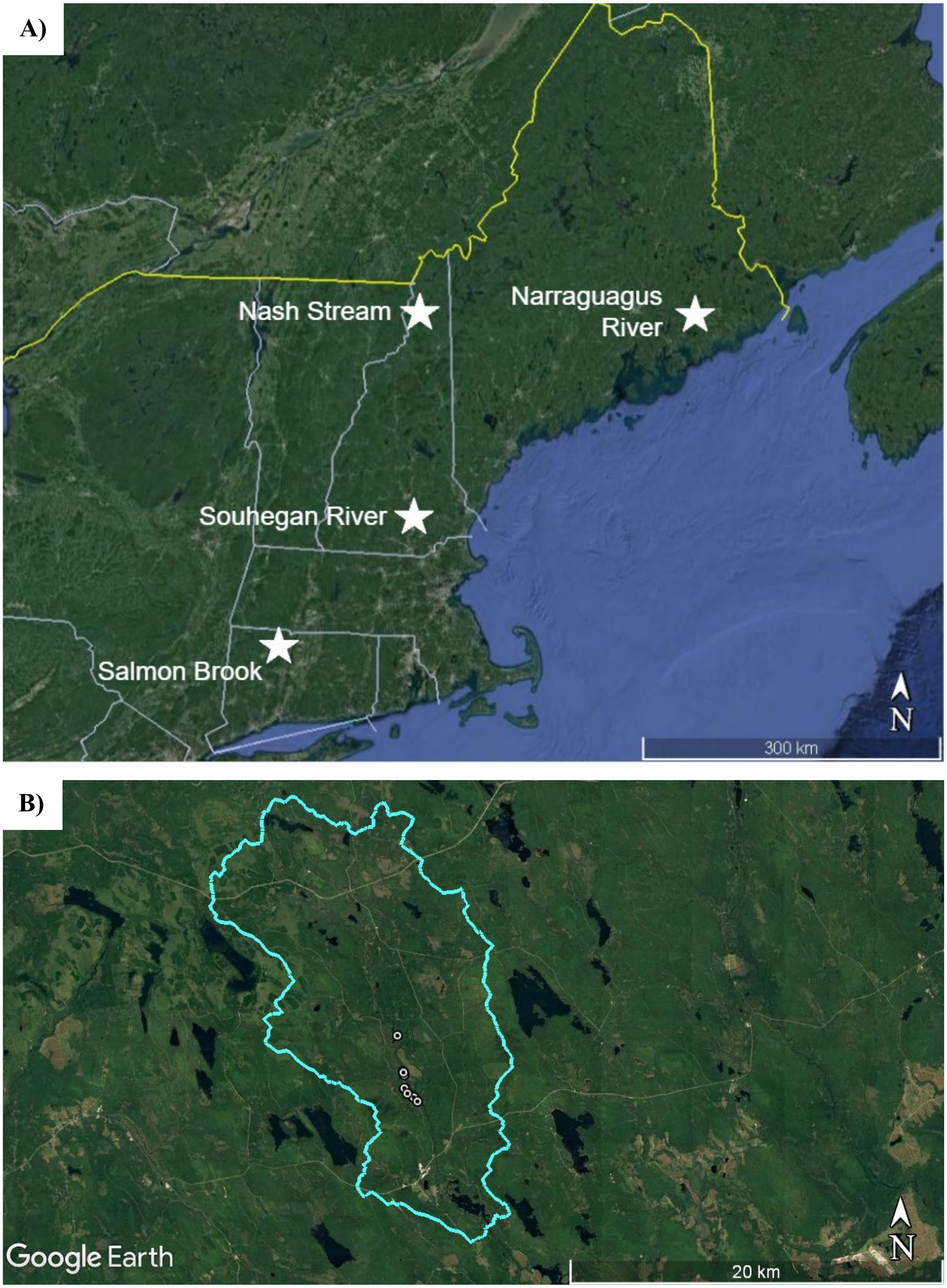


Figure 4. (A) Study sites throughout New England. (B) A closer view of the 10 sites (white dots) within the upper Narraguagus River watershed (cyan line). Due to the scale, some sites appear to overlap.

Table 3. (A) Characteristics and (B) list of sites assessed throughout New England.

A)

Waterway	Watershed (km^2)	Number of Sites	Site Type	Details	LW First Present
Narraguagus River	169	10	Active Restoration	5 PALS 5 Griphoist	2017-2020
Nash Stream	88	2	Active Restoration	2 ELJs	2012
Souhegan River	443	1	Passive Restoration	1 logjam	2010
Salmon Brook	53 50	2	Natural Recruitment	1 logjam; 1 large wood piece	Unknown; Prior to 2015

B)

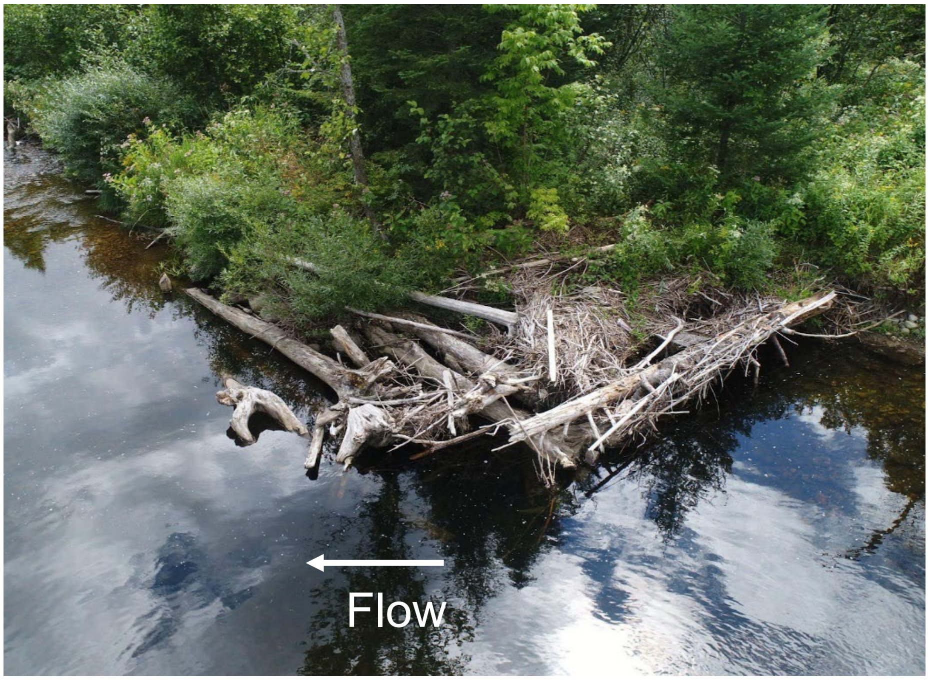
Waterway	Site Abbreviation	Site Details
Narraguagus River	28 P	28 Pond – GH
	ATV GH1	ATV Bridge – GH, most upstream
	ATV GH2	ATV Bridge – GH, upstream of the bridge
	ATV PALS	ATV Bridge – PALS, downstream of the bridge
	HL US	Humpback Landing – PALS, upstream
	HL DS	Humpback Landing – PALS, downstream
	HB PALS	Humpback Brook – PALS
	SB GH	Sinclair Brook – GH
	SB PALS	Sinclair Brook – PALS
	30-35 L GH	30-35 Landing – GH
Nash Stream	ELJ1	Engineered Logjam 1 – upstream
	ELJ2	Engineered Logjam 2 – downstream
Souhegan River	MVD06	MVD06 cross section at the MVD site
Salmon Brook	CP	Christensen's Pond
	SBP	Salmon Brook Park

A)

B)

Figure 5. Aerial photographs (sUAS) of two sites on the Narraguagus River in Maine. (A) Post-assisted log structure (PALS) sites include multiple pieces of large wood fixed together to posts driven into the bed, while (B) griphoist (GH) sites include one or multiple trees pulled into the river from a nearby bank.

A)



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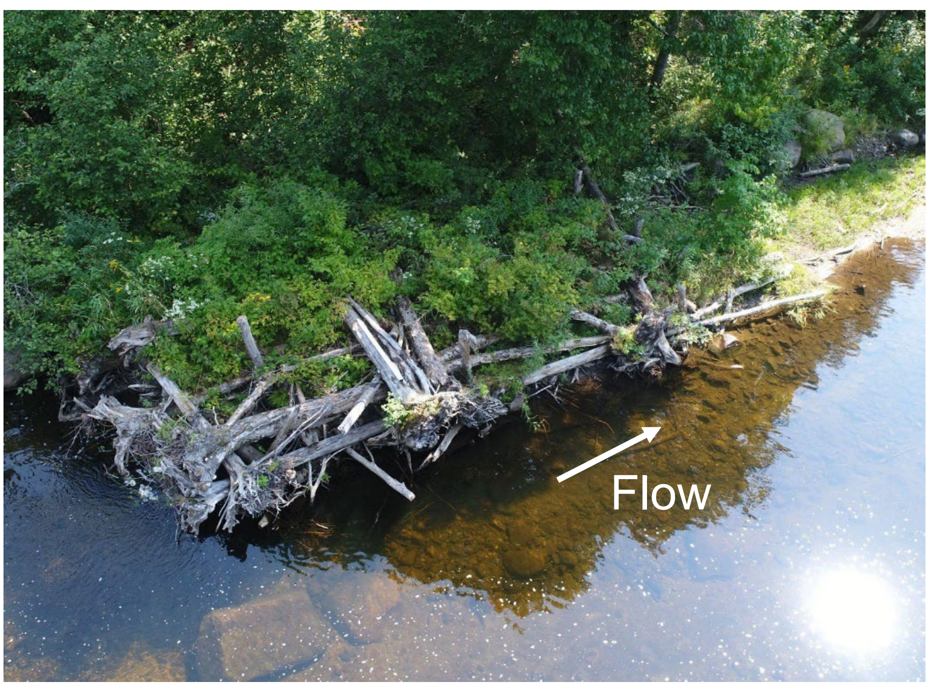


Figure 6. Aerial photographs (sUAS) of two engineered logjams (ELJs) assessed within Nash Stream in New Hampshire. During construction, sediment was placed on top of the ELJs by machinery to provide stability.

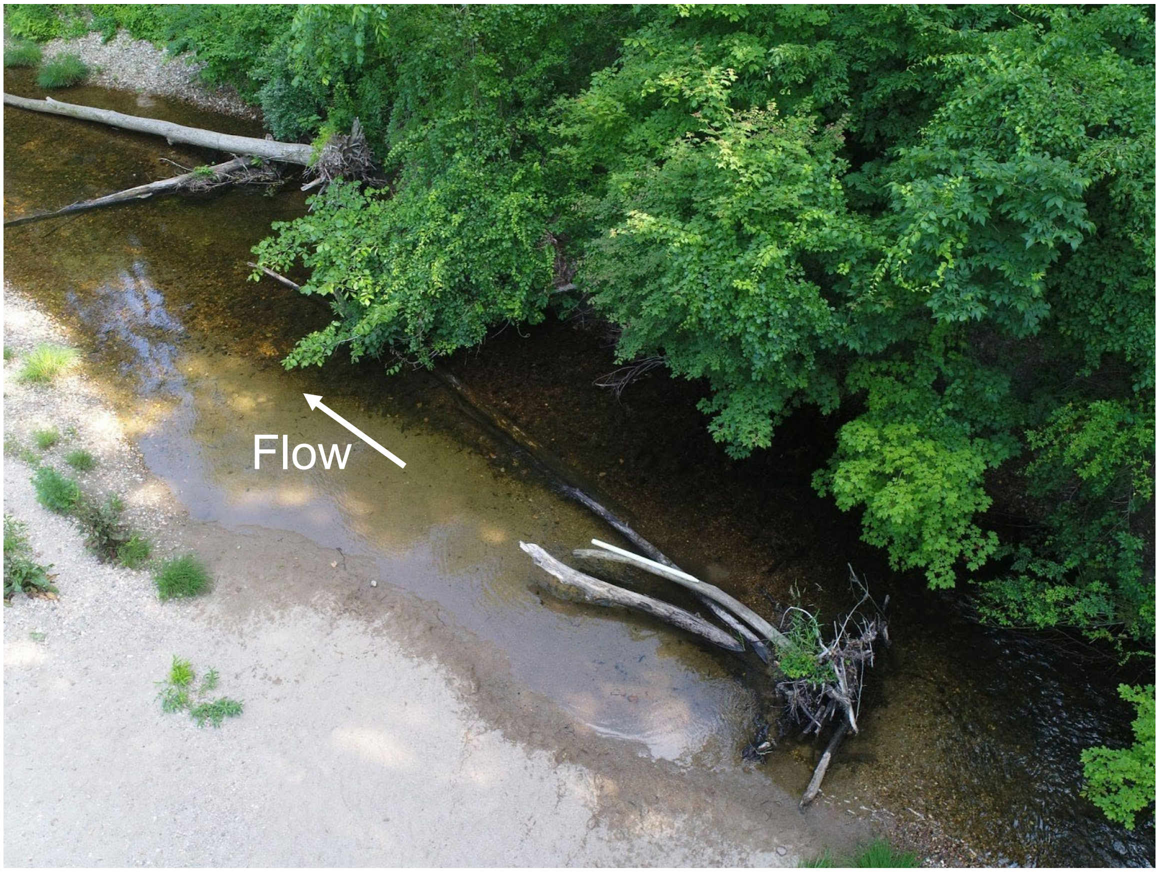


Figure 7. Large wood within the test reach at a field site on the Salmon Brook in Connecticut. Wood trunk is oriented parallel to flow with the rootwad situated upstream.

In Connecticut, I surveyed two sites on the Salmon Brook where wood was naturally recruited. One site contained a tree lying near the middle of the channel, oriented with the trunk parallel to flow and the rootwad facing upstream (Figure 7). The second site consisted of a large natural jam with multiple key pieces that together spanned the channel (not shown).

At each field site, a DJI Phantom 4 Advanced small uncrewed aircraft system (sUAS) captured photographs and videos that were later used to quantify some metrics (section 2.4.). Small uncrewed aircraft systems are battery-powered vehicles flown with the use of a remote control with a human operator. These systems have cameras attached that take photographs and videos during flight to ultimately meld multiple 2D images together to create a digital product displaying the surrounding landscape (Bierman and Montgomery, 2019). Structure from motion (SfM) is a process in which 2D images taken by a sUAS can be combined to create a 3D model and an orthomosaic image. For calibration purposes at each site, at least one piece of large wood was measured in the field, and a stadia rod was placed on top of that piece of wood before photographs were taken. sUAS aerial imagery that included a stadia rod and measured piece of large wood was scaled to the correct dimensions based on the object of known length.

All other metrics were field-measured. Around a logjam or individual wood piece, a tape was used to assess wood piece diameters, measured at both ends of the wood, where possible, to account for taper. If a rootwad was present, the width and height were measured, along with the length from the rootwad base to the farthest part of the bole (Wohl et al., 2010). Maximum logjam height was quantified using a stadia rod with an auto level referenced to a local benchmark. Research done on large wood generally establishes a specific length and diameter that instream wood must meet to be recorded during a study. These values vary between studies because the ability for a piece of large wood to become stable depends on channel geometry and expected water levels and discharge (Collins et al., 2012). For my research, I used a common threshold diameter and length of 10 cm and 1 m, respectively (Gurnell, 2013). A logjam was defined as three or more pieces of large wood touching. Sketches of each site were done to record information about specific wood pieces, orientation of wood pieces, flow divergence or convergence, deposition of sediment bars, and scour pools.

At all field locations, three cross sections were surveyed in the test reach and again in the reference reach to evaluate water depth, velocities, and substrate characteristics. Depths and substrates were recorded at 1 m intervals, while velocity measurements were recorded every 2 m across the channel (Figure 8). Velocities were measured with a Marsh-McBirney flow meter at a height above the bed equivalent to 0.4 times the total water depth (equivalent to 0.6 times the depth from the water surface; Figure 9). Substrate was estimated visually by looking down at, or grabbing, a sediment sample from the riverbed. The sample was described by the clast sizes present, in descending order of dominance. The visual estimates accounted for the following clast sizes: sand (<2 mm), gravel (2-64 mm), cobbles (64-256 mm), and boulders (>256 mm). Any vegetation, small wood pieces, organic matter, or algae present was also noted.

Additional quantitative measurements were taken around logjams. Hydraulic and geomorphic changes, such as flow deflection, sediment deposition, and scour, were visually observed and described. Flow deflection played an important role for sediment transport and formation of scour pools. As large wood becomes stable within the channel,

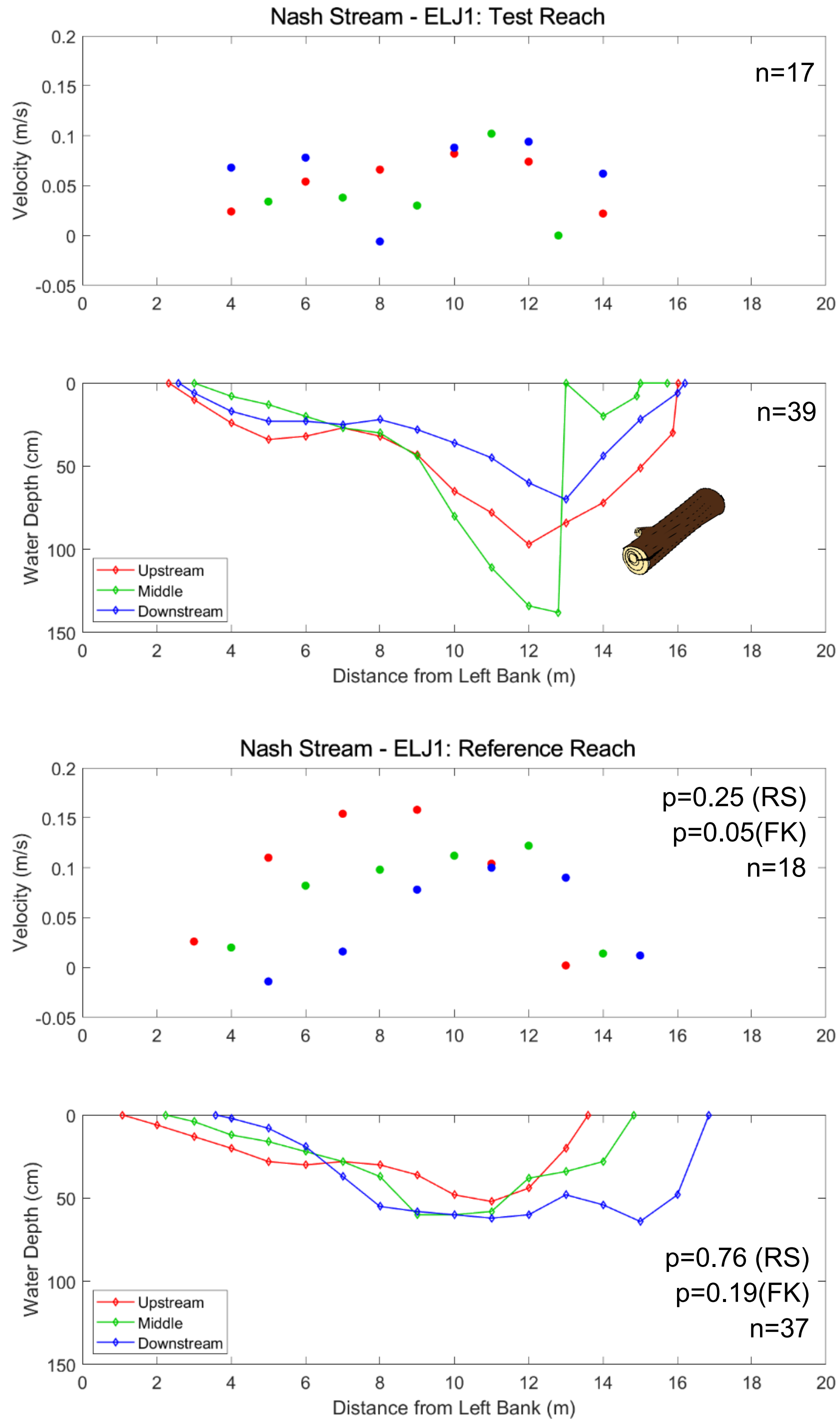


Figure 8. One example of plots that were produced to compare water depths and velocities between surveyed river reaches. The log represents the approximate location of wood placed in the test reach of the channel. Results from the rank-sum (RS) and Fligner-Killeen (FK) statistical tests to compare the medians and variances of depth and velocity data, respectively, between surveyed reaches are shown on the plot along with the number of data points in each sample.

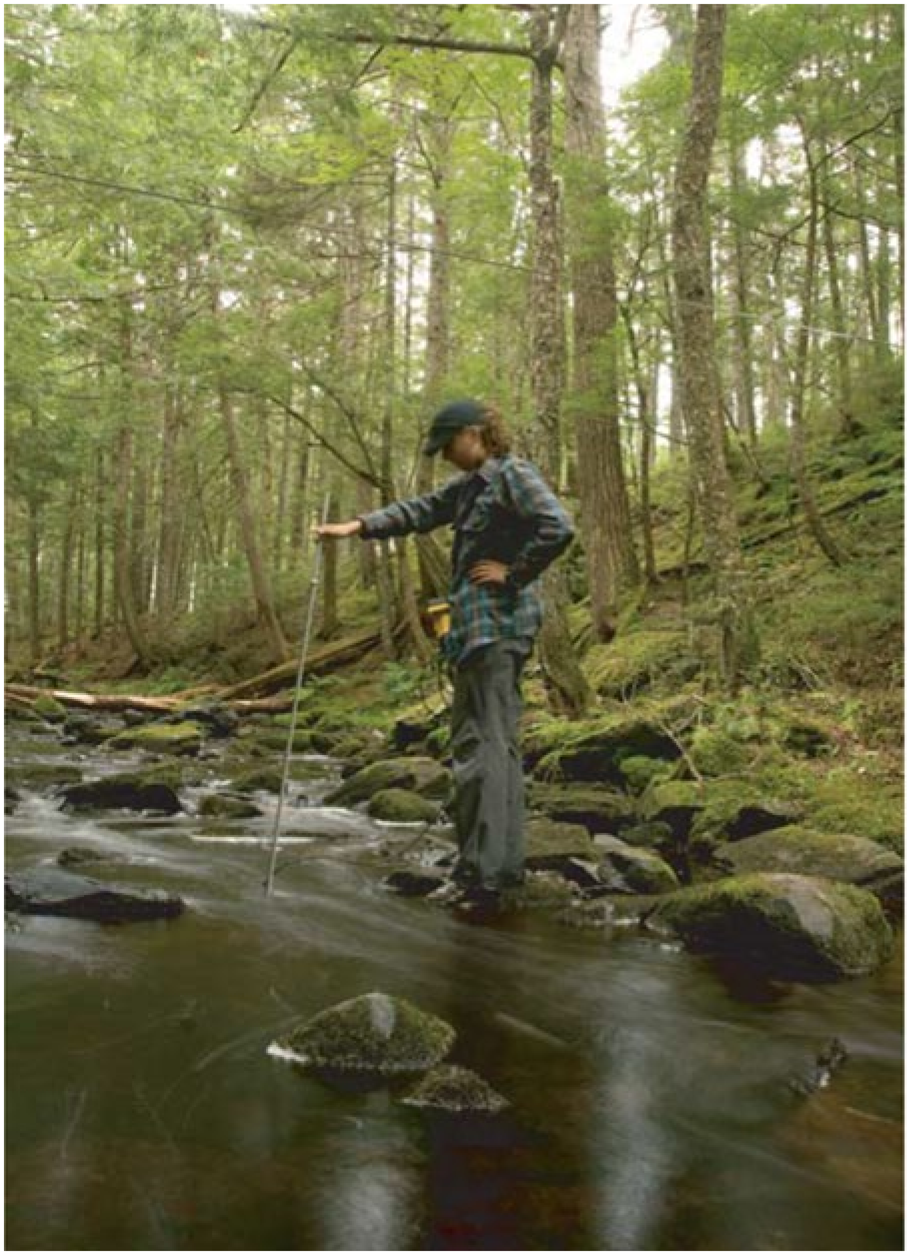


Figure 9. Liz Johnson performing velocity measurements using a Marsh-McBirney flow meter on Baker Brook in the Narraguagus River Watershed, ME (from Johnson, 2009).

flow deflection and scour create pools in some areas around instream wood and enable the deposition of sediment in others (Abbe and Montgomery, 2003). Pools offer habitat, and a combination of scour and sediment deposition around wood can provide protection and ultimately enable the formation of a floodplain (Collins et al., 2012).

Pools are an important component of suitable habitat for Atlantic salmon as they provide protection from predators, and viable spawning grounds (MacInnis et al., 2008). A method to quantify pool depth independent of discharge is to calculate the residual pool depth by subtracting the depth of the riffle crest just downstream of the pool from the total depth of the pool (Figure 10; Lisle, 1987). Where pools were present at my sites, I measured both residual depth and velocity in the deepest part of the pool and the downstream riffle crest. Measuring areas and frequencies of pools within a river can also provide beneficial data. Calculating the frequency of pools within a reach compared to the frequency of wood can provide indication about geomorphic effects of instream wood.

To investigate the 'floodplain large-wood cycle' hypothesis, evaluating sediment accumulation on top of large wood hard points, as well as grain sizes and elevation of surrounding sediment, is necessary (Collins et al., 2012). Grain size is also an important factor for ideal Atlantic salmon habitat (Armstrong et al., 2003, Wilkins and Snyder, 2011). To assess the effect of wood on grain size, recording the distribution of grain size upstream and downstream from large wood is useful (Wohl et al., 2010). For the scope of this thesis, sediment deposition around the wood was documented on the site sketch, described in terms of qualitative clast size distribution, and measured with a depth below or a height above the water surface.

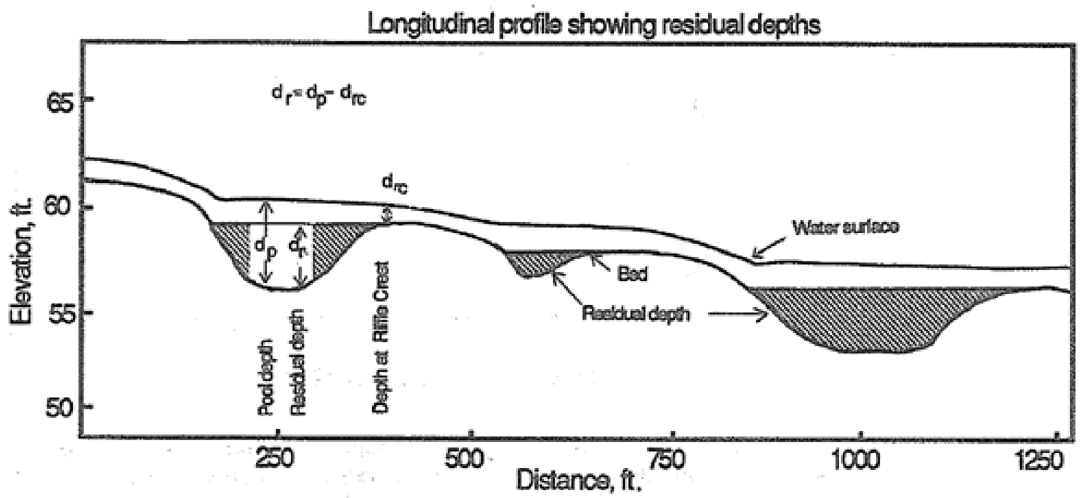


Figure 10. Schematic representation of residual pool depth measurements (from Lisle, 1987).

Field measurements related to channel geometry included bankfull width and depth. Bankfull width was identified as the point of separation between the active channel, characterized by unvegetated substrate or aquatic vegetation, and stable terrestrial vegetation or moss. Bankfull width was quantified by stretching a tape across the channel during each cross-section survey. An auto level with a reader attached to a stadia rod was used to determine water surface and bankfull heights in relation to a temporary benchmark. The auto level was also used to determine heights of sediment bars, wood pieces versus adjacent channel bed, and maximum logjam height.

2.3. Analyzing the 'Floodplain Large-Wood Cycle' Hypothesis at MVD

For each MVD cross section (Figure 3), new surveys of riverbed elevations measured during field work were brought into Microsoft Excel, and then analyzed using MATLAB to generate repeat cross section plots. At cross section MVD06 only, recent photographs were compared to those taken during past surveys, as well as Google Earth aerial images, to provide more information about how the channel and areas of large wood build up have changed over time. A timeline of events was then produced and used alongside the MVD06 repeat cross section plot to decide whether the instream wood is inducing floodplain formation. The MVD06 repeat cross section plot and aerial imagery from other sites surveyed during the summer of 2021 were then assessed to determine whether formation of islands or floodplain extensions are evident anywhere else.

2.4. Analyzing Geomorphic and Habitat Impacts of Large Wood

Photograph examination provided information about wood location and orientation within the channel, and photographs taken above the height of the canopy were analyzed in AutoCAD for calculations including the proportion of cover at each cross section, and wood load per channel area within each reach (Figures 11 and 12). Where aerial imagery analysis in AutoCAD was not applicable due to dense tree cover, jam dimensions and cover ratios were measured using 3D models of the site. SfM techniques were used in Agisoft Metashape software to convert the 2D images taken by the sUAS into 3D models. The SfM process entailed a workflow that uses pixel matching algorithms to generate point clouds from images that were then used to form a 3D model and an orthomosaic (a mosaic of several images combined into one continuous image; Figure 13; Lucy, 2015; Kim, 2018).

Cover and shade are important components for ideal Atlantic salmon habitat as they provide protection from predators and help to maintain cooler water temperatures (Nislow et al., 1999). Cover was assessed as a linear measurement two different ways at each reach. First, a percent of the channel covered by large wood (individual pieces or a logjam) was calculated. Along with that, a percent of the channel covered by any form of cover (vegetation on adjacent floodplains, a broken or turbulent water surface, the tree canopy, shade, or instream vegetation) was calculated. Because test and reference reach aerial photographs were taken at nearly the same time at a site, shade can be compared between test and reference reaches at a specific site, but not across sites. Considering shade in the calculation of cover may be problematic due to the possibility of shade changing throughout the days and between seasons. I did not monitor shade over multiple days or seasons, but within this study, shade did not appear to influence results significantly. At each site, sUAS aerial images were analyzed to determine the distance across the middle cross section within the test and the reference reaches that was covered

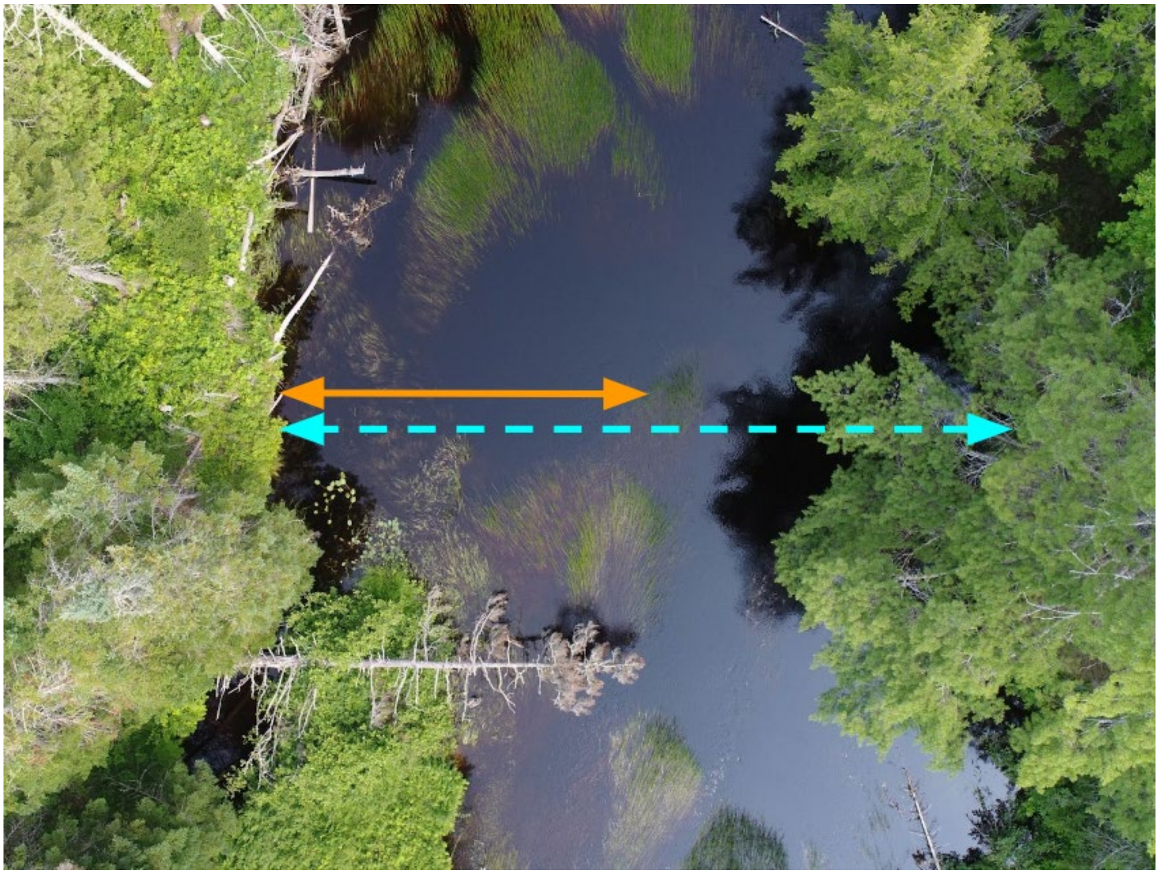


Figure 11. Graphic representation of the calculation for cover, using the portion of a cross section not covered by vegetation or wood (solid orange) versus total channel width measured in the field (dashed blue).

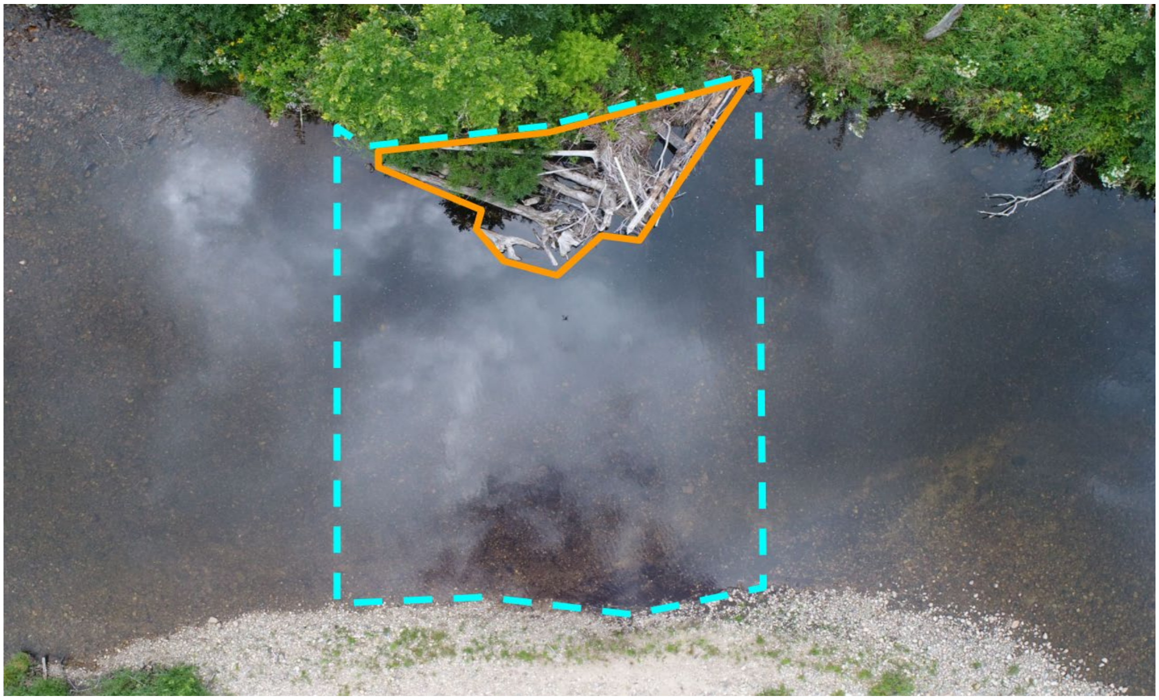


Figure 12. Aerial photograph (sUAS) showing the method for calculation of wood load area (solid orange) per channel reach area (dashed blue).

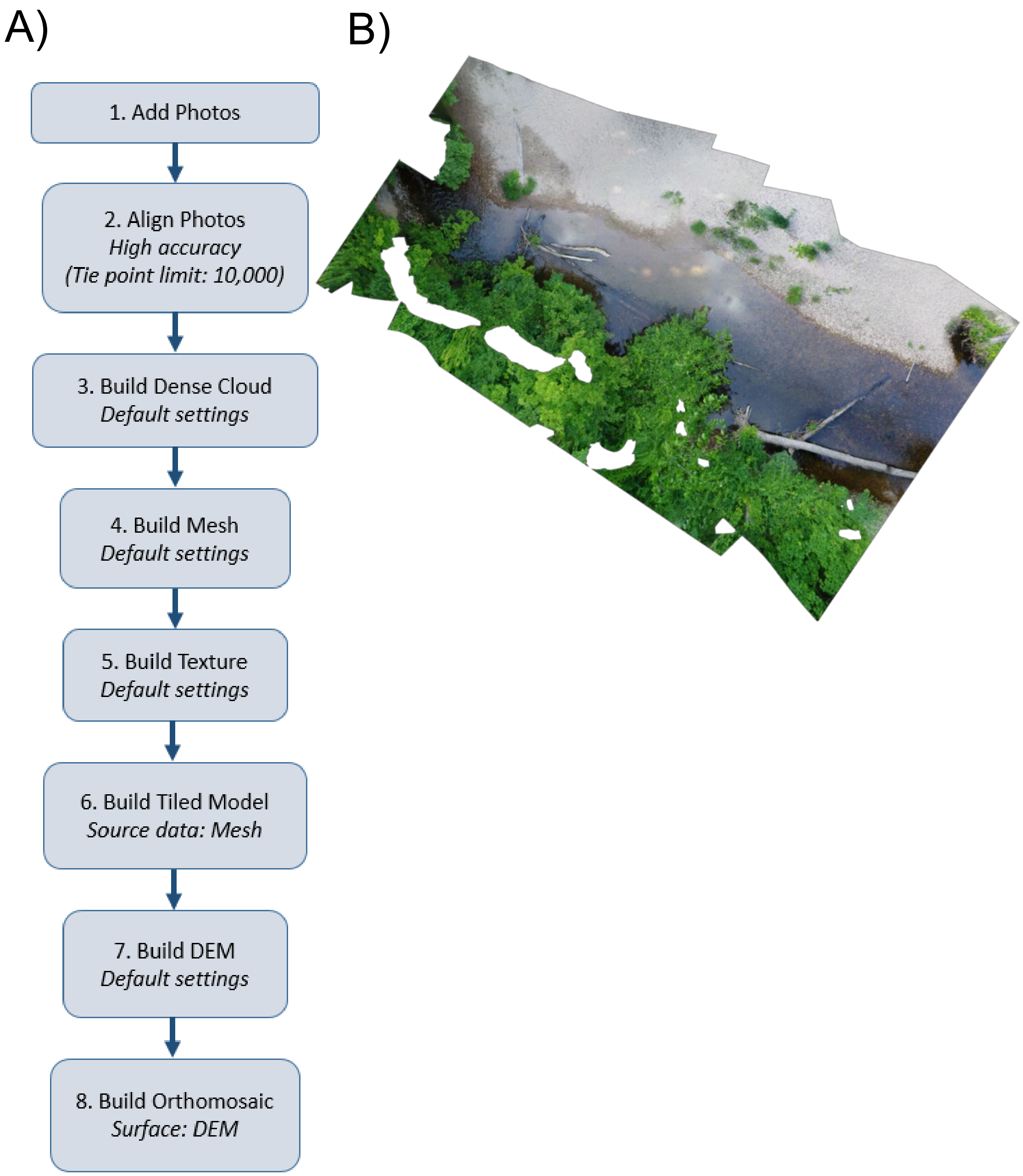


Figure 13. (A) Workflow used to create (B) an orthomosaic of sUAS photographs for each field site.

by large wood structures, and by any form of cover. The covered distance was then compared to the known bankfull width measured in the field. Linear measurements were used rather than areas because the bankfull width across the channel was known from field measurements, while covered distanced could be measured using aerial imagery.

Effects of large wood on cover and sediment variability were judged qualitatively, rather than with a statistical test. Sediment was visually estimated in the field and noted in order of dominance. While surveying in the stream, I looked below the water surface and grabbed sediment to estimate what percentages of each substrate category were present. Therefore, without a quantitative average grain size for each cross section interval surveyed, a statistical test was not feasible. Analyzing cover ratios with a statistical test was also not practical because the sample size at each reach was not large enough.

Water surface slope for a particular reach was determined with the use of ArcGIS to analyze publicly available lidar digital elevation models (Appendix E). Water surface slope is being used here as a proxy for riverbed slope. While riverbed slope and water surface slope can differ, calculating water surface slope using lidar DEMs provides more data points over a larger distance compared to using riverbed elevation data collected from field surveys (Snyder, 2009). Water surface elevations were extracted every 1 m along the river for a distance of five times the channel width for the test or reference reach, centered on the middle cross section of the corresponding reach. The elevations were plotted, and the reach slope was identified using MATLAB to find the line of best fit for a linear regression.

Once all metrics were recorded or calculated, test and reference reaches were compared to one another. For water depth and velocity, medians and variances were used to reveal how measurements in test reaches vary in comparison to those recorded in reference reaches where instream wood is not present (Table 2). Data from all three cross sections within a reach were compiled for comparing test and reference reaches. Statistical analyses were then conducted in MATLAB. I used two-tailed statistical tests to determine if results from test and reference reaches were significantly different. I also considered whether statistically significant differences were in hypothesized directions or not. The Wilcoxon rank-sum (rank-sum) test was employed at a 5% significance level to determine if median water depths and velocities were significantly different between test and reference reaches. The rank-sum null hypothesis states that the two samples are from independent populations and have equal medians. Any p-values greater than 0.05 (5%) indicated that the null hypotheses could not be rejected. Although a scientific hypothesis for median depth between test and reference reaches was not formulated because I did not have an expectation for higher or lower median depth in test reaches, differences in medians between reaches were still statistically tested and analyzed for data exploration. Fligner-Killeen (FK) tests at a 5% significance level were performed to determine if test reach variance was significantly different from reference reach variance (H2a and H2b; Table 2). The FK null hypothesis states that the two samples are from independent populations and have equal variances. Rank-sum and FK tests are nonparametric tests, appropriate for data that are non-normally distributed (Helsel et al., 2020).

3. Results

3.1. The 'Floodplain Large-Wood Cycle' Hypothesis at MVD

New surveys collected at the MVD site during the summer of 2021, compared to past surveys from years including, but not limited to, 2007-2012, 2014 and 2018 reveal up to 0.90 m of sediment deposition on top of the surface eroded by a March 2010 flood, surrounding the recruited trees (Figure 14). Photographs and videos from the sUAS flights show the deposition, as well as stable vegetation existing on the newly developing floodplain (Figure 15). In this section, I analyze many of these images in detail. Appendix B has a full catalog and timeline of related imagery.

Examination of September 2009 aerial imagery reveals a dewatered impoundment area with exposed stored sediment extending from the left (north) bank of the MVD06 cross section to around the left bank of the MVD04 cross section (Figure 16). In the September 2009 aerial image and the September 2008 repeat photographs, two pieces of large wood are seen near the left bank of the MVD06 cross section. The channel morphology in 2009 was a result of the dam removal in August 2008.

The subsequent set of repeat photographs were taken in March 2010, after the large flood that caused trees from the left bank to fall into the channel (Figure 17A). In the photographs, several more pieces of large wood are shown in the channel with the roots of the trees torn away from the left river bank at MVD06. The next available aerial imagery after the flood is from April 2011. By this time, the Souhegan River channel was bifurcated around the mid-channel island (Figure 17B). Approximately seven pieces of

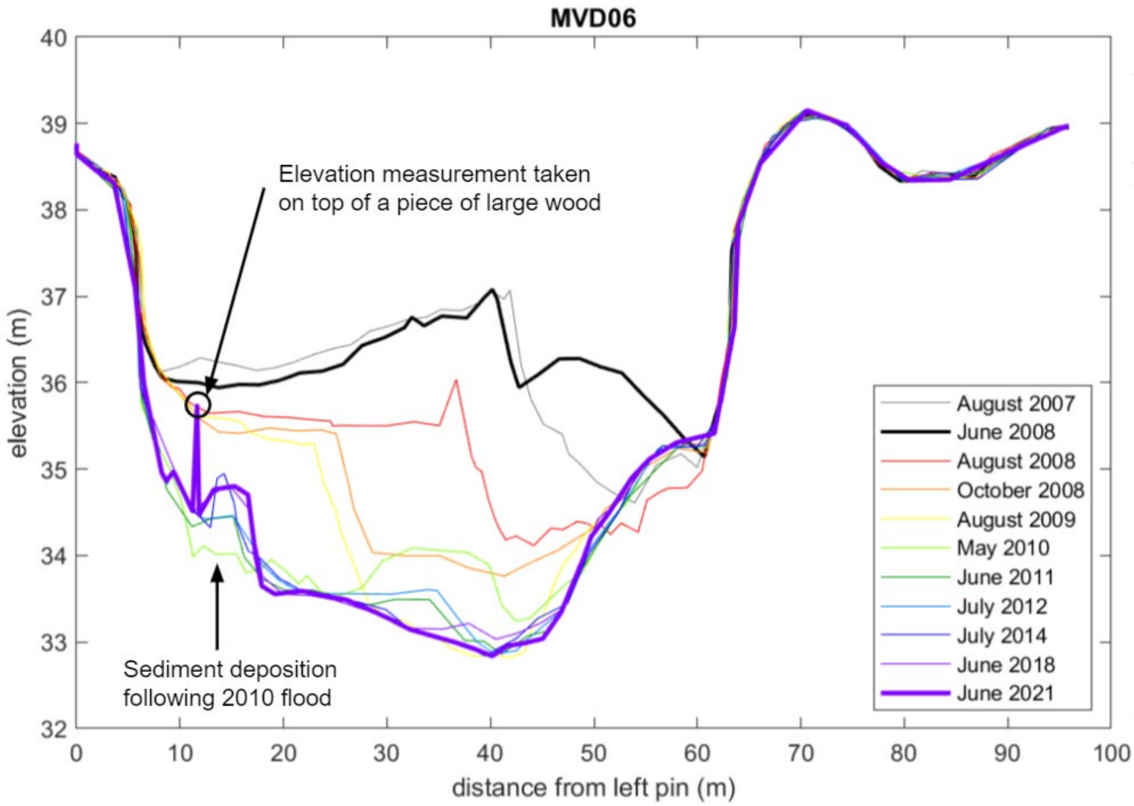


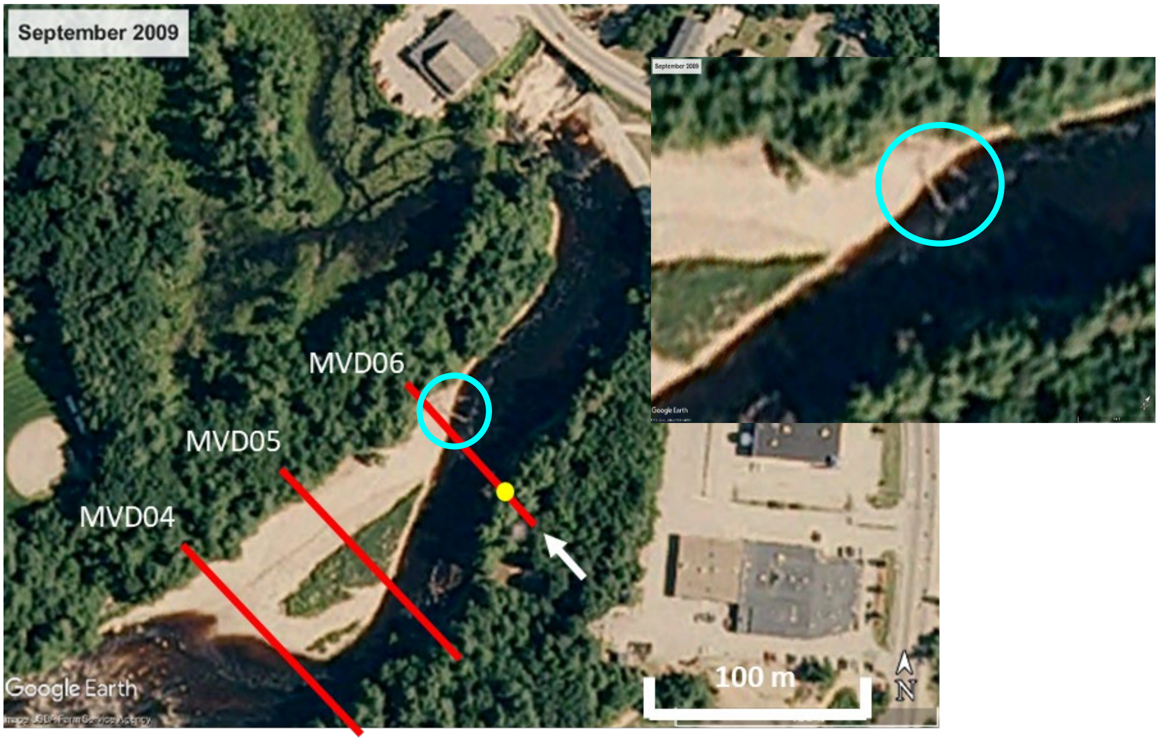
Figure 14. Channel change through time at survey cross-section MVD06, aligned from river left (north) to river right (south). Cross-section locations are shown in Figure 3. Plotted lines represent bed elevations of the Souhegan River during previous surveys. Colors correspond to dates presented in the legend. Survey comparisons shown provide evidence of channel incision in response to dam removal (August 2008-August 2009), as well as left bank erosion following floods in March 2010 (May 2010). Trees recruited during this bank erosion have induced sediment deposition (June 2011-June 2021).

A)

B)

Figure 15. sUAS photographs (A: June 2021; B: August 2021) revealing sediment deposition and subsequent vegetation growth surrounding large wood at the MVD06 cross section.

A)



B)

Figure 16. (A) Google Earth aerial imagery from September 2009, about a year after dam removal at the MVD site. Relevant MVD cross sections are labeled with red lines. Two pieces of large wood are circled in cyan. The smaller adjacent image shows a closer view of the large wood. (B) Repeat photographs taken from a photo point (yellow dot) in September 2008, looking at the left bank of the MVD06 cross section. Photographs are shown upstream to downstream.

A)

B)

Figure 17. (A) Repeat photographs taken from photo points (yellow dots in B) in March 2010, after the flood that undercut banks to allow trees to topple into the channel. The top row of photographs looks at the right bank of the MVD06 cross section in the distance, with the left and right pictures corresponding to upstream and downstream, respectively. The bottom row of photographs looks at the left bank of the MVD06 cross section. (B) Google Earth aerial imagery from April 2011, about a year after the 2010 flood. The right aerial image is centered on the MVD06 cross section.

large wood extended into the channel, oriented with the tops of the trees pointed diagonally downstream.

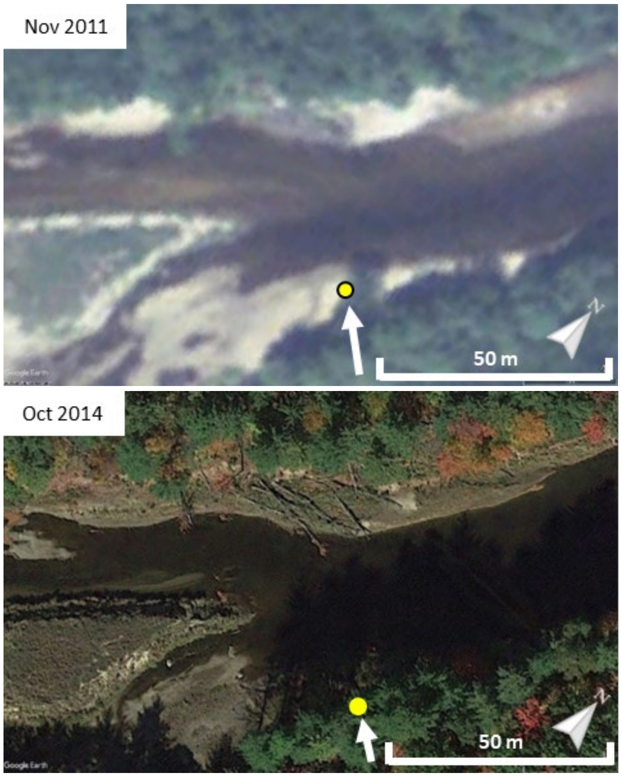
Aerial images from April 2011, November 2011, and October 2014 show sediment deposition and vegetation growth, respectively, around the large wood pieces (Figure 17B; Figure 18). Sediment deposition is also evident in the repeat photographs taken in 2010, 2011, 2012, 2014 and 2018. A sparse amount of vegetation on the extended floodplain is evident in the July 2012 photograph, while more abundant vegetation is present by the time of the July 2014 repeat photographs (Appendix B). The large wood pieces stabilized by sediment and vegetation are also seen in the same orientation in all the later aerial images.

3.2. Site Characteristics

Measurements taken in the field were compiled to compare site characteristics (Table 4). On the Narraguagus River, all of the studied active restoration sites had large wood installed between 2017 and 2020. Most of the large wood at the MVD06 site fell into the channel in 2010 after flood-induced erosion. The two engineered log jams within Nash Stream have been in the river since construction in 2012. At Salmon Brook, aerial imagery indicates that the large wood in the channel at the SBP site has been around since at least 2015. Due to the dense tree canopy at the Salmon Brook CP site, determining an installation year based on aerial imagery is not feasible.

The average diameter for key pieces at each site ranges from 14 to 46 cm, and six sites have large wood with an attached rootwad (Table 4). Logjam area (interchangeable with “wood load”) and test reach area range from 8 to 91 m^2, and 97 to 1,010 m^2,

A)



B)

Figure 18. (A) Google Earth aerial imagery from November 2011 and October 2014. The images are centered on the MVD06 cross section. (B) Repeat photographs taken from a photo point (yellow dot) in May 2010 (top row of photographs) and June 2011 (bottom row). Both panels of photographs look at the left bank of the MVD06 cross section in the distance, with the left and right pictures corresponding to upstream and downstream, respectively.

	Site Characteristics: All Sites													
	Site	Estimated Installation	Average Piece Diameter	Rootwad		Jam Dimensions		Average Bankfull Width	Dist. Between Reaches	Reach Length	Reach Area		Wood Load	
				Presence	Avg Volume	Length	Width				Reference	Test	Test	Test
		(year)	*(cm)*	*(y/n (#))*	*(m3)*	*(m)*	*(m)*	*(m)*	*(m)*	*(m)*	*(m2)*	*(m2)*	*(m2)*	*ratio*
CT	SBP	< 2015	17	yes	-	14.1	0.7	9.15	4	13.0	85.3	120.1	8.3	0.07
	CP	unk	31	no	-	3.1	17.6	24.32	15	4.0	51.8	96.4	37.2	0.39
ME	28 Pond	2017	24	no	-	21.5	15.8	20.32	57	21.5	401.0	434.7	88.1	0.20
	ATV - GH1	2020	19	yes (1)	7.4	19.3	7.3	21.99	12	19.3	389.4	424.8	76.2	0.18
	ATV - GH2	2020	15	no	-	18.5	8.3	25.78	8	13.0	341.0	337.2	45.9	0.14
	ATV - PALS	2018	14	no	-	9.0	5.5	22.57	19	9.0	311.6	201.4	11.2	0.06
	HL - PALS 1	2018	19	no	-	5.5	17.0	17.93	69	17.0	367.9	301.1	40.7	0.14
	HL - PALS 2	2018	17	no	-	17.0	4.5	14.52	9	10.3	162.2	149.7	25.9	0.17
	HB - PALS	2019	17	no	-	12.4	15.7	20.58	3	15.3	257.9	311.9	61.8	0.20
	SB - GH	2019	18	yes (2)	3.8	10.0	13.5	24.29	7	12.0	303.5	293.3	18.5	0.06
	SB - PALS	2019	24	no	-	18.2	12.4	21.01	5	18.2	353.4	377.8	63.2	0.17
	30-35 - GH	2020	44	yes	-	23.1	8.3	16.28	2	16.6	246.5	274.5	90.7	0.33
NH	ELJ 1 - US	< 2013	24	no	-	8.9	3.2	15.48	12	11.0	162.0	167.7	34.8	0.21
	ELJ 2 - DS	< 2013	28	yes (1)	1.2	12.2	3.3	13.20	29	12.0	90.4	153.8	26.0	0.17
	MVD06	2010	46	yes	-	44.7	12.0	34.40	38	30.0	651.5	1009.7	80.2	0.08

Table 4. Site characteristics at all 15 sites throughout New England. Reach length applies to the length of both the reference and test reach; the length of the reference reach was intentionally chosen to be equivalent to that of the test reach. In reference to the large wood date of installation, a "<" symbol indicates that the exact year is unknown, but installation occurred sometime during or prior to the year noted. Wood load ratio, presented in the last column, is equivalent to the wood load area in the test reach divided by the reach area.

respectively. The MVD06 site contains the largest piece diameter, logjam area, and reach area. Wood load ratio (logjam area divided by reach area) ranges from 0.06 to 0.39. The SBP site in Connecticut holds the smallest wood load, while the 28 Pond site in Maine holds the largest.

3.3. Depth and Velocity

Test and reference reach water depth and velocity measurements were plotted together for all sites to visualize channel geomorphology and hydraulics (Figures 19-21; Appendix C). For hypotheses H2a-c, 40-53% of the sites reveal no significant difference between test and reference reaches (Table 5). Moreover, significant differences tend to not have a clear direction – i.e., for each scientific hypothesis, the number of sites with expected and unexpected significant differences are similar. Expected results for hypotheses H2a, H2b, and H2c are seen at 33%, 33%, and 20% of all sites, respectively (Table 5). While no scientific hypothesis was formulated for how median depth would differ between test and reference reaches, 73% of all sites showed a significant difference in median depth between reaches. Below I consider the statistical results from the four study rivers individually.

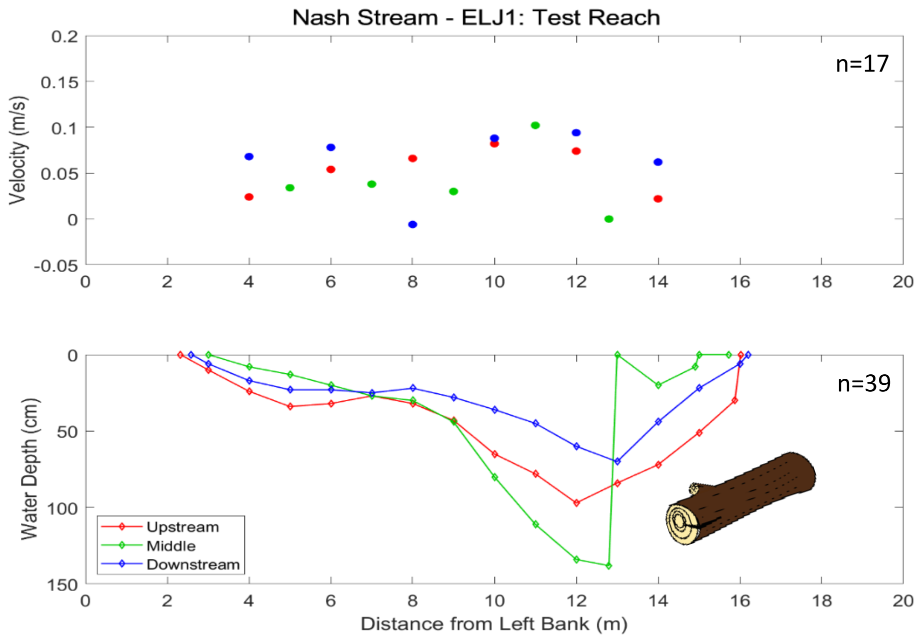
At the ten sites on the Narraguagus River in Maine, six (60%) have significantly different depth variance between test and reference reaches (Table 5). However, only two (20%) have greater variability in the test reaches, as expected with H2a. Eight (80%) sites have significantly different median depth between test and reference reaches, of which six have greater median depths in the reference reach. In terms of velocity, five (50%) sites on the Narraguagus River have significantly different variance between test and reference reaches; all five have greater variability in the test reaches, as expected with H2b. At the four (40%) sites on the Narraguagus River with significantly different median velocity between the test and reference reaches, the median velocity is higher in the test reaches, which is unexpected with H2c.

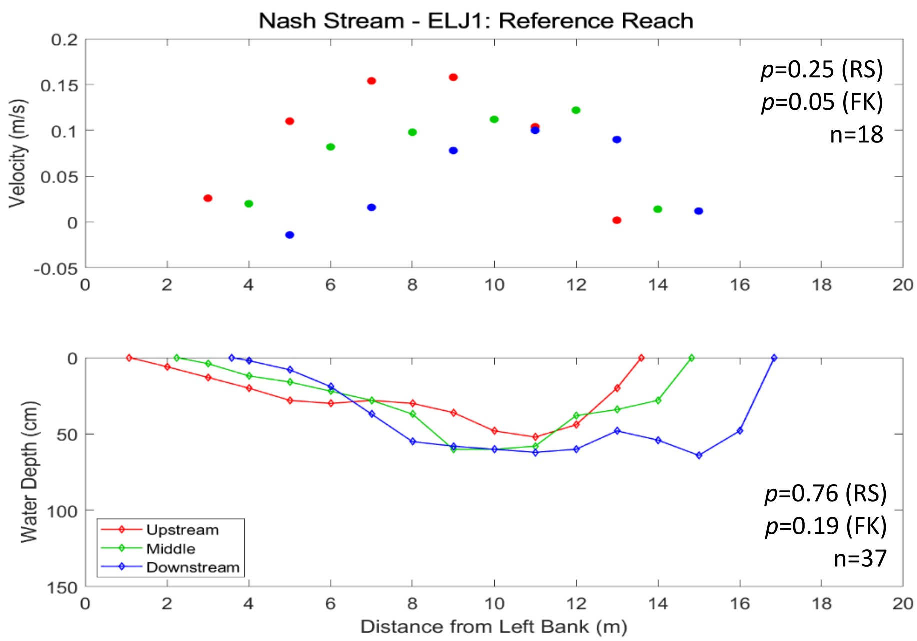
At Nash Stream, one (50%) of the two sites, ELJ2, has a significantly greater depth variability in the test reach, as expected with H2a (Figure 19B; Table 5). A significantly different median depth between reaches is seen as well at the ELJ2 site, in which the median depth is greater in the test reach. The ELJ2 site also has a significantly different velocity variance between test and reference reaches, but the greater velocity variability is in the reference reach, which is unexpected with H2b. Site ELJ2 on Nash Stream that has a significantly different median velocity between the test and reference reach has a lower velocity in the test reach as expected under H2c.

At MVD06 on the Souhegan River, the depth variance is significantly different between test and reference reaches, and is higher in the test reach, as expected with H2a (Figure 20; Table 5). In contrast, the velocity variance between test and reference reaches is not significantly different (H2b). The median velocity in the test reach is significantly different from, and lower than, the median velocity in the reference reach, as expected with H2c. The median depth is greater in the test reach, and significantly different from the median depth in the reference reach.

At the two sites within Salmon Brook, one (50%) site, CP, has a significant difference in depth variance between test and reference reaches (Figure 21A; Table 5). The CP site has greater depth variability within the test reach expected under H2a. The

A)


Nash Stream - ELJ1: Test Reach
n=17
Velocity (m/s)
n=39
Water Depth (cm)
Upstream
Middle
Downstream
Distance from Left Bank (m)


Nash Stream - ELJ1: Reference Reach
p=0.25 (RS)
p=0.05 (FK)
n=18
Velocity (m/s)
Water Depth (cm)
Upstream
Middle
Downstream
p=0.76 (RS)
p=0.19 (FK)
n=37
Distance from Left Bank (m)

B)

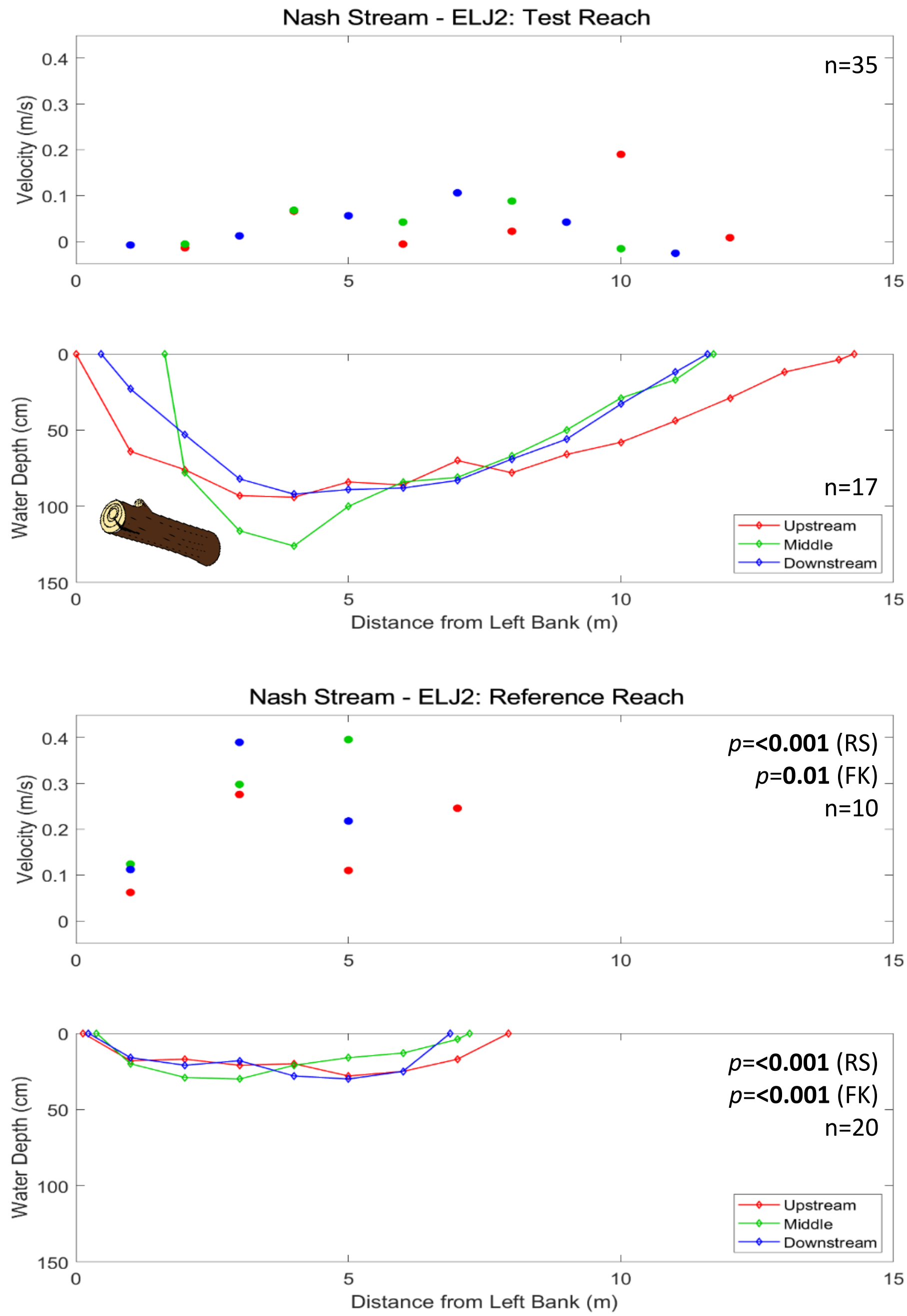


Figure 19. Water depth and velocity data measurements taken at the (A) ELJ1 and (B) ELJ2 sites in Nash Stream, NH. The log represents the approximate location of wood placed in the test reach of the channel. Results from the rank-sum (RS) and Fligner-Killeen (FK) statistical tests to compare the medians and variances of depth and velocity data between surveyed reaches are shown on the plot along with the number of data points in each sample.

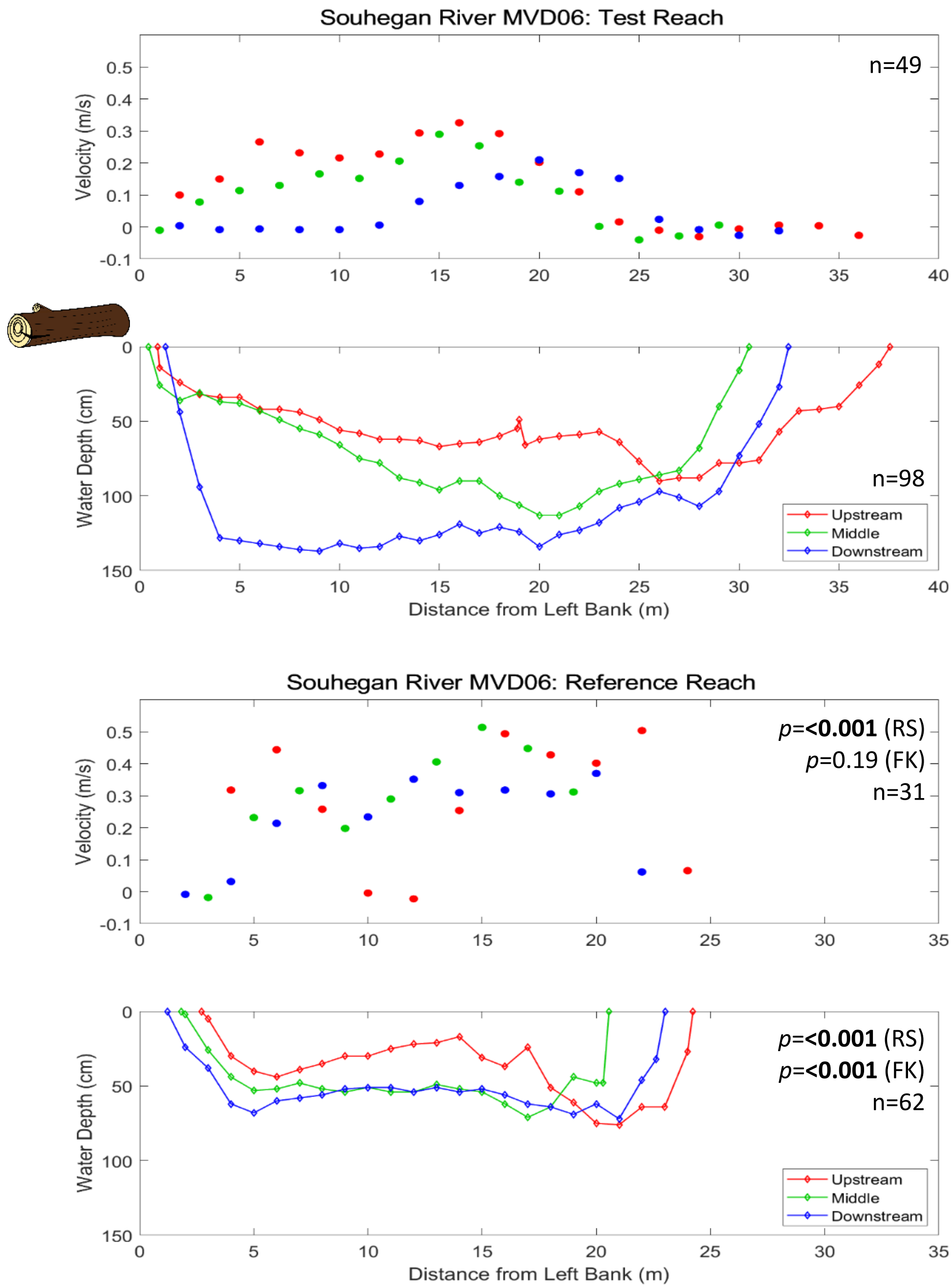
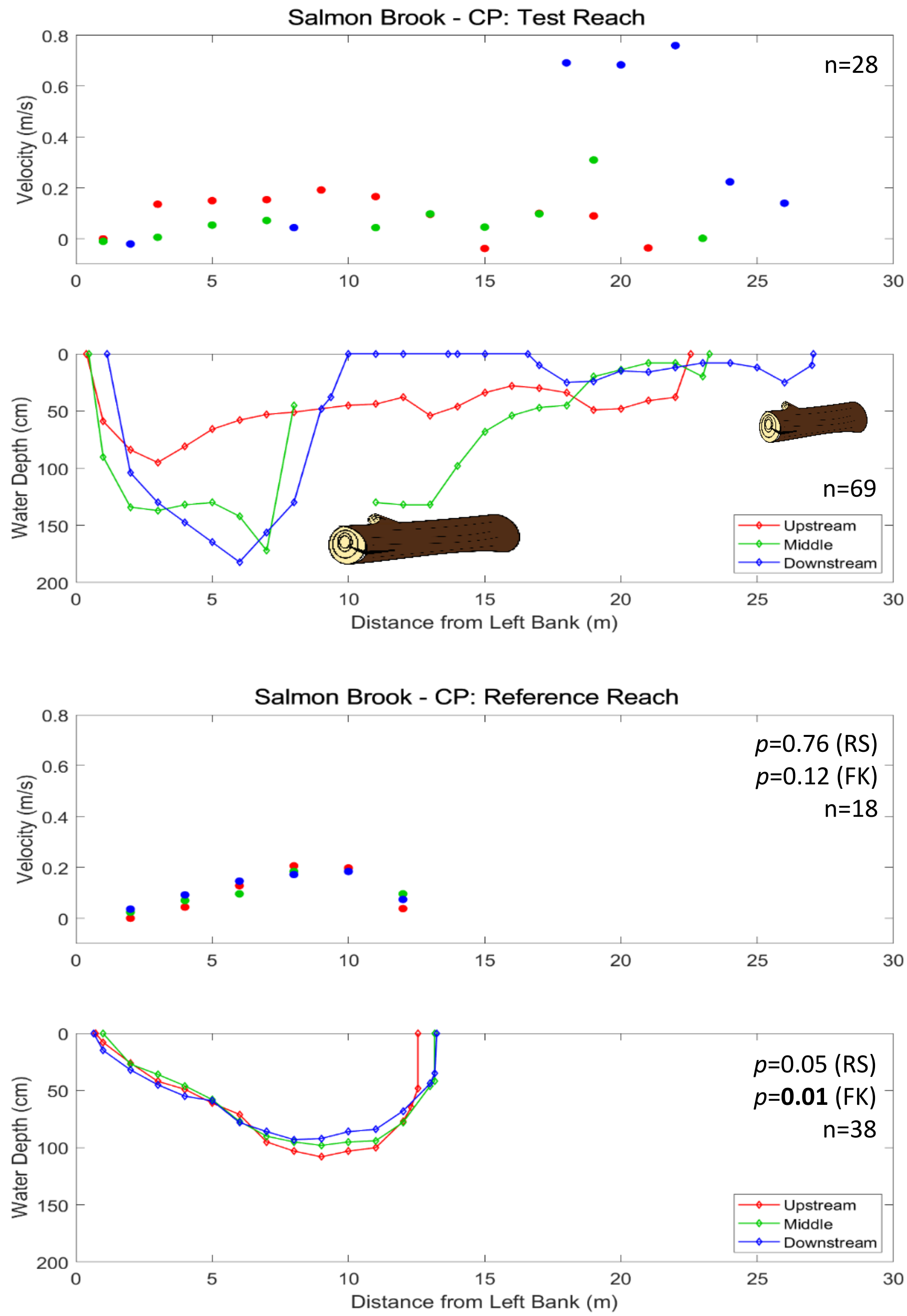


Figure 20. Water depth and velocity data measurements taken at the MVD site on the Souhegan River, NH. The log represents the approximate location of wood that was passively recruited to the test reach of the channel in March, 2010. Results from the rank-sum (RS) and Fligner-Killeen (FK) statistical tests to compare the medians and variances of depth and velocity data between surveyed reaches are shown on the plot along with the number of data points in each sample.

A)


Salmon Brook - CP: Test Reach
Velocity (m/s)
n=28
Water Depth (cm)
n=69
Upstream
Middle
Downstream
Distance from Left Bank (m)
Salmon Brook - CP: Reference Reach
Velocity (m/s)
p=0.76 (RS)
p=0.12 (FK)
n=18
Water Depth (cm)
p=0.05 (RS)
p=0.01 (FK)
n=38
Upstream
Middle
Downstream
Distance from Left Bank (m)

B)

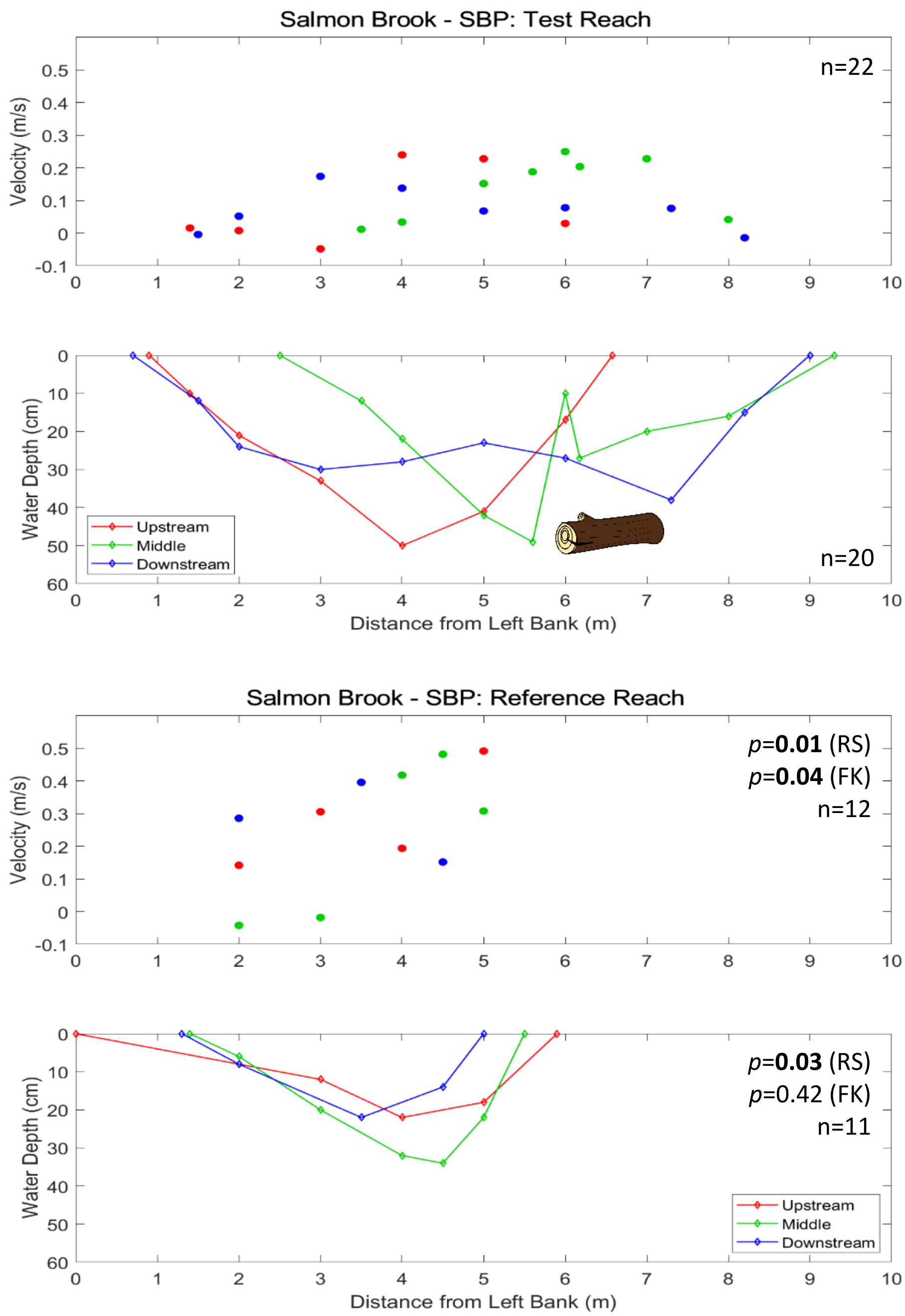


Figure 21. Water depth and velocity data measurements taken at the (A) CP and (B) SBP sites in Salmon Brook, CT. The log represents the approximate location of wood passively recruited to the test reach of the channel. Results from the rank-sum (RS) and Fligner-Killeen (FK) statistical tests to compare the medians and variances of depth and velocity data between surveyed reaches are shown on the plot along with the number of data points in each sample.

Table 5. (A) Statistical results from the rank-sum (RS) and Fligner-Killeen (FK) tests done on the water depth and velocity data collected at each site. Colors indicate the disposition of each result with respect to both the statistical hypothesis test (i.e., significant or not significant differences) and scientific hypotheses as shown in Table 5B. Blue shading indicates significant results for a test where we had no scientific hypothesis and thus no prior expectation for direction of change. (B) Summary of statistical test results by river system and scientific hypotheses.

A)

Statistics: All Sites												
Site		Metric	*p*-value		Median		Standard Deviation		n		slope (%)	
			Rank Sum	FK test	*test*	*reference*	*test*	*reference*	*test*	*reference*	*test*	*reference*
CT	SBP	Depth	**0.03**	0.42	24	18	11	8	20	11	-0.44	-0.36
		Velocity	**0.01**	**0.04**	0.07	0.30	0.09	0.18	22	12		
	Christensen's Pond	Depth	0.05	**0.01**	46	74	52	27	69	38	-0.43	-0.32
		Velocity	0.76	0.12	0.10	0.10	0.21	0.07	28	18		
ME	28 Pond	Depth	**0.001**	**0.02**	26	32	16	9	59	57	-0.36	-0.17
		Velocity	**0.03**	**<0.001**	0.26	0.18	0.23	0.11	28	29		
	ATV - GH1	Depth	0.57	**<0.001**	50	40	15	25	64	61	-0.07	-0.04
		Velocity	0.77	0.92	0.02	0.04	0.04	0.04	32	29		
	ATV - GH2	Depth	**<0.001**	0.07	27	20	12	9	76	77	-0.21	-0.16
		Velocity	0.31	0.18	0.04	0.06	0.07	0.08	37	38		
	ATV - PALS	Depth	**0.04**	0.73	39	41	8	9	34	50	-0.24	-0.17
		Velocity	**0.006**	**<0.001**	0.41	0.16	0.26	0.16	34	50		
	HL - PALS 1	Depth	0.12	**0.002**	40	46	11	16	51	61	-0.25	-0.05
		Velocity	0.05	0.99	0.18	0.10	0.10	0.10	25	30		
	HL - PALS 2	Depth	**<0.001**	0.20	45	64	17	21	38	44	-0.20	-0.23
		Velocity	**0.02**	**0.02**	0.22	0.11	0.12	0.07	18	22		
	HB - PALS	Depth	**<0.001**	0.49	46	73	17	18	60	48	-0.05	-0.03
		Velocity	0.86	0.34	0.10	0.12	0.14	0.08	30	23		
	SB - GH	Depth	**<0.001**	**<0.001**	30	50	9	19	72	72	-0.09	-0.10
		Velocity	**0.01**	**0.02**	0.11	0.04	0.12	0.10	35	36		
	SB - PALS	Depth	**<0.001**	**<0.001**	35	43	13	30	61	58	-0.11	-0.07
		Velocity	0.79	**0.001**	0.10	0.10	0.19	0.11	28	30		
	30-35 - GH	Depth	**<0.001**	**<0.001**	62	44	23	12	47	52	-0.22	-0.17
		Velocity	0.07	0.94	0.27	0.33	0.12	0.13	23	26		
NH	ELJ 1 - US	Depth	0.76	0.19	32	36	34	19	39	37	-0.57	-0.41
		Velocity	0.25	0.05	0.06	0.09	0.03	0.05	17	18		
	ELJ 2 - DS	Depth	**<0.001**	**<0.001**	70	21	30	7	35	20	-0.27	-0.45
		Velocity	**<0.001**	**0.01**	0.02	0.23	0.06	0.12	17	10		
	MVD06	Depth	**<0.001**	**<0.001**	77	52	35	17	98	62	-0.14	-0.15
		Velocity	**<0.001**	0.19	0.10	0.31	0.11	0.16	49	31		

B)

		Hypothesis H2a: depth variance			Hypothesis H2b: velocity variance			Hypothesis H2c: median velocity			median depth	
		Significant difference		No significant difference	Significant difference		No significant difference	Significant difference		No significant difference	Significant difference	No significant difference
River	# of sites	Supports	Rejects		Supports	Rejects		Supports	Rejects			
Salmon Brook	2	1	0	1	0	1	1	1	0	1	1	1
Narraguagus River	10	2	4	4	5	0	5	0	4	6	8	2
Nash Stream	2	1	0	1	0	1	1	1	0	1	1	1
Souhegan	1	1	0	0	0	0	1	1	0	0	1	0
Total	15	5	4	6	5	2	8	3	4	8	11	4
Percent	100%	33%	27%	40%	33%	13%	53%	20%	27%	53%	73%	27%

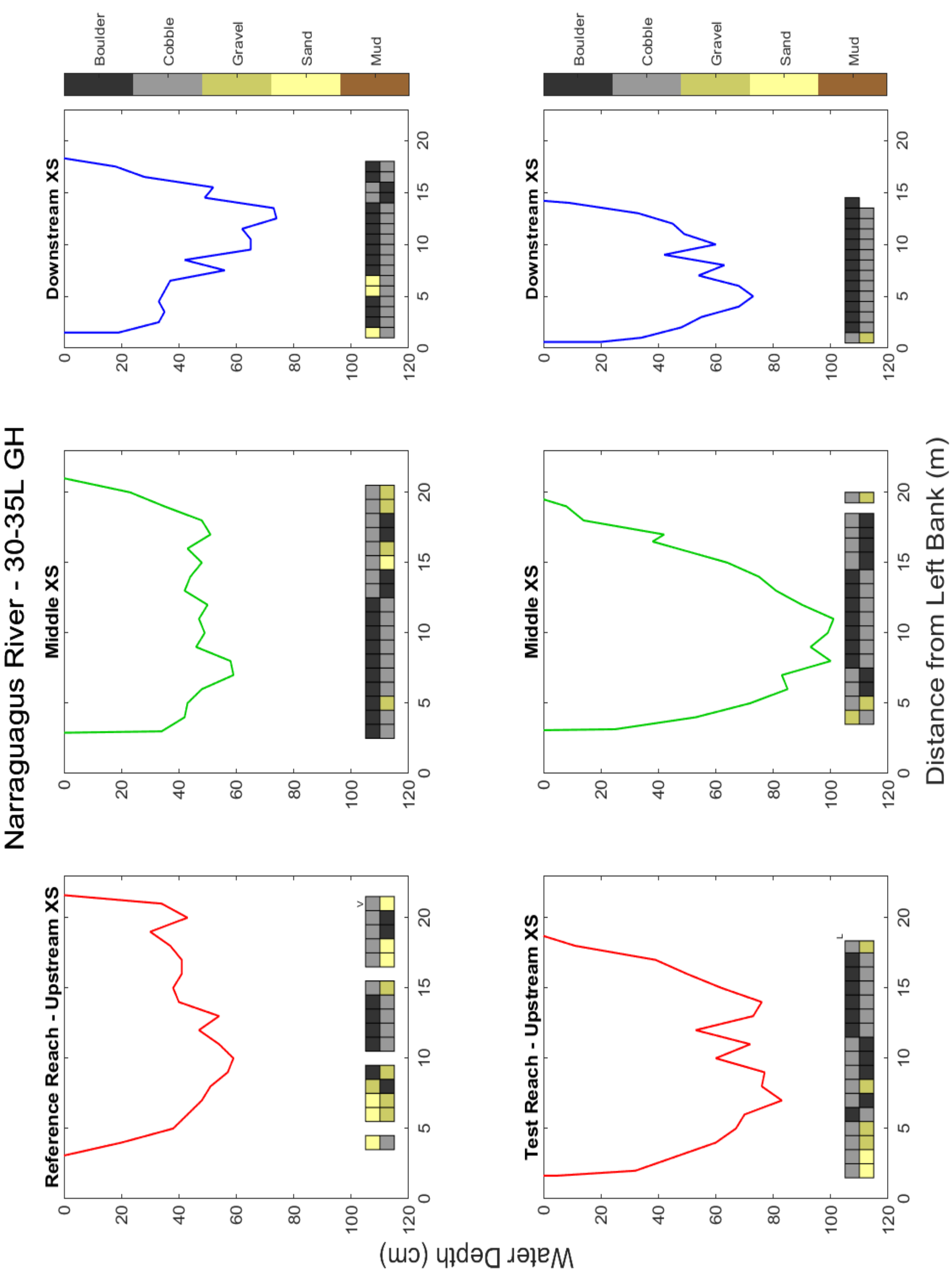
other site within Salmon Brook, SBP, has a significant difference between test and reference reaches for velocity variance and velocity medians. The SBP site has greater velocity variance within the reference reach, unexpected with H2b, but a lower median velocity in the test reach, as expected with H2c (Figure 21B; Table 5). A significant difference in median depth is also seen at the SBP site, where the median depth is greater in the test reach.

3.4. Substrate

To explain results from the depth and velocity statistical analyses, I looked to co-located and contemporaneous substrate measurements to find connections. In the following paragraphs I state the overall substrate results for each river surveyed.

For the ten sites at the Narraguagus River, the substrate ranges from mud to boulders (Appendix D). Subaquatic vegetation has a strong presence at all sites except ATV PALS and 30-35 L GH. The 30-35 L GH and 28 Pond sites have significantly different, and greater, depth variance in the test reaches, as expected with H2a (Figure 22). While cobble dominates the 28 Pond reaches, gravel is present more often in the test reach and boulders are more present in the reference reach. Vegetation is prominent in most cross sections of the 28 Pond reaches. Of the five sites with significantly different, and greater velocity variance in the test reaches, as expected with H2b, subaquatic vegetation is prominent in four sites (28 P, HL DS PALS, SB GH, SB PALS). These four sites noted also have median velocities significantly different and lower in the test reaches, as expected with H2c. The deepest part of the cross sections tends to correspond with areas of the channels where vegetation is not present (Figure 23). Two of the five

A)



Narraguagus River - 30-35L GH
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Boulder
Cobble
Gravel
Sand
Mud
Water Depth (cm)
Distance from Left Bank (m)

B)

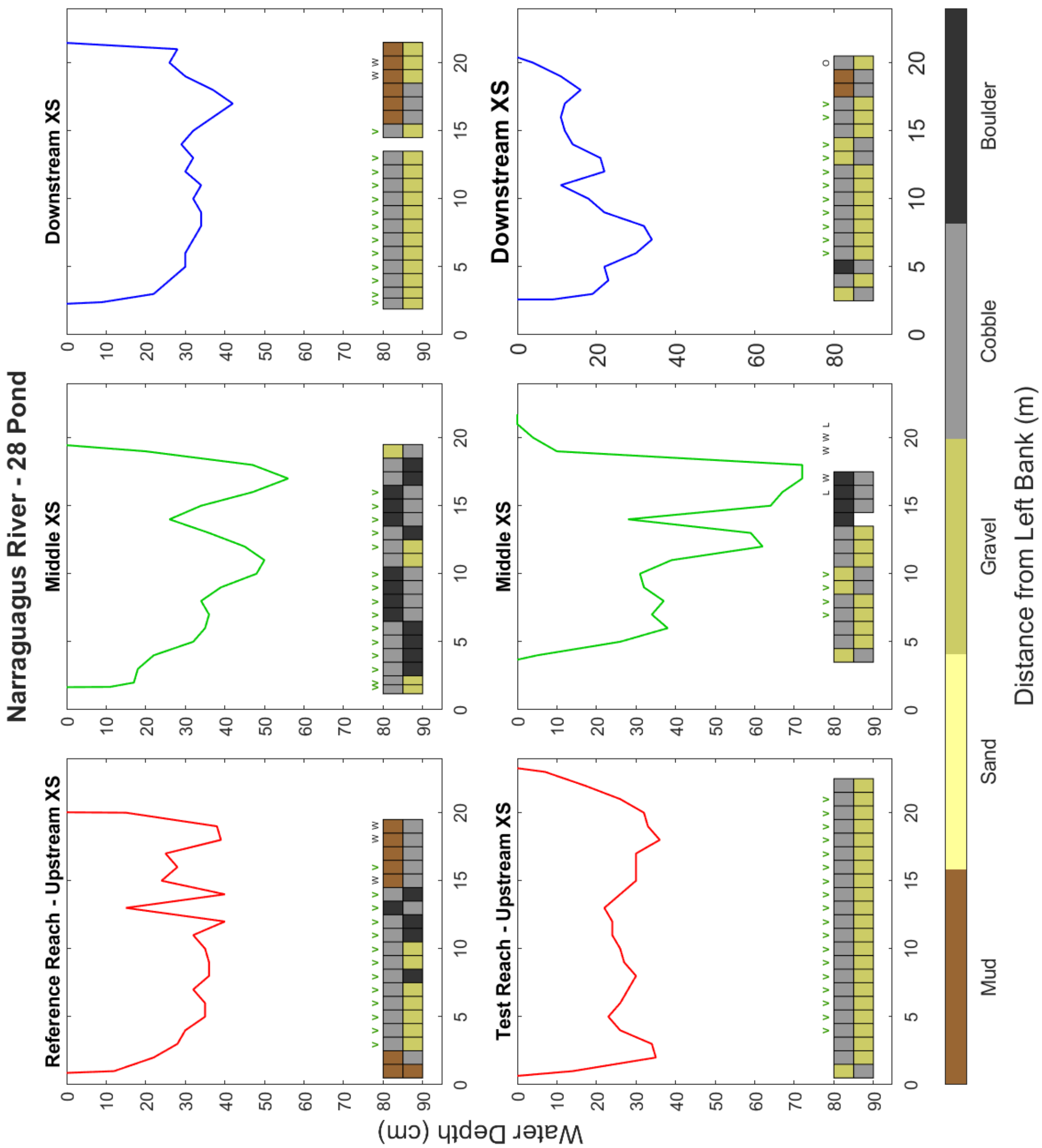
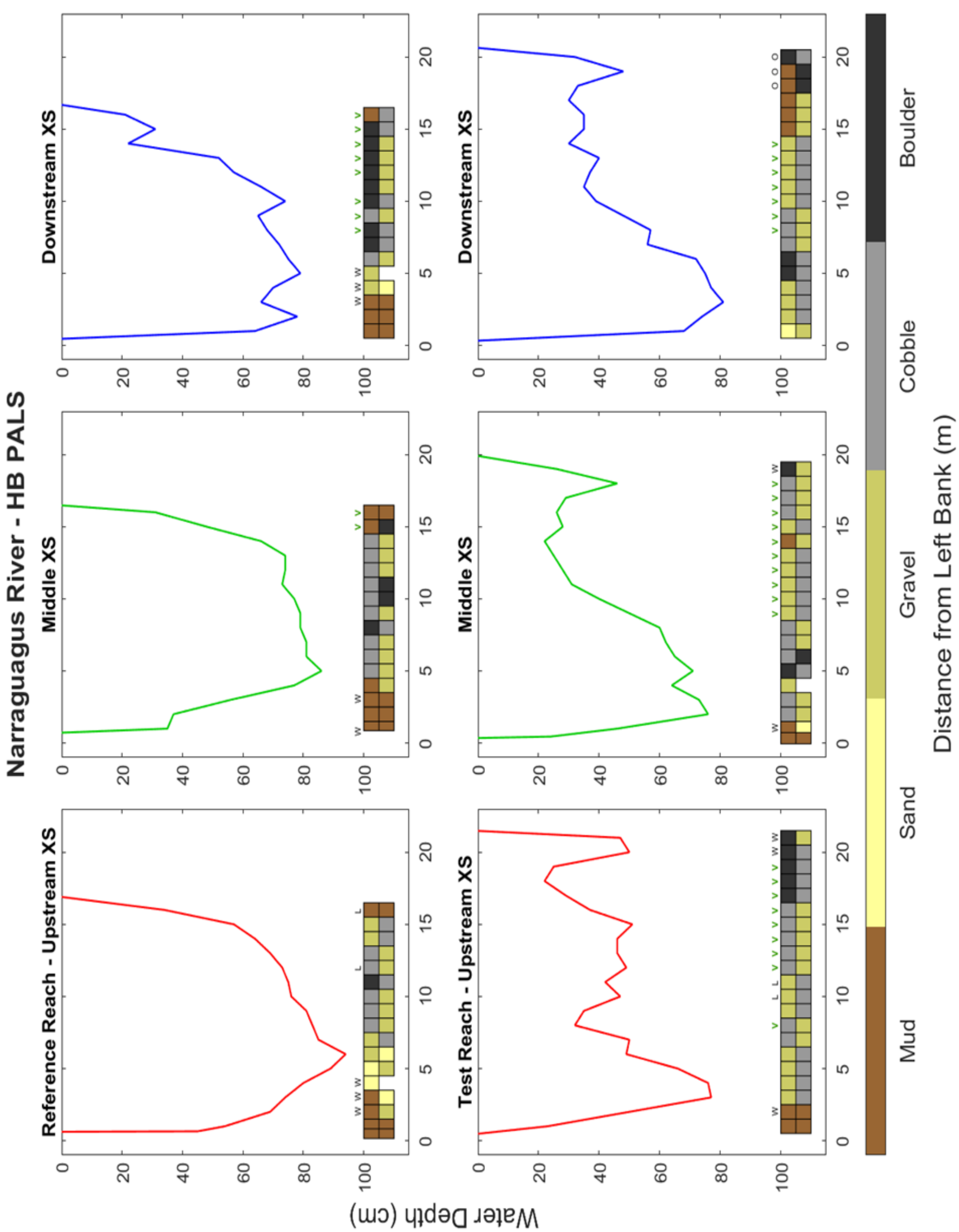


Figure 22. Substrate presence at all cross sections for both the reference and test reach at the (A) 30-35 L GH and the (B) 28 Pond sites on the Narraguagus River, ME. The top and bottom panels of colored boxes on each plot represent the primary and secondary substrate corresponding to the location within the channel, respectively. Abbreviations: A = algae, L = large wood, O = organic matter, V = subaquatic vegetation, W = wood.

A)



Narraguagus River - HB PALS
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder

B)

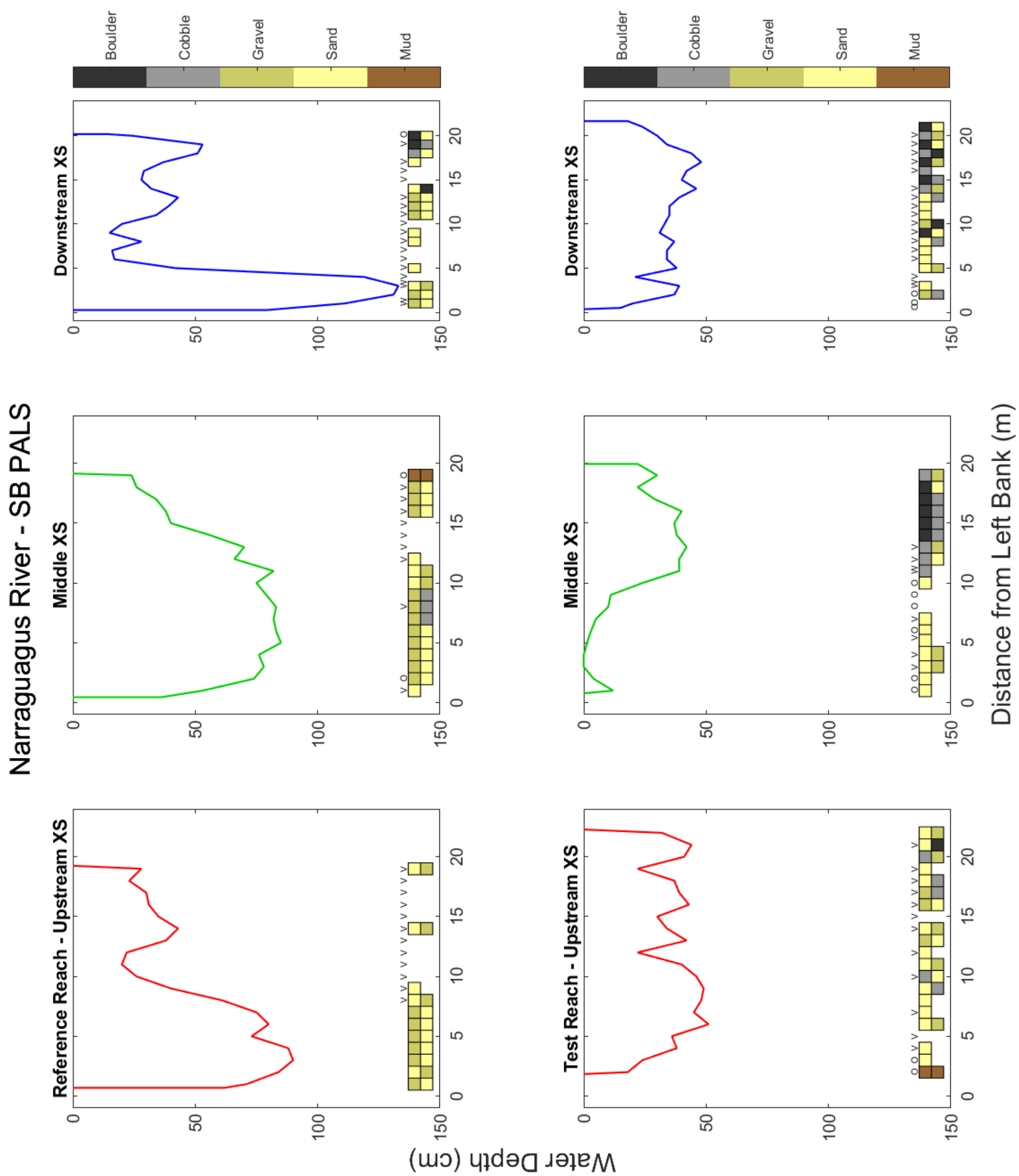


Figure 23. Substrate presence at all cross sections for both the reference and test reach at the (A) HB PALS and the (B) SB PALS sites on the Narraguagus River, ME. The top and bottom panels of colored boxes on each plot represent the primary and secondary substrate corresponding to the location within the channel, respectively. Abbreviations: A = algae, L = large wood, O = organic matter, V = subaquatic vegetation, W = wood.

sites on the Narraguagus River with median velocities significantly different and lower in the test reaches have a wider range of substrate grain sizes, as expected with H2d (ATV PALS, HL DS PALS). Smaller grain sizes are present in the test reaches of the two noted sites.

The Nash Stream sites are both gravel bedded, with some cobbles and sand (Appendix D). Qualitatively looking at substrate plots for both sites, the ELJ1 site has more wood and organic matter present within the test reach, and the ELJ2 site seems to have more sand and wood in the channel within the test reach, as expected with H2d. Only the ELJ2 site has significant differences in variability and medians for both depth and velocity.

Sand and gravel dominate the substrate at the MVD06 site on the Souhegan River (Appendix D). Qualitatively analyzing the substrate plot, the test reach has sand as the primary substrate more often than the reference reach. Differences between substrate at the test and reference reach may be influenced by the considerable difference in channel width between the reaches. The increase in width at the test reach downstream of the reference reach may allow for deposition of fines. The MVD06 site has significant differences in velocity variability and significant differences in medians for both depth and velocity.

The Salmon Brook sites are mostly dominated by gravel, with some sand and cobbles (Appendix D). Sand has more of a presence in the test reach at the SBP site, while cobble has more of a presence in the reference reach. At the CP site, the test reach has more sand and wood in the channel when compared to the reference reach.

Significant differences in depth median are only seen at the CP site, while significant differences in velocity median and both depth and velocity variances are seen at the SBP site.

3.5. Scour Pools and Sediment Bars

Of all 15 sites, 12 test reaches have at least one scour pool, and six test reaches have at least one sediment bar (Table 6). HB PALS has the largest number of pools in the test reach (4), and the highest number of sediment bars (3). Average residual pool depths for all sites range from 6-132 cm. Average velocities in the deepest part of the pools range from 0.00-0.15 m/s, while average velocities at the downstream pool crest range from 0.04-0.68 m/s.

Of the six sites with sediment bars, substrate was recorded at five bars, and includes sand, gravel, and cobble at four, five, and two sites, respectively (Table 6). The average water depth of the sediment bars ranges from -12 cm to 10 cm, where a negative depth indicates subaerial deposition.

3.6. Cover

Considering all sites and cover provided by just the large wood, the percent cover ranges from 0% to 51%, with an average of 21% (Table 7). When considering all forms of cover, the percent cover ranges from 0% to 100%, with an average of 49%. Overall, six (40%) of all 15 sites have a greater percent cover for all forms of cover at the test versus reference reach, which was expected with H2e.

At the Narraguagus River in Maine, the percent covered by large wood ranges from 0% to 42%, and averages 22% (Table 7). The percent covered by all types of cover at the sites ranges from 10% to 96%, and averages 52%. Percent cover based on all forms of cover is greater in the test reach than the reference reach, as expected with H2e, at five (50%) of ten sites on the Narraguagus River.

Within Nash Stream in New Hampshire, the percent covered by large wood averages 18% and ranges 9% to 27% (Table 7). The range of percent cover for all forms of cover is 9% to 40%, with an average of 23%. Percent cover based on all forms of cover is greater in the test reach than the reference reach, the expectation with H2e, at one (50%) of the two sites.

At Salmon Brook in Connecticut, the average percent covered by large wood is 29%, with an overall range of 7% to 51% (Table 7). The range of percent cover for all forms of cover is 26% to 100%, with an average of 81%. Expected results for hypothesis H2e are not found at either Salmon Brook site because both the test and reference reach are fully covered by the tree canopy at the CP site while the reference reach is fully covered by the tree canopy at the SBP site.

Table 6. Data collected for scour pools and sediment deposition within the test reach at each site. Substrate abbreviations: S = sand, G = gravel, C = cobble. Negative water depth values indicate sediment deposition above the water surface.

	Scour Pools and Sediment Bars: All Sites							
	Site	Pools *(#)*	Avg Residual Depth *(cm)*	Avg Pool Velocity *(m/s)*	Avg Downstream Crest Velocity *(m/s)*	Sediment Bars *(#)*	Substrate *-*	Avg Water Depth *(cm)*
CT	SBP	3	13	-	-	1	S, G	5
	Christensen's Pond	2	117	0.10	0.68	0	-	-
ME	28 Pond	1	59	0.08	0.44	1	-	10
	ATV - GH1	1	40	0.02	0.10	0	-	-
	ATV - GH2	1	6	0.03	0.04	0	-	-
	ATV - PALS	1	6	0.15	0.29	0	-	-
	HL - PALS 1	2	8	0.11	0.12	0	-	-
	HL - PALS 2	0	-	-	-	0	-	-
	HB - PALS	4	53	0.03	0.11	3	G, C, S	6
	SB - GH	0	-	-	-	0	-	-
	SB - PALS	3	24	0.00	0.14	3	S, G	-7
	30-35 - GH	1	51	-	-	0	-	-
NH	ELJ 1 - US	1	132	0.02	0.17	1	G	2
	ELJ 2 - DS	1	107	0.07	0.27	1	C, G, S	-12
	MVD06	0	-	-	-	0	-	-

Table 7. Percent cover calculated at each site. Cover measurements were done with sUAS aerial photographs, using the middle cross section at each reach.

Cover: All Sites									
	Site	Reach	Uncovered Distance: Wood	Uncovered Distance: All Cover	Channel Water Surface Width	Covered Distance: Wood	Covered Distance: All Cover	Percent Cover: Wood	Percent Cover: All Cover
			(m)	(m)	(m)	(m)	(m)	(%)	(%)
CT	SBP	Reference	-	0.00	4.10	-	4.10	-	100
		Test	6.35	5.05	6.82	0.47	1.77	7	26
	Christensen's Pond	Reference	-	0.00	12.17	-	12.17	-	100
		Test	11.09	0.00	22.77	11.68	22.77	51	100
ME	28 Pond	Reference	-	9.24	17.79	-	8.55	-	48
		Test	11.75	10.21	18.04	6.29	7.83	35	43
	ATV - GH1	Reference	-	10.73	18.26	-	7.53	-	41
		Test	19.22	12.88	21.22	2.00	8.34	9	39
	ATV - GH2	Reference	-	14.26	26.48	-	12.22	-	46
		Test	16.84	9.63	26.35	9.51	16.72	36	63
	ATV - PALS	Reference	-	18.93	34.50	-	15.57	-	45
		Test	21.14	16.50	21.80	0.66	5.30	3	24
	HL - PALS 1	Reference	-	9.65	21.02	-	11.37	-	54
		Test	13.33	11.02	16.80	3.47	5.78	21	34
	HL - PALS 2	Reference	-	9.51	14.67	-	5.16	-	35
		Test	10.58	5.57	12.80	2.22	7.23	17	56
	HB - PALS	Reference	-	7.55	15.76	-	8.21	-	52
		Test	15.61	9.27	19.56	3.95	10.29	20	53
	SB - GH	Reference	-	1.05	26.66	-	25.61	-	96
		Test	24.66	5.35	24.66	0.00	19.31	0	78
	SB - PALS	Reference	-	16.87	18.70	-	1.83	-	10
		Test	12.29	2.69	19.17	6.88	16.48	36	86
	30-35 - GH	Reference	-	7.05	18.10	-	11.05	-	61
		Test	9.6	3.92	16.42	6.82	12.50	42	76
NH	ELJ 1 - US	Reference	-	11.48	12.59	-	1.11	-	9
		Test	9.30	7.61	12.73	3.43	5.12	27	40
	ELJ 2 - DS	Reference	-	5.02	6.84	-	1.82	-	27
		Test	9.21	8.51	10.07	0.86	1.56	9	15
	MVD06	Reference	-	18.74	18.74	-	0.00	-	0
		Test	30.07	30.07	30.07	0.00	0.00	0	0

4. Discussion

4.1. The 'Floodplain Large-Wood Cycle' Hypothesis at MVD

Based on repeat photographs taken after the March 2010 flood, sediment deposition around the large wood pieces adjacent to the left bank of the MVD06 cross section began at some time before May 2010 (~2 months post-event; Figure 18; Appendix B). Based on aerial imagery, vegetation growth around the large wood began before October 2014 (~4 years post-event; Figure 18; Appendix B). The continued presence of the large wood pieces surrounded by sediment and vegetation in each aerial image after 2014 suggests that the geomorphic changes induced have been stabilized by, and may be a result of, the large wood pieces within the channel and resulting herbaceous vegetation (Appendix B).

Collins et al. (2012) used the Queets and Hoh Rivers in Washington as examples of rivers where 'Floodplain Large-Wood Cycle' processes have occurred. To account for the influence of channel dimensions on key piece (wood large enough to become stable within the river) size, the ratio of tree bole diameter (*Db*) to bankfull depth (*h*) was one parameter explored within the study (Abbe and Montgomery, 2003). Key pieces within the Queets River had a ratio of $Db/h > 0.5$. Using a maximum bankfull depth of 160 cm and average large wood piece diameter of 46 cm, the same ratio at the MVD site equates to $Db/h = 0.29$. Another parameter considered during the study was key piece ratios of wood length (*L*) to bankfull width (*w*), which equated to $L/w > 0.5$ for channels less than 50 m wide (Abbe and Montgomery, 2003). At the MVD06 site, with an average wood length of 17 m and a bankfull width undisturbed by the logjam of 46 m measured from

April 2011 Google Earth aerial imagery, the ratio becomes $L/w = 0.38$ (Figure 17; Appendix B). Based on the above ratios, the large wood at the MVD06 site would likely not be stable in rivers similar to that of the Queets River in Washington. The ratios do not quantify river slope, which may be an important factor for large wood stability, as the MVD06 site is within a moderate-gradient part of the river (Table 5; Appendix E). The comparison between large wood within the Queets River and the Souhegan River indicates that river systems in New England appear to have different characteristics than those in the Pacific Northwest to allow for the entrainment of smaller pieces of wood, but processes within the 'Floodplain Large-Wood Cycle' hypothesis may still be able to occur depending on factors such as sediment supply.

Based on the overall process occurring within the 'Floodplain Large-Wood Cycle', logs need to be large enough, or situated in a way that allows the wood to remain stable in the channel (Figure 1). Additionally, the large wood pieces or logjam need to resist transport downstream long enough to create flow diversion and allow for sediment deposition and subsequent vegetation growth. With large wood remaining in the channel for over 12 years at this point, the stability condition is met at MVD06 (Appendix B). Within the 12-year timespan, flow diversion, sediment accumulation, and vegetation growth have occurred around and on top of the large wood (Figure 15; Figure 18). Another aspect of the cycle describes a condition on the newly formed floodplain where trees can grow to a size large enough to eventually be recruited into the river to start the cycle over again. Collins and Montgomery (2002) note that natural-recruitment of large wood from a newly formed floodplain will not occur until 50-100 years after large wood first became situated in the channel (Figure 24). While evidence for the initial stages of

Floodplain Forests, Wood Jams, and River Restoration

Table 1. Conceptual framework for use of "restoration succession" in restoring wood jams and river dynamics.

	0 years	*1–50 years*	*50–100 years*	*100+ years*
Actions	Riparian reforestation Includes fast-growing species Levee setback or removal	In-stream structures Includes placing key pieces of building wood jams	Naturally-recruited logjams Fast-growing species form key pieces	Naturally recruited logjams Slower-growing species form key pieces
Results and Functions	Initiate future supply of wood Restore lateral erosion and avulsion	Short-term pool-forming and channel-switching functions Stable sites for forest regeneration	Long-term sustainable supply of wood jams Long-term sustainable pool-forming and channel-switching functions	

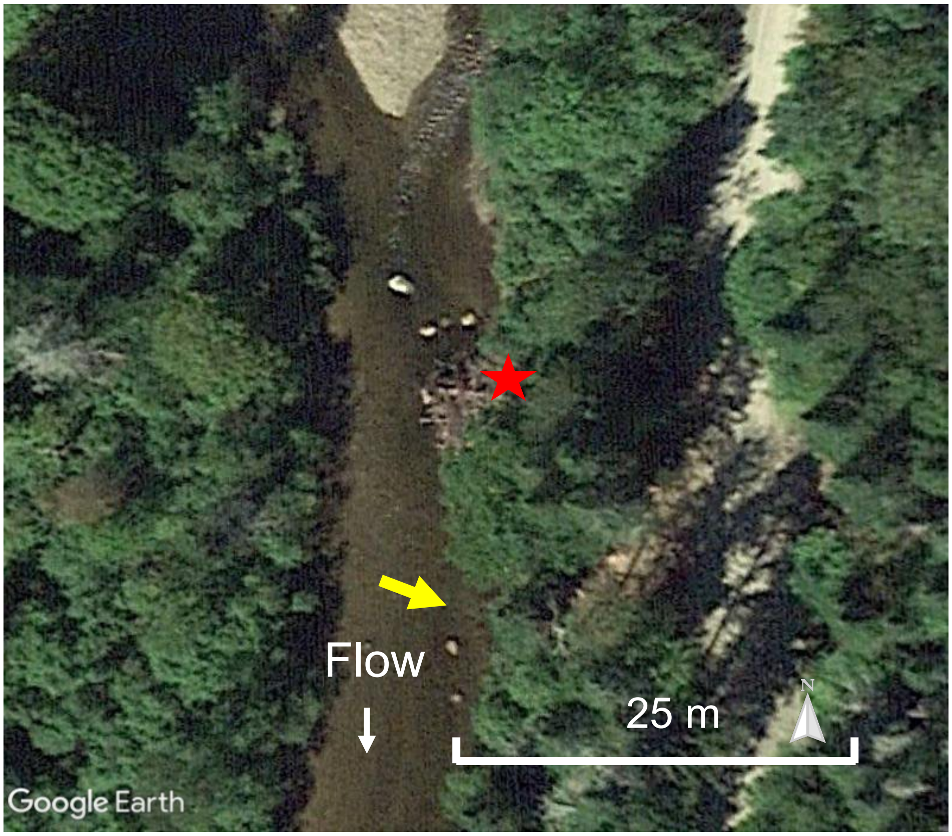
Figure 24. Expected timeline of processes resulting from the addition of large wood within river systems (Collins and Montgomery, 2002).

the ‘Floodplain Large-Wood Cycle’ and evidence of young woody vegetation (Figure 15B) can be seen at the MVD06 site, the final stage including the natural recruitment of fast-growing key species that continue the cycle to form new logjams cannot be confirmed at this time due to the limited study duration of this thesis.

The abundant supply of sand at the Souhegan River (Pearson et al., 2011) may allow the ‘Floodplain Large-Wood Cycle’ to happen there, or happen quicker, than in rivers with less sediment supply. Two other sites from this study with less apparent sediment supply show only equivocal evidence for processes similar to the ‘Floodplain Large-Wood Cycle’. In Nash Stream, a pool is present upstream and next to the ELJ2 wood structure, while downstream of the instream wood, a sediment bar adjacent to the left river bank is present and stable enough to grow a thin cover of vegetation (Figure 25A). An aerial image taken on September 17, 2013 (Google Earth) does not appear to include the sediment bar. However, different water levels at the time of each image may explain the apparent bar growth. The closest USGS gage (USGS 01130000) is located on the upper Ammonoosuc River, 300 m downstream of its confluence with Nash Stream. At noon on September 17, 2013, the discharge and gage height were approximately 10.5 m^3/s and 0.80 m. At the same time on the day the sUAS aerial images were taken (August 25, 2021), the discharge and gage height were 4.2 m^3/s and 0.66 m. Because higher water levels may have submerged the sediment bar in the 2013 (Figure 25A), the ELJ2 site does not provide strong evidence for process similar to the ‘Floodplain Large-Wood Cycle’.

At the SB PALS site on the Narraguagus River, a previously installed PALS has accumulated wood pieces to become a larger logjam (Figure 25C). Three sand and gravel bars, with an average deposition height of 7 cm above the water surface, are evident adjacent to the PALS, between the structure and the left river bank. A sparse amount of vegetation is present on the sediment bars, while subaquatic vegetation is present in the surrounding channel. Based on discussion with members of the crews who installed the PALS, at least some of the subaquatic vegetation and sand existed in the channel prior to the PALS installation. How much subsequent sediment deposition and vegetation growth occurred is unknown without a pre-installation survey. Therefore, even though sediment and vegetation are evident in aerial imagery, the SB PALS site does not provide strong evidence for process similar to the ‘Floodplain Large-Wood Cycle’. While the ELJ2 site may not provide an example of sediment deposition induced by large wood, Nash Stream does appear to have a larger supply of mobile bed sediment than the Narraguagus River based on the presence of more unvegetated gravel bars (Figure 25B). Therefore, I hypothesize that ‘Floodplain Large-Wood Cycle’ processes appear more likely to occur within Nash Stream than the Narraguagus River.

A)



B)

C)

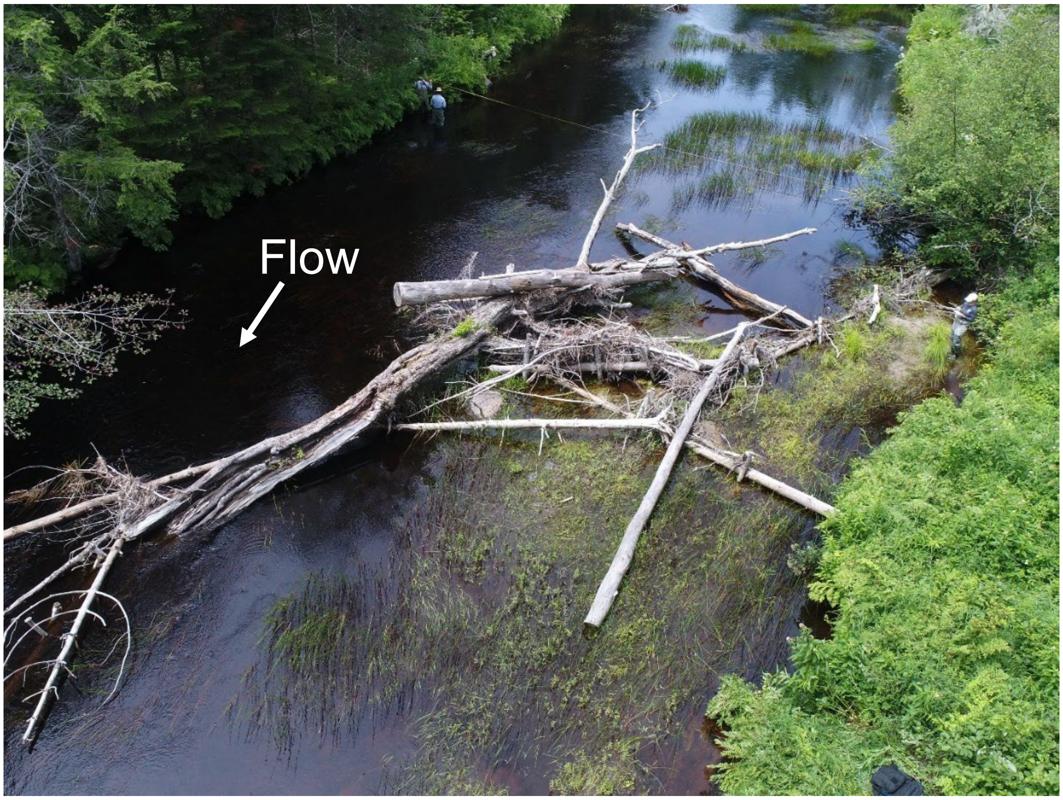


Figure 25. (A) A sediment bar downstream of ELJ2, Nash Stream, present in current sUAS photographs (2022), but apparently absent in historical Google Earth aerial imagery (2013). The engineered logjam (ELJ) is denoted by a red star. The yellow arrow indicates the location of sediment deposition seen in the sUAS photographs. (B) Sediment bars on Nash Stream, much of which are unvegetated. (C) sUAS photographs (2022) showing vegetation and sand adjacent to the SB PALS site on the Narraguagus River.

4.2. Geomorphic and Habitat Impacts of Large Wood in New England

I expected that river reaches containing large wood (test) would have more variable water depths (hypothesis H2a; Table 2). However, results do not consistently show large wood structures strongly influencing water depth variability (Table 5). At both Salmon Brook and Nash Stream, one (50%) of two sites shows significant differences between test and reference reaches and the other site shows no significant difference for all hypotheses. With ten sites total, the Narraguagus River has slightly more sites with significant differences than not (six (60%) sites for H2a, five (50%) sites for H2b, and four (40%) sites for H2c), but most of those differences are in the unexpected direction (Table 5).

For hypotheses H2a regarding depth variance, 40% of the sites reveal no significant difference between test and reference reaches (Table 5). Only 33% of sites show significant, expected results for H2a. I expected that at each site, the test reach would have greater depth variance than the reference reach. To explain these results, I considered whether vegetation and riverbed grain size may influence the effect of large wood on depth variability. When looking at substrates for the four sites with unexpected significant differences in terms of H2a, each reference reach had substrate characterized similar to the test reach (Appendix D). Two of the mentioned four sites, the HL US PALS1 and SB PALS sites, represent instances where the reference reach has thick subaquatic vegetation and deep pools, and locations where the subaquatic vegetation is shown on depth plots seems to correspond with shallower riverbeds, and adjacent pools with less vegetation (Figure 23; Figure 25c). At the four sites with unexpected significant differences, subaquatic vegetation seems to play a role in creating stable points within the river channel that divert flow to form adjacent pools.

A hypothesis was not formulated to propose how median depth would differ between test and reference reaches, but the metric was still investigated for additional data exploration. While 73% (11) of all sites showed a significant difference in median depth between reaches, the 11 sites did not have median depth results in a clear direction. Five (45%) of the 11 sites had greater median depth in the test reach and 6 (55%) of the 11 sites had lower median depth in the test reach (Table 5). Statistical results regarding median depth do not indicate a clear difference between test and reference reaches.

At all five sites in New Hampshire and Connecticut, the test reaches have more sand present than the reference reaches (Appendix D). Of the five sites, three (60%) show results expected with H2a. Two out of three sites with expected results in terms of H2a have large pools adjacent to the logjams. Sediment transport is a necessary component of scour and deposition. The availability of easily transportable sand may therefore play a role in influencing the channel alterations possible with large wood.

In terms of velocity, I expected that reaches containing large wood would have more variable (H2b) and lower median (H2c) velocities (Table 2). To have lower velocities within the test reaches, the average width and/or depth would have to increase, possibly in response to large wood structures, in comparison to the reference reach. Within the Narraguagus River, half of the sites have results expected with H2b, and none of the sites reveal unexpected results (Table 5). Of the five sites that show results expected with H2b, four sites reveal unexpected results with H2c. Of the five sites showing results expected with H2b, moderate to low gradient slopes (<1.0%) are seen at all five sites in the test and reference reaches (Table 5). None of the sites on the Narraguagus River display results expected with H2c. For the five other sites throughout New England, two sites show results unexpected with H2b, both of which also have expected results in terms of H2c. Where velocities were significantly more variable in the test reach, as expected with H2b, median velocities also tended to be higher, which is unexpected with H2c. All sites have moderate to low gradient slopes (<1.0%) within both the test and reference reaches (Table 5; Appendix E).

In reaches with large wood, I expected more variable sediment grain sizes (H2d; Appendix D). Of all 15 sites, five (33%) have more variability in the test reach substrate when compared to the reference, as expected with H2d (Appendix D). In contrast, two (13%) sites have less variability in the test reach substrate, which is unexpected with H2d. Results do not show large wood structures strongly influencing sediment grain size variability.

The grain sizes present are similar between test and reference reaches for eight (53%) of all 15 sites (Appendix D). The test reaches have presence of smaller grain sizes at five (33%) sites, two of which are on the Narraguagus River. Of the sites with smaller grain sizes in the test reach, three sites have considerably steeper slopes in the test reaches (28P test slope is 0.36%, reference slope is 0.17%; ATV PALS test slope is 0.24%, reference slope is 0.17%; CP test slope is 0.43%, reference slope is 0.32%; Table 5). Lastly, two (13%) sites on the Narraguagus River (ATV GH2 and SB PALS) have test reaches with larger grain sizes present than the reference reaches (Figure 23; Appendix D). At the two sites, the slopes within the test reaches are steeper than in the reference reaches (ATV GH2 test slope is 0.21%, reference slope is 0.16%; SB PALS test slope is 0.11%, reference slope is 0.07%; Table 5). Large grain sizes would be expected with a steeper slope, so the slope may help to explain the grain size results in this scenario. To explore grain size and variability of sediment more accurately, and make definitive statements, a quantitative analysis of river bed substrate is necessary.

I expected greater ratios of cover in test reaches compared to reference reaches (H2e). In terms of all forms of cover, including large wood, six (40%) of all 15 sites have greater ratios of cover in the test reach, as expected with H2e (Table 7). Seven (47%) sites have greater cover ratios in the reference reach, which is unexpected with H2e. The ratio of cover between test and reference reaches does not have a clear correlation with large wood structures. When only considering cover provided by large wood, the test reaches have greater cover than the reference reaches at all sites except two sites at which there is no large wood present in the middle cross section of the test reach (Table 7). These results indicate that a reach of river with newly added large wood will have more wood cover than a nearby reference reach with no wood. When considering all forms of cover though, results indicate that the rivers within this study are not lacking forms of cover other than wood, and adding large wood to the channels for the sole purpose of providing cover may not be effective.

Overall, only 33%, 33%, and 20% of surveyed sites are consistent with hypotheses H2a, H2b, and H2c, respectively (Table 5). With evidence for and against each hypothesis at both passive and active sites, large wood structures do not seem to consistently influence medians and variances of water depth and velocity. Danhoff and Huckins (2022) also found that in certain stream settings, large wood does not correlate with channel complexity. Abundance and volume of large wood within their studied rivers was inversely correlated with complexity. Danhoff and Huckins (2022) inferred that one of the reasons for their findings may be a lack of stream power in their rivers necessary for wood to create geomorphic change. The results at my sites, which are mostly low gradient, corroborate this interpretation. But my results also suggest that if sand and finer sediments are available in relatively low gradient rivers, there may be enough hydraulic energy around large wood to mobilize these sediments and generate the expected hydraulic and geomorphic changes. Sand-sized sediments also help mobilize gravel (Curran and Wilcock, 2005). The abundant supply of sand at the MVD site likely explains the geomorphic activity associated with large wood there, both in terms of ecogeomorphic metrics and floodplain development, despite its relatively low gradient (0.14% and 0.15% at the MVD06 test and reference reaches, respectively; Table 5). The Narraguagus River, on the other hand, also a relatively low gradient river (average slopes of 0.18% and 0.12% in the test and reference reaches, respectively; Table 5), has much more equivocal results and much less available sand. Sand that is mobilized in the system tends to become trapped in mainstem lakes (which are a legacy of past glaciation), or within patches of the subaquatic vegetation frequently observed there. Interestingly, in experiments done to understand the effects of large wood and vegetation on braided river systems, Mao et al. (2020) found that vegetation is more effective than large wood at creating a system of fewer and wider channels, and at increasing standard deviation of the bed elevation via scoured pools and sediment deposition. This suggests that subaquatic vegetation within the Narraguagus River may have a greater impact on the geomorphic and hydraulic attributes of the channel than the large wood structures.

4.3. Passive versus Active Wood Recruitment

For my thesis, I analyzed 15 sites throughout New England, of which only three (20%) sites are considered to have passive wood recruitment (Table 3). For the three passive recruitment sites, expected results are seen for hypotheses H2a, H2b, and H2c at two (67%), zero (0%), and two (67%) of all sites, respectively (Table 5). An unexpected result in terms of H2b is evident at one (33%) of the passive recruitment sites.

Regarding the 12 sites with active recruitment, expected results are seen for hypotheses H2a, H2b, and H2c at three (25%), five (42%), and one (8%) of all sites, respectively (Table 5). For hypotheses H2a-c, 42-58% of the sites reveal no significant difference between test and reference reaches. Significant differences tend to not have a clear direction.

The three passive sites are within the Souhegan River and Salmon Brook, both of which have a prominent availability of sand, which may explain the greater proportion of expected results for two of three hypotheses when compared to wood placement sites. To fully evaluate differences between passive and active wood recruitment, more passive and active wood recruitment sites with a wider variety of sediment grain sizes and supply would be necessary.

5. Conclusions

Evaluation of the MVD study site provided insight into the effects of instream wood in the northeastern U.S., and how these effects aligned with or differed from processes happening elsewhere. An important piece of this assessment was to determine whether the ‘floodplain large-wood cycle’ hypothesis was supported (Collins et al., 2012). I found evidence of the ‘floodplain large-wood cycle’ hypothesis at the MVD site because the large wood there induced sediment deposition and subsequent vegetation growth.

Expanding the knowledge of how large wood interacts with channel corridors has the potential to advance river restoration practices. Due to flow deflection and scour induced by large wood, I hypothesized that velocities, sediment grain sizes, and water depth would all be more variable in river reaches containing large wood, providing habitat complexity for Atlantic salmon and other cold-water fish.

Results do not clearly show large wood causing geomorphic or hydraulic impacts to the channels to support my hypotheses. A possible explanation for this may be a lack of mobile sediment at some of the rivers surveyed. Subaquatic vegetation may have also influenced the ability for large wood to alter the channel at one river. Consequently, river restoration practitioners should explore conditions at potential treatment sites to determine whether or not deliberately adding large wood to a channel is likely to achieve their objectives given site characteristics such as mobile sediment availability and stream power. In the northeastern United States, particularly where lakes reduce bedload supply downstream, river restoration projects that use large wood may have limited success at generating desired hydraulic or geomorphic responses, or restarting feedbacks such as the ‘floodplain large-wood cycle’, if the available sediments are not mobile at most flows because of local stream gradients.

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Appendix A: Literature Review

1. Introduction

This literature review analyzed the role of large wood (used interchangeably with the term “instream wood”) in channel change and stream restoration. First is an evaluation of criteria that instream wood at the Merrimack Village Dam (MVD) site must meet to confirm the creation of a fluvial landform consistent with the ‘floodplain large-wood cycle’ hypothesis (Collins et al., 2012). Then, metrics to be used within river restoration to guide intentional placement of large wood in channels is compiled and discussed.

At the MVD study site, instream wood has naturally been derived from an adjacent terrace. Evaluation of wood in this scenario can be used to identify processes induced by instream wood, and compare those to processes occurring at locations where large wood has been intentionally placed during engineered restorations.

As large wood is increasingly being used within river restoration projects throughout the northeast United States, it is crucial to ask the questions: What are the goals of this restoration, and is intentionally placed large wood producing desirable outcomes that align with those goals? To answer this question, clearly defined and quantifiable metrics need to be established.

2. 'Floodplain large-wood cycle' hypothesis

The 'floodplain large-wood cycle' hypothesis refers to a process in which large wood plays a geomorphic role in a river channel, and ultimately aids in the creation of a self-sustaining cycle (Collins et al, 2012). The process begins as large wood is recruited into a river, and becomes a stable hard point that induces the formation of a floodplain through sediment storage and flow redistribution. The newly formed floodplain then has the ability to grow trees, which can eventually be recruited into the river to initiate the cycle again.

At the Merrimack Village Dam (MVD) site in southern New Hampshire, 14 years of repeated surveys show deposition of sediment around instream wood, indicating the creation of a floodplain. It is therefore necessary to investigate whether or not the morphological changes are being induced by the large wood, and if the process aligns with the 'floodplain large-wood cycle' hypothesis.

To do so it is essential to analyze amounts and locations of scour, sediment accumulation on top of large wood hard points, grain sizes and elevation of surrounding sediment, erosion protection presence, and tree diameter in comparison to channel geometry (Collins et al., 2012). Large wood deemed key pieces stable enough to remain in the channel and accumulate smaller pieces around them typically are long, have large diameters, and have an associated rootwad. In the Nisqually River of Washington, key pieces had an average diameter of 1.0 m (Collins et al., 2012). Certain areas around the instream wood should experience lower amounts of shear stress, enabling the accumulation of sediment upstream or downstream of the key piece. Other areas, such as around the rootwad, will generate scour. The scour should then lead to the establishment of a pool upstream of the wood and deposition on top of and downstream of the tree trunk (Figure 1). Continuation of these processes will bury parts of the logjam, divert flow around the obstruction, and eventually lead to the formation of an island that may, in time, be incorporated into the adjacent floodplain (Bierman and Montgomery, 2019).

Depending on the region, whether large wood becomes stable depends on the river channel width, depth and slope, as well as specific piece dimensions, such as length, maximum diameter, growth form and rate, shade and flood tolerance, life span, and reproductive strategies (Collins et al., 2012). Since removing wood from rivers can simplify the channel, hypothesized geomorphic effects of the instream wood at the MVD may lead to more a more complex river corridor with diverse habitats and vegetation ages (Figure 2; Beechie et al., 2006)

3. River restoration

Humans have impacted our planet and its environments for thousands of years, so much so that all terrestrial landscapes that exist today have been directly or indirectly affected by human activities (Wohl, 2020). Throughout this anthropogenic history, engineers have altered rivers in several ways, including but not limited to, building dams, channelization, levee construction and wood removal. Here, I focus on the removal of large wood from rivers and surrounding floodplains. Historically, wood removal was carried out in scenarios such as deforestation or removal from the channel for navigation and flood conveyance (Abbe and Brooks, 2013). Removal of large wood from river corridors ultimately caused channels to lose complexity in terms of physical form and ecological function, and severely depleted the sources of wood available for recruitment by the river.

Many times, river restoration is done in response to anthropogenic influences, and aims to return the river to a more natural state. The practice of river restoration relates to the modification of river corridors and inputs such as water and sediment (Wohl et al., 2015). A current issue within the field of river restoration revolves around the definition of reference conditions. Reference conditions usually refer to the state of a river system before it was influenced in any way by humans. In a particular location, these conditions can be useful in order to keep in mind the history of the channel, and what processes the system may be capable of achieving again. Reference conditions should not always be sought out though, especially when anthropogenic influences have changed the surrounding environment enough, and when climate change is taken into consideration. Rivers now need to be restored to be resilient in the face of a changing climate, and handle conditions they have not encountered in the past, such as increased runoff from impervious surfaces due to urbanization (Wohl, 2020).

3.1. Goals of restoration

Since returning rivers to the state of reference conditions is not always practical or beneficial, oftentimes river restoration practices instead focus on a few desired objectives. Some common goals of river restoration include bank stabilization, fish passage, dam removal, and instream habitat improvement (Table 1; Wohl et. al, 2015). More recently, restorations have shifted toward a process-based approach, such as floodplain reconnection, rather than focusing efforts on channel form.

Oftentimes, evaluation of process-based restoration is done by recognizing how biotic organisms respond. To do so, monitoring must be prioritized and continued after any project implementation is completed. Effectiveness monitoring should be used to determine if project goals were reached, and to provide data to inform future projects (Skidmore et al., 2011). Although there are a lack of studies done on results of restoration overall, some that have been carried out have found a large number of projects resulting in low quality habitats (Palmer and Hondula, 2014). A few persistent issues occurring within restoration include the difficulty in quantifying the success or failure of certain restoration objectives, and the significant number of restorations that are measured based on metrics such as water quality, yet fail to improve river function (Wohl et al., 2015).

If dam removal is carried out to improve fish passage, the critical metric to evaluate would be whether or not the number of fish travelling through river reaches is greater than before restoration. If large wood is used to adjust the form or function of a river channel in certain ways, metrics to assess include topography induced by the instream wood, ways in which river structure changes over time, and flow velocities within the channel. If biotic diversity is the goal, habitats need to be evaluated in terms of spatial variability, and number of species present compared to pre-restoration conditions. Using sustainability as a metric of restoration is important because it highlights the importance of river dynamics and diversity for resilience and recovery (Wohl et al. 2015)

4. Large wood metrics for restoration

Research involving the effects of large wood on river systems primarily began in the Pacific Northwest region of North America (Wohl, 2020). Since then most previous studies of large wood and floodplain restorations have focused on biomes specific to states such as Washington and Colorado (Collins et al, 2012; Wohl and Beckman, 2014). Nevertheless, large wood is being used all throughout the United States. This invokes concern about which practices in relation to the addition of large wood to a channel will be successful, and what monitoring practices will be done after the restoration.

Research that has been done on large wood is hindered by the lack of a set of common metrics to make seamless comparisons between studies. Inconsistencies in variables quantified and measurement methods used make it difficult to recognize large wood patterns occurring across multiple experiments (Wohl et al., 2010). Based on a synthesis of previous studies and field work, measurable variables for large wood fall into one of the following categories: wood, geomorphic, and riparian (Table 2). Within each category, variables can be considered either level I or level II. Level I metrics should be evaluated in every study done on large wood, while level II metrics just need to be estimated when studies have more specific goals (Wohl et al., 2010).

Metrics in the “wood” category, such as wood diameter and rootwad presence, relate to dimensions, orientation, and characteristics of each piece of instream wood. Study-specific parameters include noting the tree species and age. For dimensional metrics, suggestions are made for how to record data to ensure uniformity across studies. For example, wood diameter should be measured at both ends of each piece of wood to more accurately calculate volumes.

Since some studies may have multiple sections of a channel that are not continuous (reaches), "geomorphic" metrics are measured separately for each channel reach. Geomorphic metrics relate to channel and valley dimensions and characteristics. Examples include sediment grain size, channel morphology, drainage area, and flow depth. For certain studies, estimating the amount of bank scour in relation to the total length of the stream bank may also be beneficial.

Metrics falling under the "riparian" category are also measured separately for each channel reach within the study. These measurements refer to the ecological attributes of the adjacent floodplains and riparian zones. The only metric to fall under the level I category is noting whether the study site is forested, and expanding with tree and cover types (Wohl et al., 2010).

Overall, it is critical to agree on objectives for a restoration project, and choose metrics that can be used to assess the success of the particular goals. Metrics should be clear and quantifiable, and encompass an appropriate scale. For example, biological indicators should be measured at habitat units, while floodplain connectivity, and lateral channel migration should be measured at the reach scale. Larger spanning metrics can also be measured at the watershed scale, such as hydrologic and sediment processes. The determined outcomes of the restoration need to evaluate not only the physical and ecological functions of the river, but also effects on surrounding floodplains and watershed areas (Skidmore et. al, 2011).

4.1. Stability

Stability is required for the successful use of large wood in many restoration circumstances, such as bank stabilization, yet hesitance still exists surrounding the potential for logjams to become a hazard. If not placed effectively, instream wood can become mobilized and potentially cause destruction downstream. It is especially concerning if large wood anchored with non-natural fixtures, such as wires and piles, becomes unstable. However, some studies have presented evidence that large wood that is dynamic and unanchored can be used in line with river processes to benefit river efforts (Roni et al., 2014). With that, it is important to understand factors that make large wood stable or not. When stable, large wood has important long-term benefits such as acting as a hard point in a channel to resist erosion and limit channel migration. This can be advantageous for establishment of floodplains, bank stabilization, or formation of meander bends.

The Wood Jam Dynamics Database and Assessment Model (WooDDAM), which assesses how a logjam may change through time, was created to make the act of placing large wood for restoration purposes more predictable, and therefore safer (Scott et al., 2019). The WooDDAM model provides a survey protocol for assessing wood jams that aims to be practical for use by individuals researching or conducting river restoration projects. To do so, metrics were created that can be collected in under 15 minutes with two individuals using a camera, survey equipment, and a GPS (Table 3). All of the metrics fall into one of the following categories in relation to the measurement type they best describe: hydrologic regime, reach-scale valley bottom characteristics, location and geometry of the jam, channel geometry, and physical characteristics of the jam (Scott et al., 2019). Measurements in the hydrologic regime category answer yes or no questions about typical flow events for the specific river being evaluated. Reach-scale valley bottom characteristics quantify sediment size, channel form, and the relationship between the channel and adjacent floodplains. Location and geometry of the jam answers yes or no questions about how the jam is situated in the channel, such as whether or not key pieces touch the channel bank, and how the wood jam is oriented in relation to the direction of river flow. The area around where the wood is located within the river is essential to note because existing boulders or river banks can help with stability. With this assessment, crucial questions to ask are: can the wood rise above the obstruction during high flows or break in any circumstance? (Abbe and Brooks, 2013). The channel geometry category aims to determine the slope of the channel and bankfull flow dimensions (Figure 3). Lastly, physical characteristics of the jam include the measurement of specific attributes such as the type of wood within the jam, whether or not rootwads are present, the density of the jam, and any geomorphic outcomes, such as pools and scour.

Engineered logjams should be designed to resist forces such as drag, vertical lift, and buoyancy forces (Figure 4). Naturally recruited wood should also be assessed for the possibility of instability to determine the potential for longevity in the channel. The metrics that need to be measured in order to account for these forces include the water velocity, the surface area of wood that is perpendicular to flow, height of the water surface, and volume of wood within a jam (Abbe and Brooks, 2013).

4.2. Geomorphic functions

Large wood can be useful to facilitate the establishment of numerous geomorphic functions. If a central goal of restoration is channel reconfiguration, large wood can be used to induce meander bends and alter the channel planform or geometry (Figure 5). In the case of desired floodplain reconnection, objectives are focused on increasing the frequency and depth of surrounding floodplain inundation (Wohl et al., 2015). Instream wood creating an elevated landform can be useful to divert water onto the floodplains during high flow events.

A study assessing several 3rd-4th order streams aimed to determine the extent of large wood in Downeast Maine, and what types of geomorphic functions the wood was providing to the river channels (Magilligan et al., 2008). To do so, many measurements were taken, including individual wood piece measurements such as diameter and length, position of the wood within the channel and in relation to the bankfull height, orientation, and type of wood (Figure 6). Measurements taken for logjams included the overall size, orientation of pieces, position in the channel, and total number of pieces within the jam. Magilligan et al. (2008) also observed indications of sediment storage or pool formation induced by instream wood. General measurements to describe the channel and watershed (longitudinal profile, channel gradient, and watershed drainage area) were noted as well.

How the large wood is oriented in relation to river flow within the channel plays a crucial role in the formation of pools and the storage of sediment (Figure 7; Magilligan et al., 2008). The study found that most instream wood pieces were oriented parallel to the flow or angled with rootwads facing upstream. These observed orientations resulted in a minimal number of pools, and only 5-20% of wood inducing sediment storage, which contrasts finding by Abbe and Brooks (2013; Figure 1).

The presence of a rootwad attached to a piece of instream wood is extremely beneficial for stability. Snags are most stable when the rootwad is facing upstream and the wood tip is pointed downstream. This configuration allows water flow to reroute around the wad and create eddies that will help bury portions of the rootwad and make it more stable. Once the wood is stable, this diversion of flow continues, allowing for the entrapment of sediment and debris that will help induce floodplain formation. Rootwads are important for influencing the center of mass of a piece of large wood, increasing force against the streambed, and acting as an obstruction to divert flow and create scour (Abbe and Brooks, 2013). To determine the stability of a rootwad on a certain piece of wood, some key measurements to record include the radius of the rootwad versus the wood itself, the trunk volume, relative water surface height, and river flow. The water depth and flow characteristics play key roles in determining the buoyant forces acting against the instream wood. Bed roughness is also critical to calculate resistant forces that may help to stabilize the wood (Abbe and Brooks, 2013).

4.3. Ecological Function

There are various ways in which instream wood has the ability to increase and diversify ecological functions and habitats within a river corridor. Although quantifying ecological performance is generally less straightforward than measuring physical properties, previous researchers have documented several useful ecological indicators. Measurable variables include water quality values (turbidity, dissolved nutrients, pH), and responses by periphyton (i.e., bacteria and algae), macroinvertebrates, fish, and other indicator species (USBR & ERDC, 2016).

The project may be considered a success then if it results in an increase in advantageous features per habitat unit (100 square meters) over time (National Research Council, 2004). It is important to quantify relevant metrics in order to assess the success of goals. For instance, in terms of fish, rivers including large wood should focus on factors such as the capability for fish passage around the wood, gravel for spawning, cover, creation of pools, and any other morphological adjustments. Less important metrics for this goal included measuring damage, movement or rotation of the wood. While these factors impact stability, the outcome of increased habitat can still be reached (Skidmore et al., 2011).

In certain areas around a logjam, wood should be providing a zone of decreased shear stress where smaller grain sizes can remain in place. The diversity of sediment grain sizes within a river can provide additional habitats for aquatic organisms. Therefore, it is important to measure locations of scour and sediment build up when assessing the functionality of a jam (Abbe and Brooks, 2013).

Along with this, amounts of surface area for a piece of wood and of the total logjam are key factors in creating increased habitats. While a large stable log is necessary to begin jam formation, additional smaller pieces of wood that get trapped within the jam are vital to create a diverse riverine ecosystem (Abbe and Brooks, 2013). In terms of habitat diversity, the number and size of features such as pools and bars should also be quantified, along with how much of the jam is below the bankfull water surface versus above the surface. Complementing submerged large wood pieces that provide habitat and protection for fish, wood above the surface creates habitat for birds and mammals, and access to the river for predators (Abbe and Brooks, 2013).

4.4. Atlantic salmon habitat

To dive deeper into specifics for habitat assessment, studies done in relation to Atlantic salmon (*Salmo salar*) habitat will be analyzed. The decline of Atlantic salmon in the northeastern U.S. likely stems from a combination of many anthropogenic actions. Activities such as logging, wood removal from rivers, and river channelization simplified stream reaches throughout eastern North America (MacInnis et al., 2008). Simplified rivers with less or no wood loads are thought to have hindered Atlantic salmon in their pursuits to find ideal habitats for rearing and spawning. In order to recover a declining population in Maine, ongoing restoration efforts use large wood to increase salmon habitats. Since conservation has continued for over 140 years, it is crucial to determine the effectiveness of current restoration practices (National Research Council, 2004).

For Atlantic salmon to thrive, rivers require habitat complexity to cater to all stages of their life cycles (Table 4). Salmon need cool water temperatures, places to hide from predators, access throughout the river for migration, and mobile gravel beds that can be used for spawning. Large wood is therefore a beneficial tool to use in order to provide suitable salmon habitat. Instream wood can create pools and cover for protection from predators, provide shade to regulate water temperatures, scour away fine sediments, and ultimately diversify the river environment (Dolloff and Warren, 2003). Many restoration efforts being carried out in Maine are using large wood to improve Atlantic salmon habitat, meaning that it is essential to define measurable metrics to evaluate whether the created habitats are actually preferred by the fish.

A study done in Nova Scotia looked at multiple reaches of Brierly Brook, a third-order tributary, to compare available Atlantic salmon habitat in sections restored using large wood versus unrestored sections lacking large wood. To induce a riffle-pool sequence, large wood was placed in a way that formed pools every five to seven bank-full river widths (MacInnis et al., 2008). Then, in order to quantify the habitat being used for spawning, redds (a depression created by salmon in the riverbed used to lay eggs) were counted multiple times per week for the duration of spawning season. Within Brierly Brook, the study noted an increase in Atlantic salmon spawning following restoration efforts, finding redds associated with pools, and both intentionally placed and naturally occurring large wood. Locations with either artificial and natural instream wood were chosen first for spawning, and stream reaches with large wood had more redds overall than reaches without (MacInnis et al., 2008). This indicates that if a restoration goal is to increase Atlantic salmon spawning habitat, creating riffle-pool sequences should be prioritized.

Overall, ideal habitat within Brierly Brook consisted of a few key features, including reaches with a meandering planform that exhibited a riffle-pool sequence, were somewhat narrow, and had adequate shade. Grain sizes of gravel or cobble that were not covered by silt or sand were favored by Atlantic salmon, along with vegetated banks, a mature forest in the adjacent riparian zone, and plenty of large wood (MacInnis et al., 2008).

Another study conducted in coastal Maine and northern New Brunswick, Canada, that looked more closely at sediment aimed to predict potential Atlantic salmon habitat locations using the relationship between salmon and preferred riverbed grain size (Figure 8). Favorable conditions for rearing habitat include median grain sizes of 16-256 mm, 0.5-0.75 m/s flow velocities, water depths of 17-26 cm, and loosely packed bed materials (Hendry and Cragg-Hine, 1997; Hendry and Cragg-Hine, 2003). Ideal habitat for salmon during the spawning phase of their lives includes gravel sediments on the riverbed that are mobilized often, which can be estimated by calculating bed shear stress and Shields parameter. Along with this, a median grain size (D50) of between 16 mm and 64 mm is suitable for red creation (Warner, 1963; Hendry and Cragg-Hine, 1997).

A study focused in Vermont assessed 3rd- and 4th-order streams to predict favorable conditions for salmon during the first spring and summer of their lives. Salmon rearing habitats are generally shallow areas consisting of coarse gravel, cobbles, and small boulders (Nislow et al., 1999). To keep the study consistent, all the streams used did not have riffle-pool structures, and water temperature and turbidity were similar. Water temperatures ranged between 14.1ºC and 15.4ºC.

Assessment of available habitat within the studied rivers was done by first measuring currents speeds at different locations and depths. Then, a snorkel survey was conducted to determine which areas the young salmon were occupying. For this portion of the study, results concluded that in spring months, salmon prefer slower current velocities (0.08-0.18 m/s with a predicted optimal velocity of 0.127 m/s), while faster velocities (0.21-0.57 m/s) were preferred in summer months (Table 5; Nislow et al., 1999).

The study also aimed to determine if microhabitats preferred by salmon were successfully being created by instream structure additions. In four different streams, channel reaches with large wood were compared to reaches without intentionally placed structures. Large wood placement in streams revealed an increase in the number of available microhabitats that salmon prefer during spring months. Instream wood decreased surrounding current speeds and created deeper microhabitats for salmon to reside. To enable conservation of energy, early-season (spring) Atlantic salmon favored the slower velocities induced by the large wood. During the late season (summer), salmon also want to minimize risks related to predation, which leads to a strong preference for the deeper microhabitats (Table 6; Nislow et al., 1999).

Benthic samples were also collected to assess whether or not instream wood increased the number of invertebrates common in salmon diets. In this specific study, more benthic organisms overall were found in the reaches containing large wood, but no difference was observed in the number of organisms specifically important for salmon. Sediment size, overhead cover, and stream width also did not differ between reaches with and without the instream structures.

Overall, restoration should focus on creating microhabitats preferred by early-season Atlantic salmon to improve survival rates (Nislow et al., 1999). In this study, the intentional placement of large instream structures did improve early-season habitats for young salmon, and therefore should be beneficial to restoration practices.

4.5. Floodplain restoration and sustainability

A desire to expand the knowledge of large wood distribution within northeastern US streams prompted a study located throughout New Hampshire's White Mountains and the Adirondacks, New York. Most streams represented secondary forests, which occur after clear-cutting of forests or land abandonment (Warren et al., 2009). It is worth noting that these disturbances were done in the past, but are no longer actively taking place. In reference to the surrounding riparian area, criteria measured during the study included dominant tree species, average basal area, and average tree age determined by tree-ring dating.

Forest regeneration must address the specific species of trees since certain species grow larger more quickly, but others are more durable in jams (Collins and Montgomery, 2002). Characteristics of different types of trees also influence the way a piece of wood will act when introduced within a river channel. To ensure forces are estimated correctly for a certain wood type, it is necessary to determine the volume, weight, moisture content, and specific gravity of the wood in question (Abbe and Brooks, 2013). The type of tree is also relevant because the majority of the time in streams, hardwoods (with some exceptions such as oaks) decay quicker than conifers (Warren et al., 2009). The biogeochemical stability of wood relates to the process of decay for specific pieces of large wood being considered. Although decaying wood becomes weaker and less stable over time, wood that is continuously saturated can be preserved for long periods. Along with how much of the wood is located above versus below the water surface, type of wood, ratio of wood surface to volume, and size of the large wood all impact the rate of decay. Forest decay coefficients corresponding to specific tree species can be used alongside the present log mass to determine what the mass of the log will be in the future (Abbe and Brooks, 2013). Large wood intentionally placed in rivers should be designed so that its lifespan exceeds the time it takes for growth of wood on adjacent floodplains to reach sufficient size and then be recruited into the channel.

General stream dimensions, such as mean bankfull width, watershed area, and stream gradient were also quantified during the study (Warren et al., 2009). Measurements pertaining to instream wood involved piece length, diameter, and volume of wood within the bankfull channel. Wood jams were assessed only if they provided functional processes, such as entrainment of sediment, flow diversion, or organic matter retention. If this standard was met, the number of pieces and dimensions of the accumulation were recorded.

Overall patterns examined as a result of measured variables within the channel were large wood volume, large wood frequency, large log (>30 cm) frequency, and wood jam frequency (Warren et al., 2009). Results indicated that the most important metric positively influencing all of the mentioned variables was riparian forest age (Figure 9). This conclusion highlights the importance of forest restoration and promotion of old-growth forests alongside the use of large wood during river restoration to ensure long-term wood recruitment.

While engineered jams can be beneficial in the short term to create pools and provide channel diversity, if the ultimate project objectives revolve around the creation of a self-sustaining river, then an emphasis must be placed on establishing riparian forests. Early stages of restoration should include engineered jams and reforestation of the riparian zone, which would include planting trees that can become large quickly (Table

7). These trees can then be recruited to the river, and act as key pieces for logjams while slower-growing tree species are left to mature. Doing so provides the river system with available large wood that can be recruited and form jams (Collins and Montgomery, 2002). Criteria needs to assess whether or not wood currently in the channel will remain for a long time, and if the floodplain is being restored in a way that will provide large wood to the river in the future.

Surveying the surrounding riparian area to determine recruitment potential for the adjacent floodplain includes measurements such as diameter at breast height of living trees, tree species, distance of trees from the bankfull width, and decay stage. Even if the adjacent floodplain currently lacks large wood available for recruitment, management practices and regulations may actually increase amounts of large wood accessible to the river in the future (Magilligan et al., 2008).

5. Conclusion

Large wood can be used within the practice of river restoration to provide numerous benefits to river systems. To ensure that the application of instream wood is appropriate and worthwhile, metrics to measure its effectiveness must be determined and agreed upon. Variables to be measured should be clearly defined, quantifiable, and aligned with overall project goals.

This literature review has provided examples of several metrics that can be used alongside the intentional placement of large wood (Table 8). For the scope of my thesis, in which several metrics will be measure at field location throughout New England, the extensive list of metrics was narrowed down to the following:

- Individual wood piece dimensions and description (orientation, location, rootwad)
- Logjam dimensions
- Scour: amounts, locations
- Sediment: amounts, locations, substrate characterization
- Pool formation: depth, frequency
- Water velocities
- Channel geometry

At the MVD study site, the metrics measured helped determine whether large wood present at the site has induced processes detailed by the ‘floodplain large-wood cycle’ hypothesis (Collins et al., 2012). These measurements provide valuable information about processes capable of occurring in New England due to the presence of instream wood.

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Figures

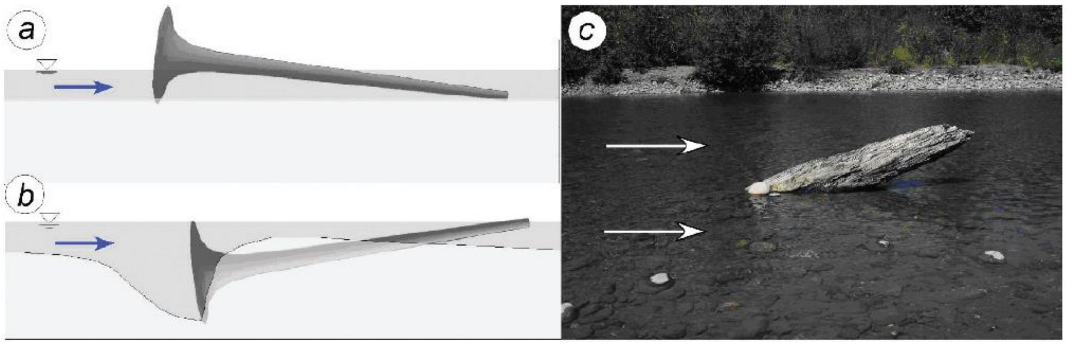


Figure 1. The process of (A) large wood becoming stable in a river channel, and (B) inducing a scour pool upstream and sediment deposition downstream until burial. (C) An example of a buried piece of instream wood partially exposed above the water surface. Arrows indicated direction of water flow (Abbe and Brooks, 2013).

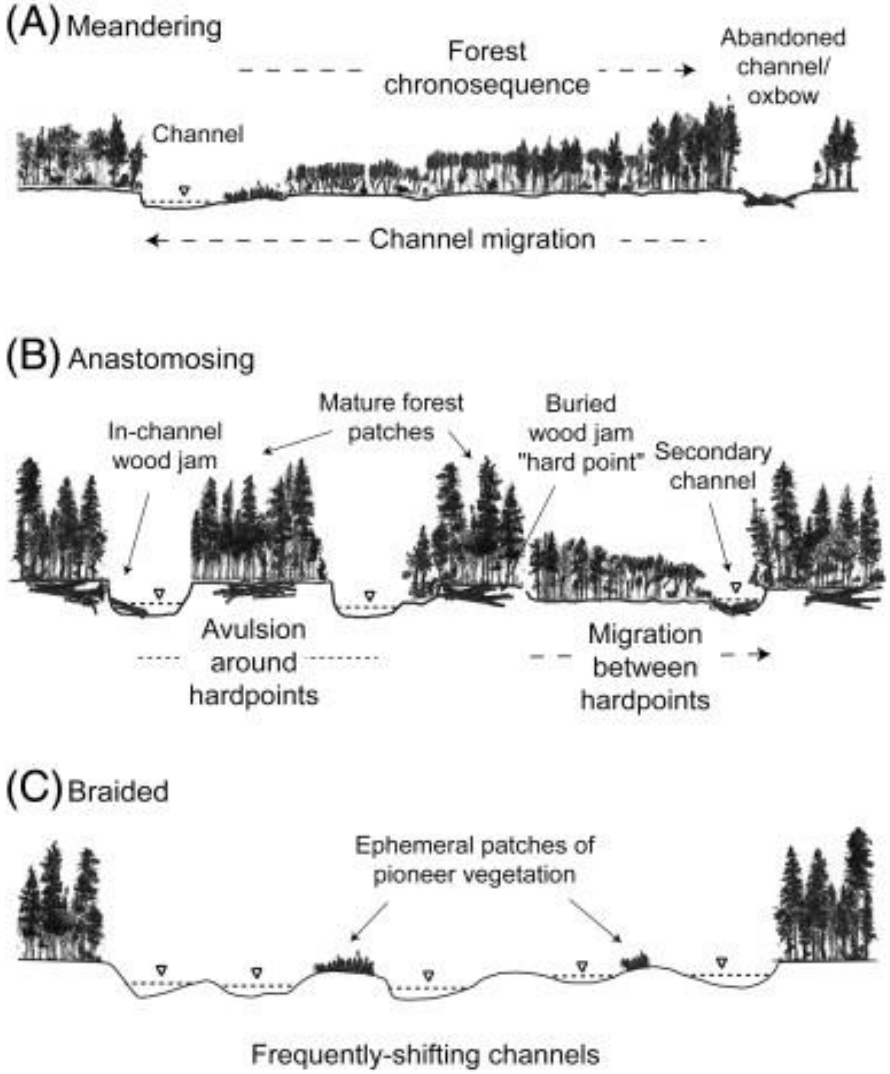


Figure 2. Forest ages and patterns for three types of river channel planforms. (A) In meandering channels, forest age is determined by meander migration rates across the floodplains. (B) Anastomosing channels consisting of floodplain islands induced by stable pieces of large wood have forest patches with a larger diversity of ages. Forest ages depend on stability of the patches. (C) Due to frequent mobility, braided rivers consist mainly of ephemeral patches of vegetation within the channel boundaries (Collins et al., 2012).

Table 1. Common goals for river restoration projects (Wohl et al., 2015).

Goal	Description
Esthetics/recreation/education	Activities that increase community value: use, appearance, access, safety, and knowledge
Bank stabilization	Practices designed to reduce or eliminate erosion or slumping of bank material into the river channel; this category does not include stormwater management
Channel reconfiguration	Alteration of channel geometry, planform, and/or longitudinal profile and/or daylighting (converting pipes or culverts to open channels); includes meander restoration and in-channel structures that alter the thalweg
Dam removal/retrofit	Removal of dams and weirs or modifications/retrofits to existing dams to reduce negative impacts; excludes dam modifications that are simply for improving fish passage
Fish passage	Removal of barriers to upstream/downstream migration of fishes; includes the physical removal of barriers, construction of alternative pathways, and migration barriers placed at strategic locations along streams to prevent undesirable species from accessing upstream areas
Floodplain reconnection	Practices that increase the inundation frequency, magnitude, or duration of floodplain areas and/or promote fluxes of organisms and materials between channels and floodplain areas
Flow modification	Practices that alter the timing and delivery of water quantity (does not stormwater management); typically but not necessarily associated with releases from impoundments and constructed flow regulators
Instream habitat improvement	Altering structural complexity to increase habitat availability and diversity for target organisms and provision of breeding habitat and refugia from disturbance and predation
Instream species management	Practices that directly alter aquatic native species distribution and abundance through the addition (stocking) or translocation of animal and plant species and/or removal of exotic species; excludes physical manipulations of habitat/breeding territory
Land acquisition	Practices that obtain lease/title/easements for streamside land for the explicit purpose of preservation or removal of impacting agents and/or to facilitate future restoration projects

Table 2. Suggested metrics to be measured when completing research related to instream wood (Wohl et. al., 2010).

Levels	Notes
Wood – measured for each piece	
Level I	*Notes*
1. Length	Whole piece and length in bankfull channel
2. Diameter	≥1 measurement
3. Orientation	Angle with respect to downstream bank
4. Root wad	Note if present, including orientation with respect to flow
5. Jams	Spatial distribution and size (no. pieces per jam, or total dimensions of jam)
6. Accumulation[a]	11 categories
7. Status[b,c]	Decay class (six categories), burn status (three categories)
8. Stability[d]	Six categories
Level II	
9. Species	Note species or general category (e.g., deciduous/coniferous)
10. Submergence	Measure in relation to stage
11. Age	Tree-ring counting or radiocarbon dates
12. Biomass/density	Based on volume and wood density
13. Function	Characteristics of wood function include sediment storage (note if present; ideally, measure dimensions and grain size), pool scour (note if present; ideally, measure dimensions), backwater pools (note if present; ideally, measure dimensions), flow deflection, energy dissipation, and bank stabilization
Geomorphic (channel and valley) – measured for each reach	
Level I	
1. Channel gradient	Average streambed or water-surface gradient at study reach
2. Channel width	Average bankfull channel width at study reach
3. Flow depth	Either bankfull or at time of measurement
4. Grain size	Bed-material size distribution; D_{50} and sorting at minimum
5. Discharge	Bankfull, mean annual, peak annual, or at time of measurement
6. Reach length	Length of channel along which wood is measured
7. Channel morphology	Cascade, step-pool, plane-bed, pool-riffle, dune-ripple, braided
8. Drainage area	Area drained by study reach
9. Elevation	At study reach, and range for catchment
10. Valley side slope	Average or maximum side slope values
11. Confinement	Ratio of channel width/valley-bottom width
12. Connectedness	Ratio of channel width/distance to valley wall
13. Disturbance history	Wildfire, blowdown, insect infestation, hillslope mass movements, avalanches
14. Management history	Timber harvest, percent roaded, tie-driven, dams, diversions, etc.
Level II	
15. Bank scour	Visual estimate of percentage of total stream bank length
Riparian – measured for each reach	
Level I	
1. Forested	Yes/no, deciduous/conifer, note cover type if not forested (e.g., willow or herbaceous dominated meadow, bedrock)
Level II	
2. Dominant species	Where forested, note forest type(s)/species of trees
3. Source[e]	Six categories
4. Seral stage	Young, mid-successional, or mature
5. Floodplain survey	Dimensions and spatial density of wood on forest floor
6. Basal area	Measure of the cross-sectional area of standing trees at breast height (may be measured by species)
7. Site potential	Rate of tree growth, time to reach maturity, longevity of trees

Note: Level I lists metrics that we propose should be included in all studies; Level II lists those metrics that are more study-specific.

[a] Accumulation classes: debris jam (part of a jam of three or more pieces), tree/rootwad (associated with a living tree or rootwad), boulder (associated with a boulder in the stream), meander (caught on the outside of a bend), bar (sitting on a point, alternate, or mid-stream bar), bedrock (caught on bedrock), beaver dam (incorporated in a beaver dam), bank (embedded in the bank, buried by soil or other bank materials), log step (forms a step in the stream, can be partially buried in streambed or not buried), buried in bed (portion of log buried in streambed, but not functioning as a step), none/other (specify if something else). A piece can have more than one class.

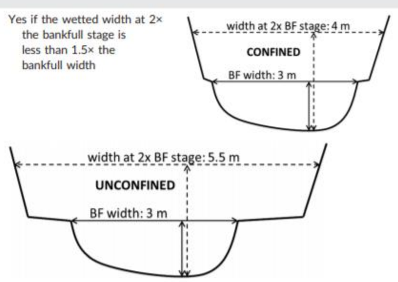
[b] Decay classes: rotten (very soft wood that can be pulled apart easily by hand), decayed (moderately soft wood that cannot be pulled apart easily), bare (no bark or most bark is gone), limbs (limbs still attached, may have most or all bark intact), bark (all bark intact, a relatively new piece of wood), needles/leaves (green or brown needles/leaves still attached, very fresh piece of wood, tree may appear to be living).

[c] Burn classes: unburned, partially burned, completely burned.

[d] Stability classes: unattached/drift (entire piece is contained within bankfull channel and no portion is buried or pinned), bridge (both ends above bankfull channel, center suspended above channel), collapsed bridge (two ends above bankfull channel, broken in middle), ramp (one end in channel, the other end above bankfull channel), pinned (all or a portion is lodged beneath other pieces of wood in the stream), buried (all or a portion is buried in the streambed).

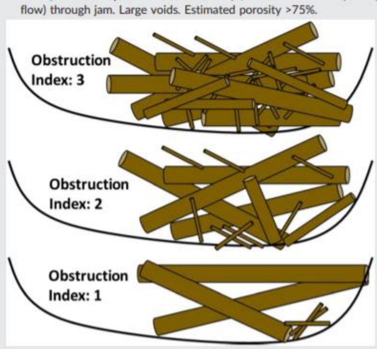
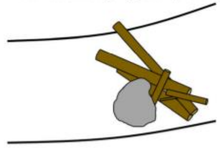
[e] Source classes: unknown (source of wood cannot be determined), riparian (sources of wood appears to be valley bottom adjacent to the channel), hillslope (wood originates from a steeper landform adjacent to the valley bottom; either a depositional feature such as a moraine, or the valley wall), floated (fluvial transport from upstream), hillslope mass movement/debris flow, avalanche (recruitment via moving snow), bank undercutting, other (other clearly defined source such as debris flow; explained in comments section).

Table 3. Metrics to quantify when using WooDDAM (Scott et al., 2019).

Measurement	Database variable ID	Unit	Description	Justification
River	river		Full name of river	
Jam number	jam_num		One unique number per jam in a stream.	
Survey number	survey_num		Denotes whether an observation represents an initial survey (survey_num = 1) or a repeat survey (survey_num > 1)	
Descriptive location	loc_descriptive		Location relative to noticeable landmarks and position in channel (e.g., left or right bank)	
Latitude	lat		Decimal degrees, e.g., "± ###.#########"	
Longitude	lon		Decimal degrees, e.g., "± ###.#########"	
Perennial?	perennial	y, n	Yes if the stream experiences surface flow year-round on an average water year	Indicates whether live woody vegetation may establish in channel and potentially stabilize wood jams (Dunkerley, 2014; Opperman, Meleason, Francis, & Davies-Colley, 2008; Opperman & Merenlender 2007)
Flashy?	flashy	y, n	Yes if high flow events involve rapid increases in flow stage (e.g., low flow to bankfull in less than 24 hr)	Wood jam structure may behave differently under rapid versus slowly rising high flows, altering porosity and resulting drag force on jam. Flashy streams may be more likely to mobilize wood than non-flashy streams (Braudrick, Grant, Ishikawa, & Ikeda, 1997; Kramer & Wohl, 2016).
Sustained peaks?	sustained_peaks	y, n	Yes if high flow events are characterized by durations over approximately one week	Sustained high flow may result in greater rearrangement of jam structure influencing porosity and resulting drag force (Kramer & Wohl, 2016)
Ice jams?	ice_jams	y, n	Yes if in a typical water year, the river transports enough large ice pieces to cause ice jams in the reach surrounding the wood jam	Ice jam breakup floods can be more erosive than non-ice floods (Prowse & Culp, 2003; Rood, Goater, Mahoney, Pearce, & Smith, 2007) and car transport large amounts of wood, even at low flows (Boivin, Buffin-Bélanger, & Piégay, 2017).
Melt-driven?	melt_driven	y, n	Yes if in a typical water year, high flows are driven by the melt of snow or glacial ice	Diurnal flow fluctuations from melt flows can lead to substantial packing of jam material, reducing porosity.
Bankfull depth	bfd	metres	Bankfull depth that best characterizes the reach around the jam (see solid vertical line in confinement diagram below)	Provides information on hydraulic forces exerted on jam by high flow
Bankfull width	bfw	metres	Bankfull width that best characterizes the reach around the jam (see solid horizontal line in confinement diagram below)	
Local slope	s_percent	%	From above to below sediment wedge behind wood jam, or the slope that best characterizes the reach around the jam	
Visual clast size	clast_size	s, g, c, b, br	Visual estimate of dominant clast size on bed in reach surrounding jam: Sand [s] (<2 mm), Gravel [g] (2–64 mm), Cobbles [c] (64–256 mm), Boulders [b] (>256 mm), Bedrock [br]	Indicates channel roughness and relative energy level
Bedform	bedform	sb, pr, pb, sp, c	from Montgomery and Buffington (1997): sand bed [sb], pool-riffle [pr], plane-bed [pb], step-pool [sp], cascade [c]	
Planform	planform	s, m, a, b	Straight if one channel and sinuosity <1.5 [S], meandering if one channel and sinuosity >1.5 and evidence of migration (point bars, cut banks) [m], anastomosing if multiple channels and vegetated islands [a], braided if multiple channels and non/sparsely vegetated islands [b].	
Isolated?	isolated	y, n	Yes if no wood surrounding jam within sight or 5 channel widths upstream/ downstream, whichever is shorter	Wood load can relate to wood transport capacity (Kramer & Wohl, 2016); isolated wood jams may be less stable.
In side channel?	side_channel	y, n	Yes if bulk of wood resides in a channel with approximately less than half the cross-sectional area at bankfull flow of the main channel	Indicates relative channel transport capacity
Floodplain present?	fp_present	y, n	Yes if floodplain surface exists within valley near jam	Indicates rate of change in transport capacity as flow increases above bankfull (Wohl, 2011)
Confined?	confined	y, n	Yes if the wetted width at 2× the bankfull stage is less than 1.5× the bankfull width 	
Touches bed?	touch_bed	y, n	Yes if any key pieces touch channel bed	Describes jam geometry (Figure 1) and key piece interactions with valley bottom morphology that can influence stability (Davidson, MacKenzie, & Eaton, 2015)
Touches banks?	touch_bank	y, n	Yes if any key pieces touch channel bank	
Touches floodplain surface?	touch_fp	y, n	Yes if any key pieces of the jam contact floodplain surface (including woody vegetated bar tops in anastamosing channels)	
Touches valley wall?	touch_valley_wall	y, n	Yes if any key pieces of the jam contact valley wall surface (including terraces and objects fixed to valley wall like trees, stumps, infrastructure, etc.)	
Touches outer bend?	touch_outer	y, n	Yes if any key pieces of the jam contact the outer bend of the channel. If no outer bend exists (e.g., straight channel) this must be no.	
Touches inner bend?	touch_inner	y, n	Yes if any key pieces of the jam contact the inner bend of the channel. If no inner bend exists, this must be no.	
Occupies thalweg?	occ_thal	y, n	Yes if any key pieces are in or above the thalweg.	
Channel spanning?	chan_span	y, n	Yes if any key pieces or a combination of multiple key pieces together touch both channel banks	
Parallel orientation?	parallel_to_flow	y, n	Yes if the bulk of the jam is longer (parallel to flow) than it is wide (perpendicular to flow)	
Key pieces >15 degrees?	key_over_15_deg	y, n	Yes if any key pieces are at an angle over ~15 degrees relative to horizontal	Provides a threshold estimate of the rate of key pieces submergence (and buoying) during high flows

(continues)

Table 3. (continued)

Obstruction index (1–3)	obstruct_index	1–3	**3:** Can't see light coming through most of the jam. Creates backwater and flow through jam is heavily obstructed. Estimated porosity <25%. **2:** Can see light coming through the jam, but you may not be able to see through the jam in all spots. Flow likely interacts with wood but still flows through. Noticeable change in water surface elevation from upstream to downstream side of jam. Estimated porosity 25-75%. **1:** Can see through most parts of the jam. Water flows freely (or would flow freely at high flow) through jam. Large voids. Estimated porosity >75%. 	As an alternative to visual estimates of porosity (see section 3.1), describes porosity and drag force experienced by jam during high flow
Morphologically impactful?	morph_impact	y, n	Yes if jam significantly impacted morphology around it (e.g., scour pools, bank erosion, deposited bars, sediment wedges)	Indicates sufficient stability to influence bed material sediment dynamics
Buried?	buried	y, n	Yes if any key pieces are at least partially buried by sediment	Buried key pieces are likely more stable than those resting on the bed (Bilby, 1984; Merten et al., 2010)
Key pieces above bankfull?	key_above_bf	y, n	Yes if any key pieces extend above bankfull depth. If jam touches floodplain surface, this must be yes.	If above bankfull depth, key pieces are less likely to float at bankfull flow.
Fines?	fines	y, n	Yes if there are fine pieces of fluvially transported plant material or sediment visible on/in the jam	Indicates jam has withstood flows of stage at least as high as highest fine material deposited atop jam
Pinned?	pinned	y, n	Yes if any key pieces are pinned on a relatively immobile object (e.g., large boulders, live and nonsapling trees, midchannel bars that have been stabilized by vegetation, and bridge piers) 	Pinning (or anchoring, bracing) stabilizes key pieces during high flows (Merten et al., 2010), especially if key pieces cannot float over pinning object at bankfull flow.
Pinning object above bankfull?	pin_obj_above_bf	y, n	Yes if the object the jam is pinned on extends above bankfull depth. If jam is not pinned, this must be no.	
Decay class	decay_class	1–5	Scale paraphrased from Harmon, Woodall, and Sexton (2011) to describe key pieces. Most jams in rivers will be Categories 1–3, although some floodplain jams could be more decayed. 1: Sound, freshly fallen, intact logs with no rot, fine twigs attached with tight bark. 2: Sound log sapwood partly soft but cannot be pulled apart by hand, many fine twigs are gone and remaining fine twigs have peeling bark. 3: Heartwood is still sound with piece supporting its own weight, sapwood can be pulled apart by hand or is missing, wood colour is reddish-brown or original colour, only branch stubs are remaining which cannot be pulled out of log. 4: Heartwood is rotten with piece unable to support own weight, a metal pin can be pushed into heartwood, branch stubs can be pulled out. 5: There is no remaining structural integrity to the piece with a lack of circular shape as rot spreads out across ground, rotten texture is soft and can become powder when dry, wood colour is red-brown to dark brown	Indicates key piece resistance to breakage and density, which may impact stability (Macvicar & Piégay, 2012; Merten, Vaz, Decker-Fritz, Finlay, & Stefan, 2013; Wohl & Goode, 2008)
In situ?	in_situ	y, n	Yes if any of the key pieces of the jam are sourced from the banks directly adjacent to the jam	In situ key pieces may be anchored to bank material, increasing resistance to mobilization
Rootwads?	rootwads	y, n	Yes if any rootwads are attached to any pieces in the jam	Indicates potentially higher complexity (Braudrick et al., 1997; Davidson et al., 2015; Merten et al., 2010) and potential interaction with relatively stable living vegetation (Dunkerley, 2014), both of which can increase stability
Live wood?	live_wood	y, n	Yes if live woody vegetation is growing on or proximal to the jam.	
Multitrunk?	multi_trunk	y, n	Yes if any key pieces have multiple trunks	
Survey picture time	pic_time_survey	HH:MM	Used to reference photographs taken of jam for use in detecting change during resurveys	
Date of survey	date_survey	YYYY/MM/DD	Used to put resurvey data in temporal context, if resurvey data are provided	
Survey notes	notes_survey		Used to provide additional context for jam characteristics	Covers important additional notes not otherwise included in the WooDDAM database, such as whether jam includes engineered pilings for stability.
Recharacterization needed	recharacterization_needed	y, n	Yes if any of the above variables (including channel dimensions) have changed since the initial survey	

(continues)

Table 3. (continued)

Resurvey picture time	pic_time_resurvey	HH:MM	Used to reference photographs taken of jam for use in detecting change during resurveys	
Date of resurvey	date_resurvey	YYYY/MM/DD	Used to put resurvey data in temporal context, if resurvey data is provided	
Resurvey notes	notes_resurvey		Used to record change while in the field and provide contextual details (e.g., which logs were lost and how channel morphology may have changed)	
Qualitative magnitude of high flow	qual_mag_high_flow	below, near, or above bankfull	Estimate of the qualitative magnitude of high flow using geomorphic and vegetation markers of recent peak flows (or gage data if available)	Predictions are given for each category of this variable, as bankfull flow acts as a mobility threshold (section 3.2; Kramer & Wohl, 2016)
Quantitative magnitude of high flow	quant_mag_high_flow	cms	Optional: the quantitative magnitude of high flow can be estimated from nearby flow gage data during the period between surveys	
Mobilized?	mobilized	y, n	Yes if upon resurvey, wood jam is found to be either no longer a jam (lost enough pieces to be less than 3 pieces touching) or completely gone from its initial position	Describes potential changes a wood jam can experience during a high flow
Lost wood?	lost_wood	y, n	Yes if large wood pieces observed in the initial survey are unable to be located in the resurvey	
Accumulated wood?	accumulated	y, n	Yes if new large wood pieces are observed in the resurvey that were not present during the initial survey	
Contracted?	contracted	y, n	Yes if the volume of the jam decreased apart from any loss of wood	
Expanded?	expanded	y, n	Yes if the volume of the jam increased apart from any accumulation of wood	

Note. Key piece refers to any wood piece that retains or supports any other wood in the jam. "y" refers to "yes", "n" refers to "no", "Y" refers to "year", "H" refers to "hour", "M" refers to minute, "cms" refers to "cubic meters per second". Channel geometry measurements describe only the channel the wood jam resides in, even if there are multiple channels across the valley bottom. We categorize measurements by whether they describe hydrologic regime (blue), channel geometry (brown), reach-scale valley bottom characteristics (red), the location and geometry of the jam (purple), and the physical characteristics of a jam (green). We also provide three example wood jams and their WooDDAM characteristics in Data S4.

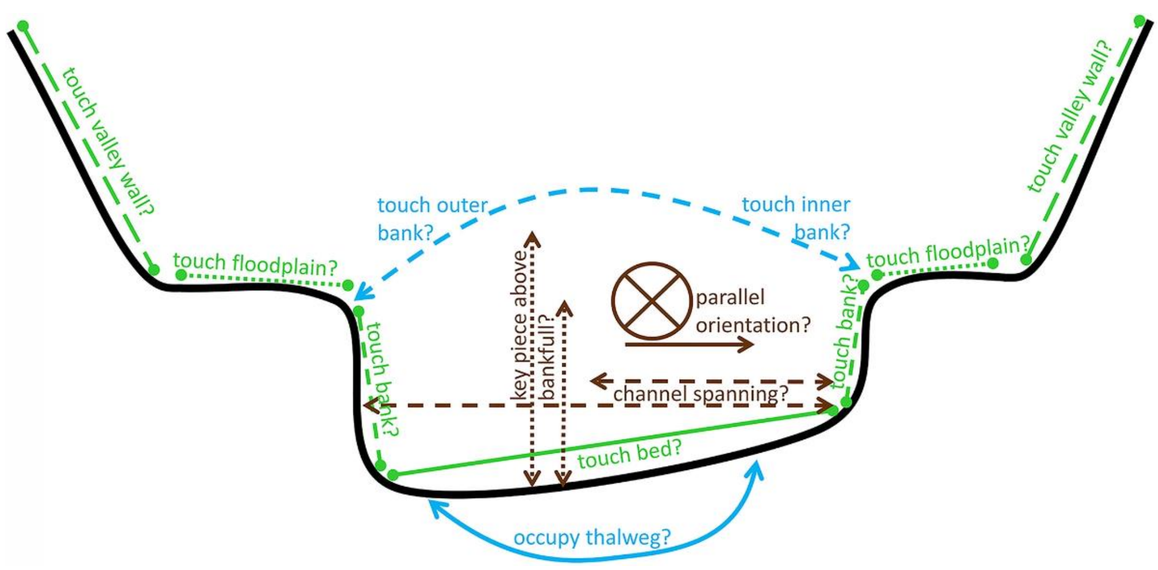


Figure 3. Examples of large wood location (blue), channel boundary (green), and wood geometry (brown) metrics to quantify (Scott et al., 2019).

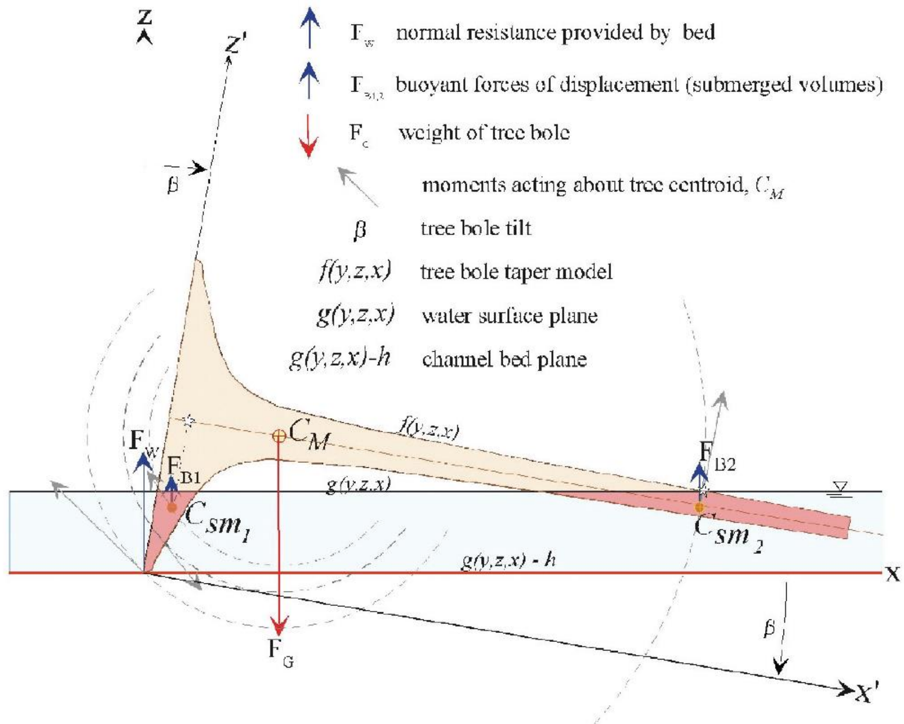


Figure 4. Different types of forces acting on a piece of large wood with a rootwad (Abbe and Brooks, 2013).

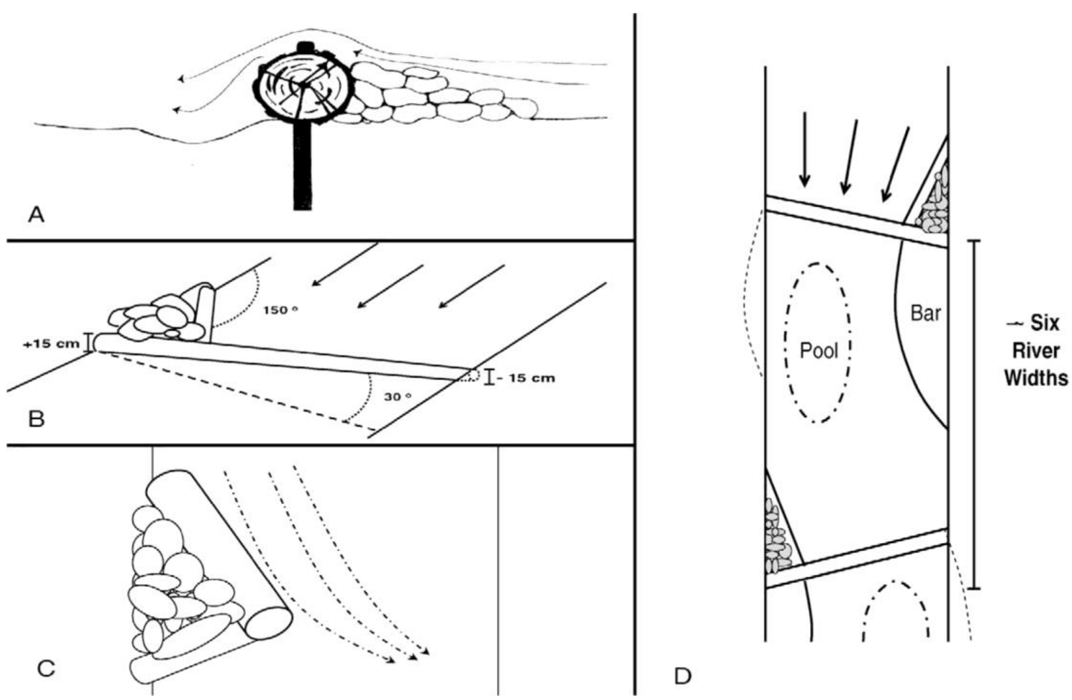
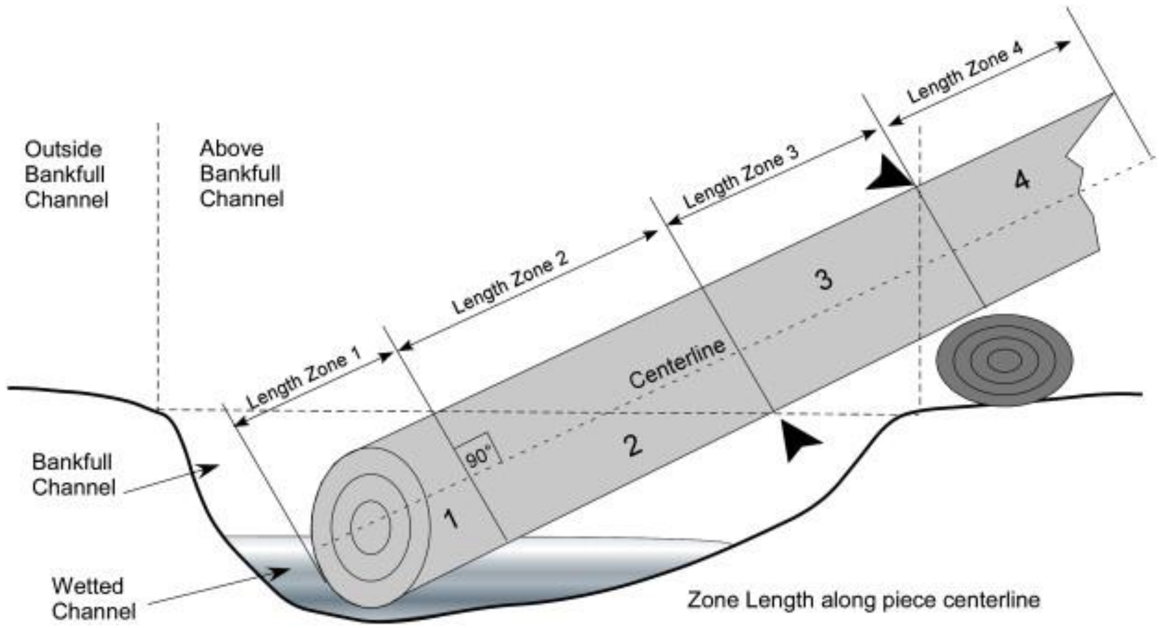


Figure 5. Example of large wood placement to induce formation of desired geomorphic functions and channel planforms. (A, B, D) Instream wood can be used to create riffle-pool sequences, which naturally form approximately every 5-7 channel widths. (C) Structures can also divert flow and promote meander bends (MacInnis et al., 2008).

(A)



(B)

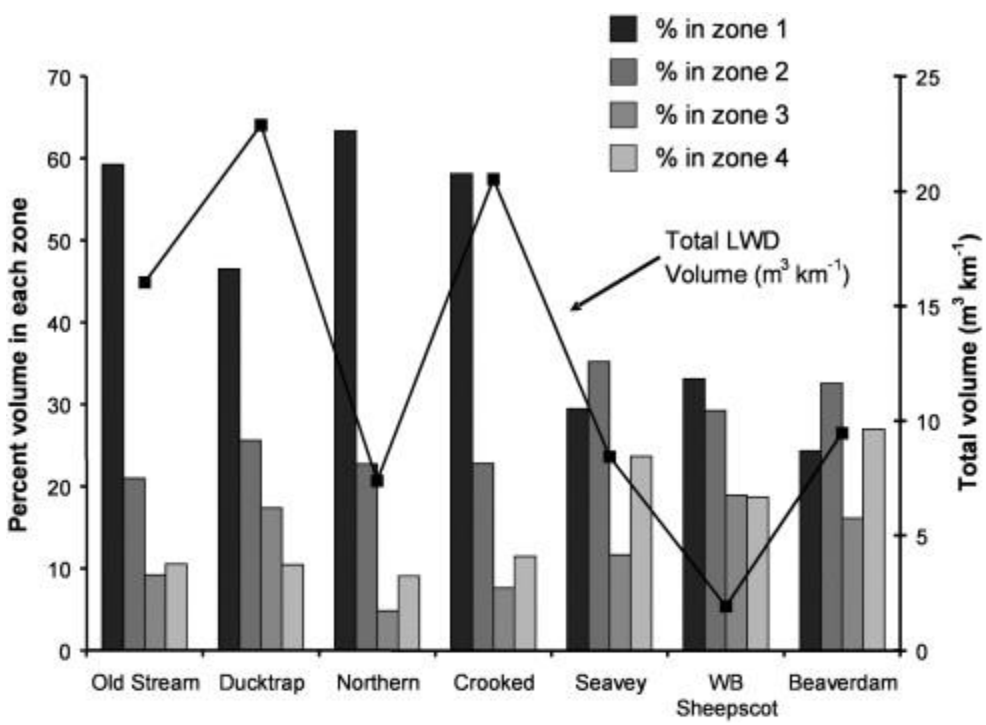
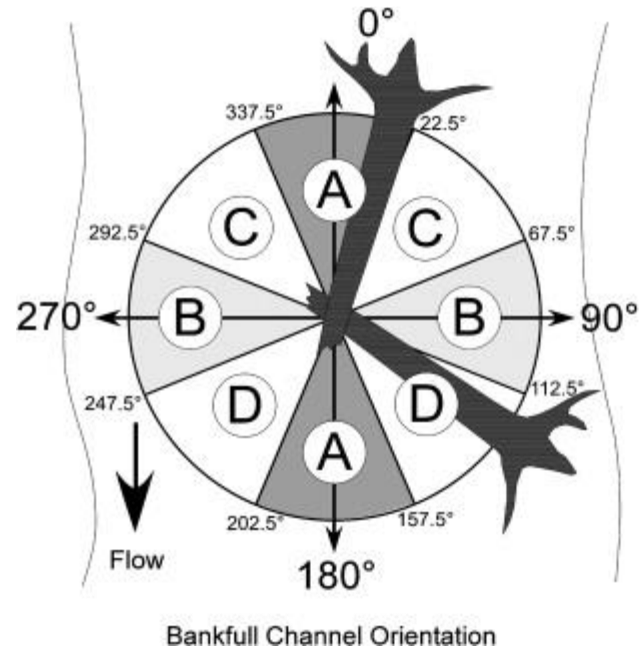


Figure 6. (A) Use of zones to specify location of wood in relation to the channel and water height. (B) Amounts of large wood found in each zone for seven different rivers in Maine, USA (Magilligan et al., 2008).

(A)



(B)

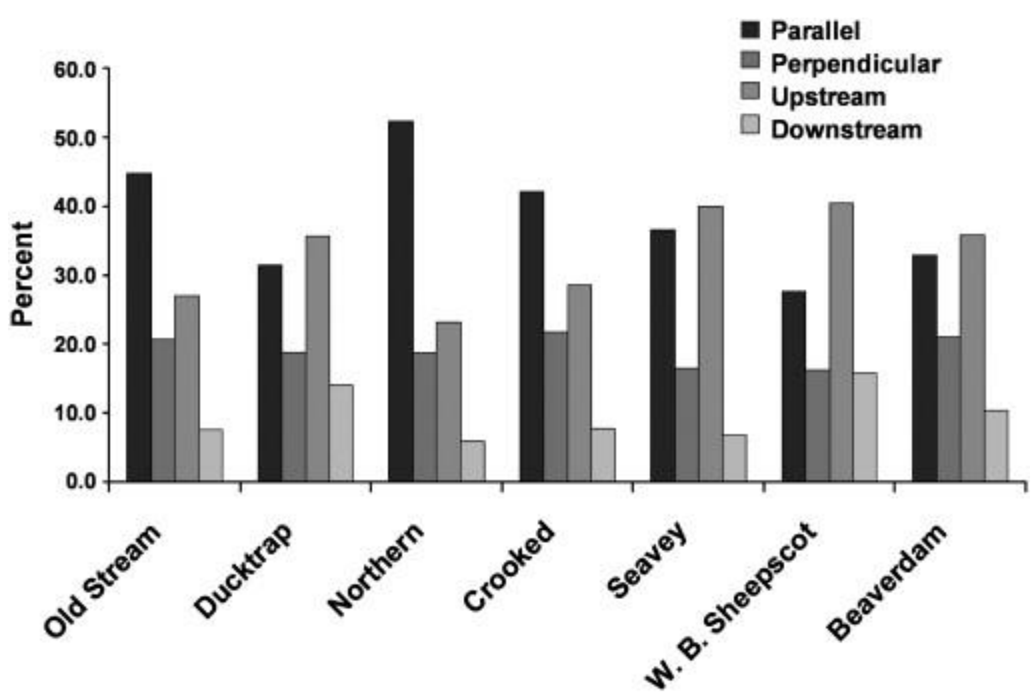


Figure 7. (A) Zones used to describe how instream wood is oriented in relation to the channel and flow direction. (B) Percentages of large wood found in each zone for seven different rivers in Maine, USA (Magilligan et al., 2008).

Table 4. Habitat criteria reported throughout literature for (A) spawning, (B) nursery, and (C) rearing life stages of Atlantic salmon (Armstrong et al., 2003).

(A)

Reported habitats used by spawning Atlantic salmon

Species	Habitat variable	Measure	Values	Authors
Atlantic salmon (*Salmo salar*)	Water velocity	Mean	40 cm s^{-1}	Heggberget (1991)
			53 cm s^{-1}	Moir et al. (1998), Beland et al. (1982)
		Range	35–80 cm s^{-1}	Beland et al. (1982)
		Minimum	>15–20 cm s^{-1}	Crisp and Carling (1989)
	Water depth	Mean	50 cm	Heggberget (1991)
			25 cm	Moir et al. (1998)
			38 cm	Beland et al. (1982)
		Range	17–76 cm	Beland et al. (1982)
	Substrate size	Median grain size (combined for several species)	22 mm	Kondolf and Wolman (1993)
			5.4–78 mm	Kondolf and Wolman (1993)
			20–30 mm	Crisp and Carling (1989)
		Mean particle size	20.7 mm	Moir et al. (1998)
		Mean particle size	100 mm	Heggberget (1991)
	Depth in gravel of egg burial	Mean	15–25 cm	Bardonnet and Bagliniere (2000)
	Percentage fines	Material <1 mm	5.4%	Moir et al. (1998)
		Range	2.3–8.0%	Moir et al. (1998)

(B)

Reported nursery habitat used by Atlantic salmon

Species	Habitat variable	Measure	Values	Authors
Atlantic salmon (*Salmo salar*)	Snout water velocity	Range	5–15 cm s^{-1}	Morantz et al. (1987)
		Range	10–30 cm s^{-1}	Rimmer et al. (1984)
	Mean column velocity	Range	20–40 cm s^{-1}	Crisp (1993, 1996)
		Minimum	>5–15 cm s^{-1}	Heggenes et al. (1999)
		Maximum	<100 cm s^{-1}	Heggenes (1990)
		Range	10–30 cm s^{-1}	DeGraaf and Bain (1986)
	Water depth	Maximum (for fry)	<10 cm	Heggenes et al. (1999)
		Range (for fry)	20–40 cm	Morantz et al. (1987)
		Preference (for 0+)	<25 cm	Symons and Heland (1978)
				Kennedy and Strange (1982)
				Morantz et al. (1987)
				Heggenes (1990)
				Crisp (1993)
		Range	5–65 cm	Heggenes (1990)
		Maximum	<100 cm	Morantz et al. (1987)
				Heggenes (1990)
				Heggenes et al. (1999)
	Substrate size	Range	16–256 mm	Symons and Heland (1978)

(continues)

Table 4. (continued)

(C)

Reported rearing habitat used by Atlantic salmon

Species	Habitat variable	Measure	Values	Authors
Atlantic salmon (*Salmo salar*)	Snout water velocity	Range	5–35 cm	Morantz et al. (1987)
		Range	0–20 cm	Heggenes et al. (1999)
		Range	10–50 cm	Rimmer et al. (1984)
	Mean column velocity	Maximum	>60 cm	Heggenes et al. (1999)
		Maximum	<120 cm	Morantz et al. (1987)
		Minimum	<20 cm	Heggenes et al. (1999)
		Utilised preference	50–65 cm	Symons and Heland (1978)
		Utilised preference	10–65 cm	Heggenes (1990)
	Water depth	Range	25–60 cm	Symons and Heland (1978), Rimmer et al. (1984), Morantz et al. (1987), Heggenes (1990)
		Range	20–70 cm	Heggenes (1990)
	Substrate size	Range	64–512+ mm	Symons and Heland (1978), Heggenes (1990) Heggenes et al. (1999)

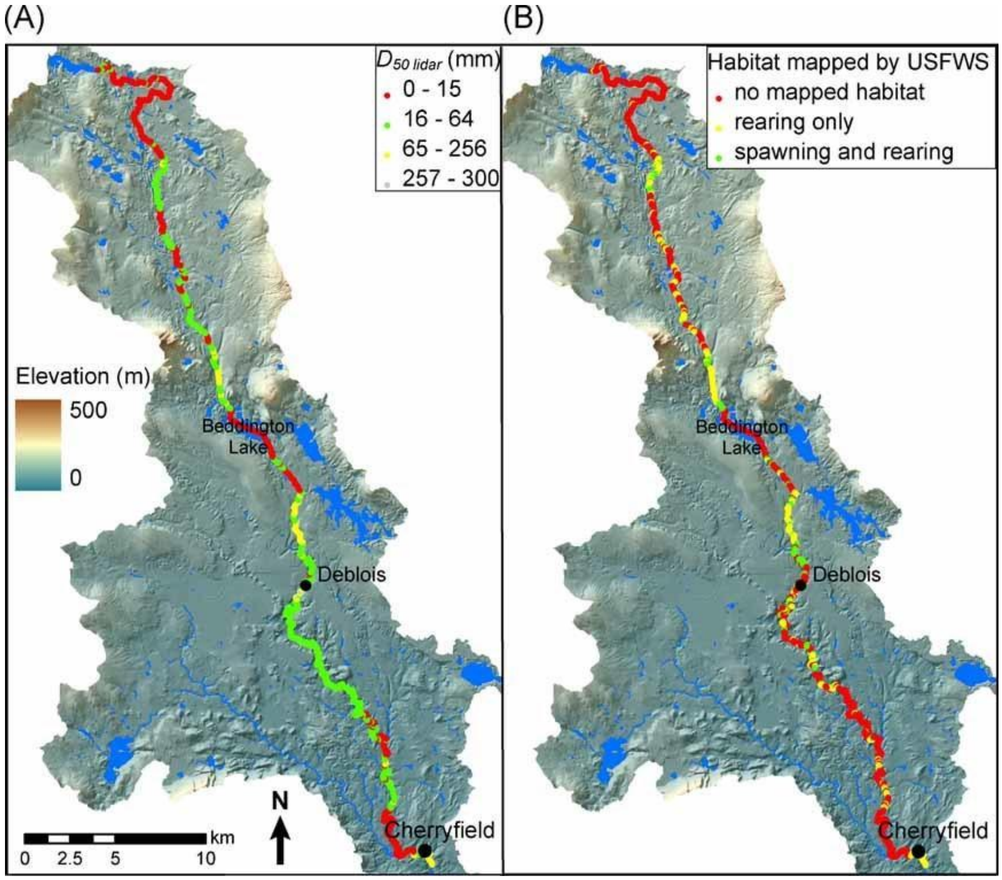


Figure 8. Two maps of the Narraguagus River, Maine. (A) Median bed grain sizes predicted by lidar, where favorable grain sizes for Atlantic salmon are 16-256 mm (green and yellow). (B) Habitat locations for Atlantic salmon according to USFWS maps (Wilkins and Snyder, 2011).

Table 5. Preferred stream velocities for early versus late season Atlantic salmon for six streams in Vermont, USA. (Nislow et al., 1999).

Season†	Velocity category (m/s)	Preferred	Most preferred	Most individuals
Early	1 (0.01–0.08)	3	1	1
	2‡ (0.08–0.18)	**5**	**5**	**5**
	3 (0.18–0.28)	0	0	0
	4 (0.28–0.38)	0	0	0
Late	1 (0.01–0.21)	1	1	2
	2‡ (0.21–0.57)	**5**	**5**	4

† Early season = May through mid-June; late season = mid-July through August.

‡ Optimal velocity category.

Table 6. Microhabitat depths preferred by early versus late season Atlantic salmon for six streams in Vermont, USA. Preferred categories are those with values greater than 0.25 (Nislow et al., 1999).

Fish season	Categories			
	1 (0–10 cm)	2 (10–20 cm)	3 (20–30 cm)	4 (30–40 cm)
Early	0.18 (0.068)	0.369 (0.06)	0.235 (0.056)	0.216 (0.073)
Late	0.039 (0.018)	0.428 (0.141)	0.319 (0.112)	0.214 (0.171)

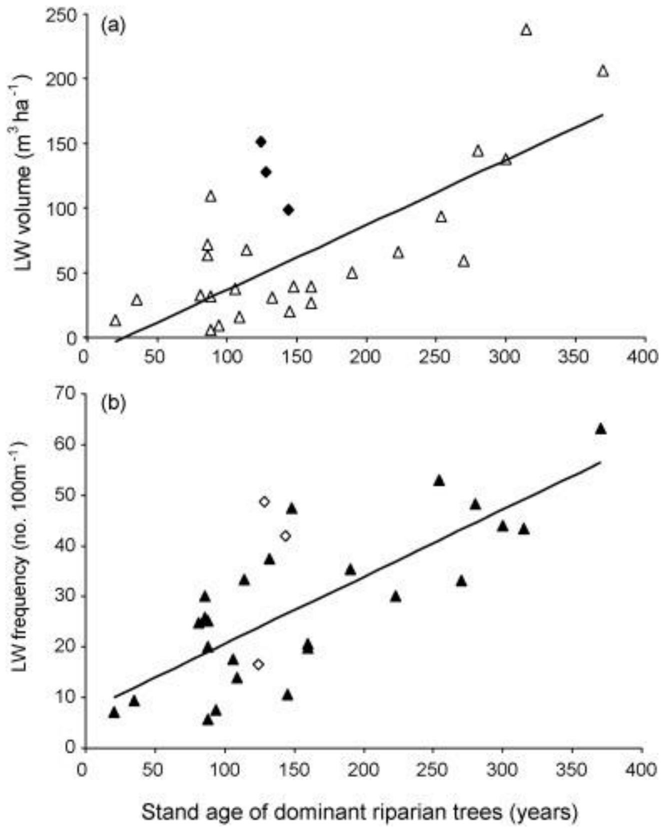


Figure 9. (A) Large wood volume and (B) frequency versus age of riparian trees in the surrounding floodplain for studied river channels. Diamonds show sites with mature forests containing old-growth trees (Warren et al., 2009).

Table 7. Timeline of "restoration succession" process, to be applied when using large wood in river restoration projects (Collins and Montgomery, 2002).

	0 years	1–50 years	50–100 years	100+ years
Actions	Riparian reforestation	In-stream structures	Naturally-recruited logjams	Naturally recruited logjams
	Includes fast-growing species	Includes placing key pieces of building wood jams	Fast-growing species form key pieces	Slower-growing species form key pieces
	Levee setback or removal			
Results and Functions	Initiate future supply of wood	Short-term pool-forming and channel-switching functions	Long-term sustainable supply of wood jams	
	Restore lateral erosion and avulsion	Stable sites for forest regeneration	Long-term sustainable pool-forming and channel-switching functions	

Table 8. Potential metrics and associated documentation.

Metric	Function(s)	Documentation
Wood dimensions: diameter, length, volume	Floodplain formation, stability	Collins et al., 2012; Magilligan et al., 2008; Warren et al., 2009; Wohl et al., 2010
Wood density	Stability	Abbe and Brooks, 2013; Wohl et al., 2010
Wood orientation	Floodplain formation, stability	Scott et al., 2019; Magilligan et al., 2008; Wohl et al., 2010
Wood location within the channel	Floodplain formation, stability	Magilligan et al., 2008; Scott et al., 2019; Warren et al., 2009
Wood submergence	Habitat, stability	Abbe and Brooks, 2013; Scott et al., 2019; Magilligan et al., 2008; Wohl et al., 2010
Surface area of wood/jam	Habitat, stability	Abbe and Brooks, 2013
Rootwad presence and dimensions	Floodplain formation, stability	Abbe and Brooks, 2013; Collins et al., 2012; Scott et al., 2019; Wohl et al., 2010
Wood species	Floodplain restoration, longevity, stability	Abbe and Brooks, 2013; Collins et al., 2012; Magilligan et al., 2008; Wohl et al., 2010
Decay class	Floodplain restoration, longevity, stability	Abbe and Brooks, 2013; Magilligan et al., 2008; Scott et al., 2019; Wohl et al., 2010
Wood age: actual age, seral stage	Longevity, stability	Collins et al., 2012; Wohl et al., 2010
Wood source	Recruitment potential	Wohl et al., 2010
Logjam characteristics: dimensions, pieces per jam,	Floodplain formation, habitat, stability	Abbe and Brooks, 2013; Magilligan et al., 2008;

location, orientation of pieces, volume		Scott et al., 2019; Warren et al., 2009; Wohl et al., 2010
Accumulation category (Table 2)	Floodplain formation, habitat stability	Wohl et al., 2010
Scour: amounts, locations	Floodplain formation, habitat: pool formation	Abbe and Brooks, 2013; Collins et al., 2012; Wilkins and Snyder, 2011; Wohl et al., 2010
Sediment: amounts, locations, grain sizes, note deposition or removal	Floodplain formation, habitat (Atlantic salmon)	Collins et al., 2012; MacInnis et al., 2008; Magilligan et al., 2008; Scott et al., 2019; Wilkins and Snyder, 2011; Wohl et al., 2010; Wohl et al., 2015
Pool formation: depth, area, frequency	Habitat (Atlantic salmon)	Nislow et al., 1999; Skidmore et al., 2011; Wilkins and Snyder, 2011; Wohl et al., 2010
Erosion protection presence	Floodplain formation, habitat	Collins et al., 2012; Nislow et al., 1999
Flow deflection	Channel form alteration, floodplain formation, floodplain reconnection, habitat	Collins et al., 2012; Wohl et al., 2010
Water velocities	Habitat (Atlantic salmon), longevity, stability	Abbe and Brooks, 2013; MacInnis et al., 2008; Nislow et al., 1999; Wilkins and Snyder, 2011; Wohl et al., 2015
Bank stabilization	Channel form alteration	Wohl et al., 2010
River structure changes (i.e., meander formation)	Geomorphic alterations, habitat	MacInnis et al., 2008; Scott et al., 2019; Skidmore et al., 2011; Wohl et al., 2015
Cover provided	Habitat (Atlantic salmon)	Nislow et al., 1999; Skidmore et al., 2011; Wilkins and Snyder, 2011

Shade provided / resulting water temperature	Habitat (Atlantic salmon)	Collins et al., 2012; MacInnis et al., 2008; Wilkins and Snyder, 2011
Fish passage capability	Habitat	Skidmore et al., 2011; Wilkins and Snyder, 2011
Biotic organism response (i.e., number of fish)	Habitat (Atlantic salmon)	Nislow et al., 1999; Skidmore et al., 2011; USBR & ERDC, 2016; Wohl et al., 2015
Number of redds	Habitat (Atlantic salmon)	MacInnis et al., 2008
Water quality (i.e. turbidity, dissolved nutrients, pH, temperature)	Ecological, habitat	USBR & ERDC, 2016; Wohl et al., 2015
Channel geometry: width, flow depth, bankfull depth, gradient, reach length, longitudinal profile	Habitat, useful for comparison to large wood	Abbe and Brooks, 2013; Collins et al., 2012; Nislow et al., 1999; MacInnis et al., 2008; Magilligan et al., 2008; Scott et al., 2019; Warren et al., 2009; Wilkins and Snyder, 2011; Wohl et al., 2010
Channel characteristics: discharge, morphology, reach elevation, bedform, bed roughness	Useful for comparison to large wood	Scott et al., 2019; Wilkins and Snyder, 2011; Wohl et al., 2010
Valley characteristics: drainage area, side slopes, confinement, connectedness, disturbance/management history	Recruitment potential	Magilligan et al., 2008; Warren et al., 2009; Wohl et al., 2010
Forest characteristics: dominant species, age, dimensions and spatial density of trees, cross-sectional area of standing trees, tree distance from bankfull width	Habitat, recruitment potential	MacInnis et al., 2008; Magilligan et al., 2008; Warren et al., 2009; Wohl et al., 2010

Appendix B – Timeline of the ‘Floodplain Large-Wood Cycle’ Hypothesis at MVD

A progression of geomorphic changes at the MVD site was examined using repeat photographs taken at set photo points during repeat surveys, Google Earth aerial imagery, and sUAS images taken during the summer of 2021.

<u>Repeat Photographs and Individual Photographs</u>

All sets of repeat photographs are from the MVD06 cross section. Image sequences progress from upstream to downstream as you read from the left to right side of the page. “Left bank” and “Right bank” indicate the side of the stream from which the photos were taken.

April 2008 – Left bank

April 2008 – Right bank

September 2008 – Left bank

September 2008 – Right bank

June 2009 – Left bank

June 2009 – Right bank

March 2010 – Left bank

March 2010 – Right bank

May 2010 – Left bank

May 2010 – Right bank

June 2011 – Left bank

June 2011 – Right bank

July 2012 – Right bank, individual photograph

The following photograph was taken from the right bank, downstream of cross-section MVD06.

July 2014 – Left bank

July 2014 – Left bank, individual photographs

The following photographs were taken from the left bank, on the MVD06 extended floodplain.

June 2018 – Left bank

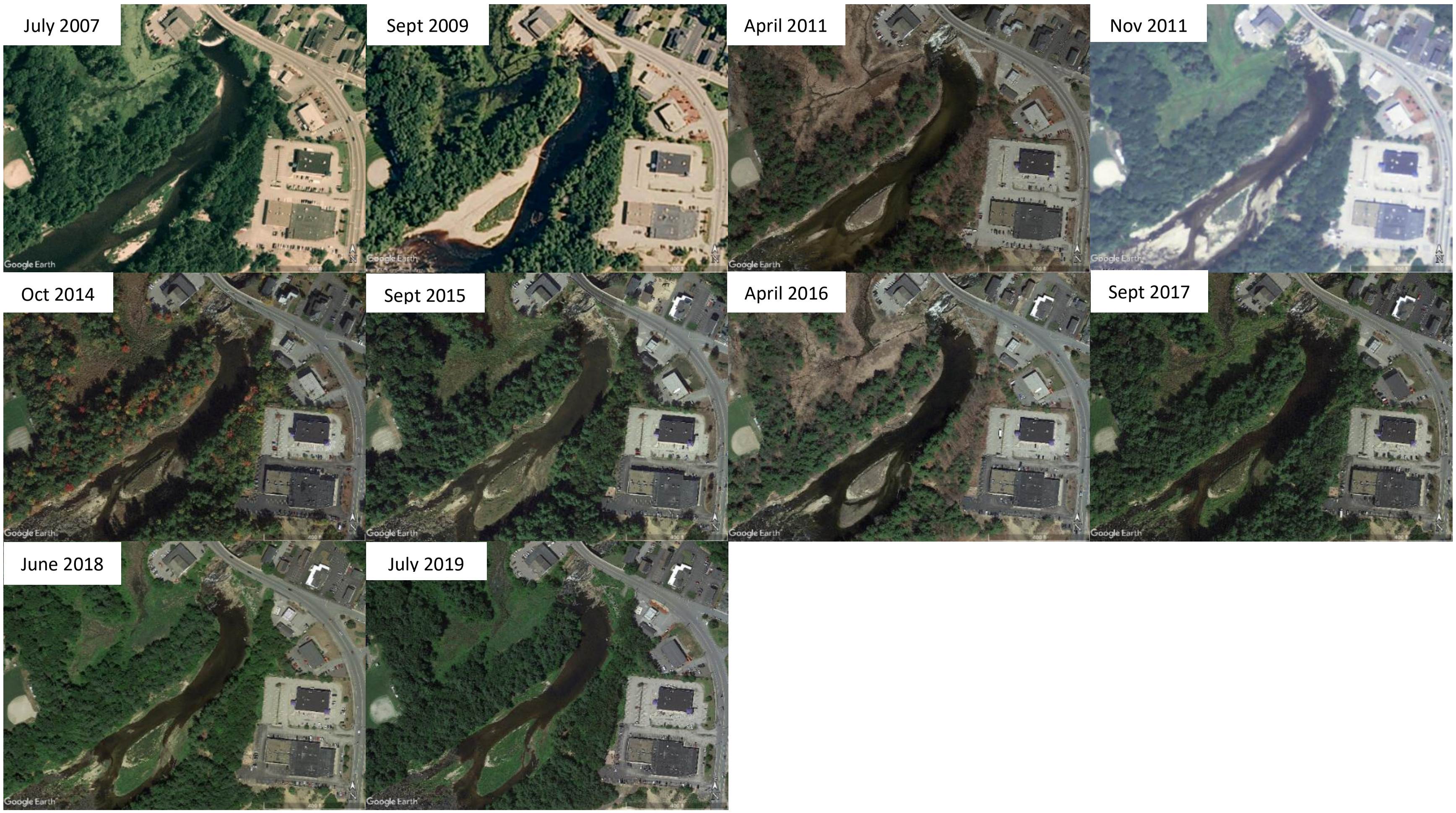
June 2018 – Right bank

June 2021 – Left bank

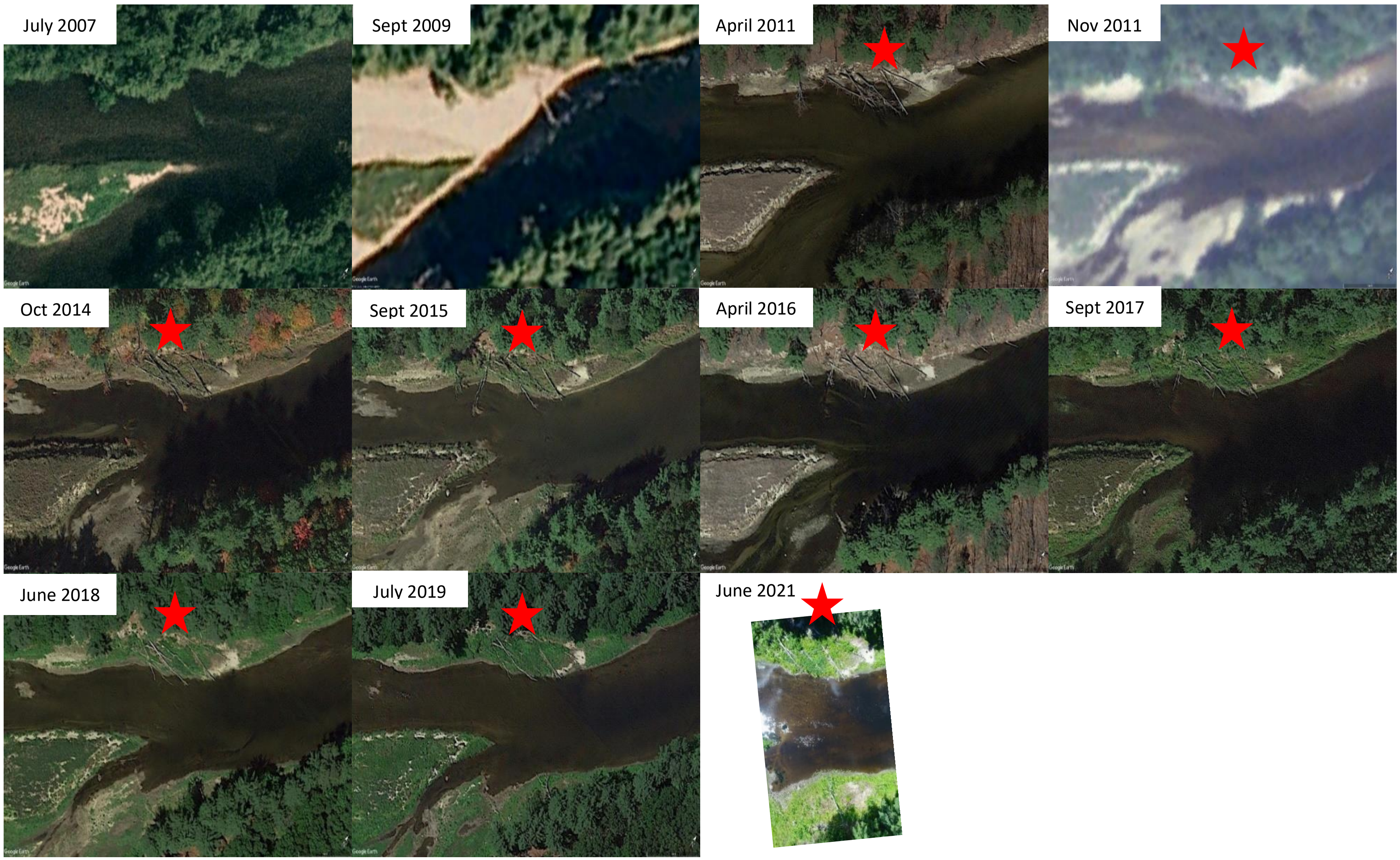
June 2021 – Right bank

Aerial Imagery Progression

Aerial images showing a section of the MVD site between cross-sections MVD04 to MVD08 (the location of the former impoundment). The images, taken from Google Earth, span from July 2007 to July 2019.



Aerial images showing the MVD06 cross section through time, from July 2007 to June 2021. All images, except the June 2021 sUAS image, are historical images from Google Earth. The red star is adjacent to the location of the area of large wood being studied.



The following sets of images were taken using a sUAS during the 2014, 2018, and 2021 summer seasons.

July 2014

Aerial images of MVD06 cross section with the top of the images corresponding to downstream.

Looking upstream toward the MVD06 cross section.

June 2018

Looking upstream toward the MVD06 cross section.

Looking downstream toward the MVD06 cross section.

June 2021

Looking upstream toward the MVD06 cross section.

Aerial image of MVD06 cross section with the top of the image corresponding to downstream.

Aerial image of MVD06 cross section with the top of the image corresponding to upstream.

August 2021

Aerial image of MVD06 cross section with the top of the image corresponding to upstream.

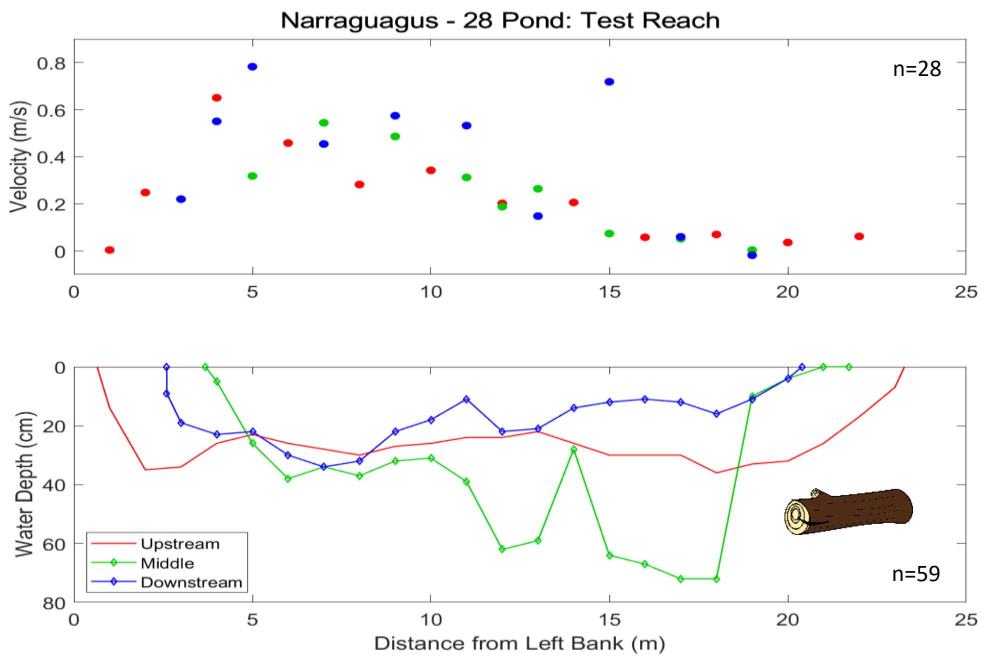
At the left bank for the MVD06 cross section, looking downstream from the upstream end of the extended floodplain containing large wood.

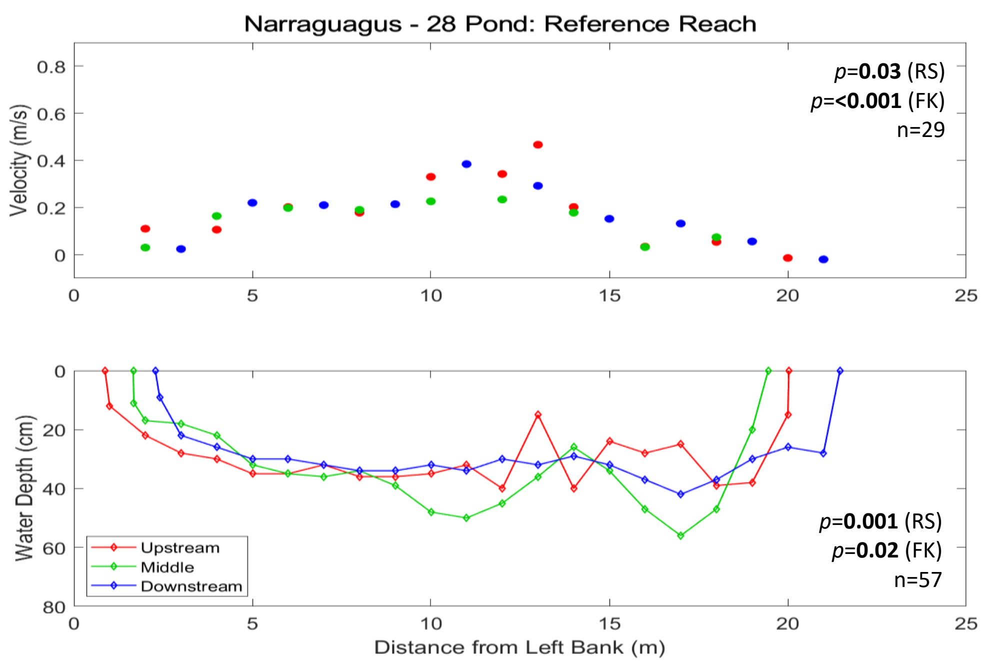
Appendix C – All Sites: Velocity and Depth Cross Sections

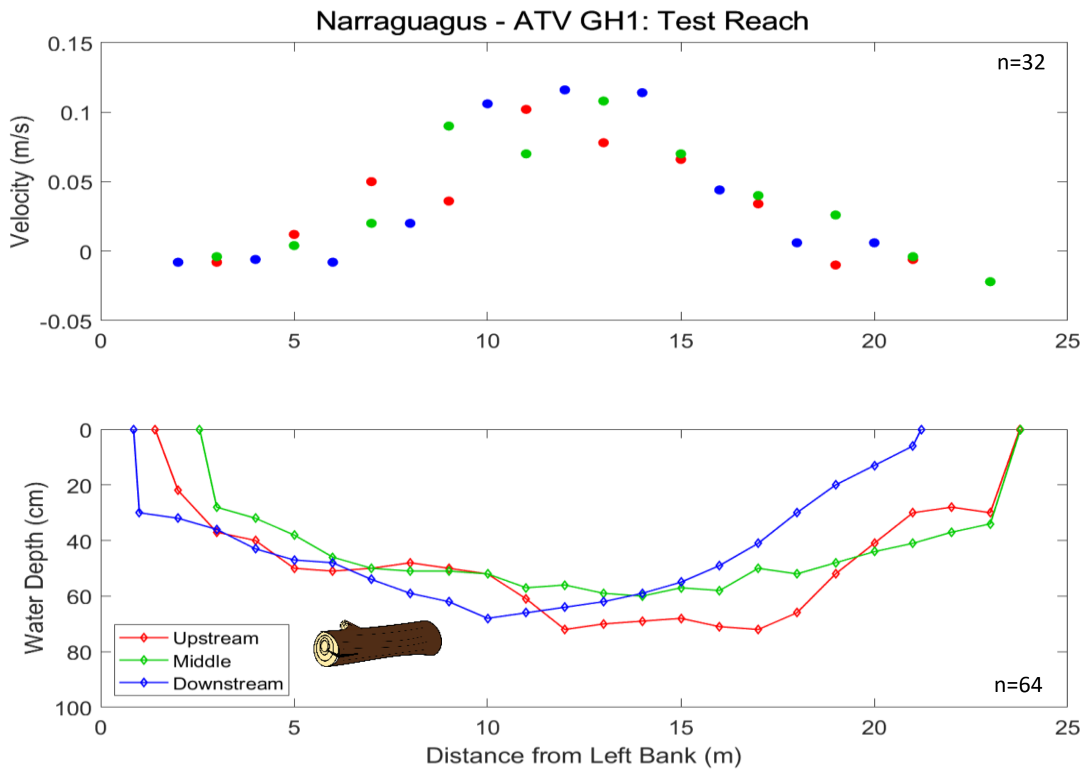
Abbreviations: FK = FK statistical test, RS = rank-sum statistical test

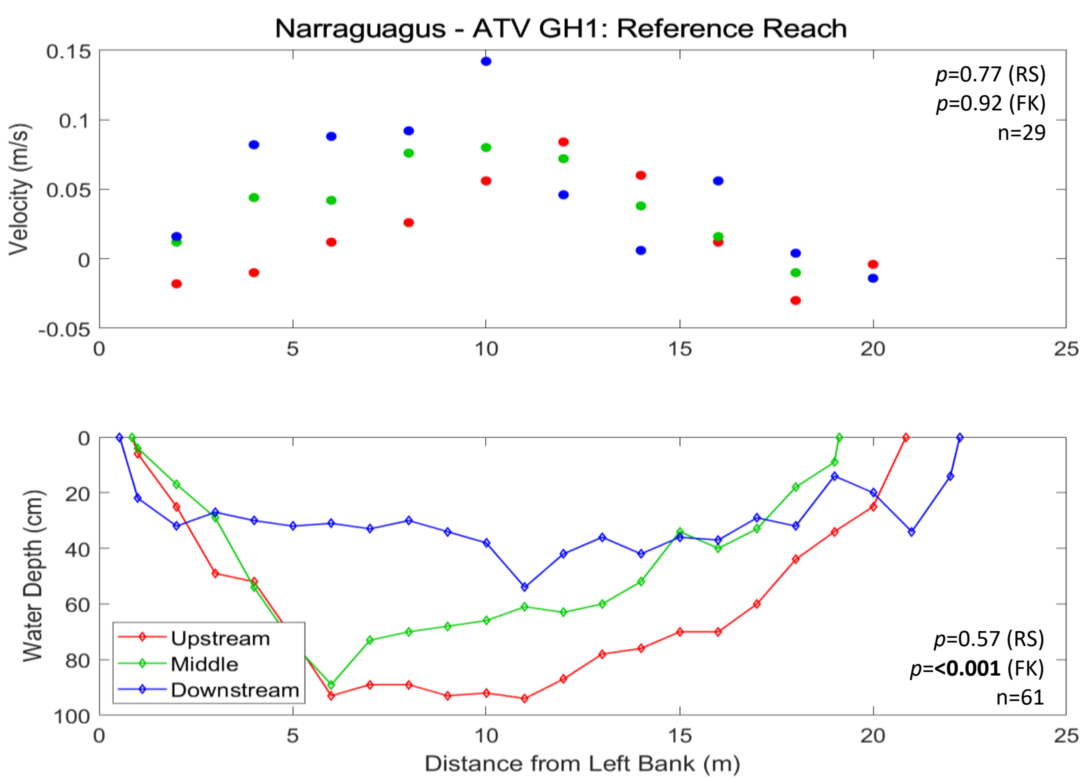
Note: Wood icons indicate the location of the large wood piece or logjam within the channel.

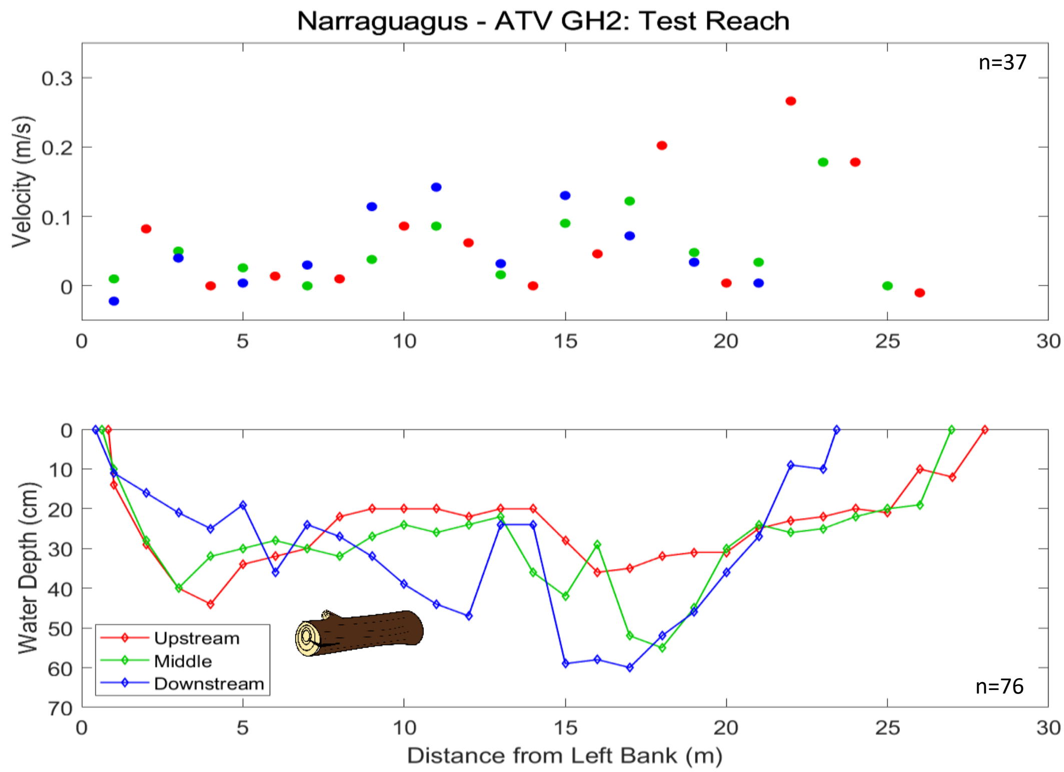
<u>Narraguagus River, ME</u>



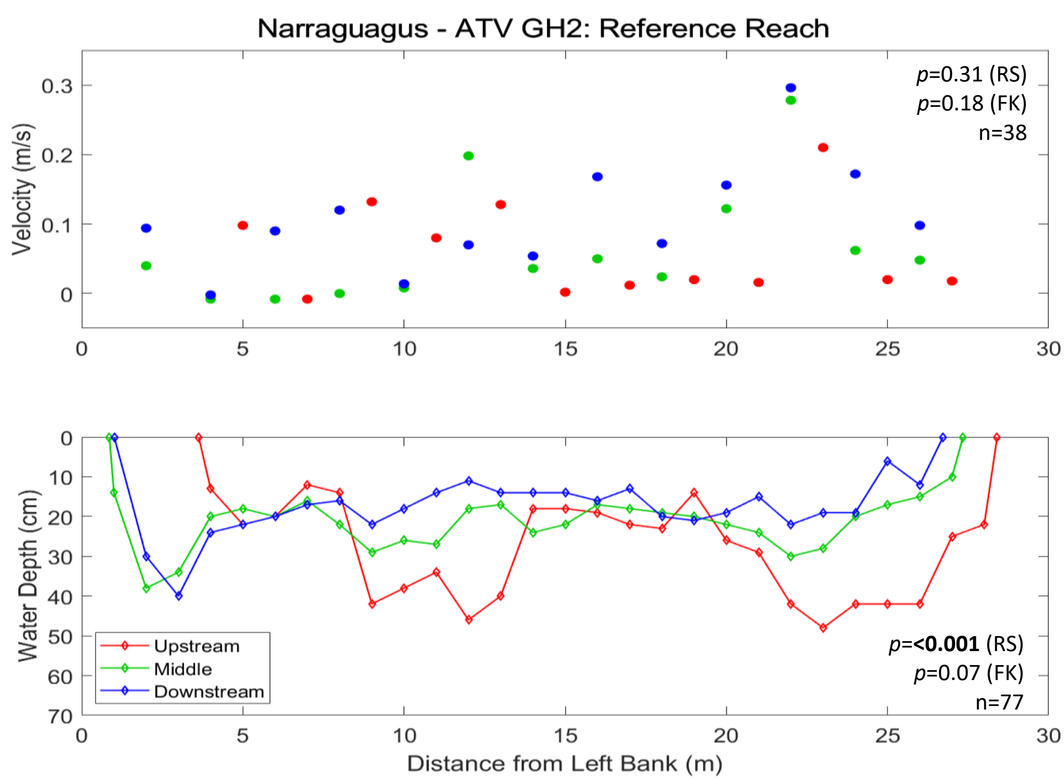



Narraguagus - ATV GH1: Test Reach
Velocity (m/s)
n=32
Water Depth (cm)
Upstream
Middle
Downstream
n=64
Distance from Left Bank (m)

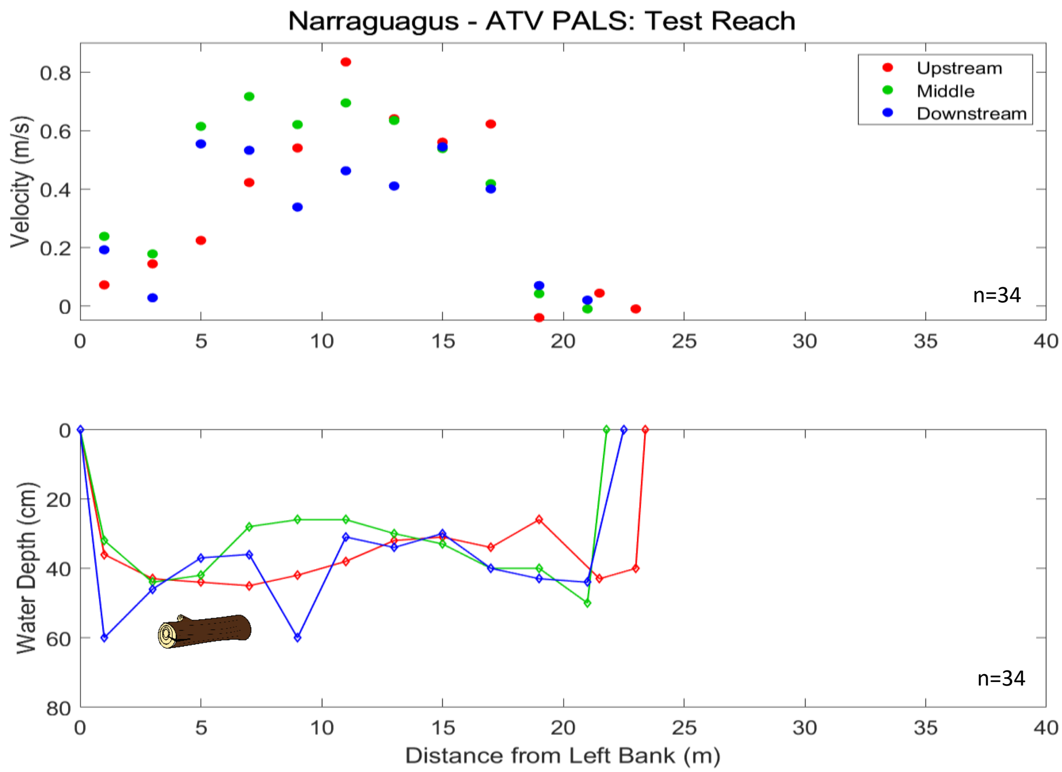

Narraguagus - ATV GH1: Reference Reach
Velocity (m/s)
p=0.77 (RS)
p=0.92 (FK)
n=29
Water Depth (cm)
Upstream
Middle
Downstream
p=0.57 (RS)
p=<0.001 (FK)
n=61
Distance from Left Bank (m)

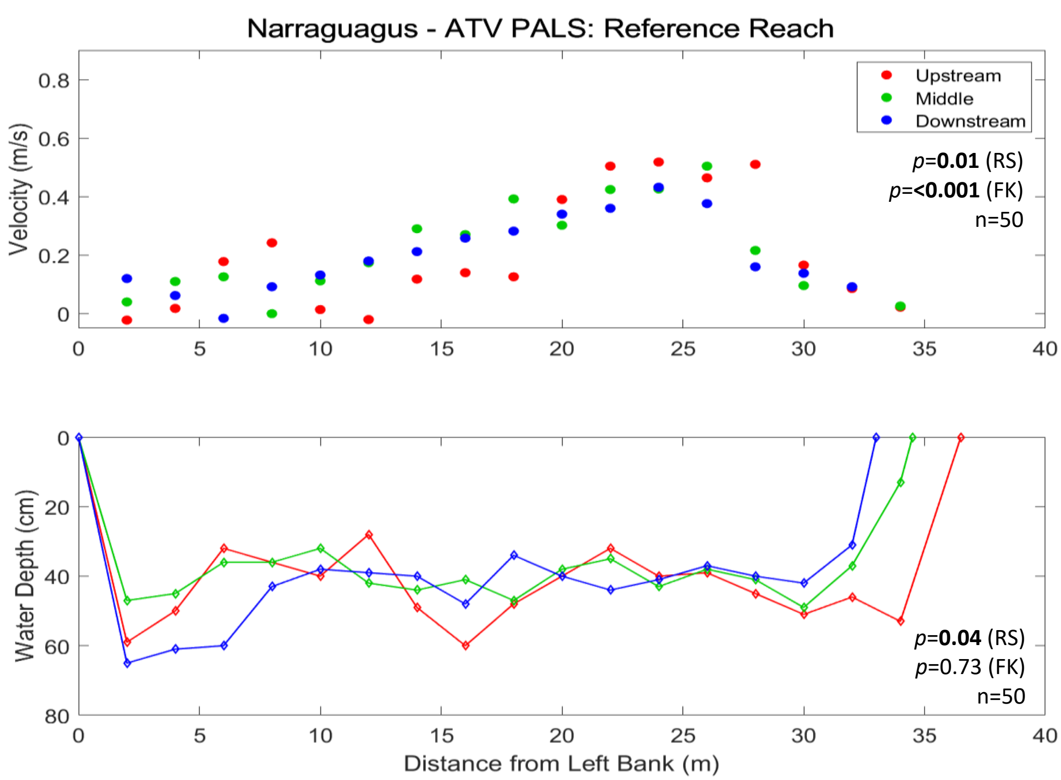


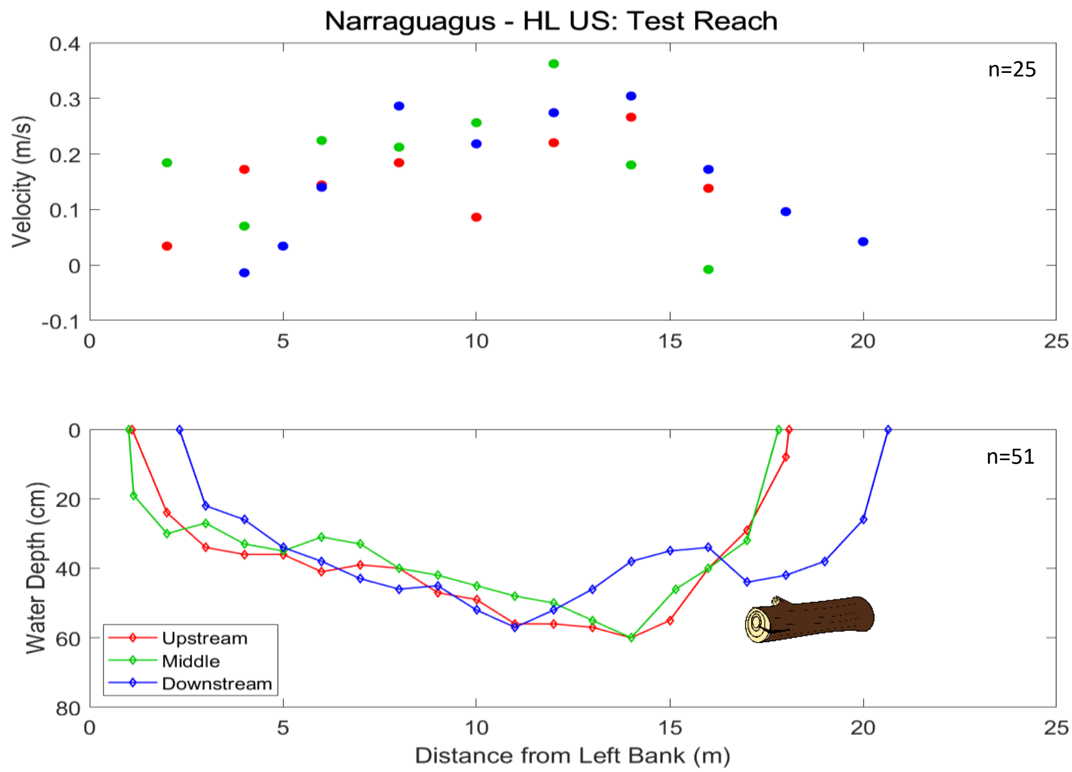
Narraguagus - ATV GH2: Test Reach
n=37
Velocity (m/s)
Water Depth (cm)
Upstream
Middle
Downstream
n=76
Distance from Left Bank (m)

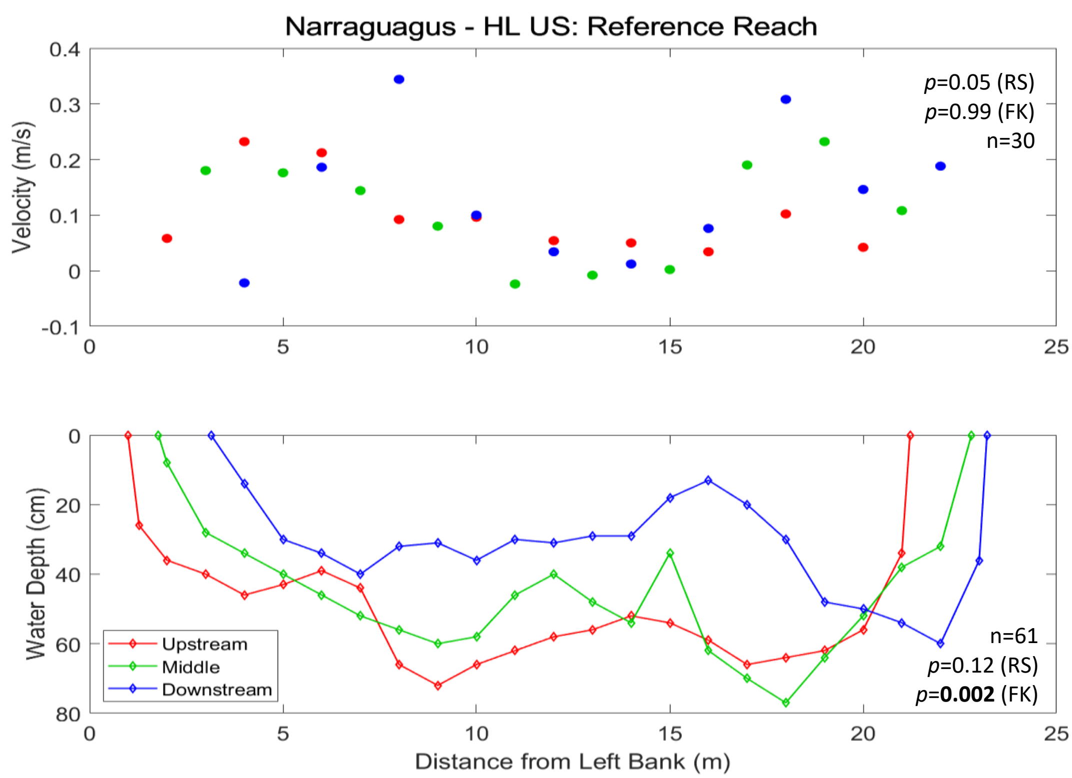


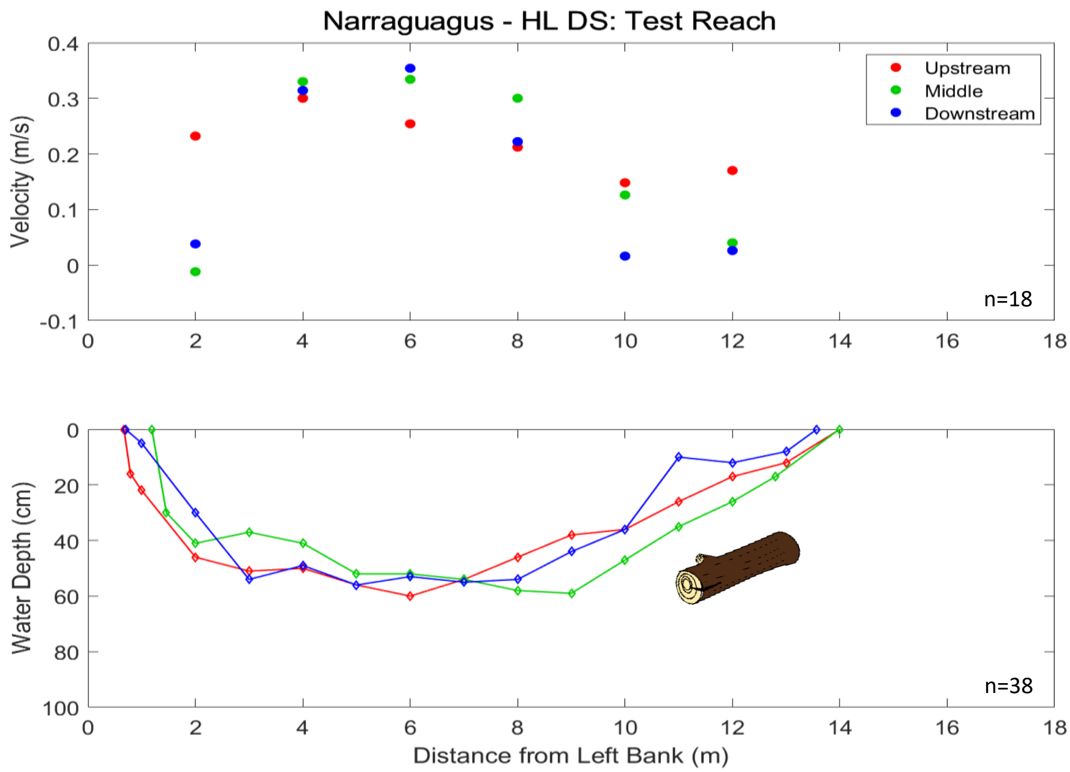
Narraguagus - ATV GH2: Reference Reach
p=0.31 (RS)
p=0.18 (FK)
n=38
Velocity (m/s)
Water Depth (cm)
Upstream
Middle
Downstream
p=<0.001 (RS)
p=0.07 (FK)
n=77
Distance from Left Bank (m)

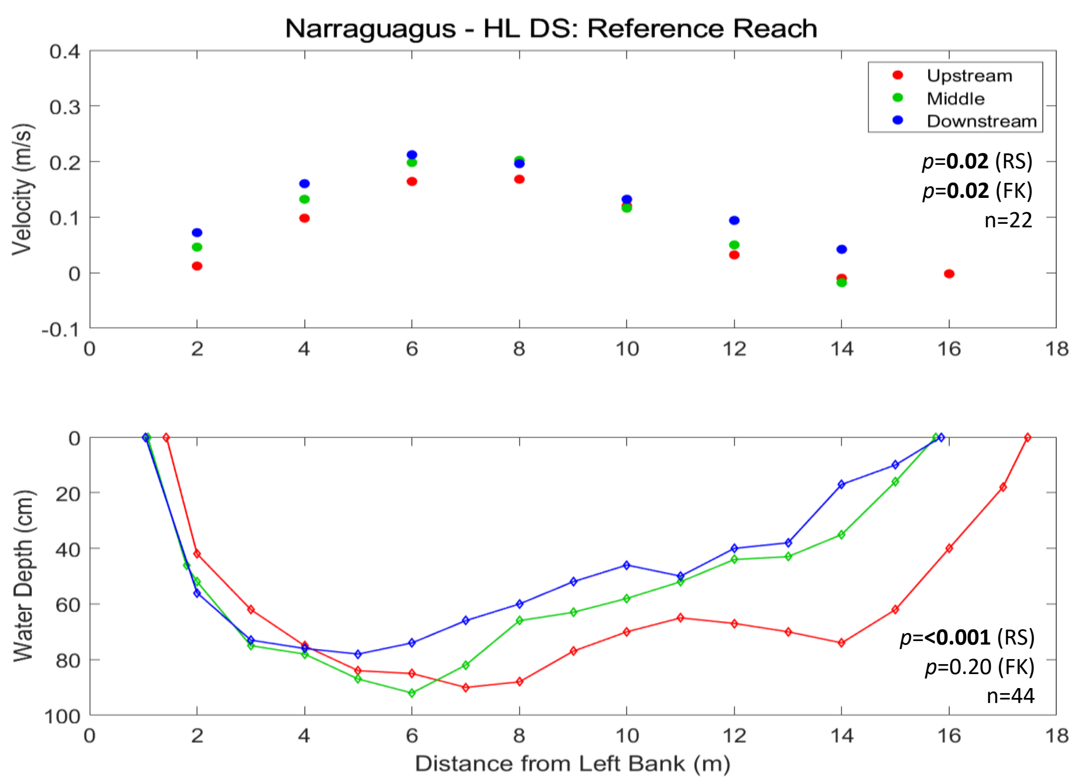

Narraguagus - ATV PALS: Test Reach
Velocity (m/s)
Upstream
Middle
Downstream
n=34
Water Depth (cm)
n=34
Distance from Left Bank (m)

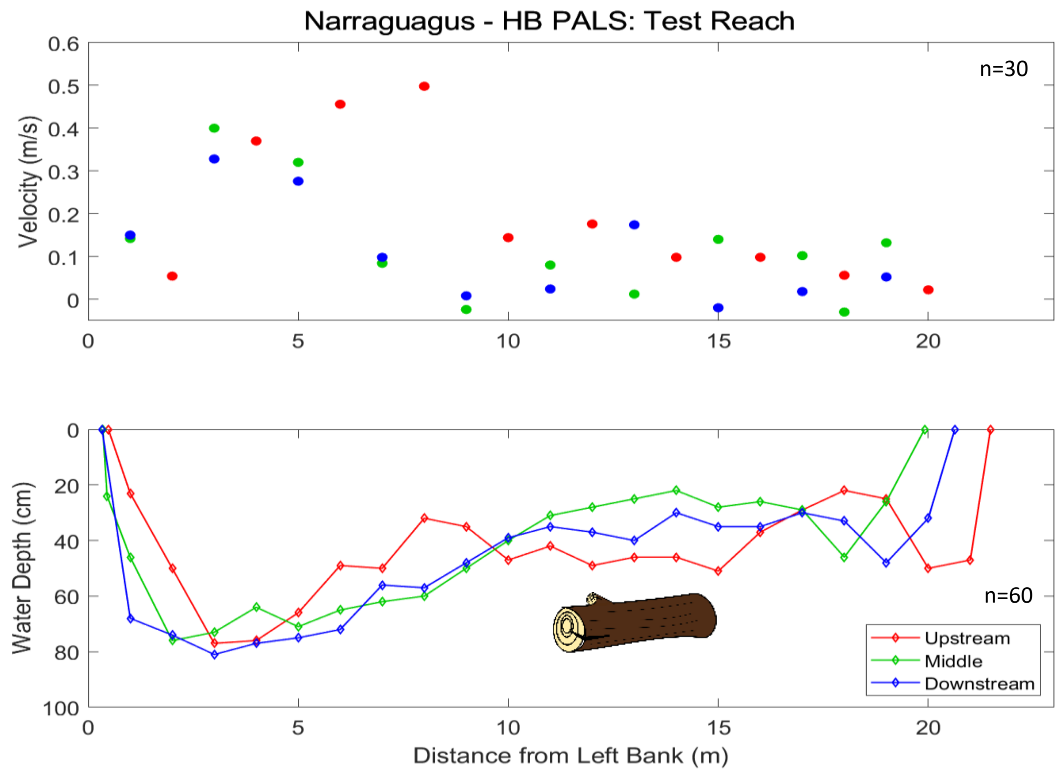

Narraguagus - ATV PALS: Reference Reach
Velocity (m/s)
Upstream
Middle
Downstream
p=0.01 (RS)
p=<0.001 (FK)
n=50
Water Depth (cm)
p=0.04 (RS)
p=0.73 (FK)
n=50
Distance from Left Bank (m)

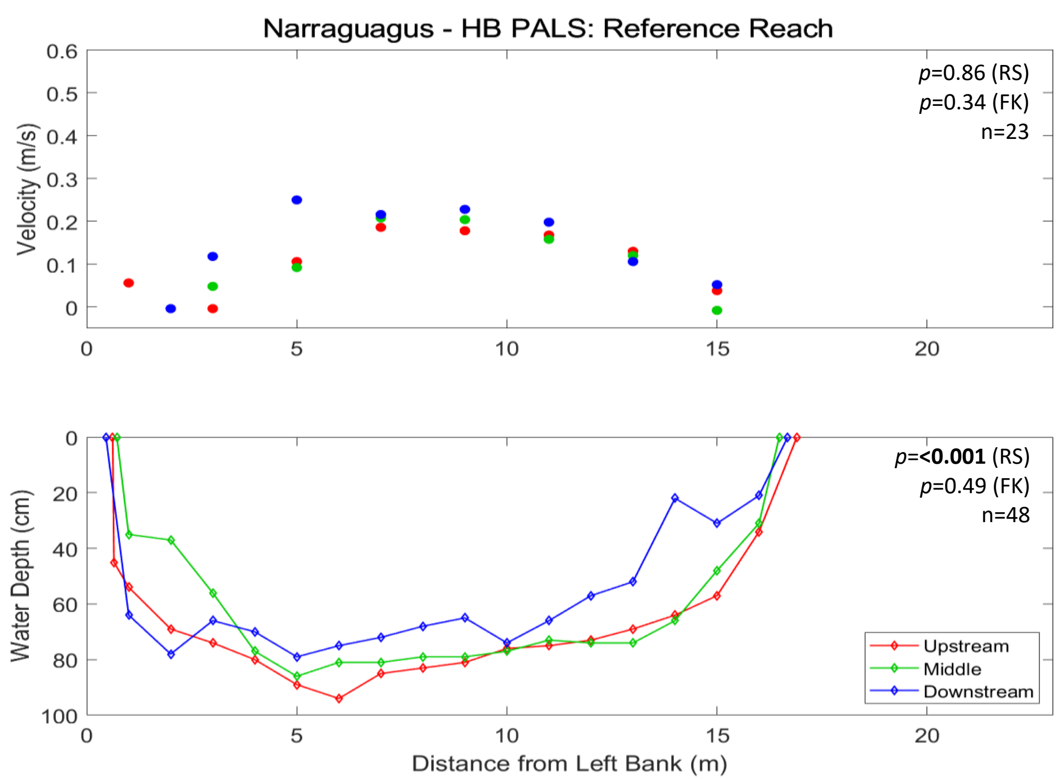

Narraguagus - HL US: Test Reach
n=25
Velocity (m/s)
n=51
Water Depth (cm)
Upstream
Middle
Downstream
Distance from Left Bank (m)

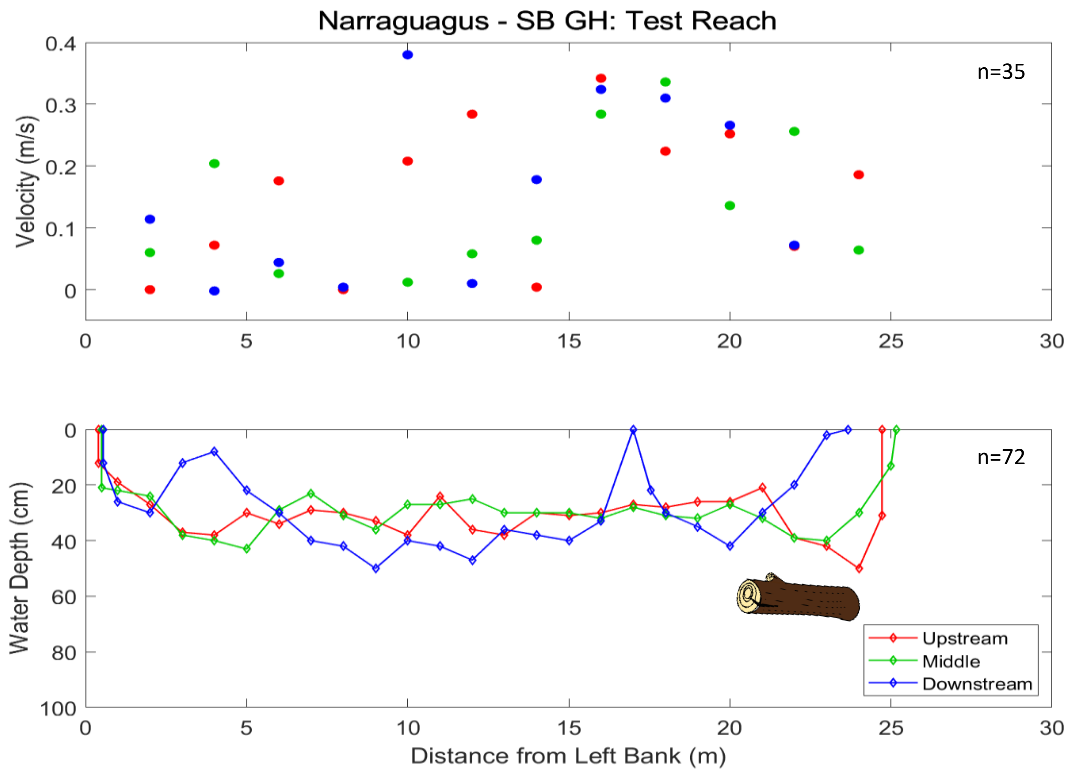

Narraguagus - HL US: Reference Reach
p=0.05 (RS)
p=0.99 (FK)
n=30
Velocity (m/s)
Water Depth (cm)
Upstream
Middle
Downstream
n=61
p=0.12 (RS)
p=0.002 (FK)
Distance from Left Bank (m)

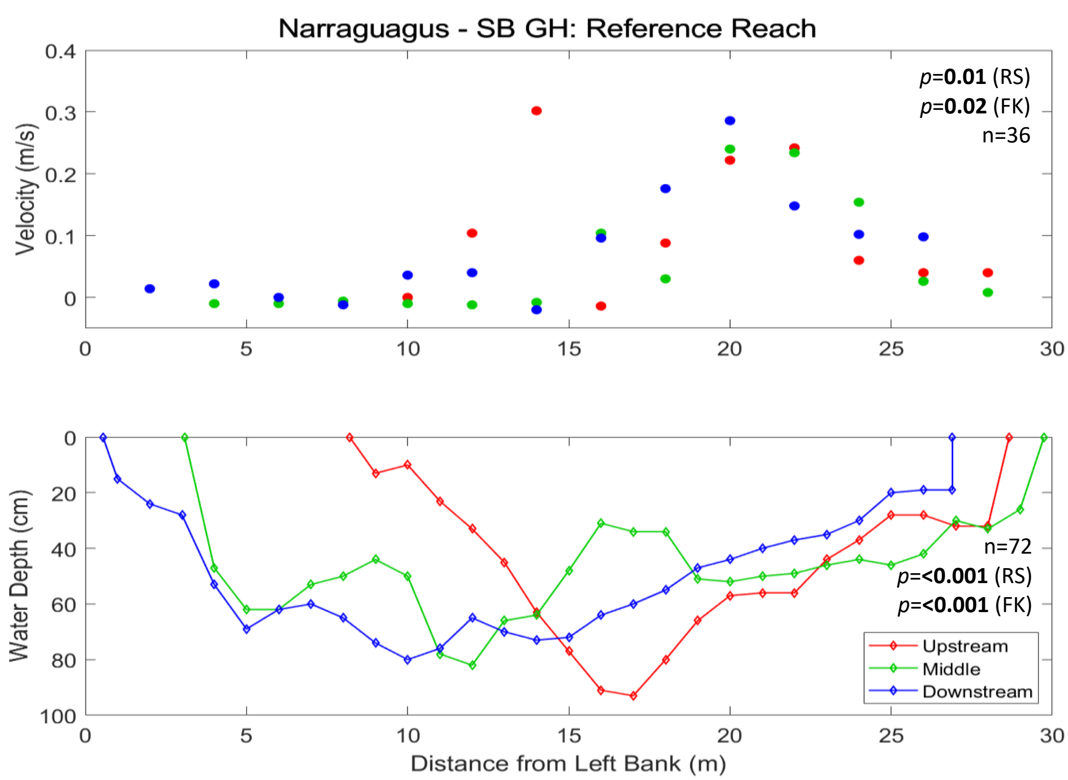

Narraguagus - HL DS: Test Reach
Velocity (m/s)
Upstream
Middle
Downstream
n=18
Water Depth (cm)
n=38
Distance from Left Bank (m)

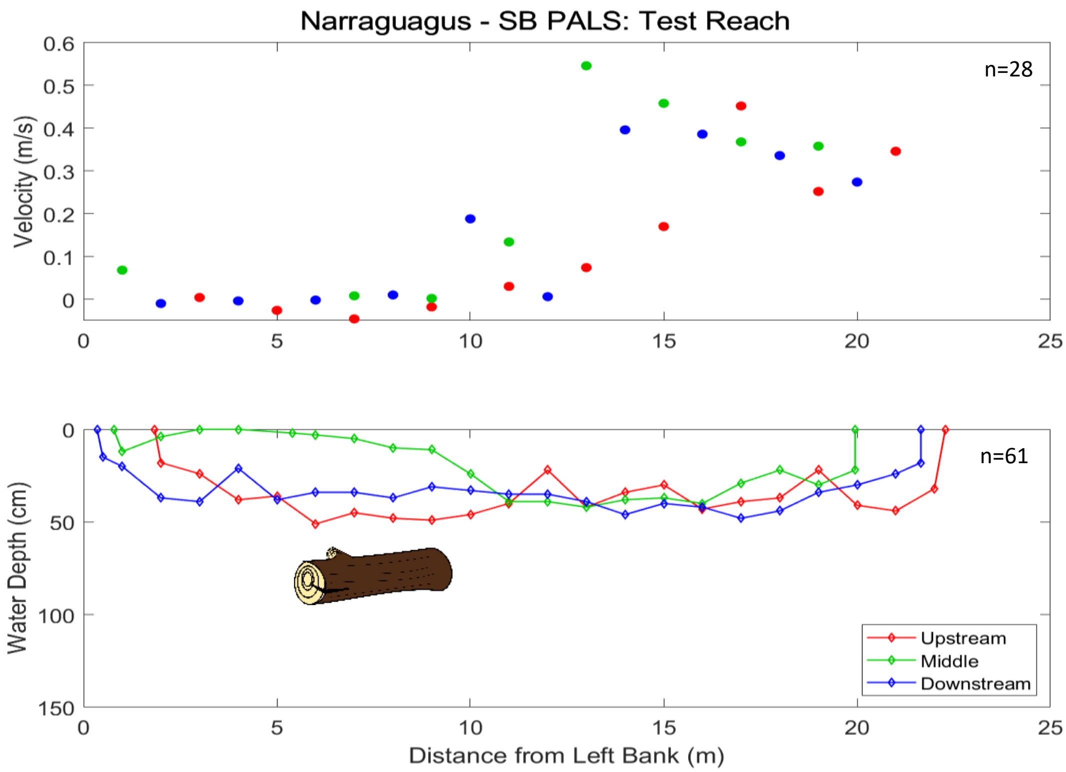

Narraguagus - HL DS: Reference Reach
Velocity (m/s)
Upstream
Middle
Downstream
p=0.02 (RS)
p=0.02 (FK)
n=22
Water Depth (cm)
p=<0.001 (RS)
p=0.20 (FK)
n=44
Distance from Left Bank (m)

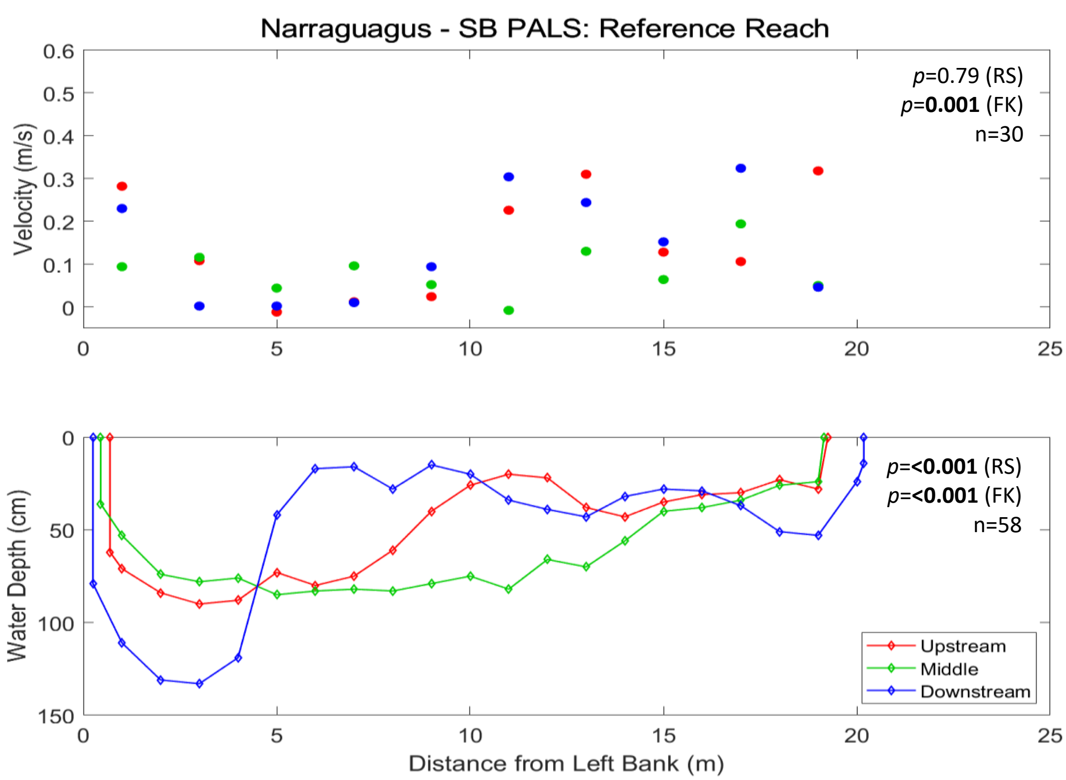

Narraguagus - HB PALS: Test Reach
Velocity (m/s)
n=30
Water Depth (cm)
n=60
Upstream
Middle
Downstream
Distance from Left Bank (m)

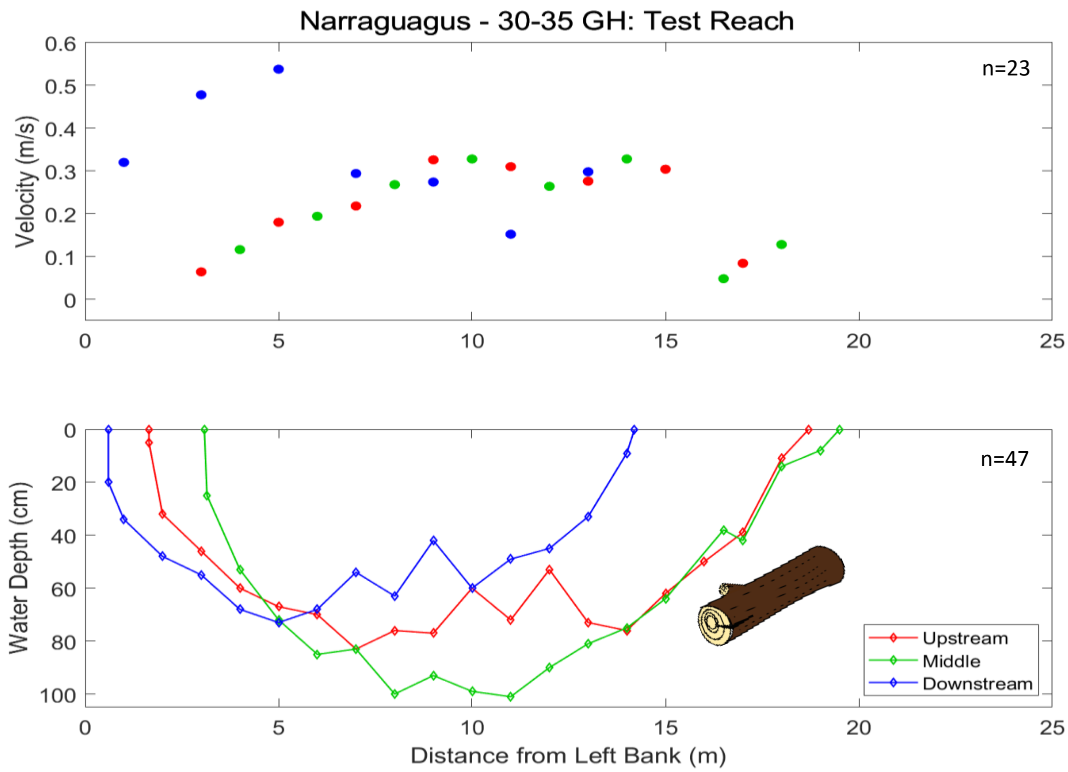

Narraguagus - HB PALS: Reference Reach
Velocity (m/s)
p=0.86 (RS)
p=0.34 (FK)
n=23
Water Depth (cm)
p=<0.001 (RS)
p=0.49 (FK)
n=48
Upstream
Middle
Downstream
Distance from Left Bank (m)

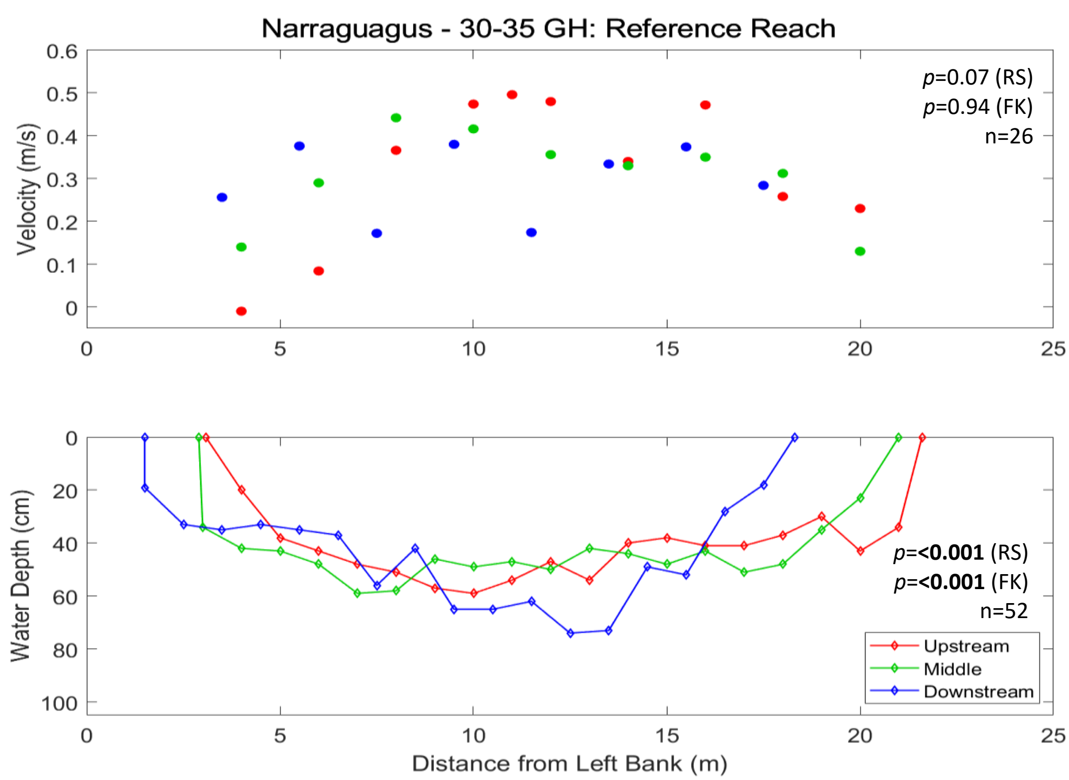

Narraguagus - SB GH: Test Reach
Velocity (m/s)
n=35
Water Depth (cm)
n=72
Upstream
Middle
Downstream
Distance from Left Bank (m)


Narraguagus - SB GH: Reference Reach
Velocity (m/s)
p=0.01 (RS)
p=0.02 (FK)
n=36
Water Depth (cm)
n=72
p=<0.001 (RS)
p=<0.001 (FK)
Upstream
Middle
Downstream
Distance from Left Bank (m)

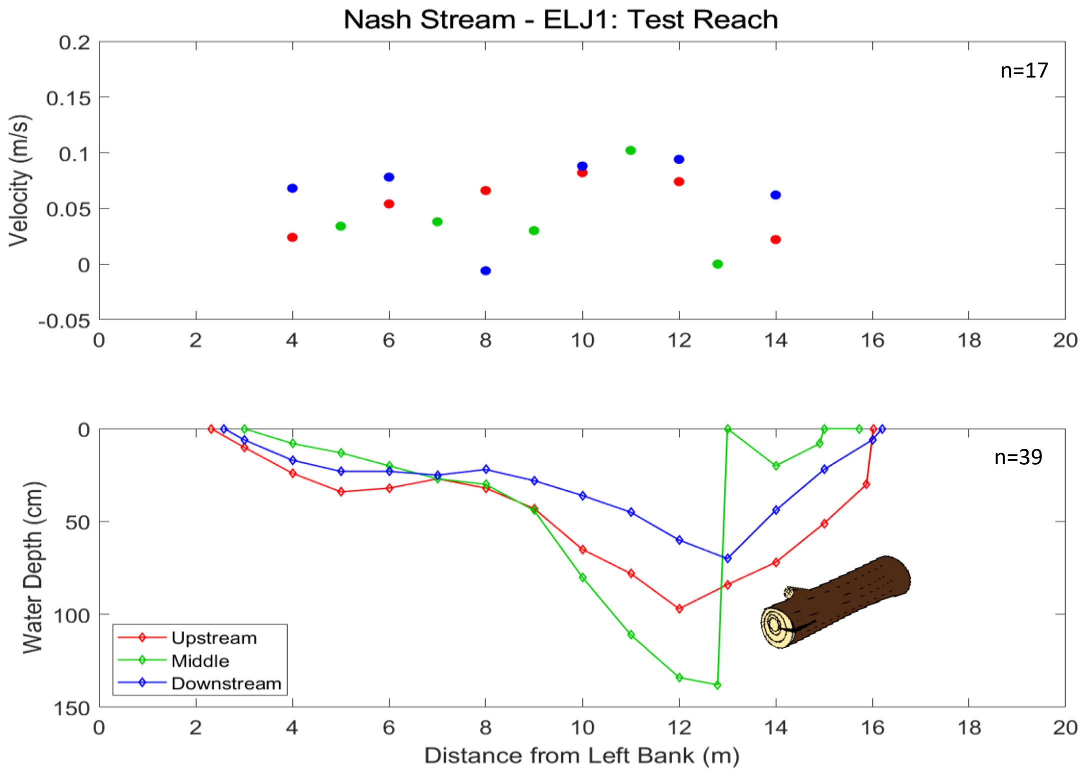

Narraguagus - SB PALS: Test Reach
Velocity (m/s)
n=28
Water Depth (cm)
n=61
Upstream
Middle
Downstream
Distance from Left Bank (m)

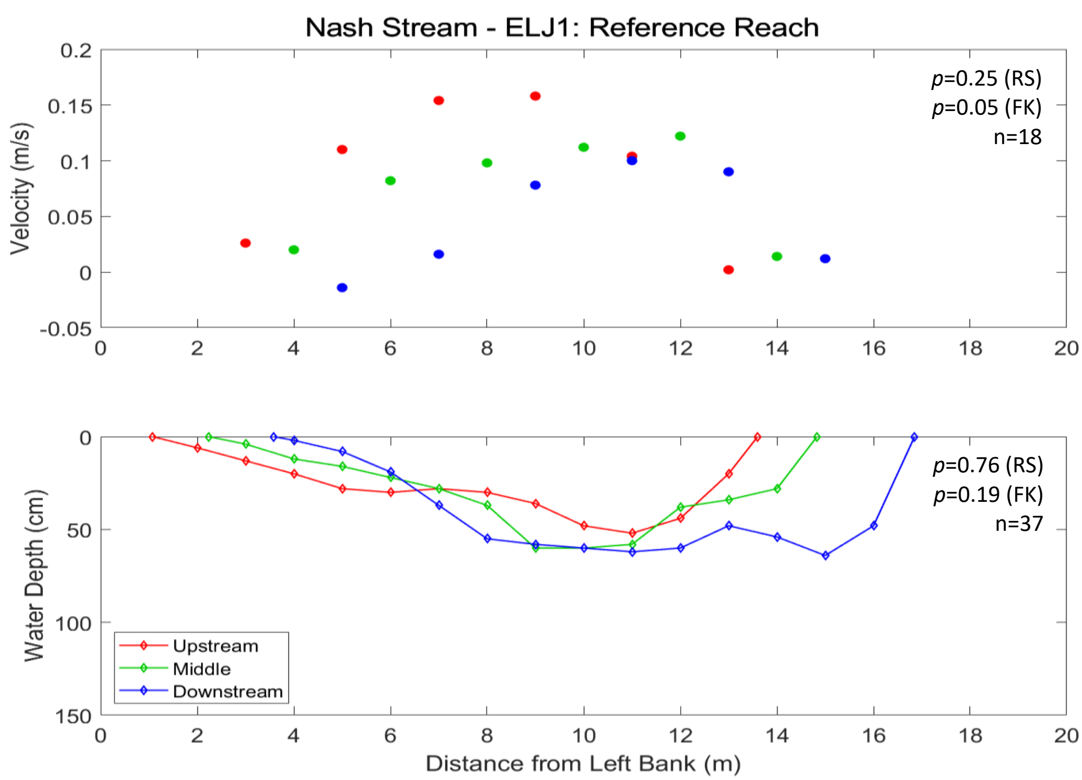

Narraguagus - SB PALS: Reference Reach
Velocity (m/s)
p=0.79 (RS)
p=**0.001** (FK)
n=30
Water Depth (cm)
p=**<0.001** (RS)
p=**<0.001** (FK)
n=58
Upstream
Middle
Downstream
Distance from Left Bank (m)

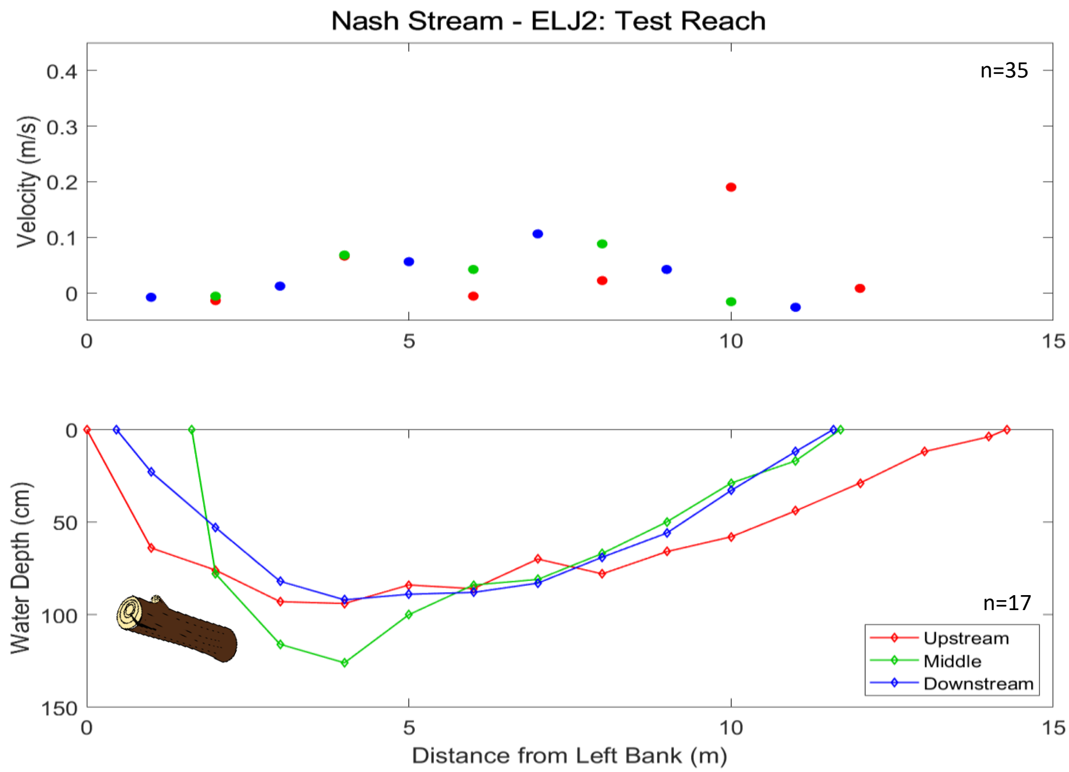

Narraguagus - 30-35 GH: Test Reach
Velocity (m/s)
n=23
Water Depth (cm)
n=47
Upstream
Middle
Downstream
Distance from Left Bank (m)

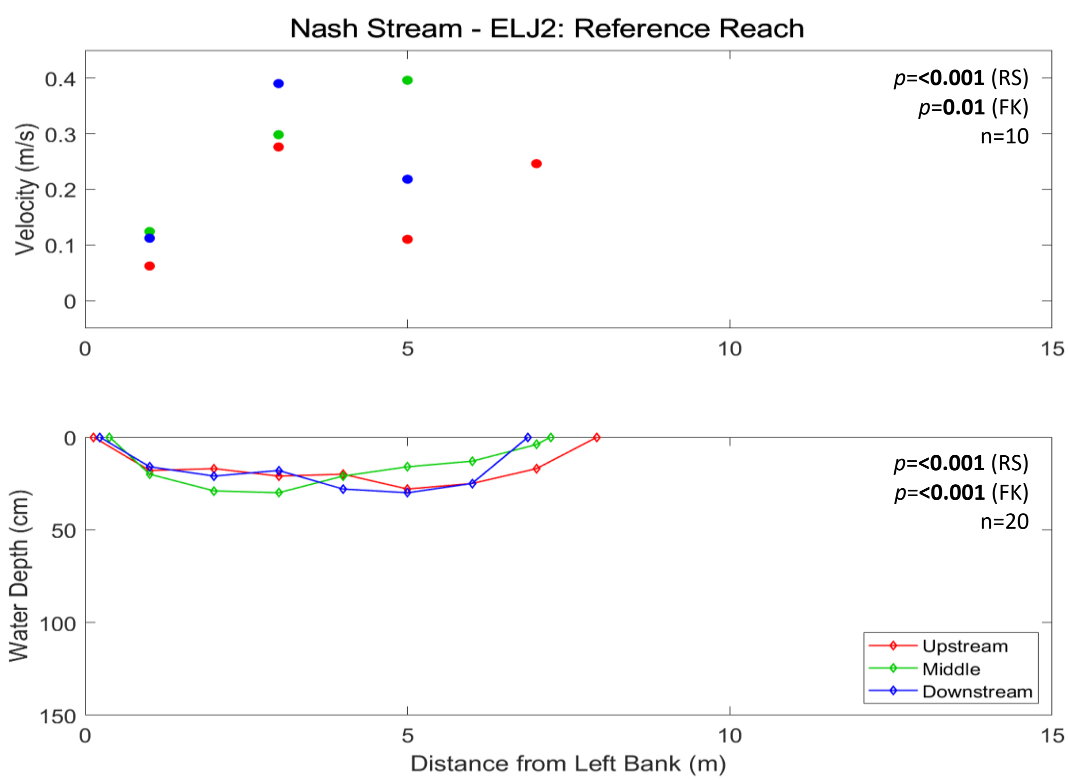

Narraguagus - 30-35 GH: Reference Reach
Velocity (m/s)
p=0.07 (RS)
p=0.94 (FK)
n=26
Water Depth (cm)
p=<0.001 (RS)
p=<0.001 (FK)
n=52
Upstream
Middle
Downstream
Distance from Left Bank (m)

Nash Stream, NH



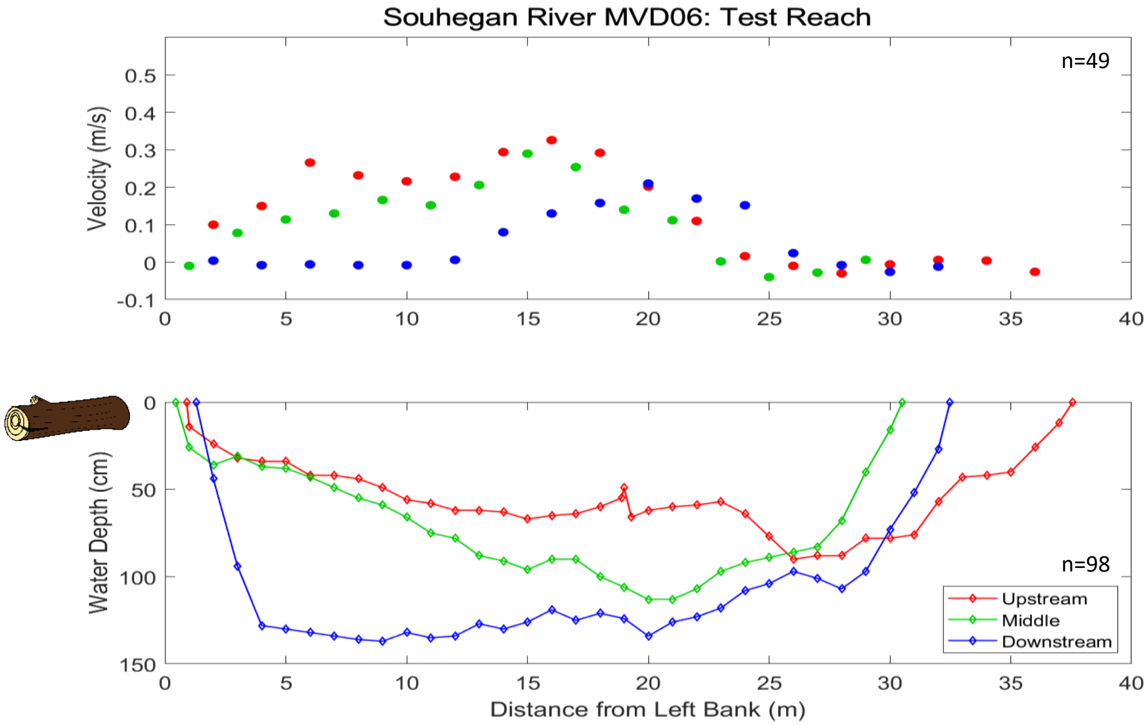


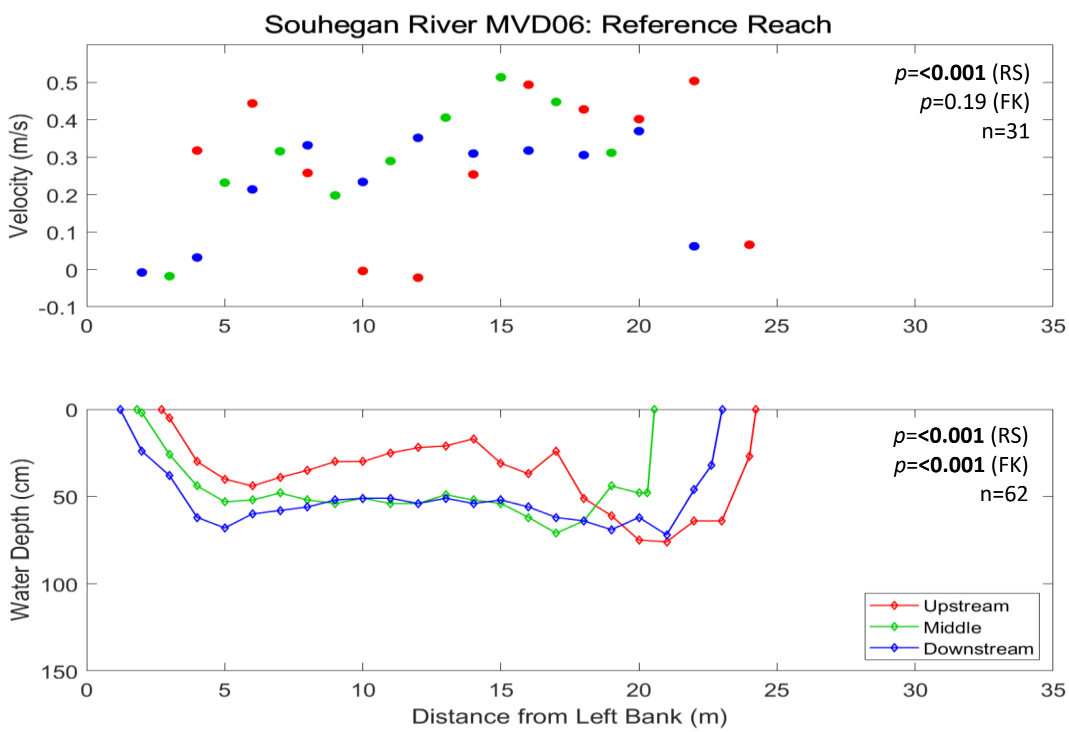

Nash Stream - ELJ2: Test Reach
n=35
Velocity (m/s)
n=17
Upstream
Middle
Downstream
Water Depth (cm)
Distance from Left Bank (m)


Nash Stream - ELJ2: Reference Reach
p=<0.001 (RS)
p=0.01 (FK)
n=10
Velocity (m/s)
p=<0.001 (RS)
p=<0.001 (FK)
n=20
Upstream
Middle
Downstream
Water Depth (cm)
Distance from Left Bank (m)

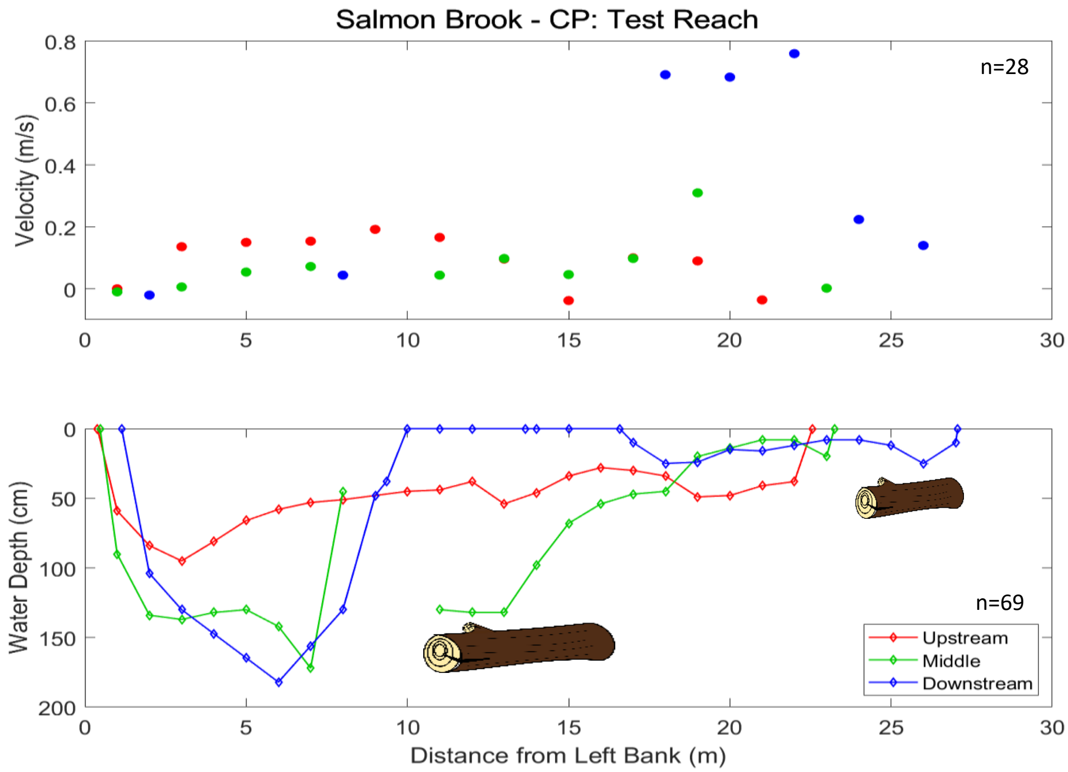
<u>Souhegan River, NH</u>

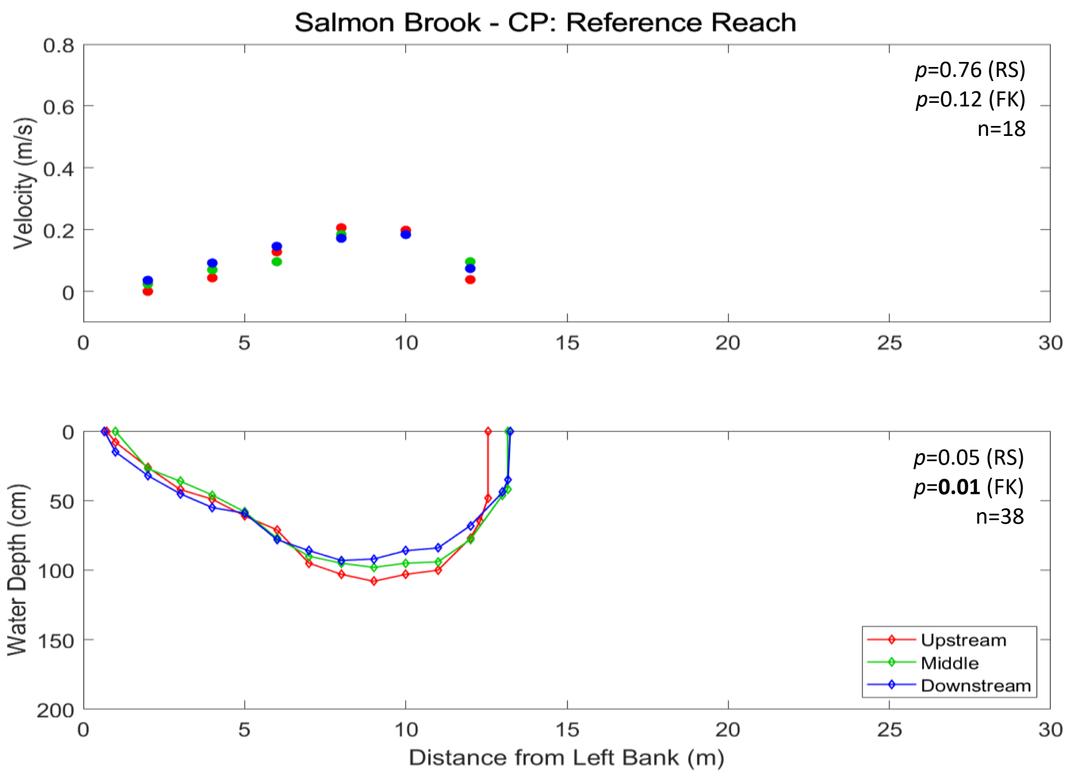
Large wood at the MVD06 site is within the floodplain adjacent to to the channel, rather than in the water.



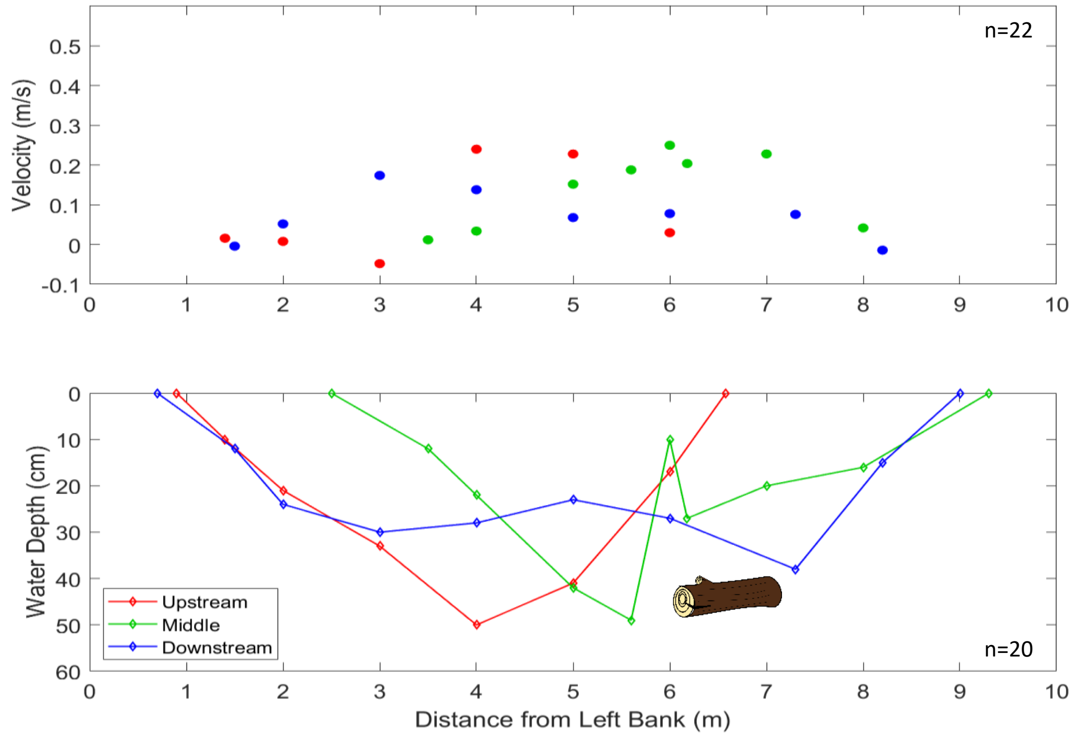


Salmon Brook, CT

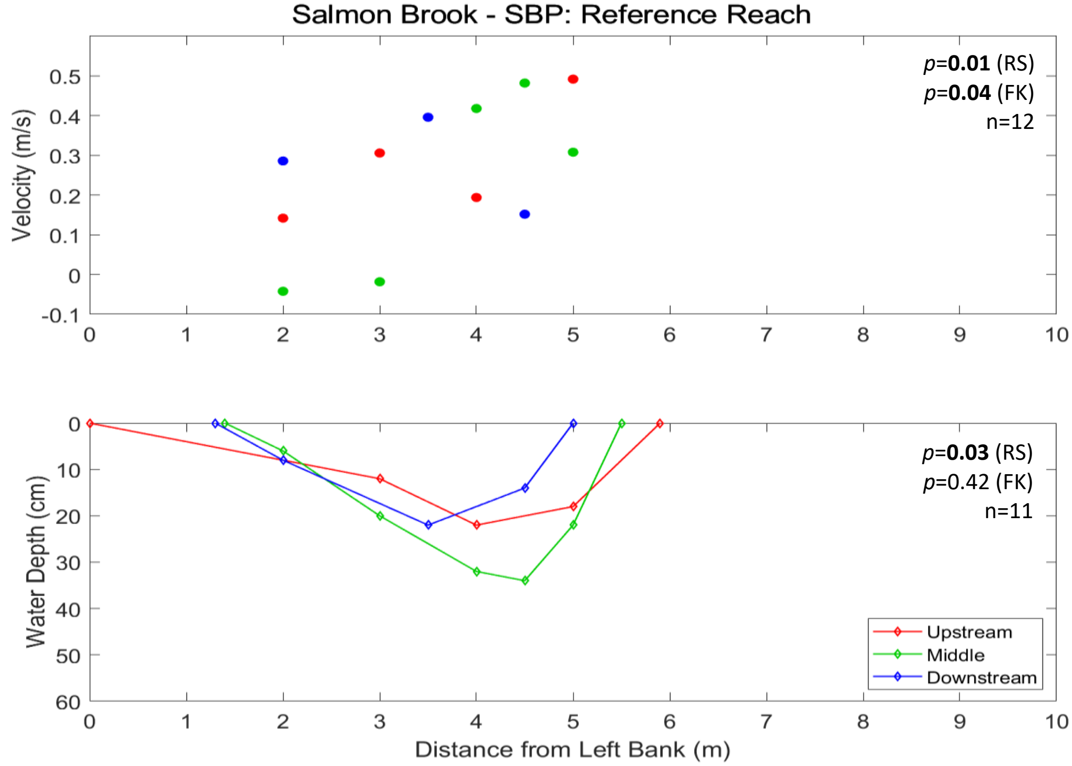




Salmon Brook - SBP: Test Reach



Salmon Brook - SBP: Reference Reach

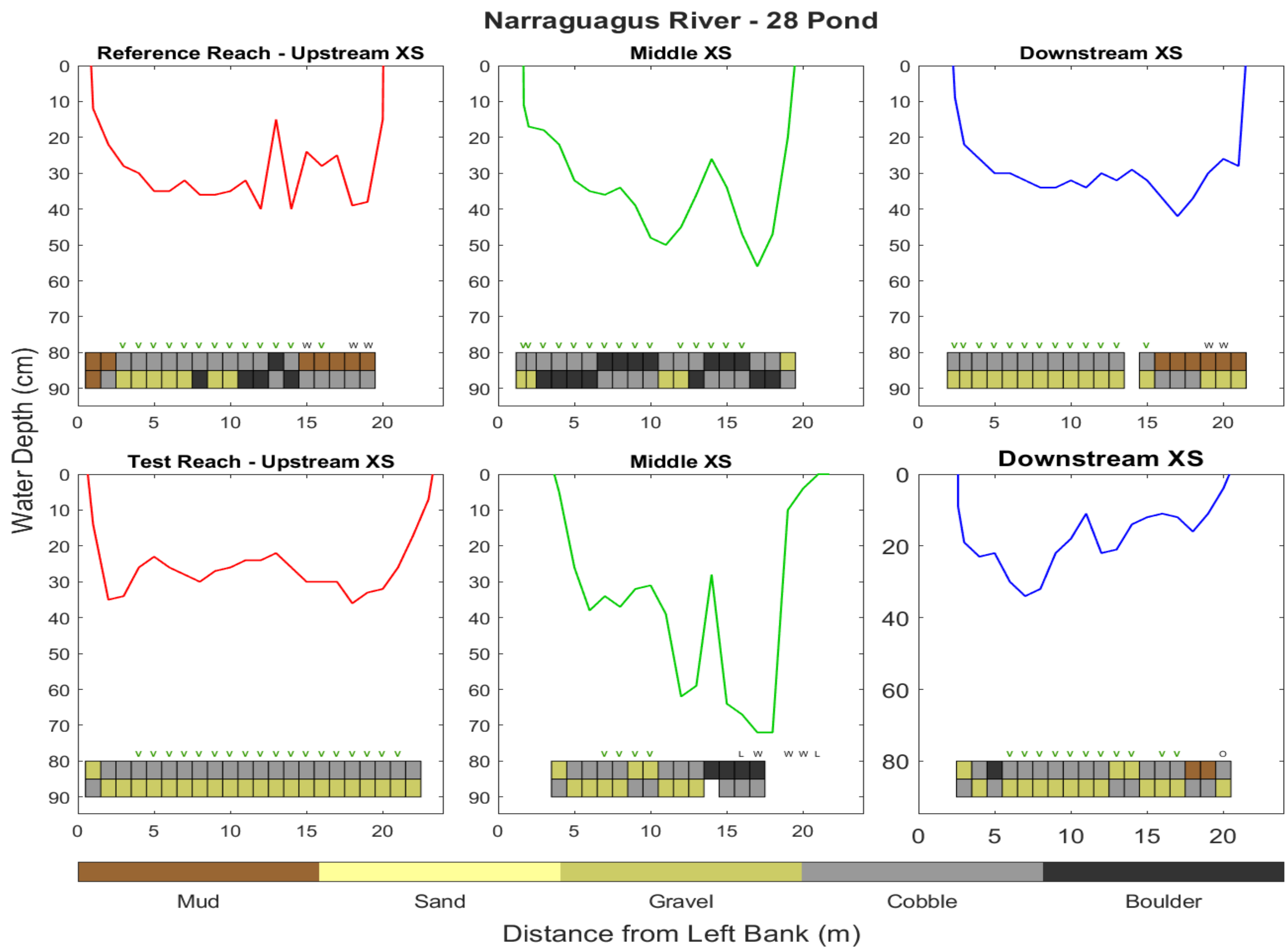


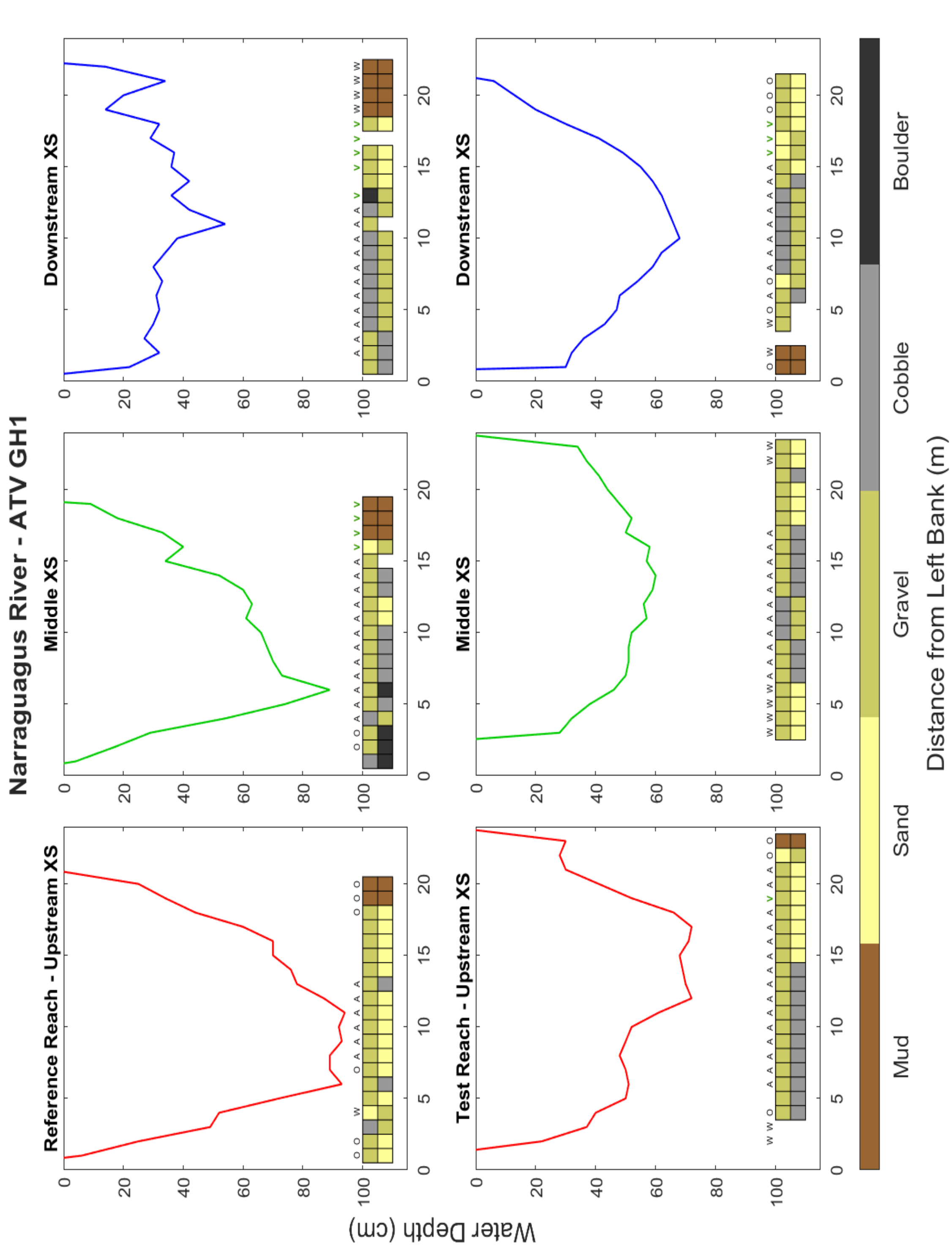
Appendix D – All Sites: Substrate Profiles

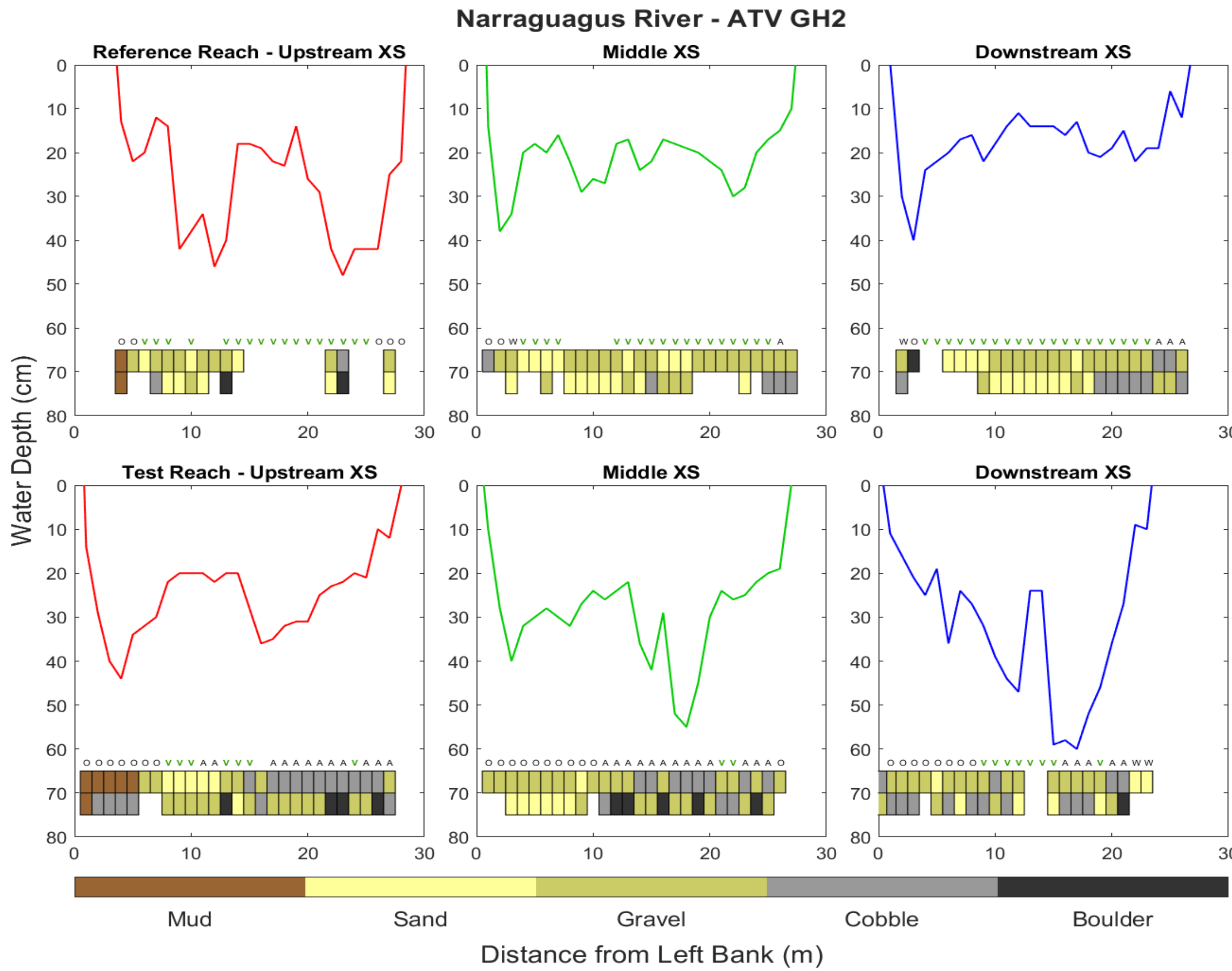
Abbreviations: A = algae, L = large wood, O = organic matter, V = subaquatic vegetation (green text), W = wood (small pieces, ex. twigs)

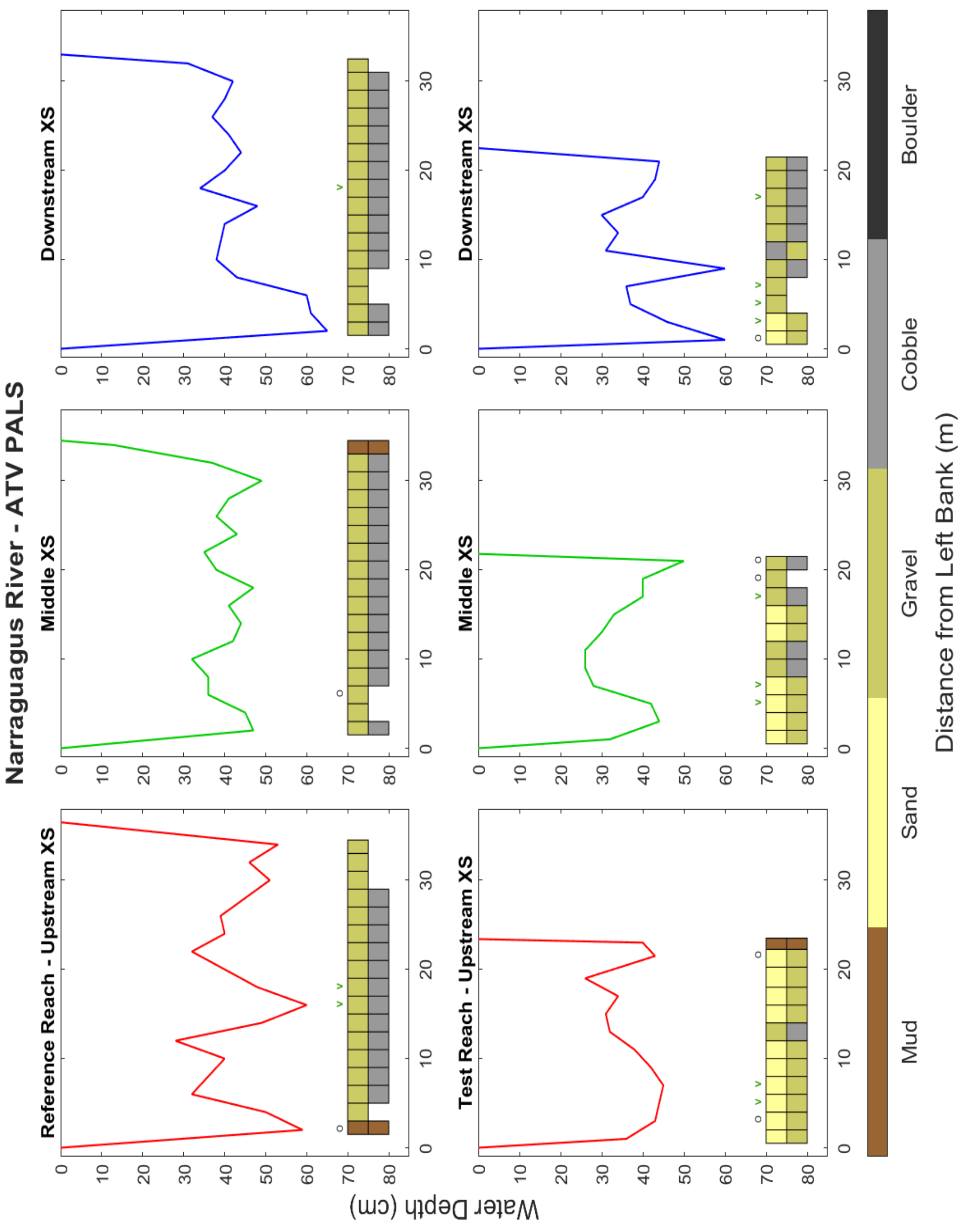
Note: Two rows of substrate data are displayed on each plot. The top and bottom rows represent the primary and secondary substrate present at the corresponding position along the cross section, respectively.

Narraguagus River, ME

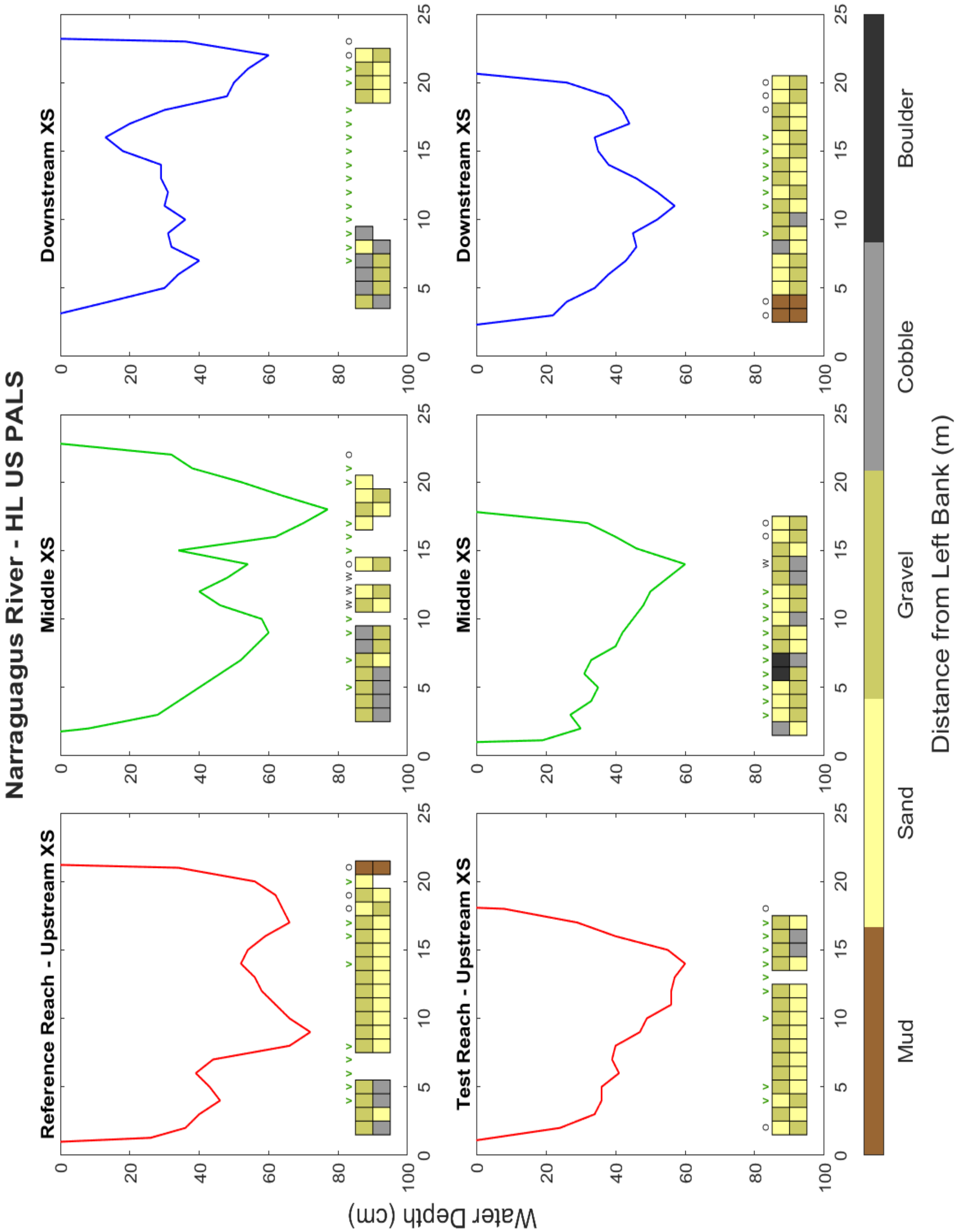


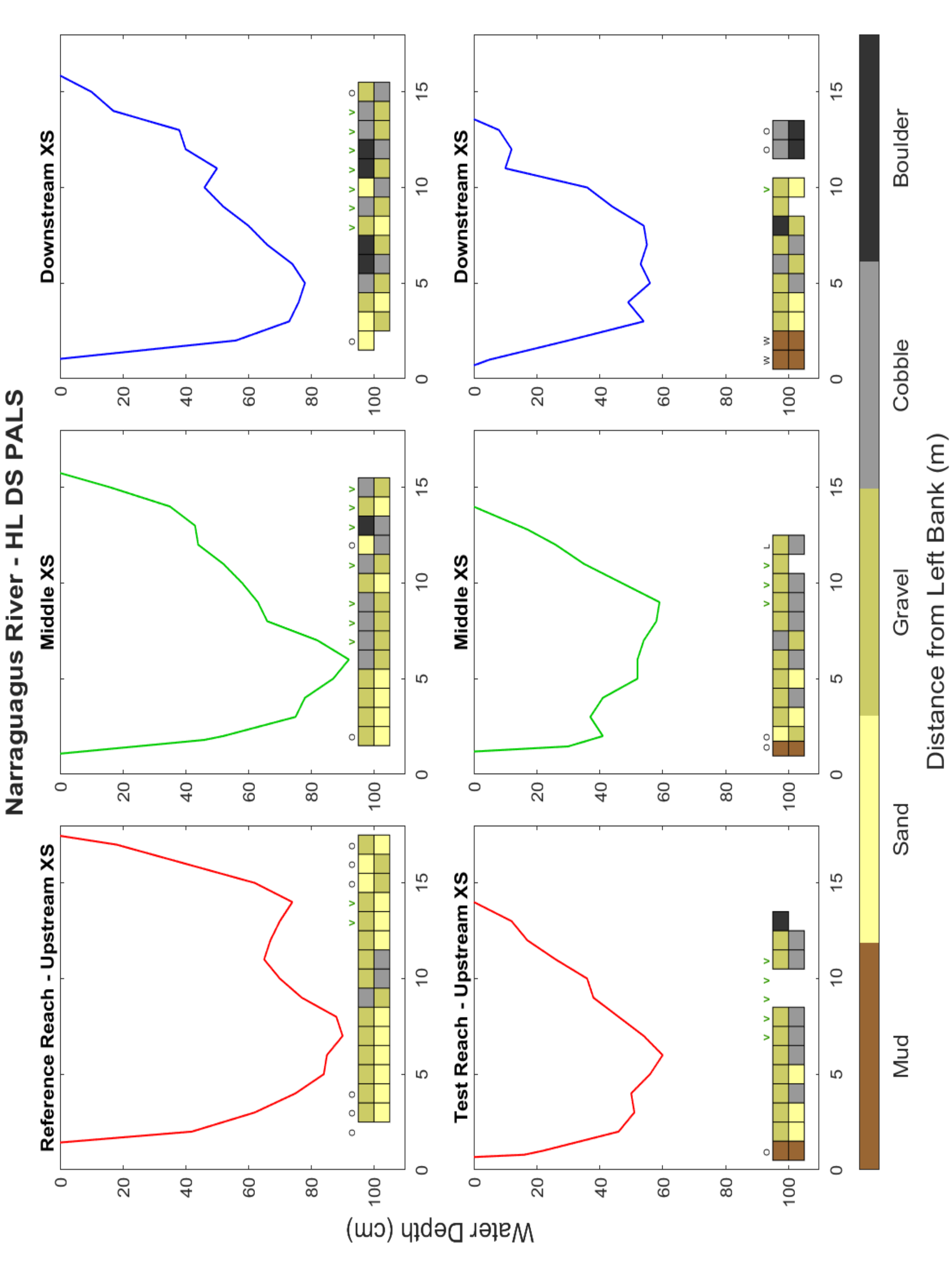

Narraguagus River - ATV GH1
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder


Narraguagus River - ATV GH2
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Mud
Sand
Gravel
Cobble
Boulder
Distance from Left Bank (m)

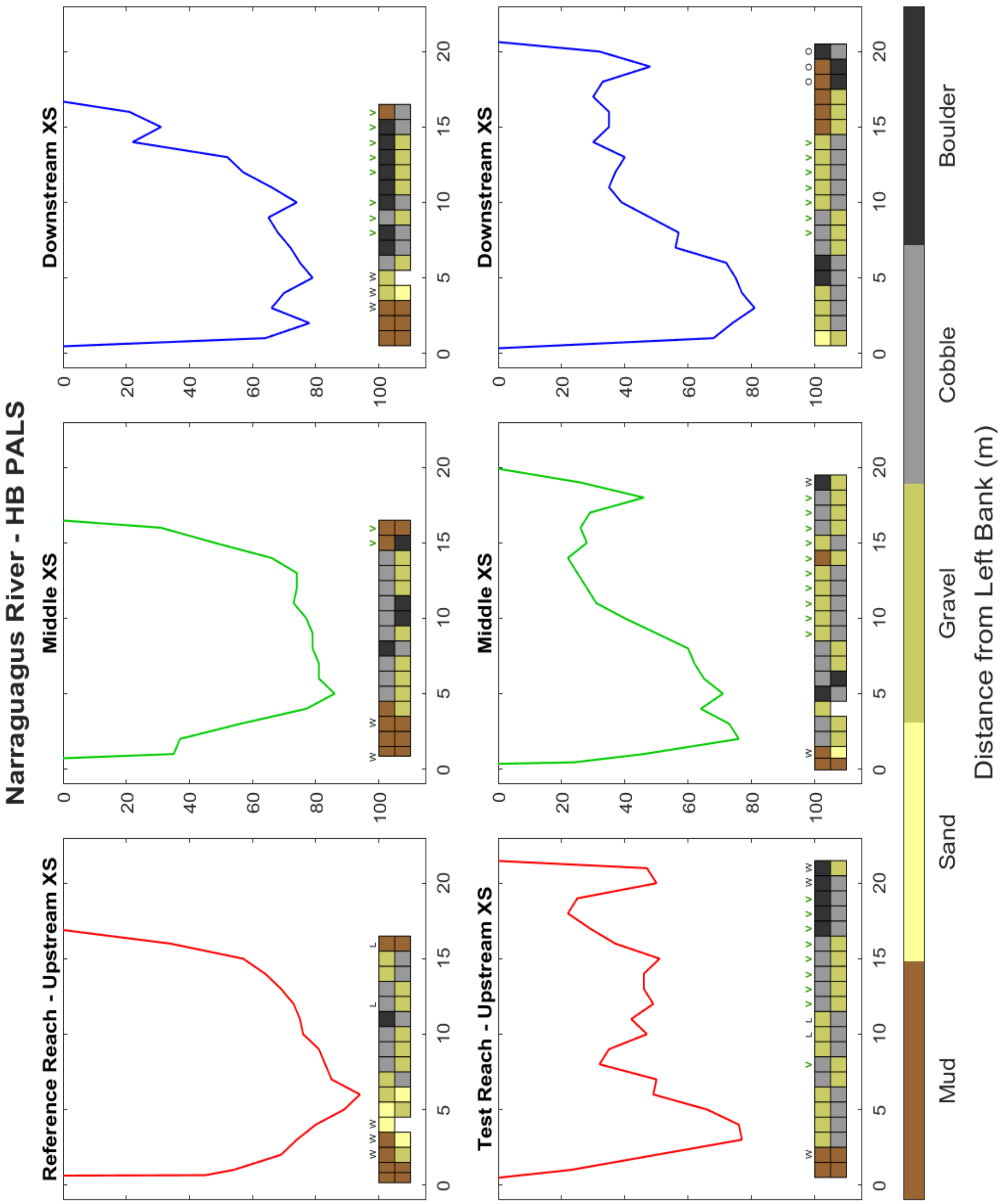


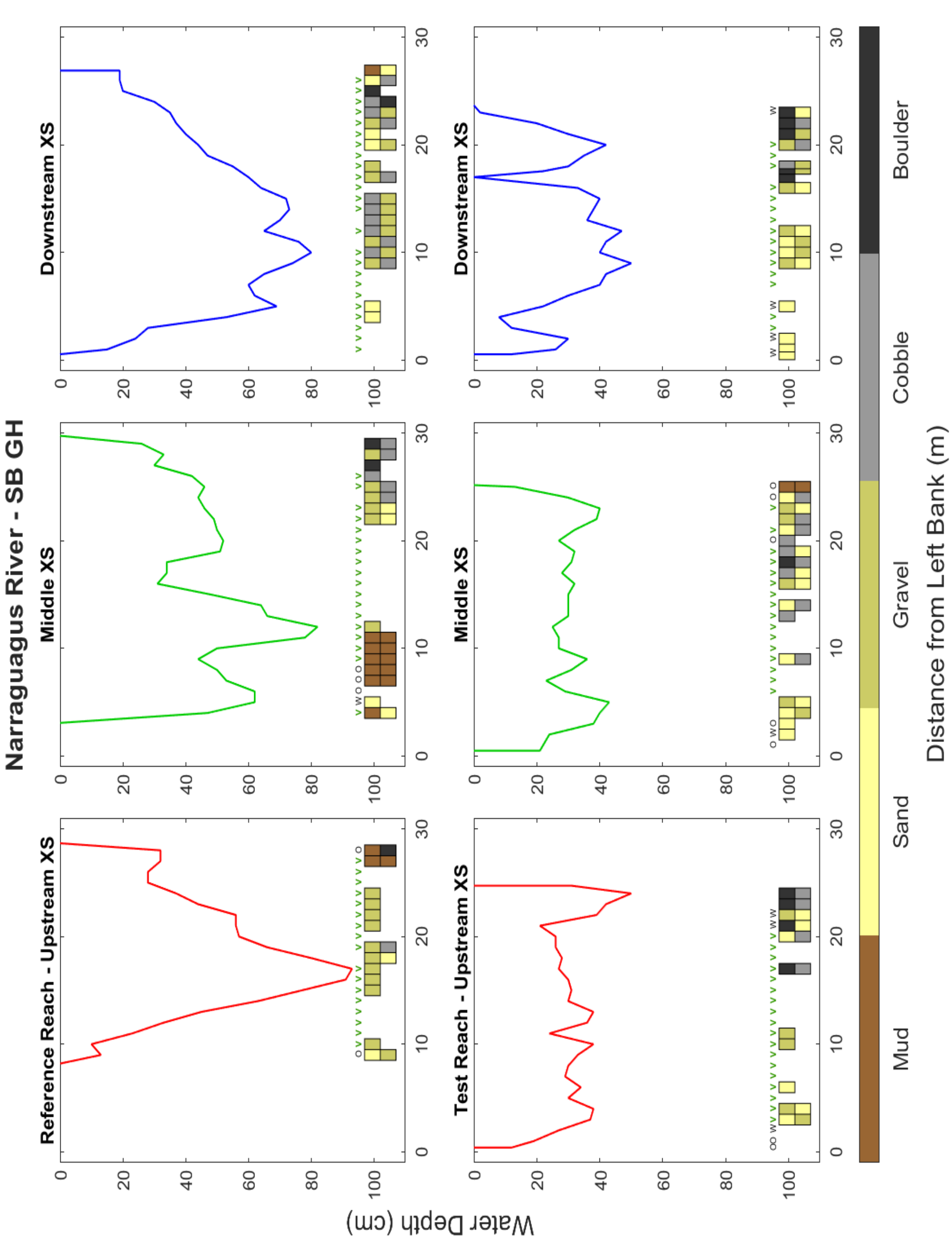
Narraguagus River - ATV PALS
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder


Narraguagus River - HL US PALS
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder

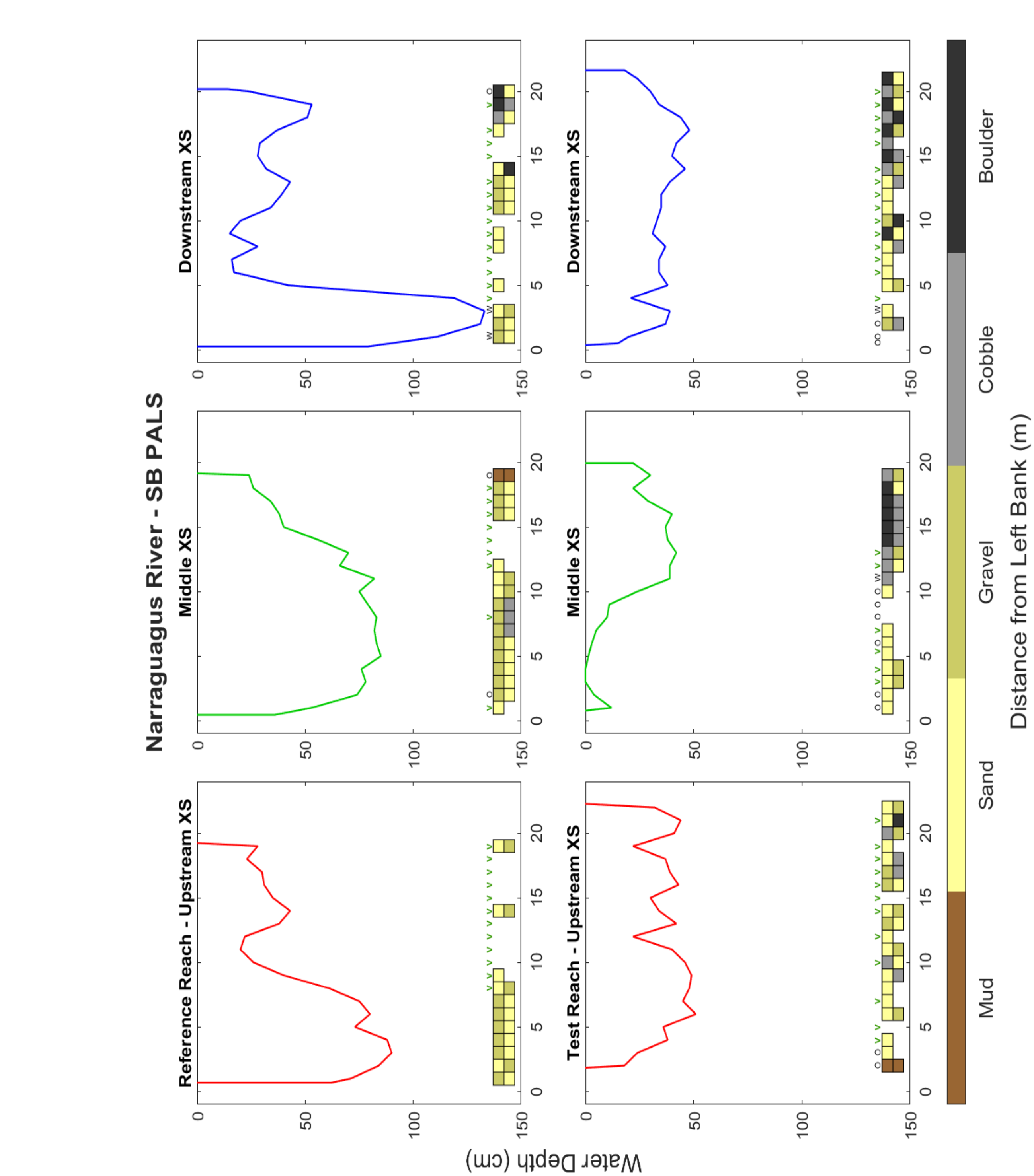


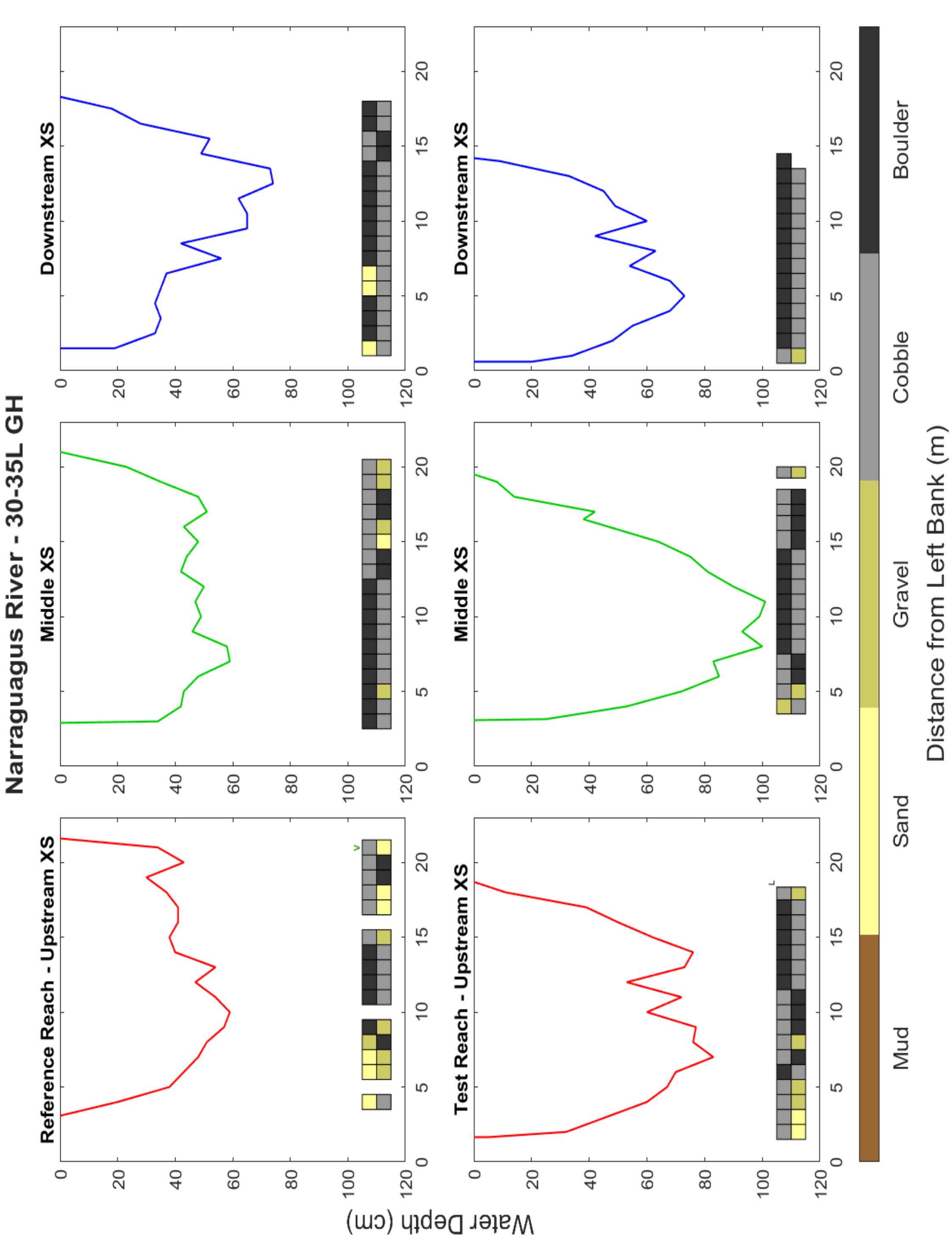
Narraguagus River - HL DS PALS
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder


Narraguagus River - HB PALS
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder



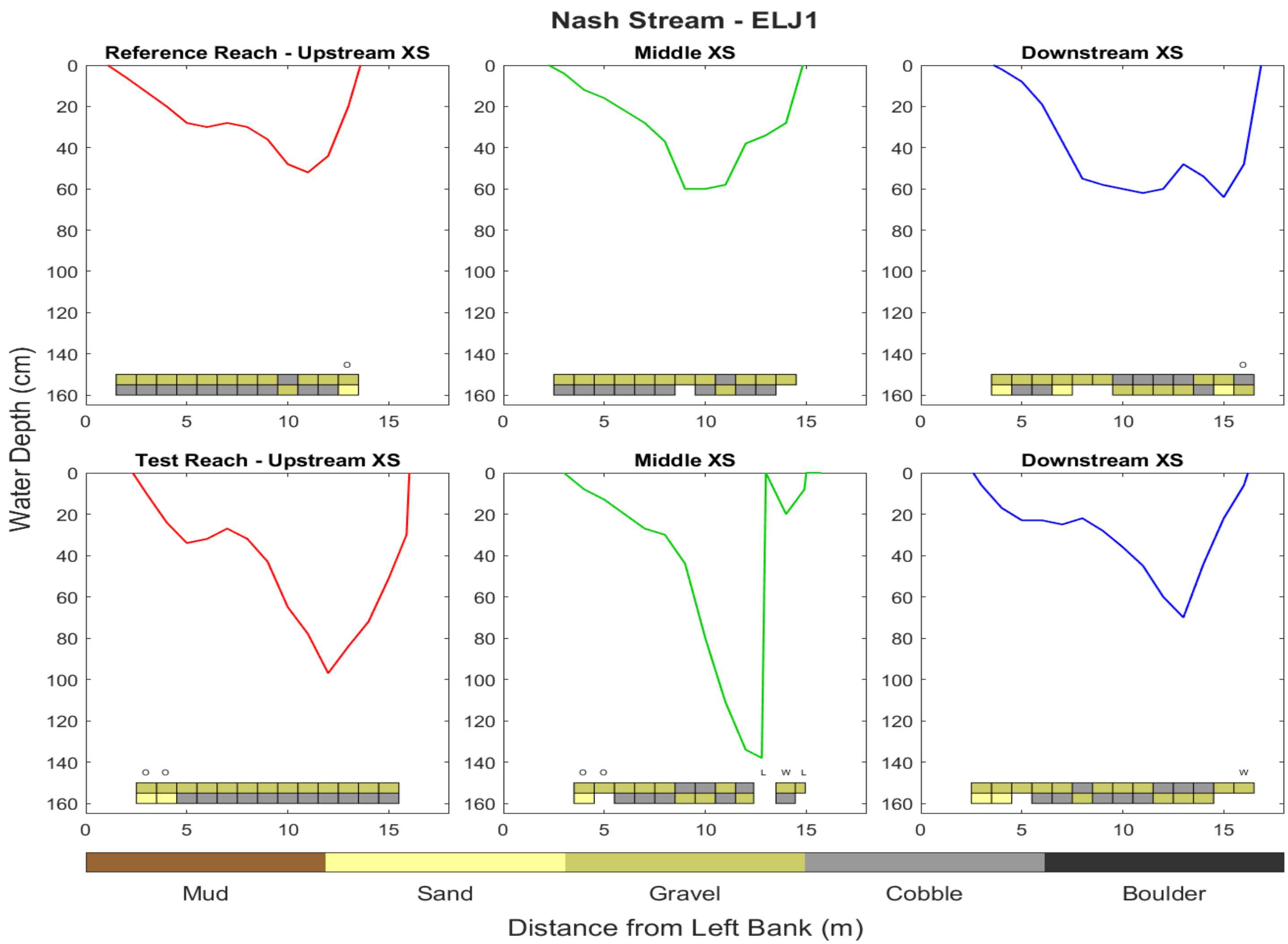
Narraguagus River - SB GH
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder

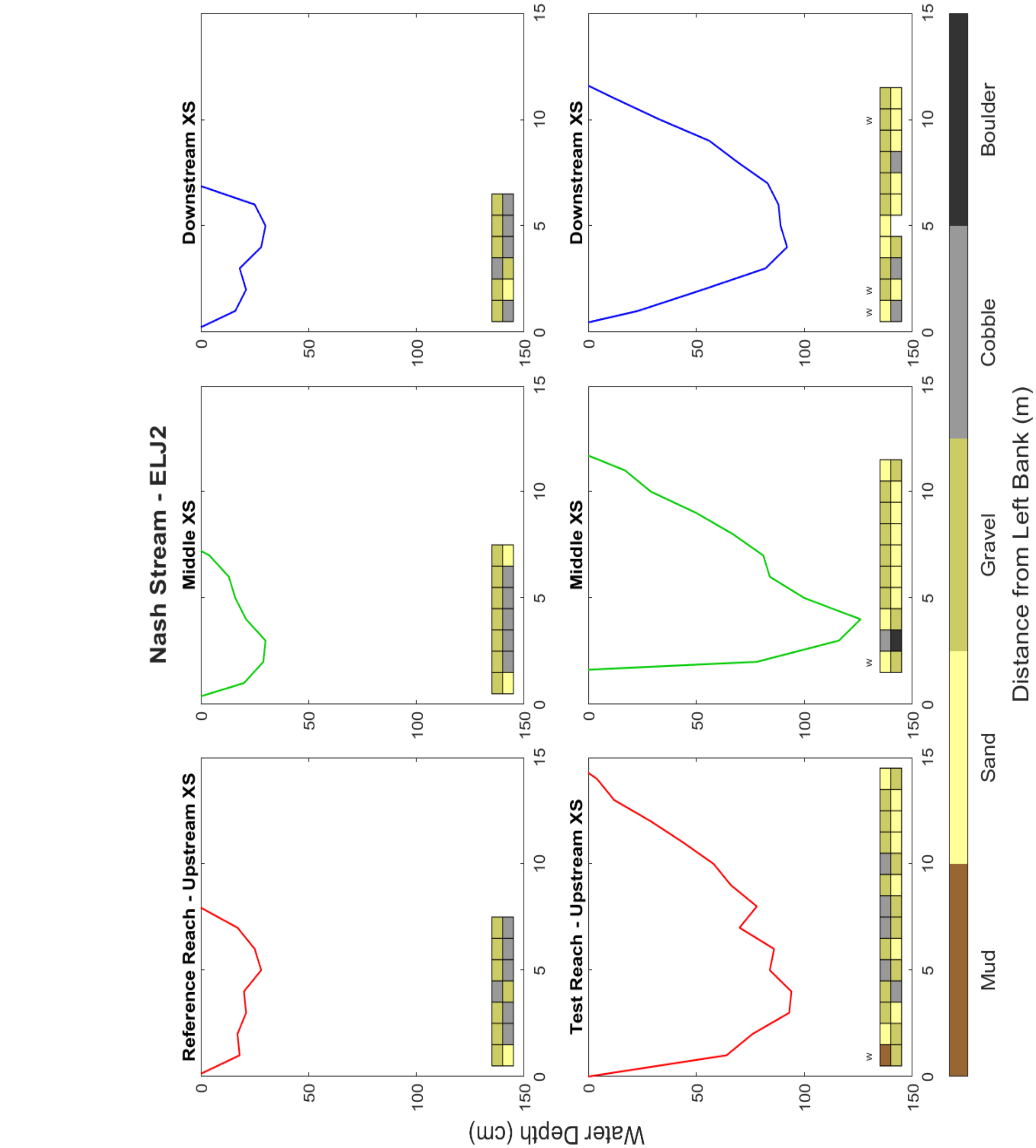

Narraguagus River - SB PALS
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder



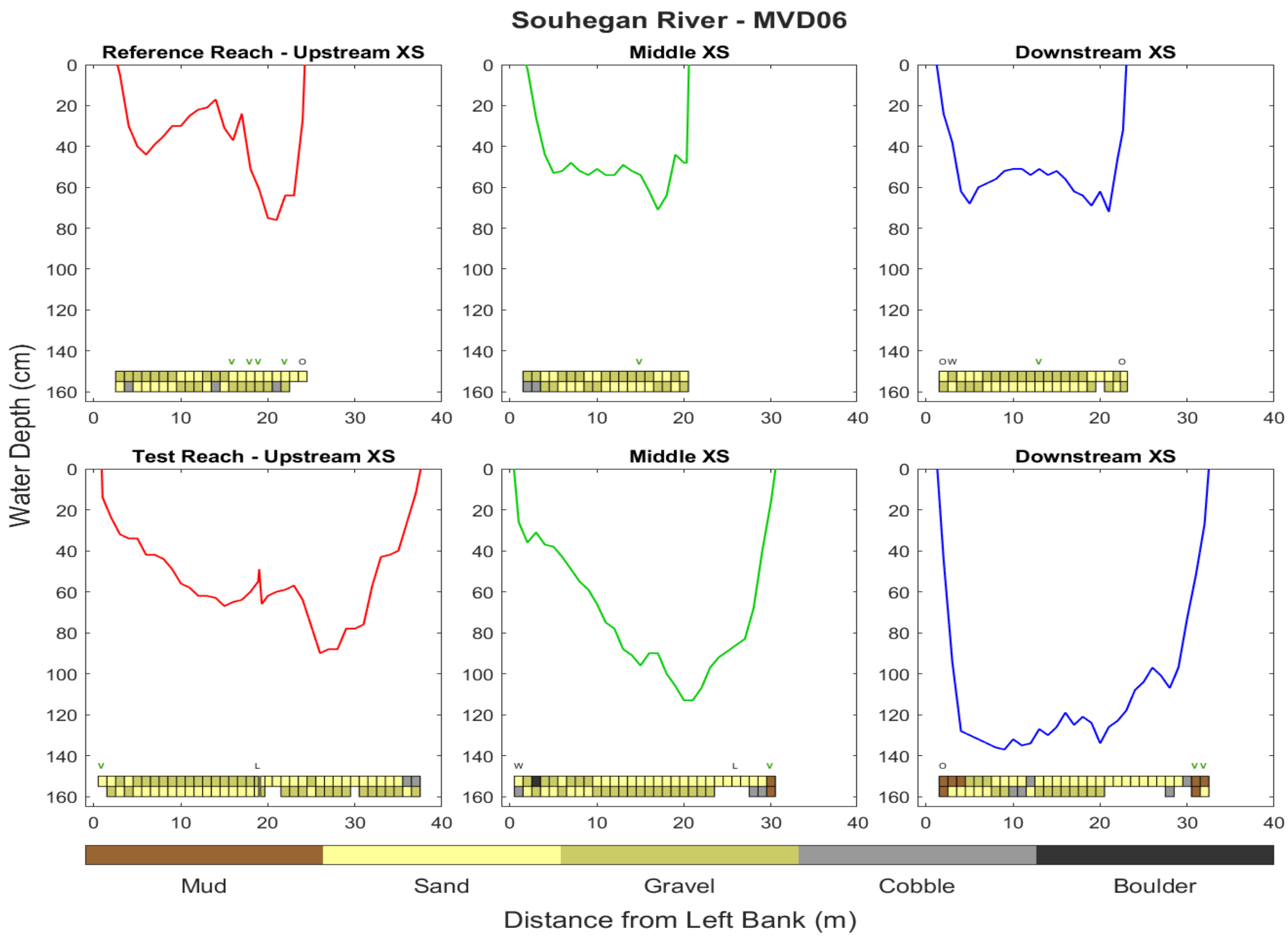
Narraguagus River - 30-35L GH
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder

Nash Stream, NH

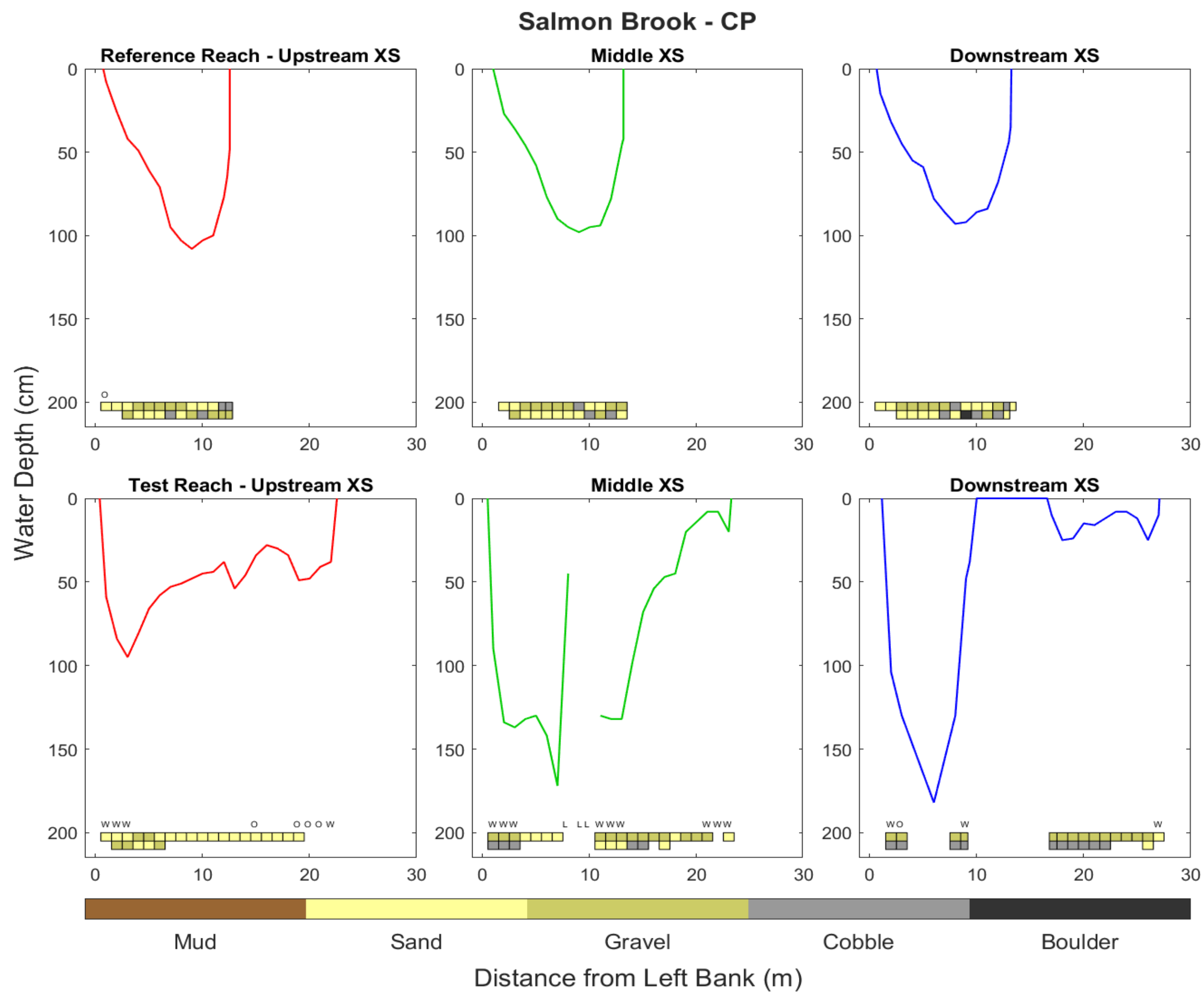


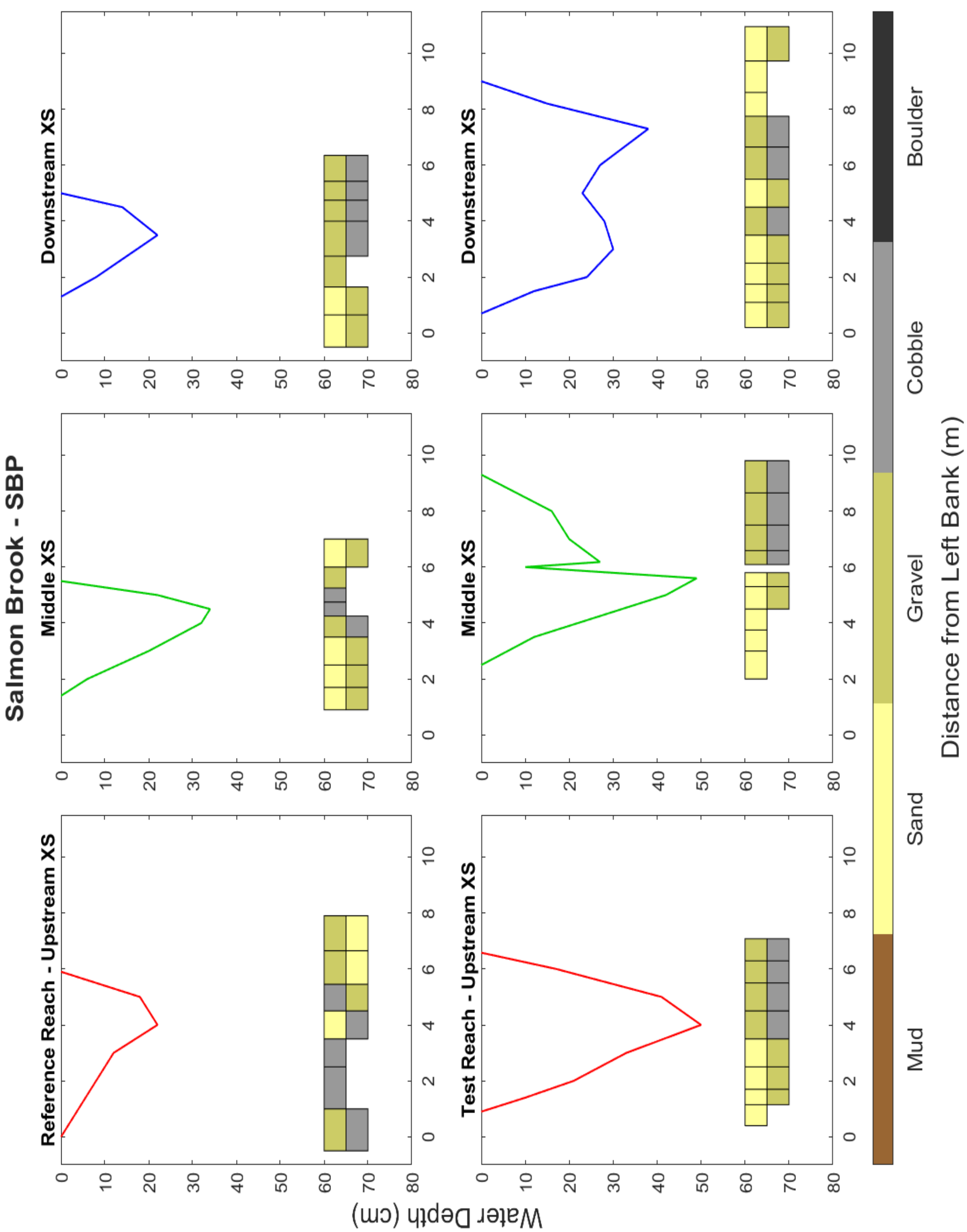

Nash Stream - ELJ2
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder

Souhegan River, NH



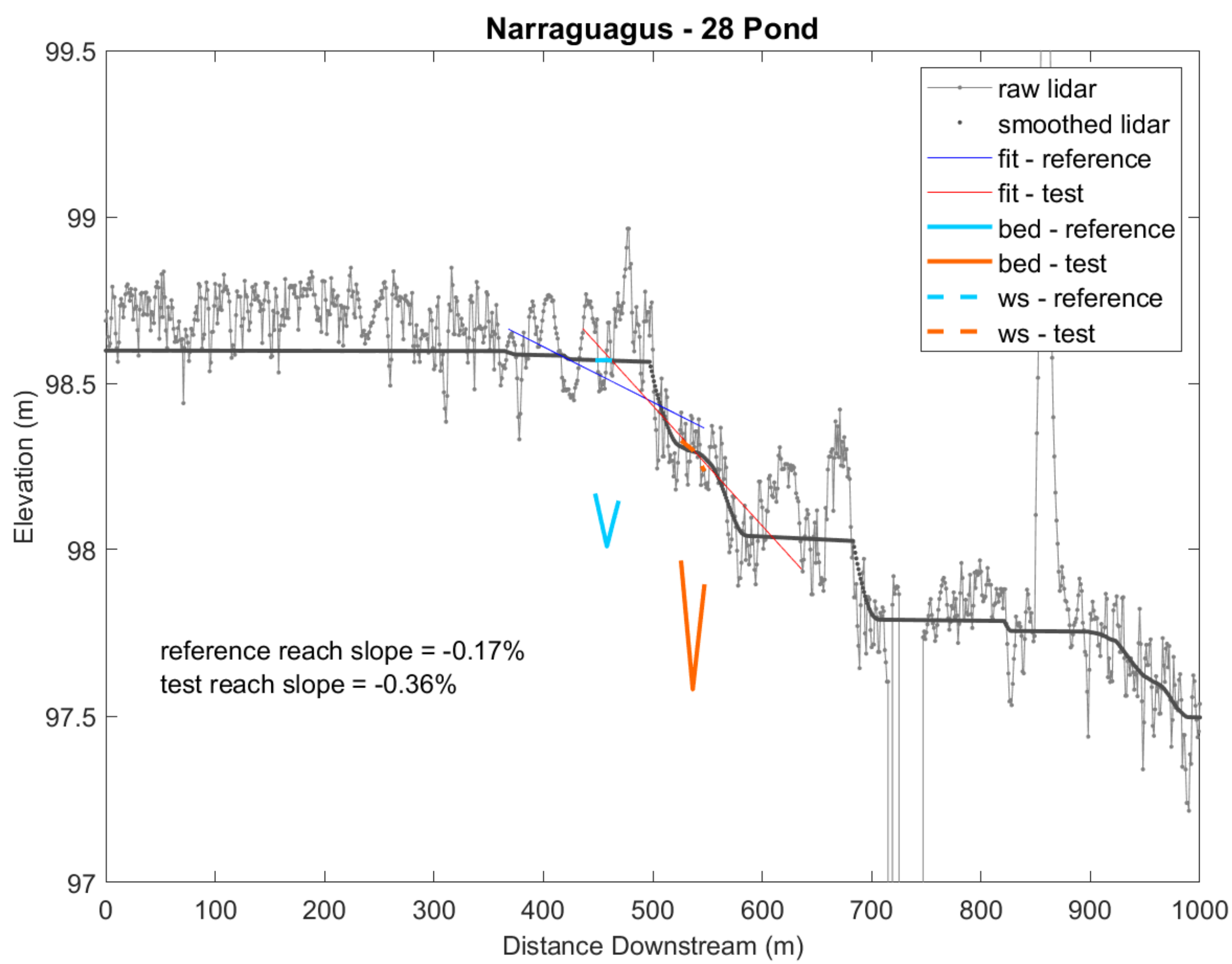
Salmon Brook, CT

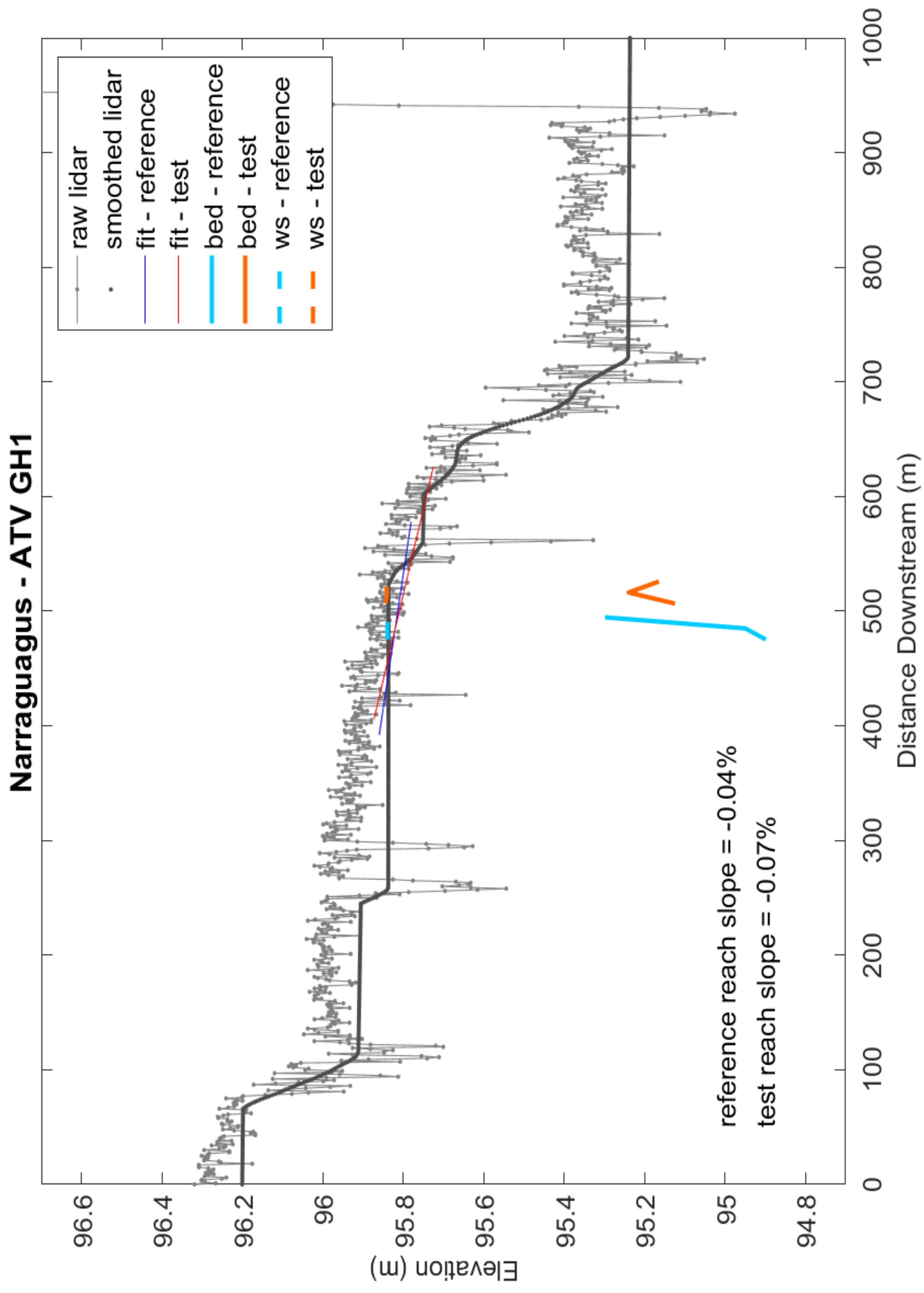



Salmon Brook - SBP
Reference Reach - Upstream XS
Middle XS
Downstream XS
Test Reach - Upstream XS
Middle XS
Downstream XS
Water Depth (cm)
Distance from Left Bank (m)
Mud
Sand
Gravel
Cobble
Boulder

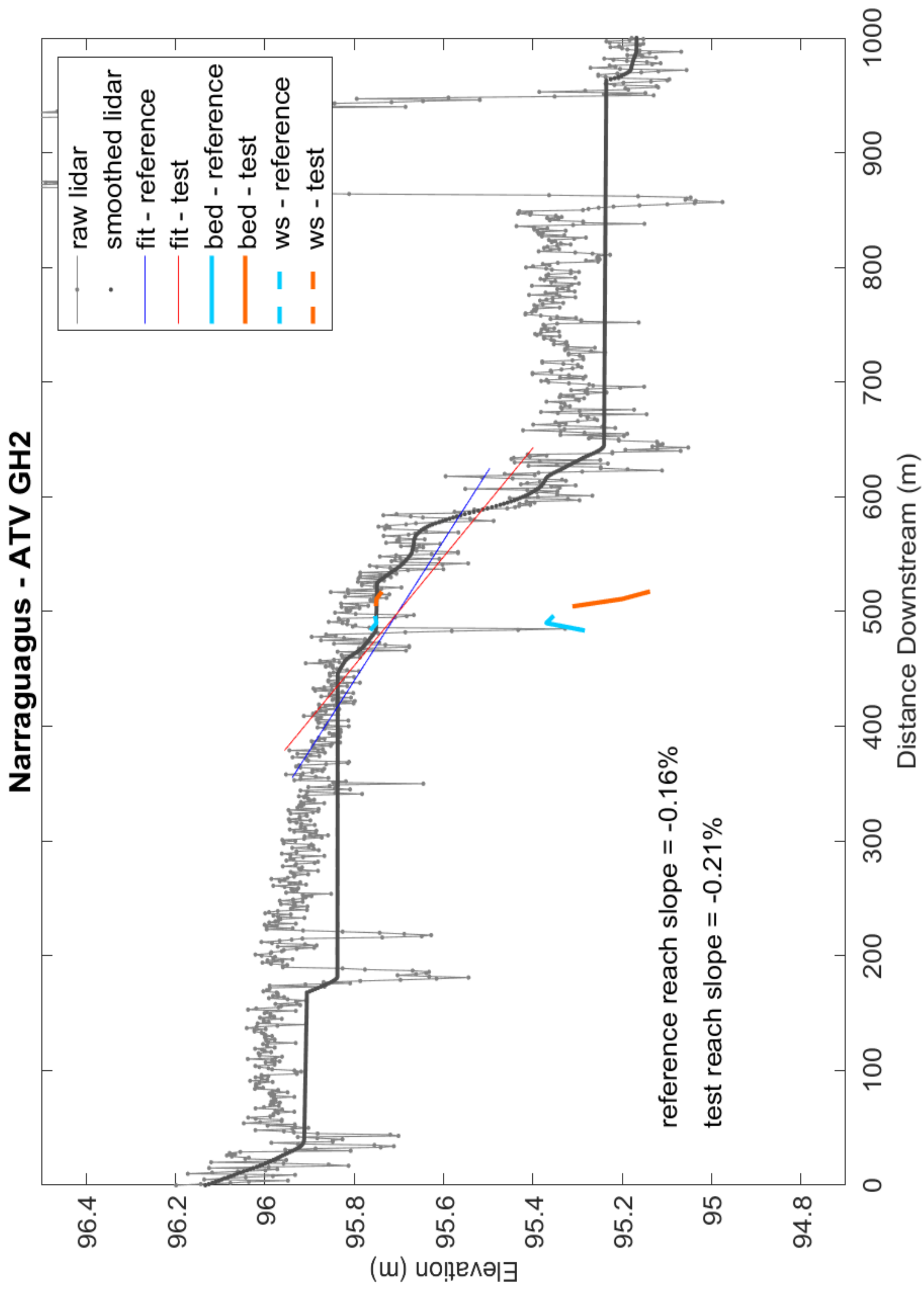
Appendix E – All Sites: Water Surface and Longitudinal Profiles

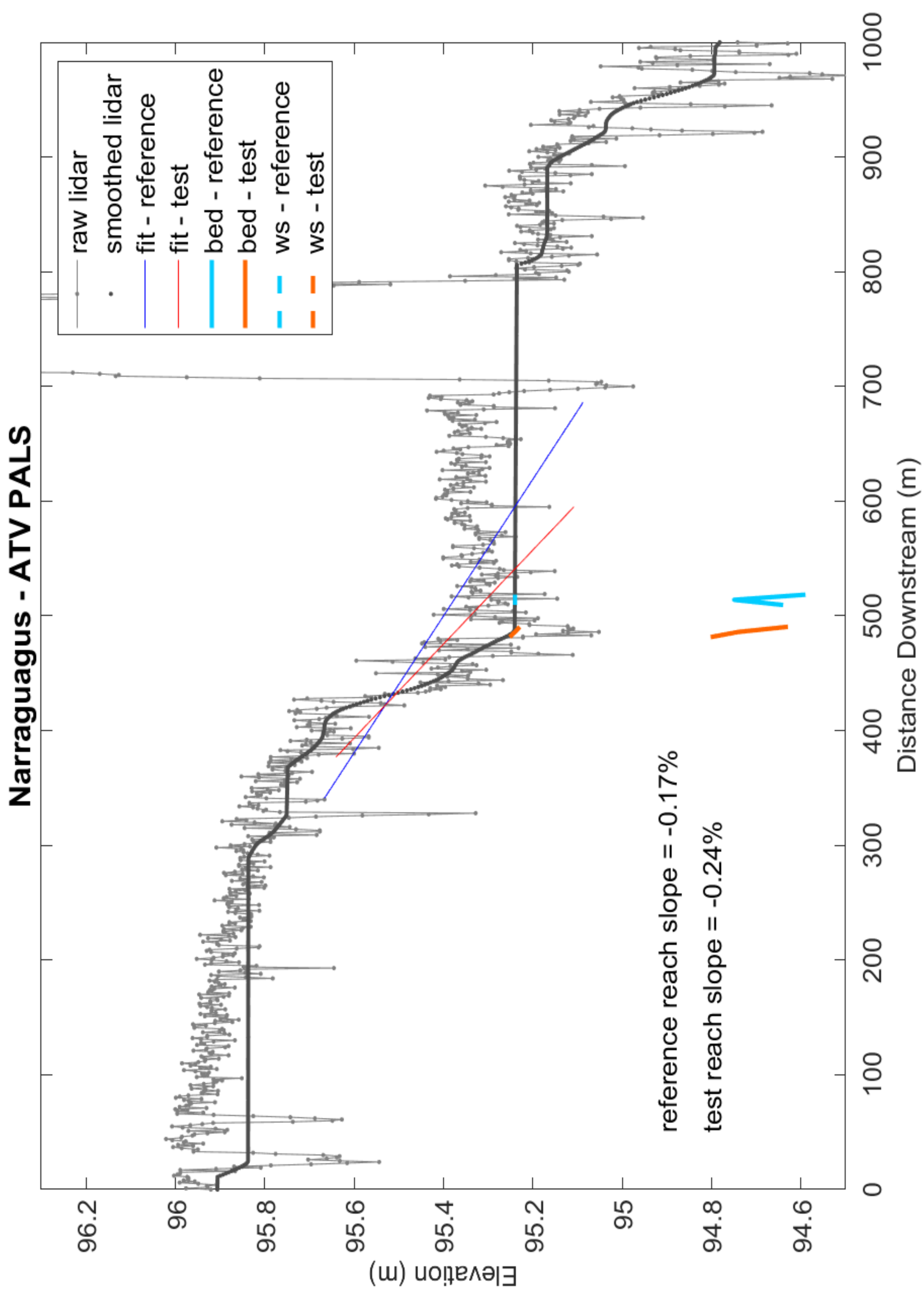
Narraguagus River, ME



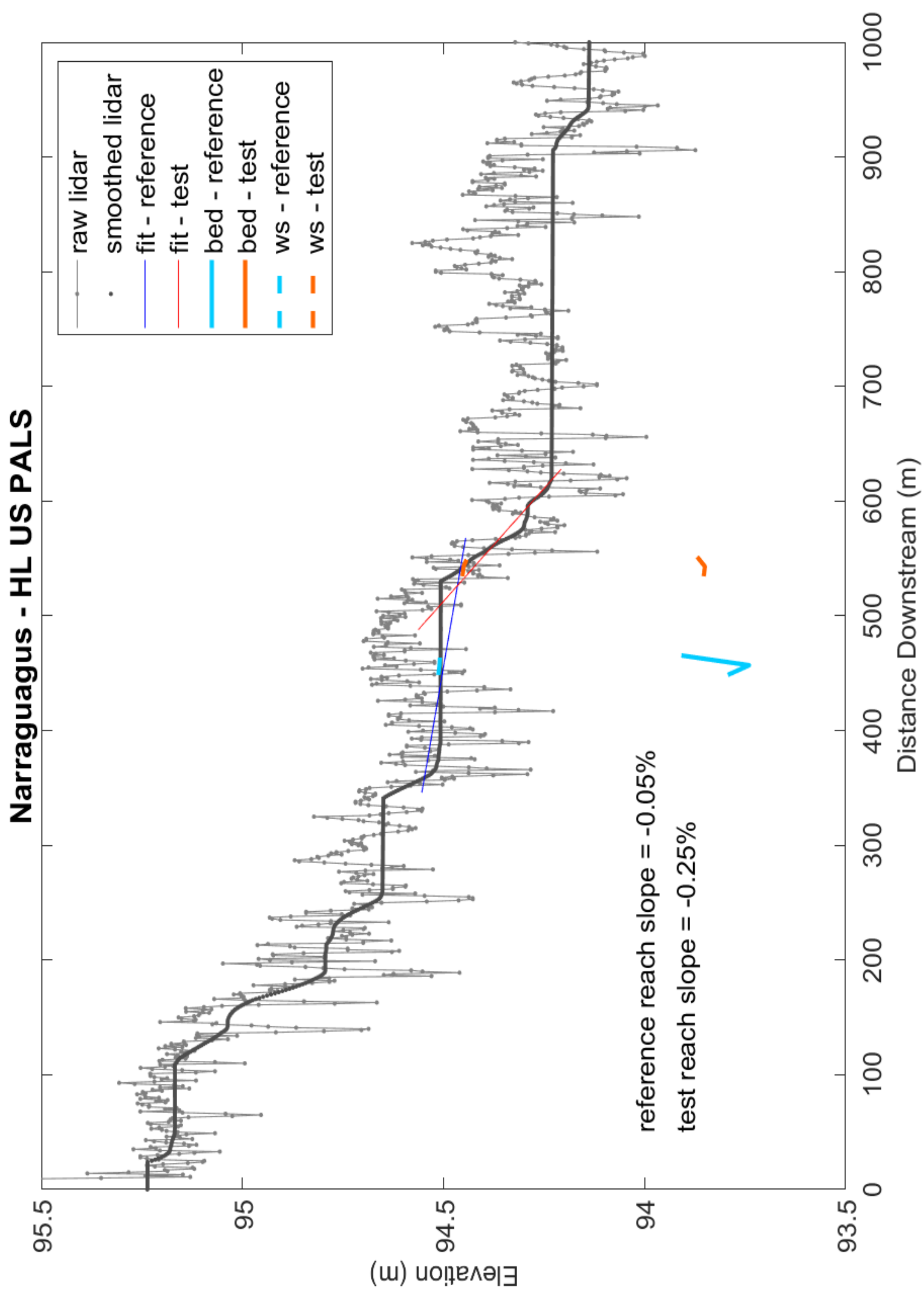


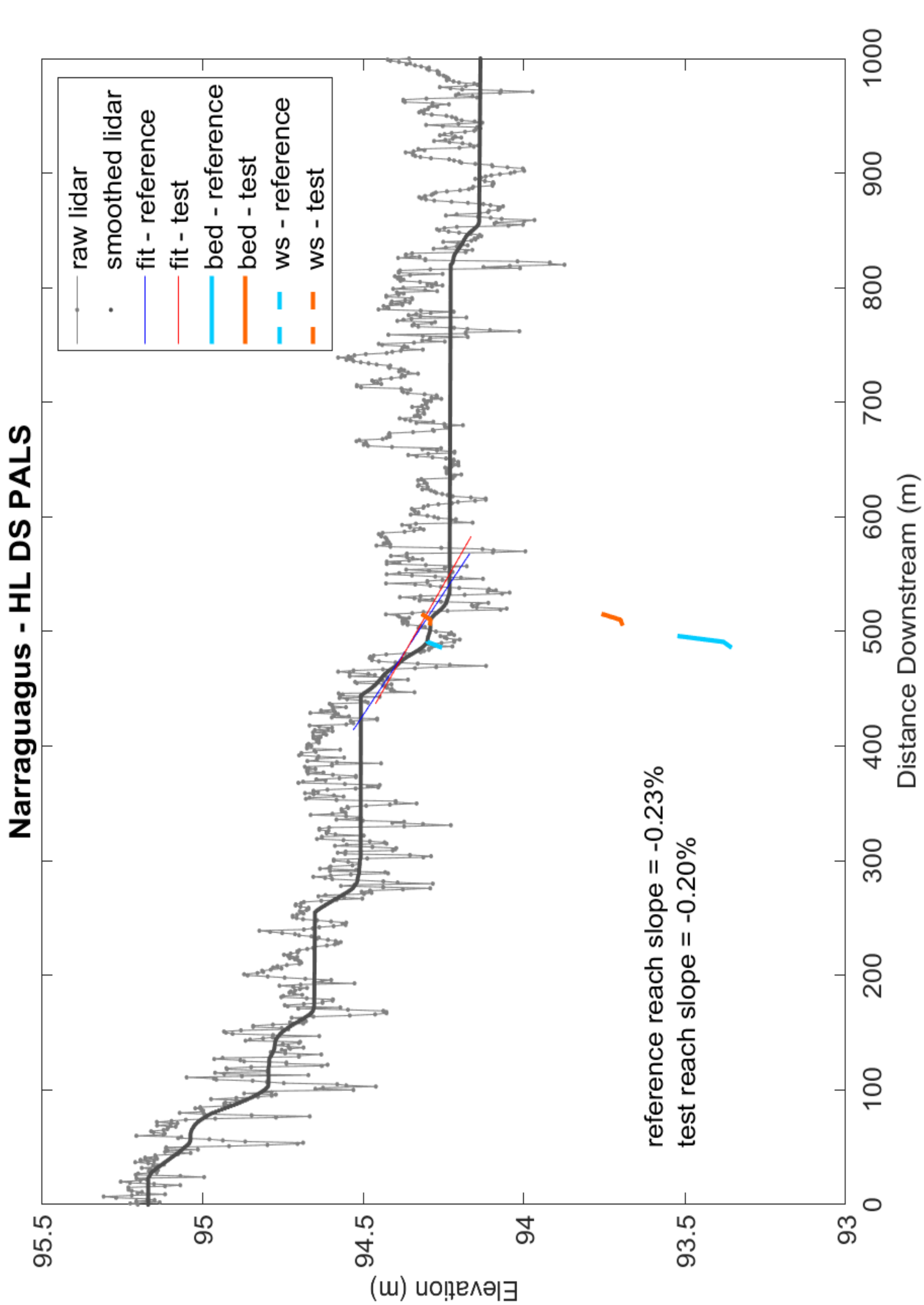
Narraguagus - ATV GH1
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.04%
test reach slope = -0.07%
Elevation (m)
Distance Downstream (m)

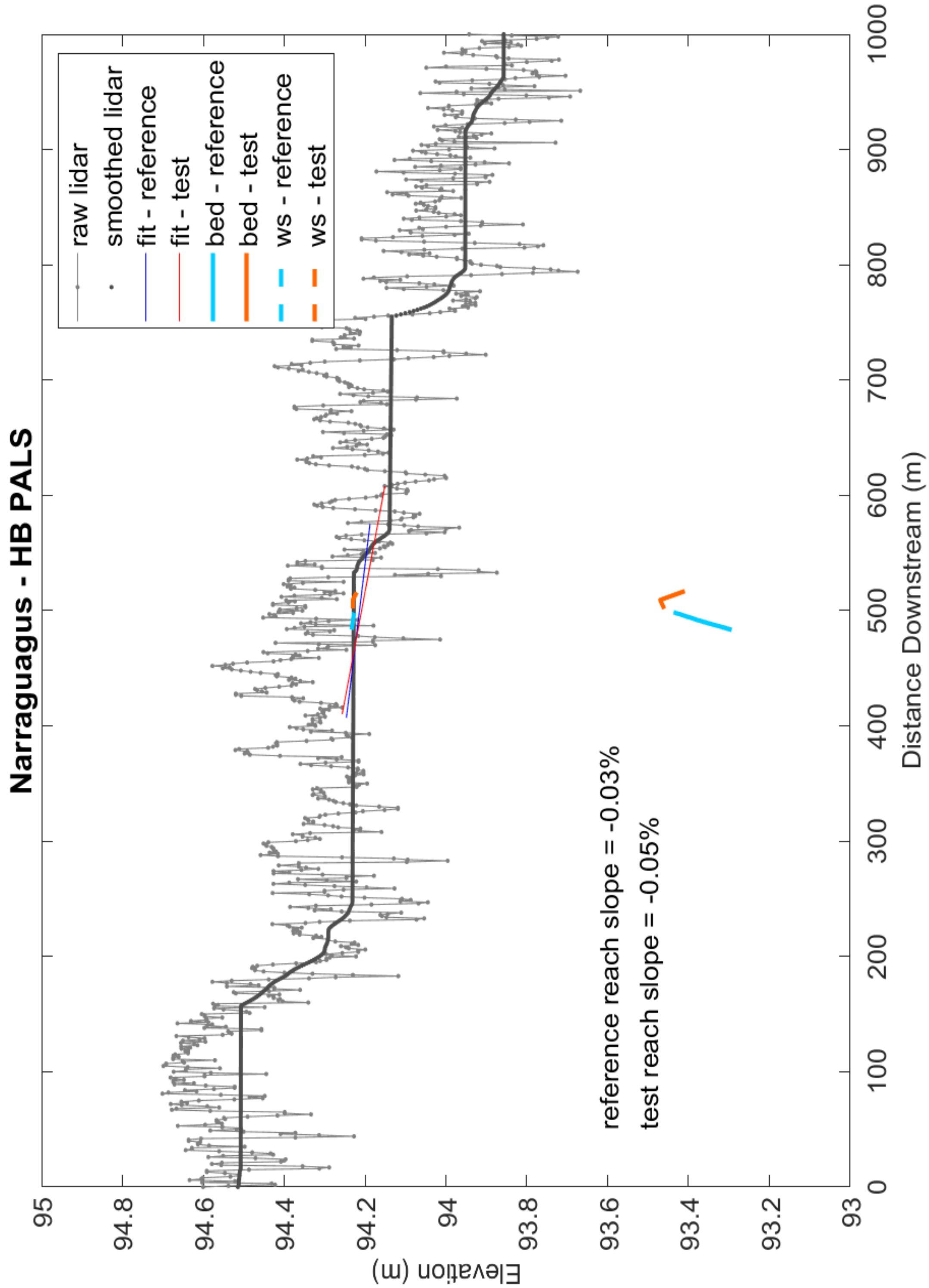

Narraguagus - ATV GH2
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.16%
test reach slope = -0.21%
Elevation (m)
Distance Downstream (m)
96.4
96.2
96
95.8
95.6
95.4
95.2
95
94.8
0
100
200
300
400
500
600
700
800
900
1000



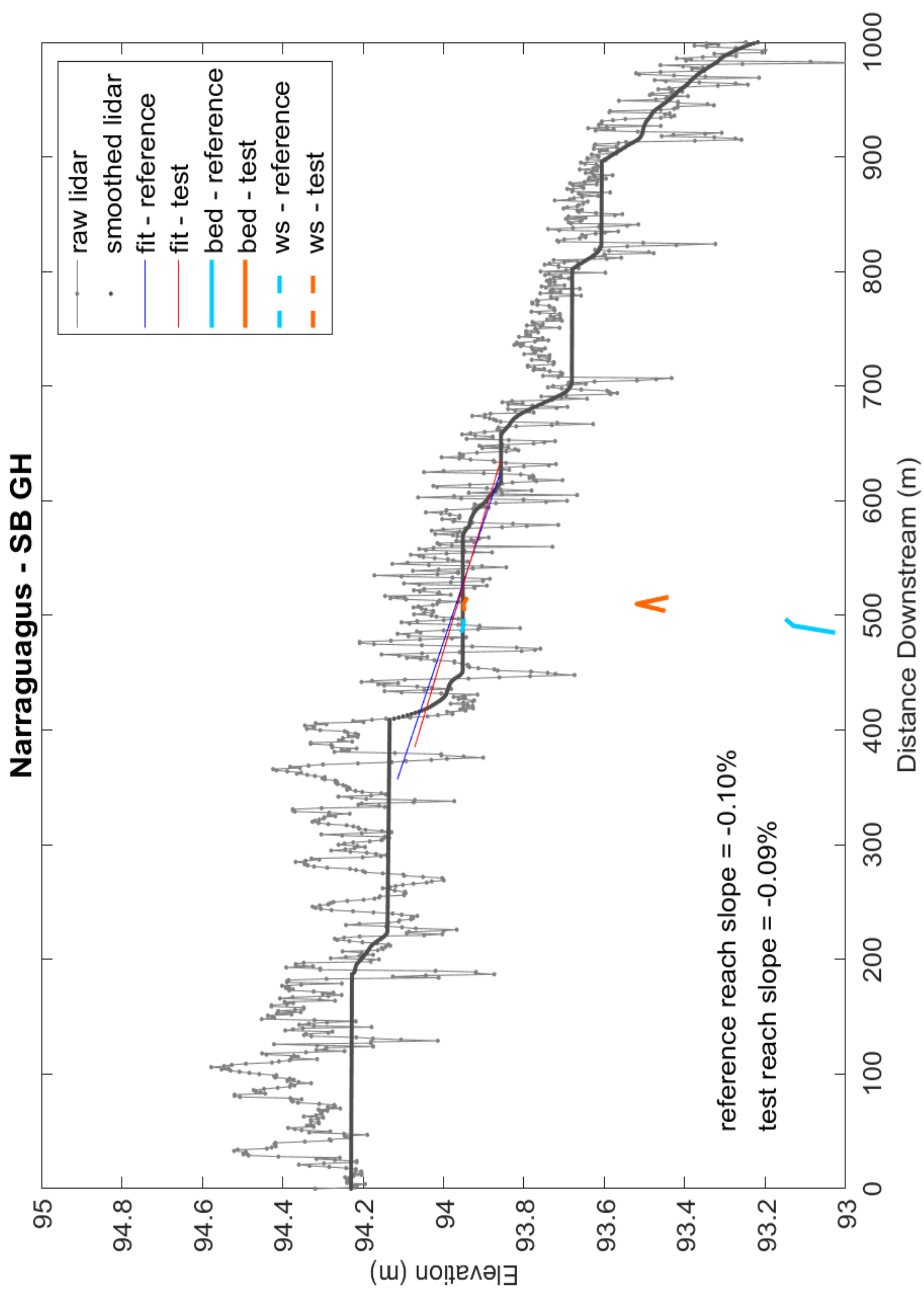
Narraguagus - ATV PALS
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.17%
test reach slope = -0.24%
Elevation (m)
Distance Downstream (m)
96.2
96
95.8
95.6
95.4
95.2
95
94.8
94.6
0
100
200
300
400
500
600
700
800
900
1000


Narraguagus - HL US PALS
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.05%
test reach slope = -0.25%
Elevation (m)
Distance Downstream (m)
95.5
95
94.5
94
93.5
0
100
200
300
400
500
600
700
800
900
1000

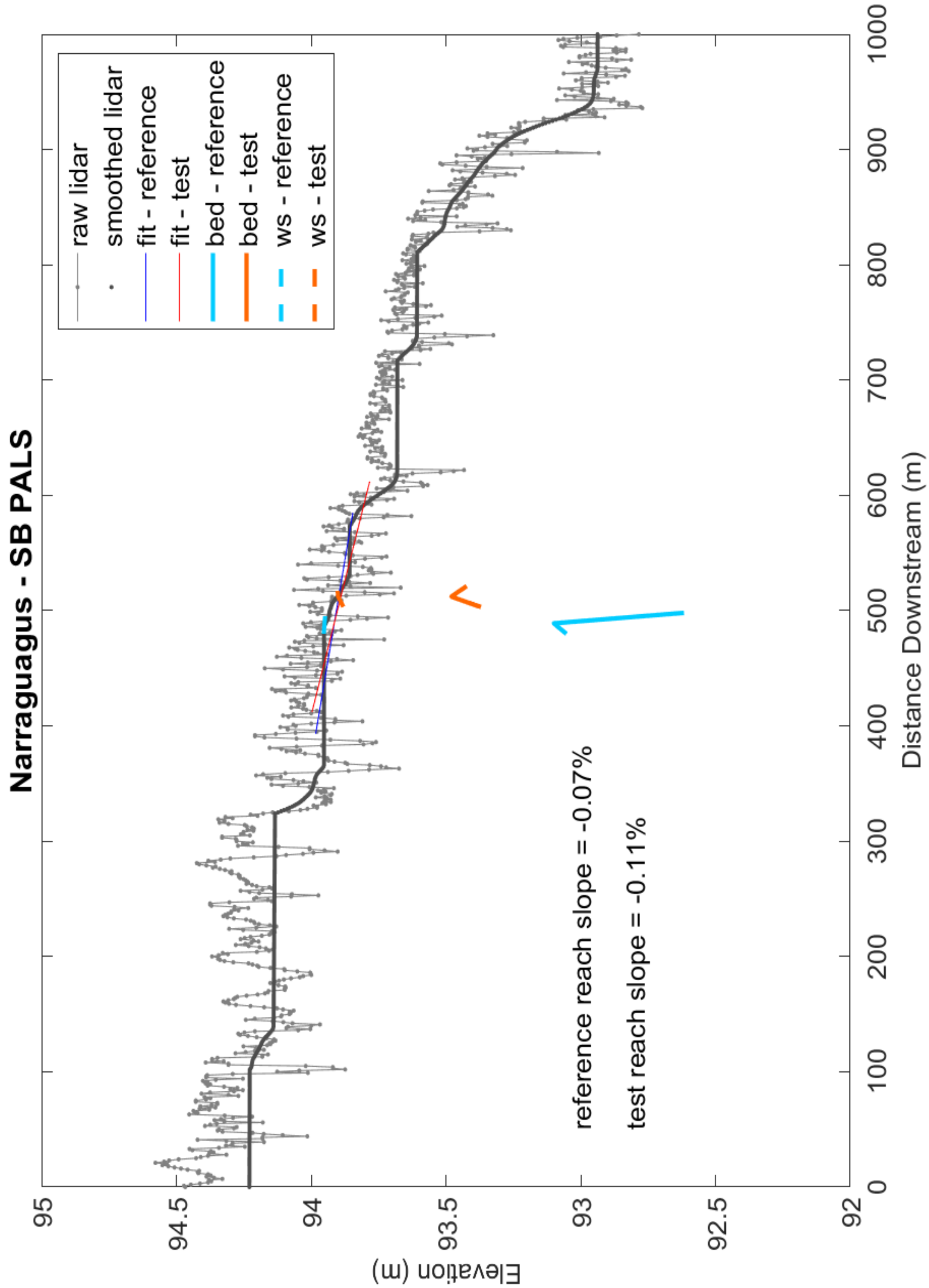

Narraguagus - HL DS PALS
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.23%
test reach slope = -0.20%
Elevation (m)
Distance Downstream (m)
95.5
95
94.5
94
93.5
93
0
100
200
300
400
500
600
700
800
900
1000



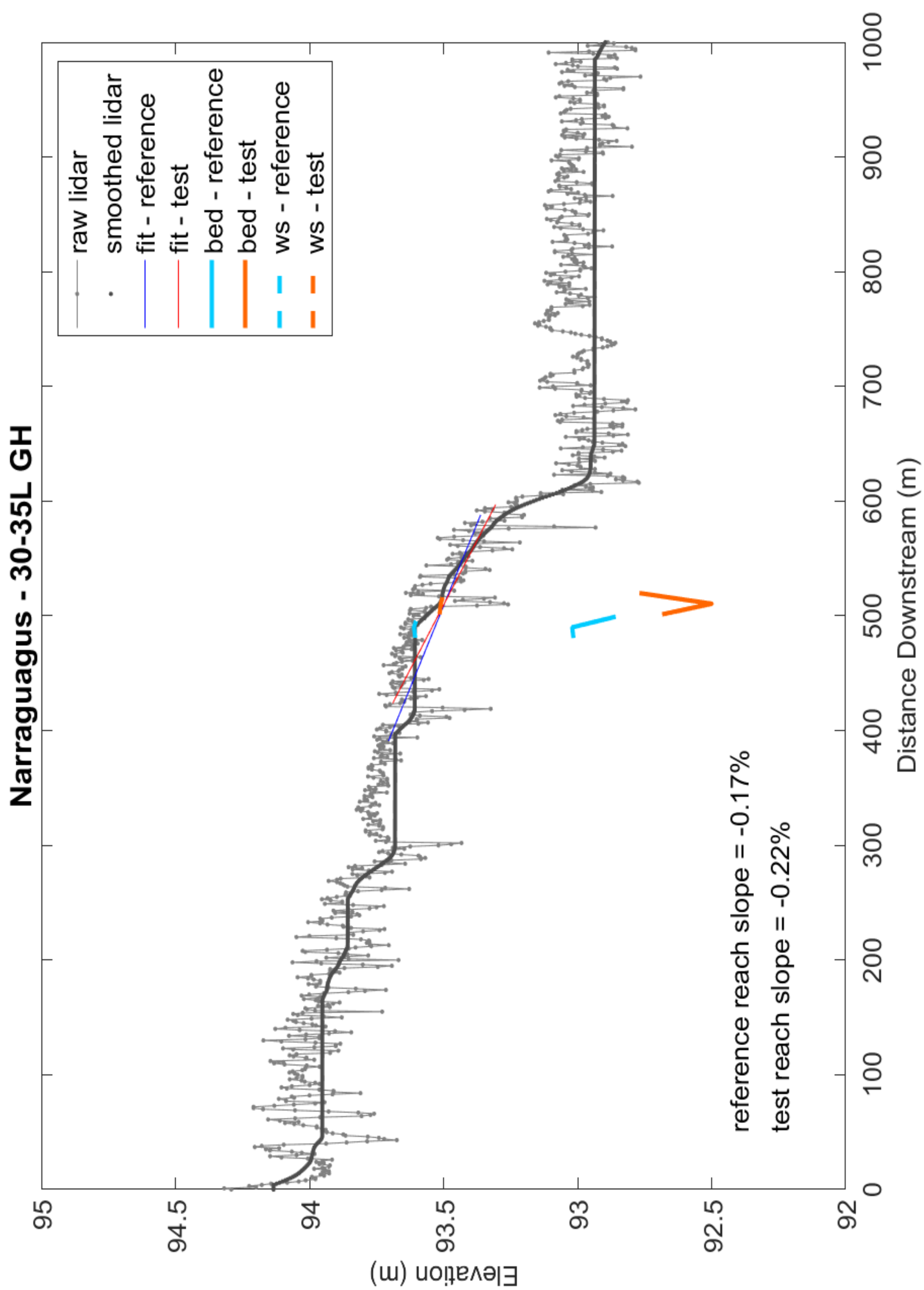
Narraguagus - HB PALS
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.03%
test reach slope = -0.05%
Elevation (m)
Distance Downstream (m)



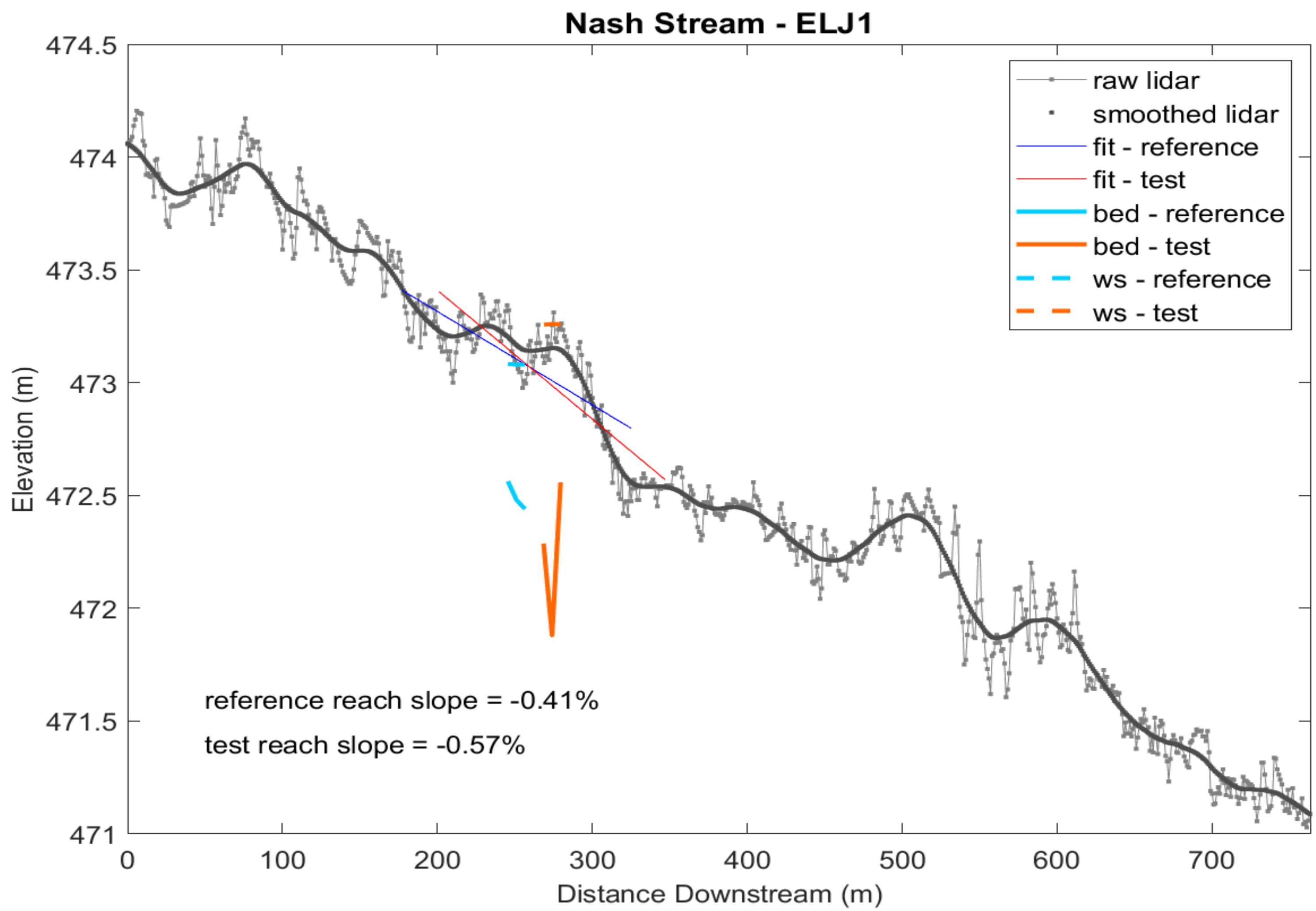
Narraguagus - SB GH
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.10%
test reach slope = -0.09%
Elevation (m)
Distance Downstream (m)
95
94.8
94.6
94.4
94.2
94
93.8
93.6
93.4
93.2
93
0
100
200
300
400
500
600
700
800
900
1000

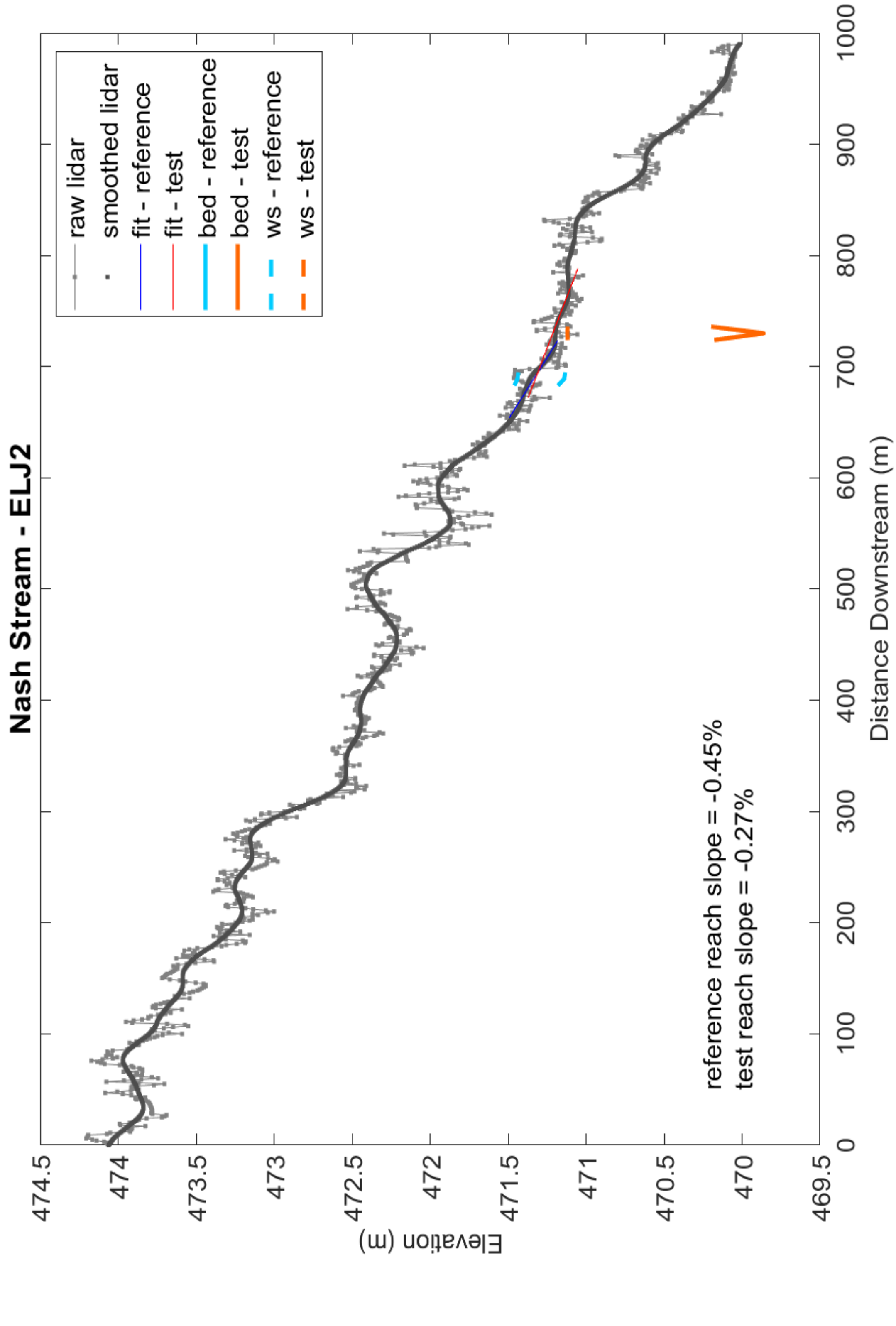


Narraguagus - SB PALS
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.07%
test reach slope = -0.11%
Elevation (m)
Distance Downstream (m)
95
94.5
94
93.5
93
92.5
92
0
100
200
300
400
500
600
700
800
900
1000


Narraguagus - 30-35L GH
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.17%
test reach slope = -0.22%
Elevation (m)
Distance Downstream (m)
95
94.5
94
93.5
93
92.5
92
0
100
200
300
400
500
600
700
800
900
1000

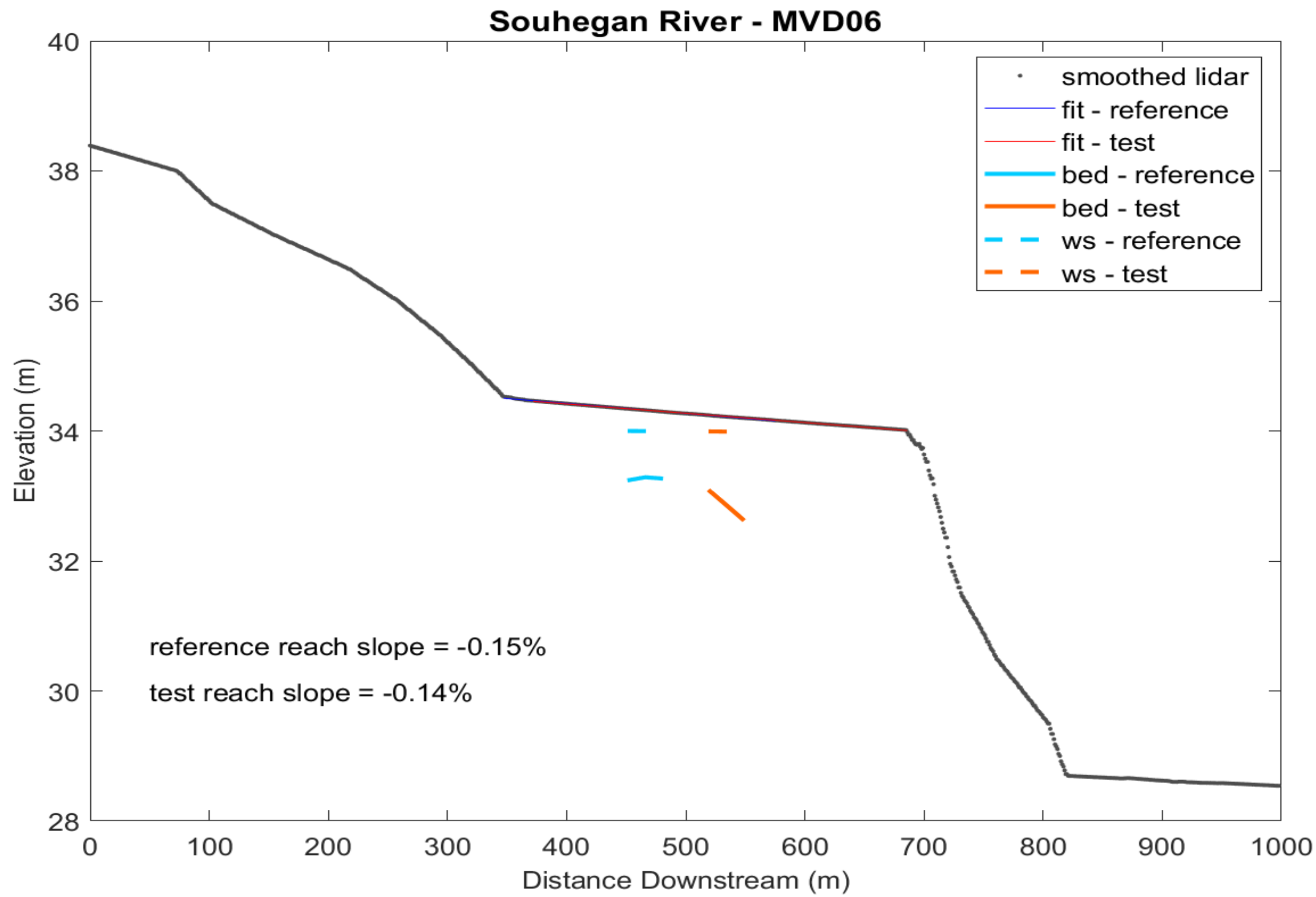
Nash Stream, NH



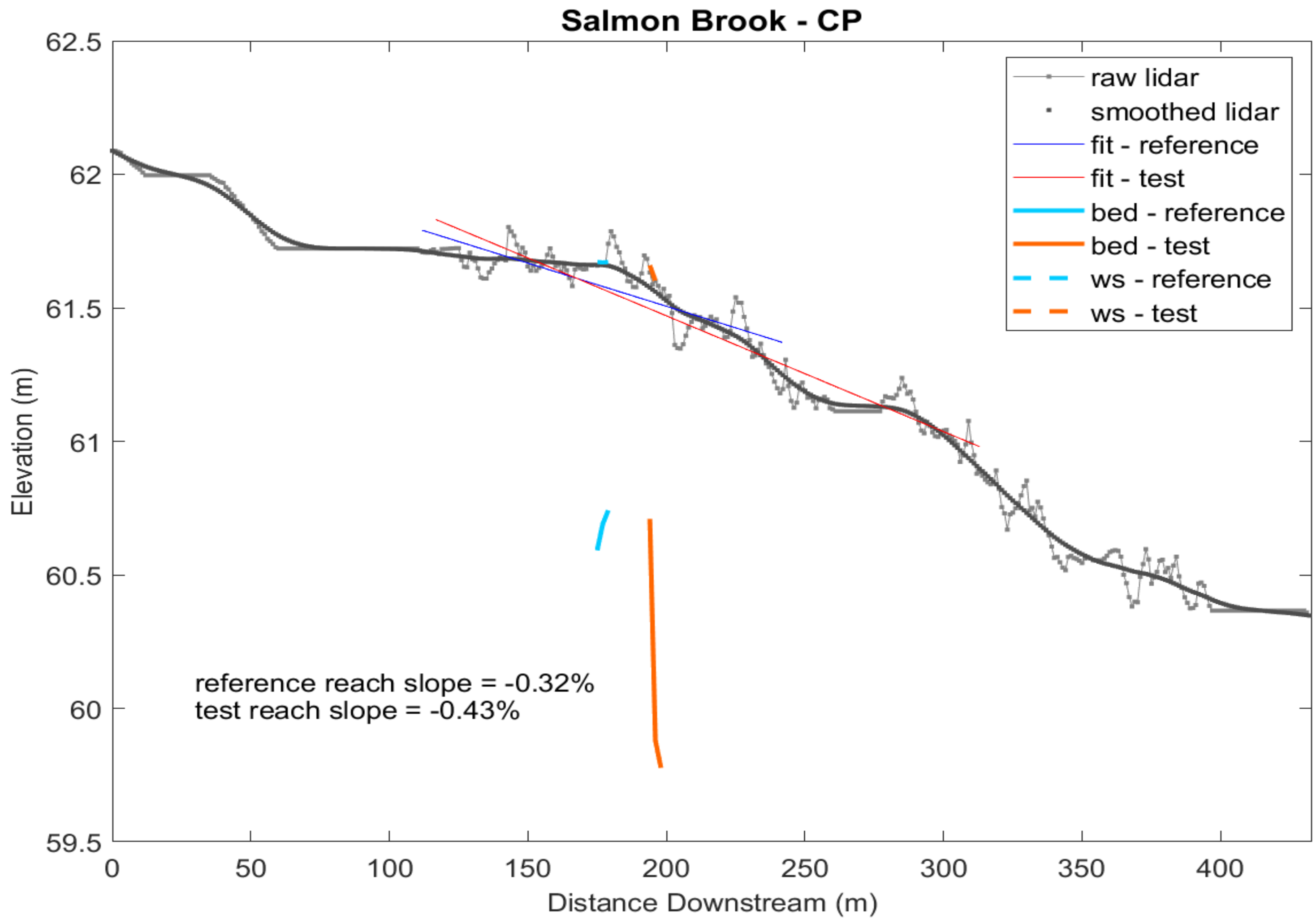


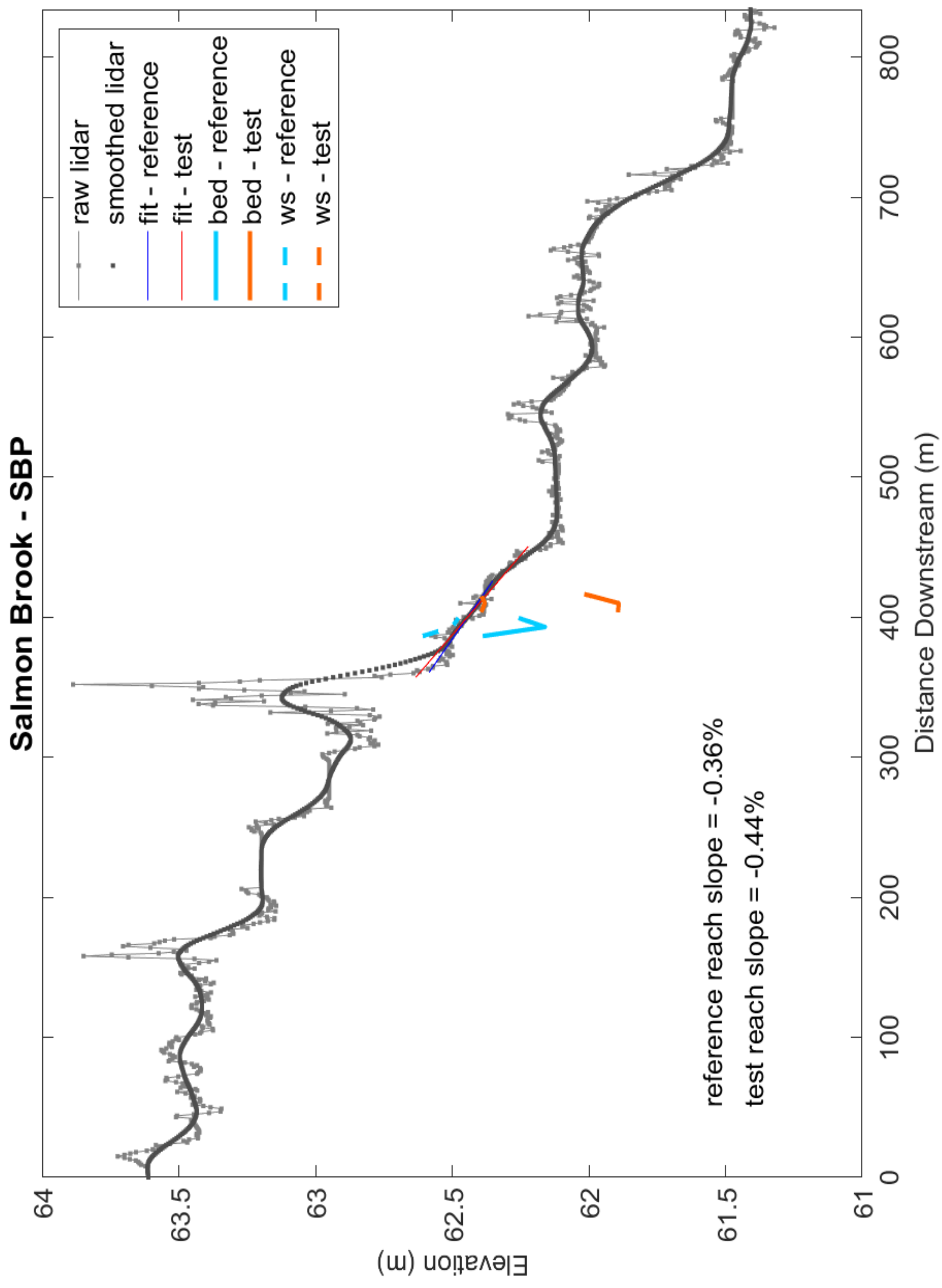
Nash Stream - ELJ2
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.45%
test reach slope = -0.27%
Elevation (m)
Distance Downstream (m)
474.5
474
473.5
473
472.5
472
471.5
471
470.5
470
469.5
0
100
200
300
400
500
600
700
800
900
1000

Souhegan River, NH



Salmon Brook, CT




Salmon Brook - SBP
raw lidar
smoothed lidar
fit - reference
fit - test
bed - reference
bed - test
ws - reference
ws - test
reference reach slope = -0.36%
test reach slope = -0.44%
Distance Downstream (m)
Elevation (m)
0
100
200
300
400
500
600
700
800
61
61.5
62
62.5
63
63.5
64