THESIS

RELATIVE INFLUENCES OF VALLEY GEOMETRY AND WOOD ON SEDIMENT DISTRIBUTION IN BISCUIT BROOK, NY

Submitted by

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ABSTRACT

RELATIVE INFLUENCES OF VALLEY GEOMETRY AND WOOD ON SEDIMENT DISTRIBUTION IN BISCUIT BROOK, NY

Sediment storage in mountain streams is commonly associated with level of valley confinement. In unconfined channels, sediment is stored in the floodplain and active channel in a network of secondary channels with abundant in-stream large wood. The influence of wood on sediment distribution is potentially significant in alluvial reaches with low valley confinement and continuous wood recruitment. Biscuit Brook, a headwater stream in the Catskill Mountains of New York State, is discontinuously laterally confined: flow paths through wide, hydraulically rough reaches alternate downstream with flow paths through incised bedrock. Alluvial reaches in Biscuit Brook contain substantial large wood and are actively adjusting to the large sediment pulse caused by Hurricane Irene in 2011. This study 1) quantifies relative influences of valley geometry and wood on sediment distribution and storage, and 2) examines whether either wood, valley geometry, or their combination is the primary driver of sediment distribution and storage. I surveyed 57 cross sections, measured bed grain sizes at 19, 100-m longitudinal segments, and mapped 50 wood accumulations during the summer of 2018 to document the relationships between wood, valley geometry, and sediment storage in Biscuit Brook. To address the research objectives, I examine statistical correlations between variables using single and multiple regressions. Because direct measurement of sediment storage in Biscuit Brook was not possible in 2018 given the time and scope of this study, I use median grain size, gradation coefficient, and modeled velocity as proxies for sediment storage. I assess storage via modeled velocity of existing conditions in Biscuit Brook through cross-sectional geometry associated with the presence of wood. I then compare to a model of a no-wood scenario by virtually removing wood in the model. I also compare modeled velocity through differing valley geometries. Results indicate that both wood and valley geometry are significant for sediment distribution and storage, but valley geometry exerts a stronger control. I recommend that valley geometry be considered for more strategic wood placement in stream restoration project design.

ACKNOWLEDGEMENTS

I am grateful to everyone who helped me with the success of this project. My advisor, Ellen Wohl, provided me invaluable guidance, support, feedback, and inspiration. I look forward to our continued working relationship and friendship. My committee members, Sara Rathburn and Ryan Morrison, taught meaningful classes and provided helpful research suggestions. None of this would be possible without support from the New York City Department of Environmental Protection (NYCDEP). In early 2016, I accepted a NYCDEP fluvial geomorphology internship with Dany Davis as my supervisor. At that time, I did not predict that the position would put me on a path leading to a Master's degree, and also that I would connect with such extraordinary mentors. Dany, thank you for your abundant help in the field, for sharing your vast knowledge of the Catskill landscape, and for helping me become a fluvial geomorphologist. Mark Vian and Emily Polinsky, thanks for your constant support and feedback. A special acknowledgement goes to Cassidy Ryan, who excelled at fieldwork and brought curiosity, creativity, and positivity that helped us succeed during the summer of 2018. Also in the field, I received assistance from the SUNY Ulster Watershed Conservation Corps and interns from Connecticut College led by Doug Jones. Thank you all for your dedication to this project. To the current and former graduate students in the CSU Geomorphology lab, especially my 2017 cohort Juli Scamardo and Ethan Ader, thank you for sustaining an environment that facilitates friendship, productivity, and balance. Finally, I'd like to thank my family for all the wonderful support, and for instilling a sense of natural curiosity that led me to become a scientist.

TABLE OF CONTENTS

INTRODUCTION

Mountainous headwater streams commonly contain alternating zones of steep, highly confined bedrock and wide, low gradient alluvial reaches. Variation of valley geometry, which includes channel characteristics such as slope and confinement, through interspersed bedrock and alluvial segments is an example of longitudinal heterogeneity, and creates potential for variation in flow depth, velocity, substrate, planform, sediment storage, and wood load (Stanford et al. 1996, Wohl et al. 2018). This study examines the relationship of wood, valley geometry, and sediment storage (Figure 1) in Biscuit Brook, a headwater stream in the Catskill Mountains of New York State that has discontinuous lateral confinement due to flow paths through incised bedrock. Sediment storage in Biscuit Brook and similar mountain streams is typically associated with level of valley confinement (Stanford et al. 1996, Wohl 2010, Hauer et al. 2016, Wohl et al. 2018). In wide alluvial reaches, sediment is stored in the floodplain and active channel in a network of secondary channels with abundant in-stream large wood. Wood increases lateral connectivity of water and decreases longitudinal connectivity of sediment (Fryirs 2007, Wohl and Beckman 2011). These changes in connectivity lead to enhanced sediment retention and habitat formation. Alluvial reaches between lengths of bedrock channel presumably result from drastic differences in transport capacity between hydraulically smooth and laterally constricted bedrock reaches, and hydraulically rougher reaches with gentler slope and wider cross-sectional area. However, the influence of large wood on sediment storage in alluvial segments is also significant (Keller and Swanson 1979, Collins et al. 2012, Wohl 2017, Wohl and Scott 2017). The question remains whether wood or valley geometry more effectively enhances sediment storage within small mountain streams such as Biscuit Brook. This question is potentially significant in the context of sediment management because, although human alterations do not typically modify valley geometry, management can be designed to add or retain wood within valleys.

Models for quantifying sediment load associated with log jams have been developed and tested (Nakamura and Swanson 2003, Wohl and Scott 2017) and many researchers have identified sediment dynamics associated with longitudinally varying valley confinement (e.g. Shroba et al. 1979, Yochum et al. 2017). The gap in research that examines both wood and valley geometry in relation to sediment storage, along with the sparse distribution of wood studies in the eastern US (Wohl 2017), leads to the research question: What are the relative influences of wood and valley geometry on sediment distribution in Biscuit Brook?

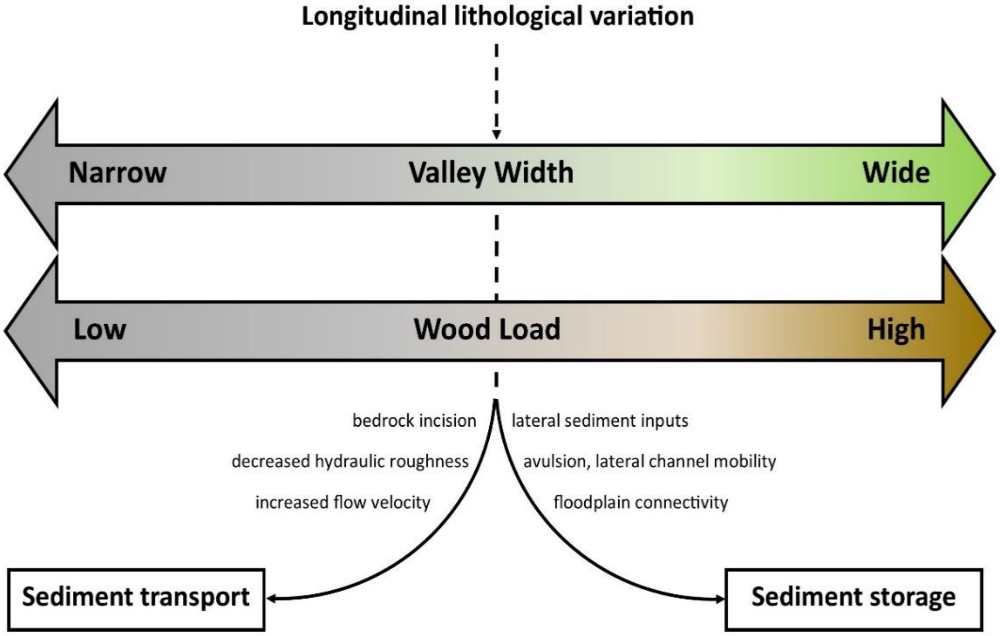


Figure 1. Conceptual diagram of ranges of valley width, wood load, and their relations to sediment transport and storage. Longitudinal lithological variation is the primary driver at the geologic scale (entire watershed and long timespans). Processes associated with valley width and wood load, listed by curved arrows, also facilitate sediment transport or storage at smaller spatial and shorter time scales.

Gilbert (1877, 1914) described bedrock channels as zones where transport capacity exceeds sediment supply. Bedrock conduits for sediment transport are generally of much higher gradient than alluvial reaches (Tinkler and Wohl 1998). High gradient and hydraulically smooth bedrock reaches have substantially more stream power than rough alluvial reaches. Reductions in stream power in bedrock streams are located at bends in bedrock canyons, outlets to alluvial sections, and at canyon entrances during high flows as backwater forms (O'Connor 1986, Wohl 2010). Reduction in stream power can lead to deposition (Gartner et al. 2015), and drastic reductions in stream power over a small length of stream can lead to high potential for geomorphic change at outlets from confined reaches to unconfined alluvial reaches during large floods (Shroba et al. 1979, Thompson and Croke 2013, Surian et al. 2016, Yochum et al. 2017, Gran and Czuba 2017). Changes in valley geometry characteristics, such as lateral confinement, have substantial effects on sediment deposition and storage in streams with alternating bedrock and alluvial segments.

Wood input to channels occurs via individual treefall, mass tree mortality, bank erosion, hillslope failure, floodplain erosion, beaver, and transport from tributaries and upstream channel segments (Benda and Sias 2003, Wohl 2017). Field observations suggest that individual tree mortality and bank erosion are likely the dominant sources of wood recruitment in Biscuit Brook, although mass tree mortality from microburst wind events is known to have occurred in the Catskill region, and hemlock trees *(Tsuga canadensis)* are currently at risk of mass mortality in the region due to the hemlock woolly adelgid (*Adelges tsugae*) (Yorks at el. 2000). Most likely, treefall directly into the channel is the most consistent source of wood to Biscuit Brook. Erosion associated with channel avulsion and tributary confluences leads to recruitment of large key pieces that capture sediment and coarse particulate organic matter (Benda et al. 2003). Because of the frequent bedrock segments in Biscuit Brook, and as is typical for small streams, there is a nonuniform longitudinal distribution of wood recruitment in the channel network.

There is an extensive body of knowledge on the geomorphic effects of instream wood. Depending on size and mechanism of input, wood is stored along channel margins or in the active channel either as individual pieces or partial to fully channel-spanning jams (Abbe and Montgomery 2003). Wood is capable of stabilizing banks or forcing meanders and side channels, increasing complexity within the system. Sediment dynamics altered by wood include increases in residence time and spatial grain size heterogeneity of stored sediment (Buffington and Montgomery 1999). Wood with sufficient permanence increases upstream bed elevation, decreases local slope, and alters cross sectional geometry, and can create forced alluvial reaches that would otherwise be bedrock without the presence of wood (Montgomery et al. 1996, Massong and Montgomery 2000). Log jams improve fish habitat by providing temperature refugia and facilitating removal of fine grains from potential spawning substrate in plunge pools below jams (Bouwes et al. 2016). Channels with wood follow self-enhancing feedback loops, promoting gradual channel widening, which in turn recruits more wood from the banks and floodplain and most importantly maintains channel complexity (O'Connor et al. 2003, Wohl et al. 2011, Collins et al. 2012). Sediment storage associated with wood in mountain drainages is clearly substantial and likely plays a key role in the sediment budget.

Wood is mobile and subject to hydraulic forces, abrasion, decay, and both continuous and episodic recruitment and removal (Merten et al. 2013). Conversely, geologically-controlled valley geometry is relatively permanent. Tightly confined bedrock reaches experience incision on the order of 10^3-10^6 years, depending on regional base level (Reusser et al. 2006, Cook et al. 2009). It remains unknown whether bedrock or wood affects sediment storage more significantly over diverse time scales.

STUDY AREA

Biscuit Brook lies in the Neversink watershed within the Catskill Mountains of New York State (Figure 2). The watershed is completely forested with American beech (*Fagus grandifolia*), yellow birch (*Betula alleghaniensis*), eastern hemlock (*Tsuga canadensis)*, striped maple (*Acer pensylvanicum)*, sugar maple (*Acer saccharum)*, and several other species (Mitchell et al. 1996, Templer et al. 2005). Watershed characteristics for Biscuit Brook watershed are shown in Table 1. The Catskill Mountains are composed of Devonian age sedimentary rocks (Ver Straeten 2013). Clasts and exposed bedrock in Biscuit Brook are primarily sandstone and mudstone. Red mudstone in the channel bed is significantly weaker than sandstone units and likely erodes at a much higher rate.

Table 1. Characteristics of the Biscuit Brook watershed.

Drainage Area	Watershed Elevation	Average Daily Discharge	Typical Q_2 Discharge[2]	Average Annual Precipitation[1]
10.7 km^2	610-1130 m	0.45 cms	8.75 cms	1413 mm

[1] Estimate for precipitation according to PRISM precipitation model

[2] Two-year discharge determined from flood frequency curve using NRCS Frequency Curve Determination Spreadsheet

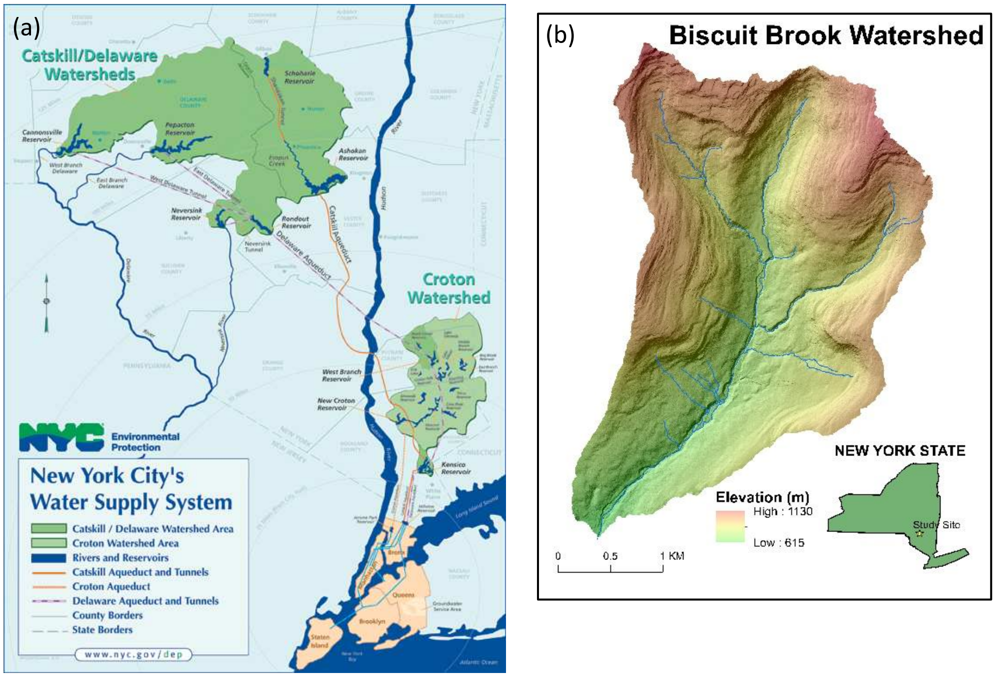


Figure 2. Map of New York City water supply (source: NYCDEP) (a) and map of Biscuit Brook watershed above the confluence with Pigeon Brook (b).

The Neversink watershed flows into the Neversink Reservoir (Figure 2), part of the New York City water supply system that is operated by the New York City Department of Environmental Protection (NYCDEP). Sediment dynamics in Catskill Mountain watersheds are of particular interest because of the high degree of investment in stream management and restoration in the region. Most management practices aim to fulfill the Filtration Avoidance Determination (FAD) every 5-10 years to avoid the need for filtration of the New York City water supply. Turbidity of water sources in Catskill watersheds is actively monitored due to continual erosion of glaciolacustrine clay deposits throughout the Catskill region. Increased turbidity during large storms leads to the use of the chemical binding agent Alum in reservoirs to enhance settling of suspended sediment in a short period of time. Stream restoration projects upstream of reservoirs specifically target suspended sediment sources to mitigate bank erosion and turbidity. Although glaciolacustrine clays are not a concern in the Biscuit Brook watershed, the importance of sediment dynamics in the NYC water supply area creates interest in the storage potential for coarse and fine sediment resulting from wood and valley geometry. Biscuit Brook is an ideal reference stream for research due to lack of development, a consistent stream gage record since 1983, abundant wood, and longitudinal variations in valley geometry (Figure 3).

Figure 3. Photos of confined bedrock reach with approximately 2m wide channel (a) and unconfined alluvial reach with log diameter approximately 50 cm (b) in Biscuit Brook.View is upstream in (a) and downstream in (b).

METHODS

Field Methods

Reach Definition

Biscuit Brook was longitudinally divided into 16 reaches: A1-A8 and B1-B8 (Figure 4) . Reaches were defined based on predominant substrate as either alluvial or bedrock. Although some bedrock may be present within alluvial reaches, reach distinctions were based on the field-observed majority of channel bed composition. Reach A4 was selected for intensive investigation because of its length, diversity of morphologic features, and significant longitudinal variability in wood abundance. A4 was divided into 8 subreaches in the field based on differences in downstream-trending process and form. Subreaches are named A4a-h from upstream to downstream and are shown in Figure 4. Characteristics of A4 subreaches are described in Table 2.

Table 2. Subreaches within the A4 reach.

Subreach Name	Length (m)	Gradient	Active Valley Width (m)	Notable Characteristics
A4a	82	4.3%	25	20% bedrock present in channel
A4b	66	4.1%	30	Contains 2 channel-spanning log jams
A4c	96	3.4%	23	Steep, little stored alluvium, contains hillslope failure
A4d	111	2.2%	27	Aggradational wedge, loss of defined channel
A4e	191	3.8%	46	Massive wood jams plug sediment upstream, split channel with hillslope failure
A4f	126	3.0%	77	Defined channel, forested floodplain
A4g	91	2.9%	71	Large landslide with wood jam at base. Downstream, large jam blocks former channel.
A4h	122	3.8%	52	Split channel with recently avulsed mainstem through forest, secondary channel adjacent to hillslope failure

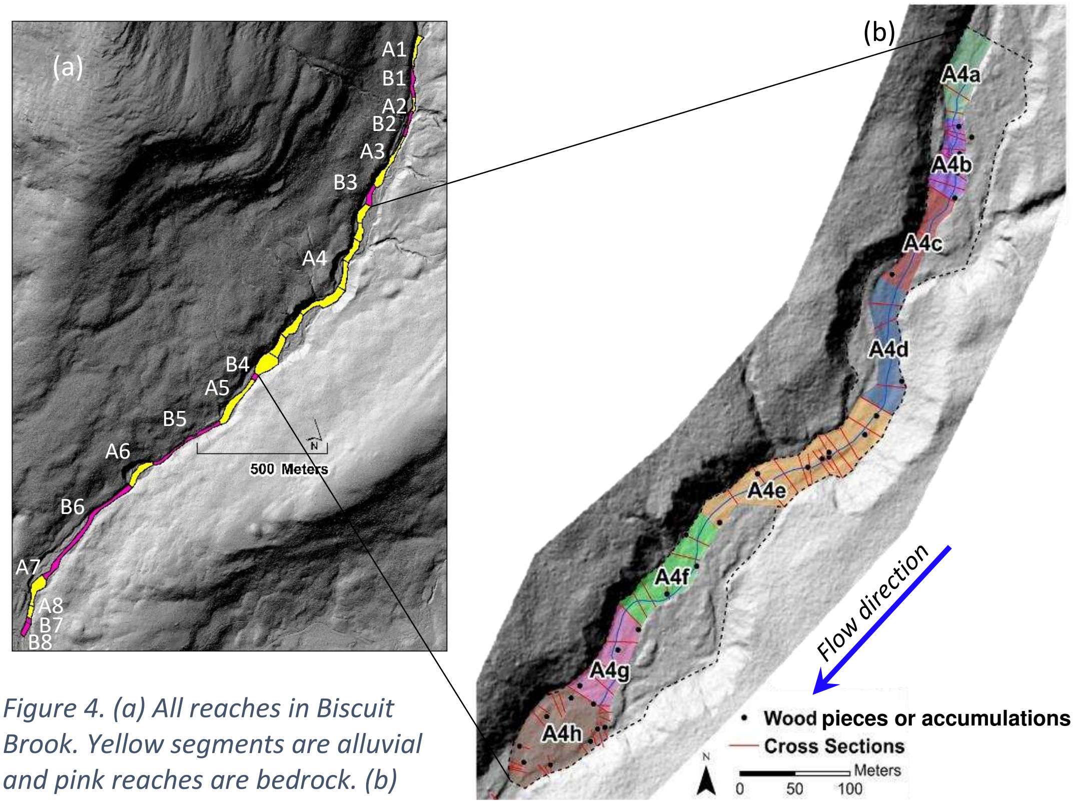


Figure 4. (a) All reaches in Biscuit Brook. Yellow segments are alluvial and pink reaches are bedrock. (b) Subreaches in A4. Red lines represent surveyed cross sections, and black dots show mapped wood in A4.

Wood and Sediment Source Mapping

Throughout all reaches in Biscuit Brook, I selected wood for mapping if it was within the bankfull channel and exerted geomorphic influence on its immediate surroundings. I visually identified geomorphic influence as sediment storage upstream, scour downstream, or redirection of flow. Fifty jams or individual pieces were described and measured for inclusion in the quantitative analysis. Table 3 lists measurements recorded in the wood surveys.

I mapped hillslope sediment sources in all reaches. Seventeen point-sources of coarse and fine sediment were mapped with a handheld Garmin GPS. I recorded length, height, visual grain-size estimates, and geomorphic process inferences at each sediment source location. Four of the 17 mapped sediment sources to Biscuit Brook are major hillslope failures in reaches A4c, A4e, and A4g, and A4h. Examples of major hillslope failures are shown in Figure 5 and were likely initiated during or exacerbated by Hurricane Irene. Sediment supply from hillslope failures is an important component of sediment distribution in Bisuit Brook, and trends in sediment distribution in proximity to hillslope sources may be examined in future studies. These potential trends are outside the scope of this project.

Table 3. Field-measured wood metrics. Length, width and height were multiplied for wood volume.

Variable	**Description**
Location	GPS coordinates
Length	Length of wood parallel to downstream direction
Width	Width of wood across channel
Height	Height from channel bed to top of concentrated wood accumulation
Diameter	Diameter of individual piece, or key piece within a jam. Key piece is the piece of large wood, usually the largest, that structurally stabilizes the log jam.

Figure 5. Examples of major hillslope failures in Biscuit Brook

Topographic Surveys

My surveying team completed 57 cross sections throughout reach A4 with a TruPulse 360˚ Laser Rangefinder (± 0.1 m resolution), an autolevel, and laser levels. We used traditional surveying techniques with the autolevel and laser levels. Rangefinder surveys were conducted by a stationary observer recording vertical elevation changes on a stadia rod at the observer's eyelevel. The stadia rod was carried to the desired cross-sectional points by a second participant. Benchmarks were established in A4 to relate all surveys to an arbitrary, internally-established coordinate system. GPS locations were recorded at benchmarks and endpoints of each cross section. In A4h, a split-channel reach, cross sections were surveyed in each branch separately.

I selected cross section locations to represent primary processes within each subreach of A4. In reaches that contained a large amount of wood, cross sections were intentionally placed upstream, over, and downstream of log jams. In order to capture the topographic impact of wood within the channel geometry, cross sections that encountered wood were surveyed over the tops of wood jams, with points of the channel bed below jams intermingled when possible. This survey technique facilitated modeling two channel geometries: one with wood and one without wood. Although this representation of wood within channel geometry tends to reroute flow around jams rather than through them when used in hydraulic models, a method for representing wood jams in channel geometry that includes porosity and through-flow is not yet available.

Sediment Data Collection

It was not feasible in the summer of 2018 to directly measure sediment storage. Instead, I measured sediment grain size as a proxy for sediment storage vs. transport. A gravelometer was used to collect sediment intermediate axes via pebble counts (Wolman 1954). Nineteen complete counts were recorded in A4a-h. Counts were distributed longitudinally along a 100 m tape laid in the channel center. Where a split channel occurred, longitudinal tapes were positioned in each branch. Transects perpendicular to the channel were established every 5 m along the tape and a set of 10 clasts was measured at each transect. Ultimately, a sediment size dataset was produced for Reach A4 with transects spaced at 5 m intervals throughout all subreaches. Sediment size distributions were obtained by grouping transects within each subreach boundary.

Data Analysis Methods

I used three methods to interpret the effect of valley geometry and wood on sediment distribution in Biscuit Brook.

1. Correlation analysis of singular predictor variables
2. Multiple linear regression
3. Significance testing of modeled velocities

Several variables used in statistical analyses were extracted from a 2013 airborne LiDAR-derived 1 m Digital Elevation Model (DEM) of the Neversink Watershed. The DEM was produced and hydrologically smoothed for the New York City watershed West of Hudson district area. A 2009 DEM for the same area also exists and was used for preliminary identification of storage and transport zones in Biscuit Brook Reach A4. GPS-based reach boundaries of A4 subreaches were overlaid on a raster created from the difference of the 2013 and 2009 DEMs. During the 2009-2013 period, Hurricane Irene, the largest hydrologic event on record, impacted the Catskill Mountains and much of New York State. I suspect that this large event recruited the majority of wood to subreach A4e and caused the majority of sediment erosion and aggradation in the DEM-difference mapped channel.

Metrics of Valley Geometry, Wood, and Sediment Distribution

I used a grain size analysis spreadsheet developed by Potyondy and Bunte (2002) to calculate d_{16}, d_{50}, and d_{84} values for each A4 subreach. This spreadsheet provided the datapoints for cumulative particle size distribution curves. Metrics of wood and valley geometry are shown in Table 4.

Table 4. Metrics of valley geometry, wood, and sediment distribution. Bold variables passed model selection criteria for single or multiple linear regression.

Metric	Method of Calculation	Source
Grain size	Grain size analysis spreadsheet	Potyondy and Bunte 2002
Gradation Coefficient	$\sigma_g = \left(\frac{d_{84}}{d_{16}}\right)^{\frac{1}{2}}$	Julien 2010
Slope	Average of 3 iterations, slope of linear regression of elevation and distance in each reach	Interpolate Line Tool, GIS 10.5.1
Bedrock Proportion	Percentage of bedrock present during pebble counts	Wolman 1954
Geologic Valley Width	Visually defined in GIS with clear bedrock valley boundaries	2013 DEM, NYCDEP
Effective Valley Width	Visually defined in GIS, verified with geo-tagged photos. Does not include terraces and other non-accessible valley bottom area.	2013 DEM, NYCDEP Field Data
Channel Width	Width of channel June 2018	Field Data
Number of channels	Average number of channels per reach, derived from number of channels present during cross-sectional surveys.	Field Data
Wood Volume	Length*Width*Height of mapped wood	Field Data
Jam Proportion	Volume of wood within jams (3+ pieces)/Total volume of wood per reach	Field Data
Constriction Ratio	Effective Valley Width/Effective Valley Width upstream	GIS 10.5.1
Backwater Ratio	Effective Valley Width/Effective Valley Width downstream	GIS 10.5.1
Sinuosity	Length of channel/straight line distance along valley	GIS 10.5.1
Valley Confinement C_v	Length of channel abutting valley wall/total length of channel	Fryirs et al. 2016
Valley Bottom Confinement C_{VB}	Length of channel abutting valley floor confinement/Total length of channel	Fryirs et al. 2016

Correlation Analyses

All wood, valley geometry, and sediment metrics in the A4 reach were input to the cor() function in base R Statistical Software. This function calculates Pearson correlation statistics for each variable as a singular predictor of and response to every other variable in the dataset. The output was trimmed in order to examine only the response of sediment distribution attributes to wood and valley geometry metrics. Correlations were compared and the most suitable variables with the highest correlations were selected for inclusion in a multiple linear regression. The median grain size (d_{50}) was selected to represent grain size, and the gradation coefficient (Julien 2010) was selected from the list of potential gradation metrics to represent variability and sorting within the sediment distribution.

I selected 8 variables for significance testing of the Pearson correlation statistic. Of the nine bolded variables in Table 4, 7 were tested directly, and the ratio of effective valley width to geologic valley width was used to represent the active proportion of the valley floor. These 8 variables relate to valley geometry or wood, and either show a high Pearson correlation value or are qualitatively inferred to be important for geomorphic processes. The 8 variables were analyzed for significance of correlation with the cor.test() function in R using a 90% confidence level. I chose the 90% confidence level because of the variability in this natural system.

Multiple Linear Regression

Multiple linear regressions of six predictive variables were created using Akaike Information Criterion corrected for small sample sizes (AICc). These regressions predicted median grain size and gradation coefficient. Because the selected predictive variables are likely colinear, and because of the small sample size (n=8 subreaches in A4), the multiple linear regressions are for qualitative analysis only and should not be used to determine sediment distribution outside of the Biscuit Brook watershed. The objective of forming multiple linear regression equations is to identify which predictive input variables have the strongest influence on sediment distribution. The selection criteria for input variables to predict grain size and gradation were based on the correlation strengths described above and the qualitative geomorphic significance.

Modeling Velocity

Velocity was used as a proxy for sediment storage potential in Biscuit Brook. Velocity can easily be measured in the field, and therefore was chosen as a suitable representative that can be measured or modeled in future studies. Areas of low velocity are more likely to store sediment, while high velocity zones will transport sediment (e.g., Shroba et al. 1979, O'Connor et al. 1986). Hydraulic models of Biscuit Brook were produced with the U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS). A steady, one-dimensional, 1.1 year flow ($Q = 4.53$ m^3/s) was routed through channel geometries that were derived from the 2013 DEM and from field cross sections. A flow of this discharge occurred in October 2017, representing a typical annual flood. Boundary conditions included a Manning's roughness value of $n=0.03$ within the channel and $n=0.038$ for the banks. Manning's values were held constant for cross sections that included wood and removed wood. Constant Manning's values served as a control for model sensitivity. Iterations were performed with alteration of Manning's in cross sections with wood to $n=0.038$ in the channel and up to $n=0.05$, but the statistical outcome remained the same. Water surface was not calibrated, but the modeled water surface was visually determined to be adequate compared to field-observed high water marks. The purpose of the modeling was to examine differences in modeled velocities associated with varying channel features, such as presence or absence of wood, changes in valley geometry that caused bedrock or alluvial reaches, and the localized effects of each. Once velocity values were calculated in the model results, a series of Welch two sample t-tests were used to statistically determine the differences in velocities caused by changes in valley geometry or wood. These tests were completed with the t.test() function in R.

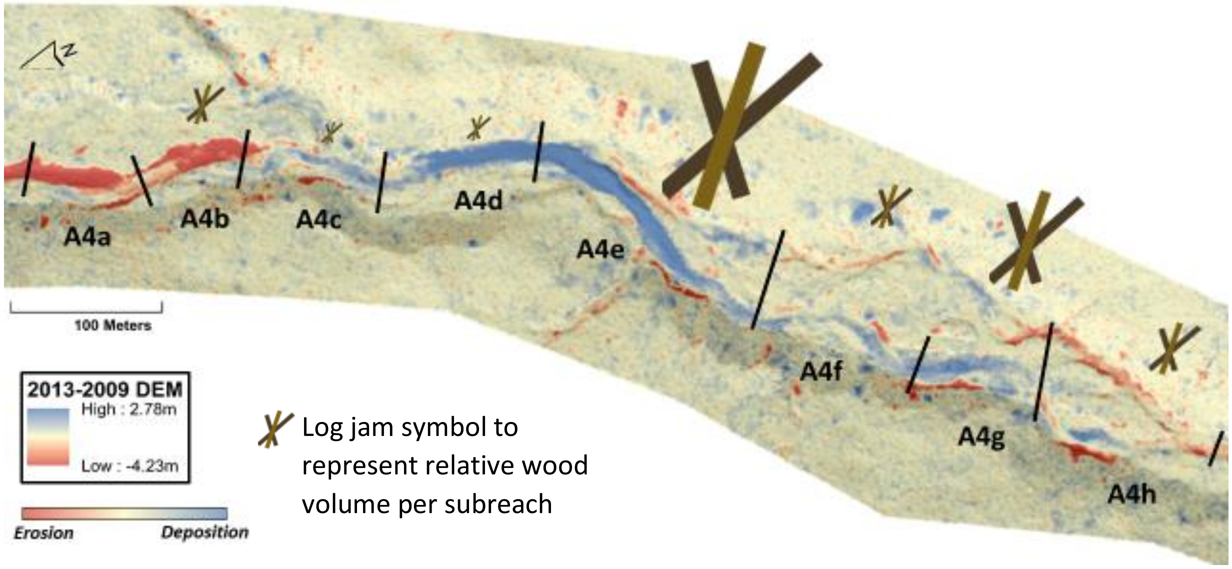
Modeled velocities from presence or absence of wood were analyzed with paired Welch two sample t-tests. The velocity values were paired because the models were run for the same cross sections in A4. One set of modeled velocities was based on the channel geometry with wood that was surveyed directly in the field. Wood was virtually removed from these cross sections by extrapolating the channel bottom from nearby channel bed points underneath or directly adjacent to the wood in order to create the cross-sectional geometry in the absence of wood. Localized effects of wood on modeled velocities were examined 20 m upstream of six major log jams within A4. Given the size of log jams in Biscuit Brook, 20 m is a representative distance to observe backwater effects and sediment storage due to wood.

The largest changes in valley geometry occur at the transitions from bedrock to alluvial reaches or vice versa. Velocities were compared statistically in bedrock versus alluvial reaches, based on model results from a DEM-extrapolated channel geometry. These comparisons included all reaches in Biscuit Brook and thus had the largest sample size. To examine localized effects of changes in valley geometry, velocities were compared in alluvial reaches 20 m upstream and 20 m downstream of bedrock reaches. Twenty-meter distances were used here for consistency with wood proximity velocities. Confidence intervals from t-tests describe the potential change in velocity caused by either wood or valley geometry. The confidence intervals were compared to determine whether valley geometry or wood has the largest influence on velocity.

RESULTS

Longitudinal Variations

Differences in elevation from 2009 to 2013 (Figure 6) allow preliminary identification of erosional and depositional zones within the A4 subreach. A4a and A4b show erosion during this time period, and A4d and A4e show the most aggradation. A4e has the largest wood volume of all the A4 subreaches. A4d can be interpreted as an aggradational wedge, or extension of the storage zone in A4e upstream of the channel-spanning jams.



Log jam symbol to represent relative wood volume per subreach

Figure 6. Map of difference in elevation between 2009 and 2013 (Dany Davis, NYCDEP), clipped to the A4 reach. High levels of erosion and incision occurred in this time period, especially during Hurricane Irene in 2011. The relative size of the log jam symbol indicates relative wood load in different subreaches. Wood load was mapped as pieces and jams within the channel, but symbols are placed outside the channel for illustrative purposes.

Table 5. A4 wood, bedrock, and 2009-2013 elevation change.

A4 Subreach	Wood Volume (m^3)	Net Elevation Change (m)	Percentage Bedrock
A4a	0	-1.2	20%
A4b	98	-0.8	7%
A4c	0.96	0.0	5%
A4d	2.75	0.6	0%
A4e	1097	0.6	0%
A4f	105	0.0	0%
A4g	494	0.1	0%

Wood Volume Color Key
Small
Medium
Large

A4h	166	-0.2	4%

Categories of wood volume in Biscuit Brook are designated based on field observations as small (0-50m^3), medium (50-250m^3), and large (>250m^3), indicated by colors of shading in Table 5. Both reaches with large wood volume experienced positive elevation change. The highest net elevation gains occurred in reaches A4d and A4e. Reaches A4a, A4b, and A4h lost sediment between 2009 and 2013, and may have eroded to bedrock, showing bedrock within the channel bed at the time of sediment surveys.

Table 6. Longitudinal variations in reach length and constriction ratio.

Reach	**Reach Length (m)**	**Constriction Ratio (Effective Width/Upstream Effective Width)**
A1	126	N/A
B1	126	0.75
A2	55	0.86
B2	104	1.20
A3	227	1.55
B3	80	0.82
A4*	885	2.69
B4	27	0.37
A5	215	1.64
B5	315	0.63
A6	137	2.02
B6	498	0.42
A7	133	2.72
A8	47	0.44
B7	21	0.94
B8	54	1.51

Range of Alluvial Reach Lengths (A4 divided)
47-227 m
Range of Bedrock Reach Lengths:
21-498 m

*A4 divided into subreaches

Reach	**Reach Length (m)**	**Constriction Ratio**
A4a	82	1.52
A4b	66	1.24
A4c	96	0.76
A4d	111	1.15
A4e	191	1.71
A4f	126	1.70
A4g	91	0.93
A4h	122	0.72

Table 6 shows longitudinal variation of reach length and constriction ratio. Six of the eight bedrock reaches have constriction ratios less than 1, and six of the alluvial reaches have constriction ratios greater than 1. The average constriction ratio of bedrock reaches is 0.82, and the average constriction ratio of alluvial reaches is 1.70.

Sediment Cumulative Frequency Distributions

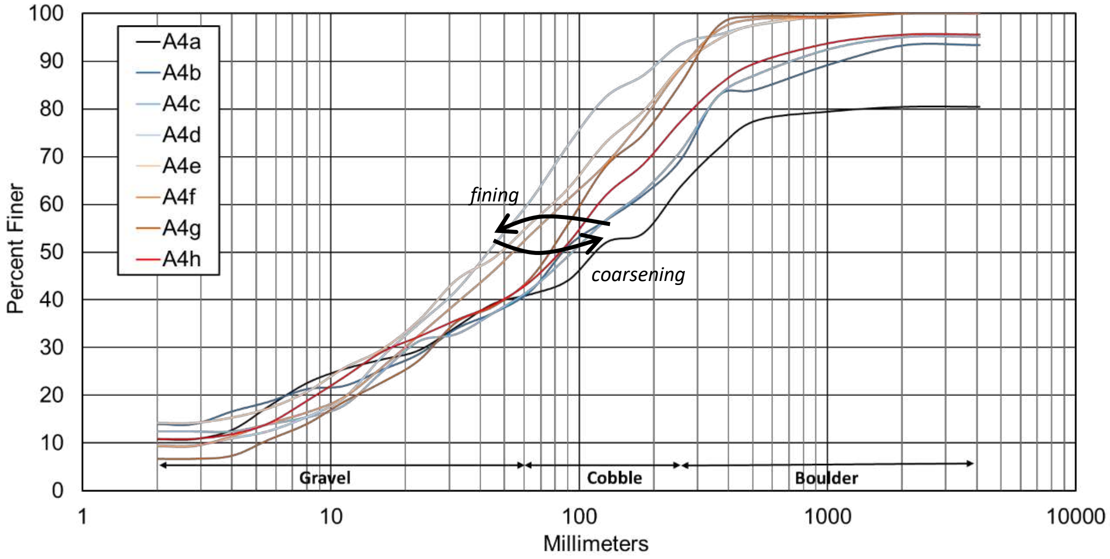


Figure 7. Particle size distributions in the A4 reach. The curved arrow highlights the fining pattern from A4a to A4e, and coarsening from A4e to A4h.

Particle size distributions of A4 reaches in Figure 7 show gradual fining downstream until the A4e subreach. A4e contains the largest wood volume and the single largest channel-spanning jam (Figure 8). Gradation also decreases until subreach A4e. Wood in A4e is an obstruction that forces sediment storage upstream.

Figure 8. A4e channel-spanning jam with researchers for scale. View faces downstream and surface flow is in the topographic low to the left of the jam.

Correlation Analyses

Median grain size and gradation coefficient were tested for correlations with singular predictive variables related to valley geometry and wood. In Table 7, I report the five highest coefficients of determination of all variables tested: jam proportion, effective width divided by geologic valley width, number of active channels, slope, and bedrock proportion. Bedrock was omitted in the calculation of d_{84} for gradation coefficient. At a 90% confidence level, four of the five predictive variables have significant correlations to median grain size and gradation. The results suggest that:

- Higher proportion of wood in a jam is associated with decreased grain size and gradation.
- More abundant active channels are associated with decreased grain size and gradation.
- Steeper slopes are associated with increased grain sizes and increased gradation.

- Higher proportion of bedrock in the channel is associated with increased grain size and gradation.

Table 7. Pearson Coefficients of Determination. Shading scales to correlation strength, and bolded rows are statistically significant.

Pearson R^2

	d50	**Direction of Correlation**	**Significance at 90% Confidence Level?**	**Gradation** $\sigma_g = \left(\frac{d_{84}}{d_{16}}\right)^{\frac{1}{2}}$	**Direction of Correlation**	**Significance at 90% Confidence Level?**
Jam Proportion	**0.69**	**-**	**p=0.01**	**0.53**	**-**	**p=0.041**
Effective Valley Width/Geologic Valley Width*	0.35	-	p=0.12	0.40	-	p=0.09
Number of Channels	**0.76**	**-**	**p=0.0045**	**0.51**	**-**	**p=0.045**
Slope	**0.45**	**+**	**p=0.067**	**0.48**	**+**	**p=0.058**
Bedrock Proportion	**0.74**	**+**	**p=0.0064**	**0.40**	**+**	**p=7.5e-6**

***Effective valley width/Geologic valley width is from here on referred to as active valley proportion.**

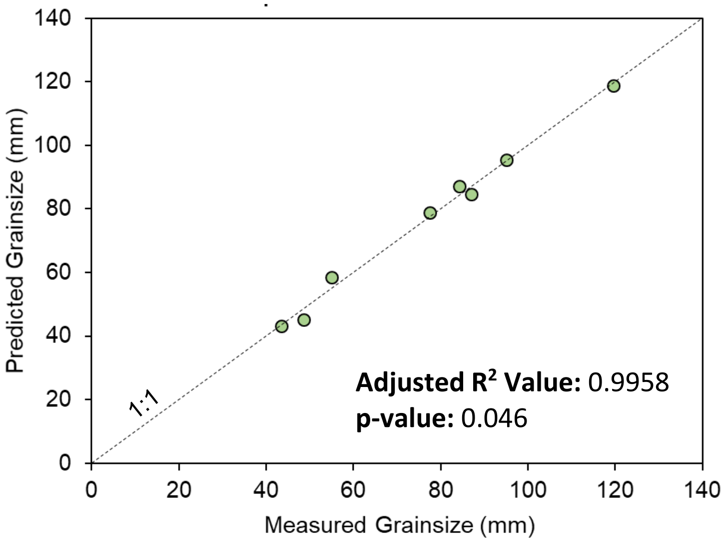
The non-significant variable reported for grain size -- effective width divided by geologic width -- can be described as the active valley proportion. The active valley proportion represents the proportion of the geologically-defined valley that is included in the active river corridor. A ratio of 1 means the entire valley is active, and as the ratio approaches 0, less of the bedrock-defined valley is active, implying past episodes of incision into no-longer accessible terraces in the valley floor. Although not significant, the trend in this active valley proportion implies that as the proportion of active valley increases, grain size and gradation decrease.

The highest coefficient of determination for grain size relationships is for the regression of grain size with the number of active channels. The number of active channels can be influenced by either valley geometry, wood, or their combination. In this scenario, I associate number of active channels with the available space within the valley for lateral channel migration and branching. The variable jam proportion produces the strongest correlation with gradation. Although it is useful to rank the correlations, wood and valley geometry coefficients of determination that are significant at the 90% confidence level are within 10% of each other and suggest that valley geometry and wood have similar relationships to grain size and gradation.

Multiple Linear Regression

A multiple linear regression of variables representing valley geometry and wood is used to qualitatively assess the strength of wood and valley geometry when combined to predict grain size and gradation. The five variables with highest correlation as singular predictive variables, with the addition of wood volume, are included in the model shown in Equation 1. The equation produces a statistically significant prediction of median grain size but is intended for conceptual use only because of the small sample size when including only A4 subreaches.

$$\begin{aligned}\textbf{Median Grain size} \\ &= 128.6 - 239.8(\textbf{Slope}) + 209.1(\textbf{Bedrock Proportion}) \\ &+ 80.92(\textbf{Active Valley Proportion}) - 68.01(\textbf{Number of Channels}) \\ &+ 8.154(\textbf{Jam Proprtion}) - 0.02420(\textbf{Wood Volume})\end{aligned} \qquad \text{(Eq. 1)}$$



Reach	Predicted d_{50} (mm)	Actual d_{50} (mm)
A4a	119	120
A4b	85	87
A4c	95	95
A4d	43	44
A4e	45	49
A4f	58	55
A4g	79	77
A4h	87	84

Figure 9. and Table 8. Median grain size predicted by the multiple linear regression compared to the measured median grain size.

The coefficients of each variable are visually represented with a bar graph to compare the relative influences on grain size.

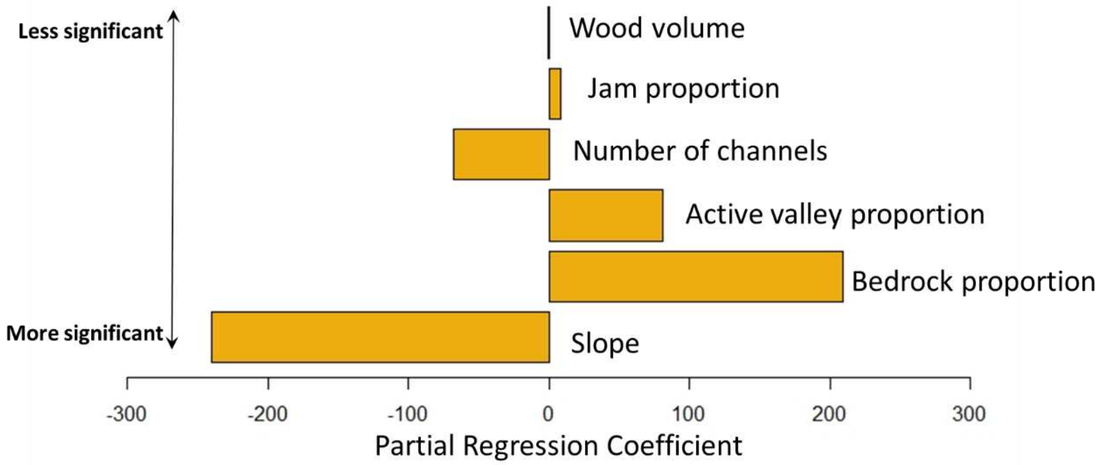
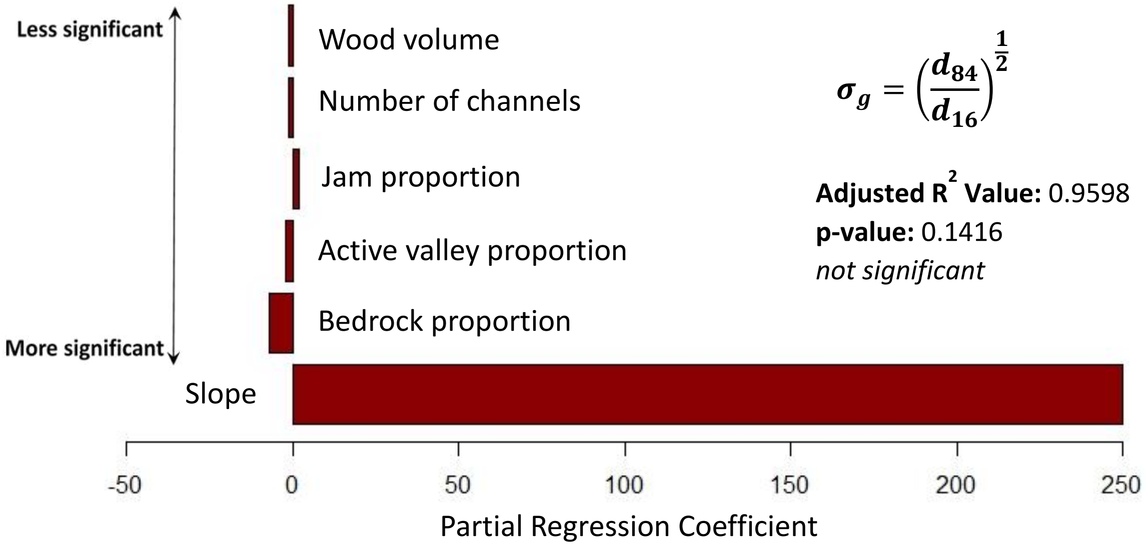


Figure 10. Partial regression coefficient estimations for median grain size, represented in a bar graph to show relative influence of each variable. Exact partial coefficient estimations are in Equation 1.

The multiple linear regression to predict grain size (Eq. 1) suggests that valley geometry metrics have more influence on grain size than wood. However, the inclusion of wood metrics in the statistically significant model implies that the combination of wood and valley geometry provides the most representative model. A multiple linear regression was also calculated to predict gradation coefficient (Figure 11) but does not produce significant results at the 90% confidence level. The regression for gradation coefficient qualitatively suggests that slope, and therefore valley geometry, is also the strongest influence on gradation coefficient.



$$\sigma_g = \left(\frac{d_{84}}{d_{16}}\right)^{\frac{1}{2}}$$

Adjusted R^2 Value: 0.9598
p-value: 0.1416
not significant

Figure 11. Partial regression coefficient estimations for gradation coefficient, represented in a bar graph to show relative influence of each variable. Estimates of partial regression coefficients are not listed in an equation because the results from the multiple regression were not statistically significant.

Modeling Velocity

Field observations confirm that bedrock reaches in Biscuit Brook are narrower, more highly confined, and have steeper slopes than alluvial reaches, making the distinction between alluvial and bedrock reaches a valid representative of valley geometry (Figure 12).

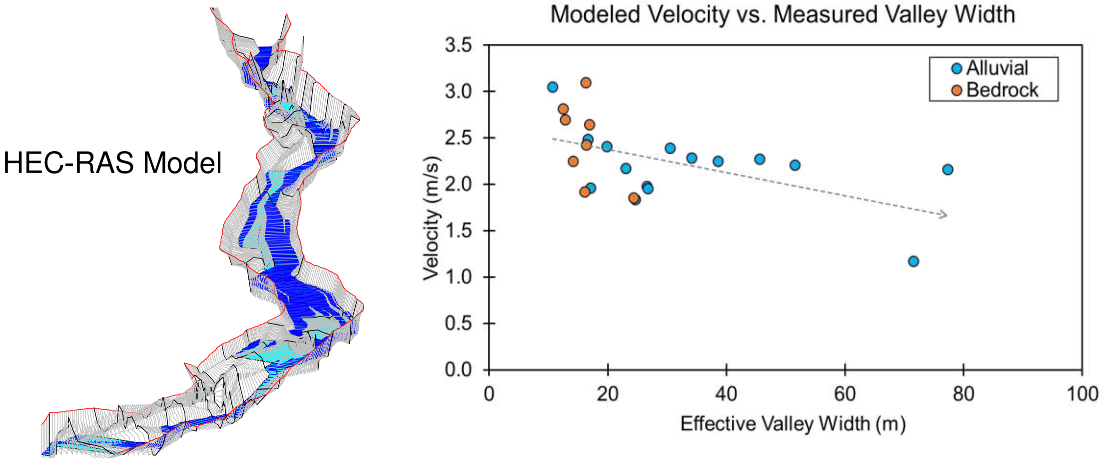


Figure 12. HEC-RAS modeled geometry example with blue modeled water surface for Q=4.53 m^3/s. A graph of modeled velocity from DEM extracted geometry in all reaches shows that bedrock substrates are generally narrower than alluvial, and that the distinction between alluvial and bedrock can be used to represent valley geometry.

To represent changes in valley geometry, I compare alluvial and bedrock modeled velocities from DEM-extracted channel geometries in Figure 13. The results of a t-test provide evidence that the difference in means of modeled velocity lies between 0.16 and 0.19 m/s. The sample number (n) for t-tests from all categories represents modeled velocities from cross sections that are either DEM or field derived. For alluvial reaches, n=1130 is from 1130 cross-sectionally averaged velocity values.

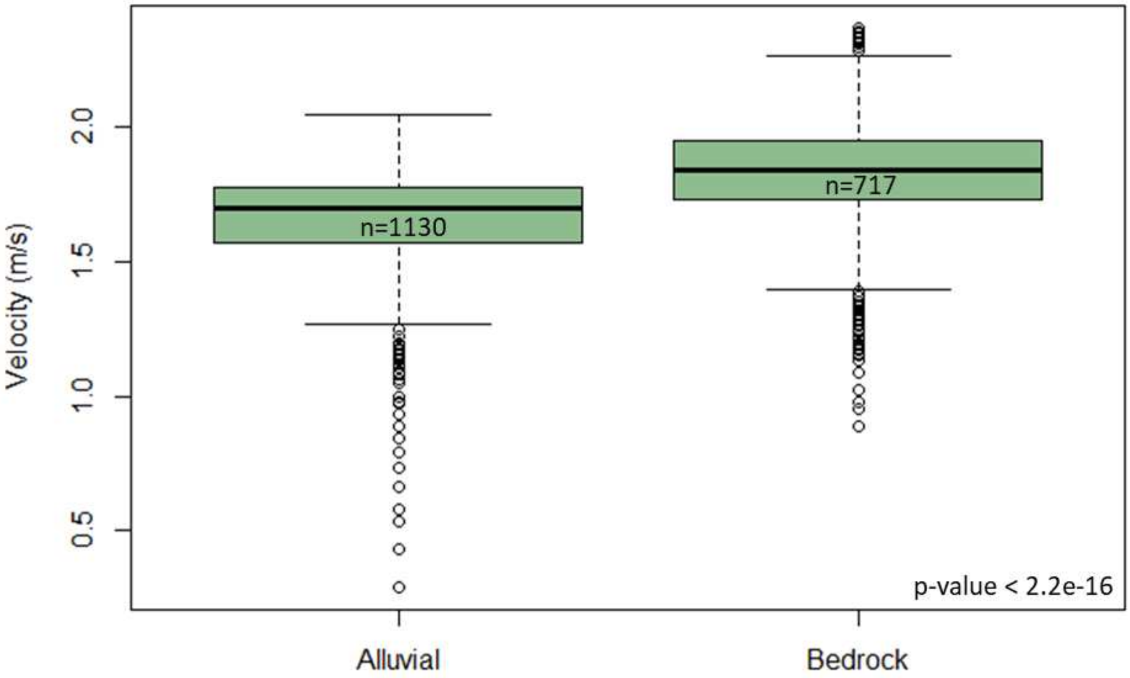


Figure 13. Modeled cross-sectional velocities through all reaches in Biscuit Brook. Velocities are categorized by cross sections that occurred in either alluvial or bedrock reaches.

During the field season, I surveyed over and under wood jams in A4 in order to virtually remove wood in the resulting hydraulic model. To determine whether there is a significant difference in modeled velocity through A4 subreaches with and without wood, I ran paired t-tests through A4 with field-measured geometry including wood, and with wood virtually removed. Figure 14 shows that velocities modeled through the entire A4 reach with and without wood do not show a significant difference.

Figure 14. A t-test for modeled velocities through the same cross sections in the A4 reach shows no significant difference in velocity through the entire A4 reach when modeled with or without wood.

The longitudinal profile in Figure 15 shows locations of 6 major log jams, shown by symbols above the modeled water surface. To investigate the localized effects of these major jams on velocity, t-tests were performed 20 m upstream of the six locations, paired with and without wood in the channel geometry. Figure 16 shows that there is a significant difference in modeled velocities with and without wood 20 m upstream of wood locations. The mean modeled velocity without wood is higher than the mean velocity with wood by 0.1-0.2 m/s.

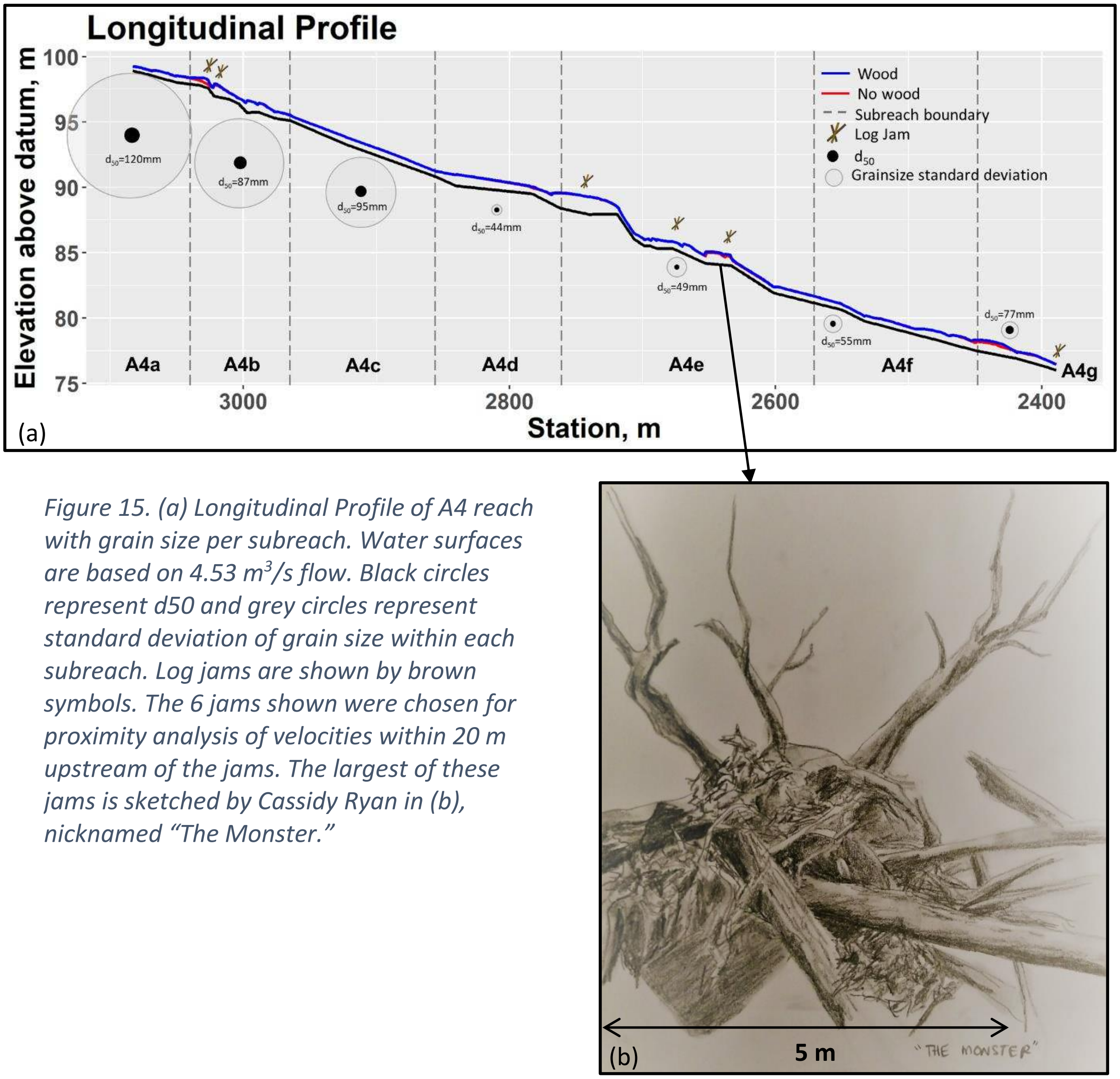


Figure 15. (a) Longitudinal Profile of A4 reach with grain size per subreach. Water surfaces are based on 4.53 m^3/s flow. Black circles represent d50 and grey circles represent standard deviation of grain size within each subreach. Log jams are shown by brown symbols. The 6 jams shown were chosen for proximity analysis of velocities within 20 m upstream of the jams. The largest of these jams is sketched by Cassidy Ryan in (b), nicknamed "The Monster."

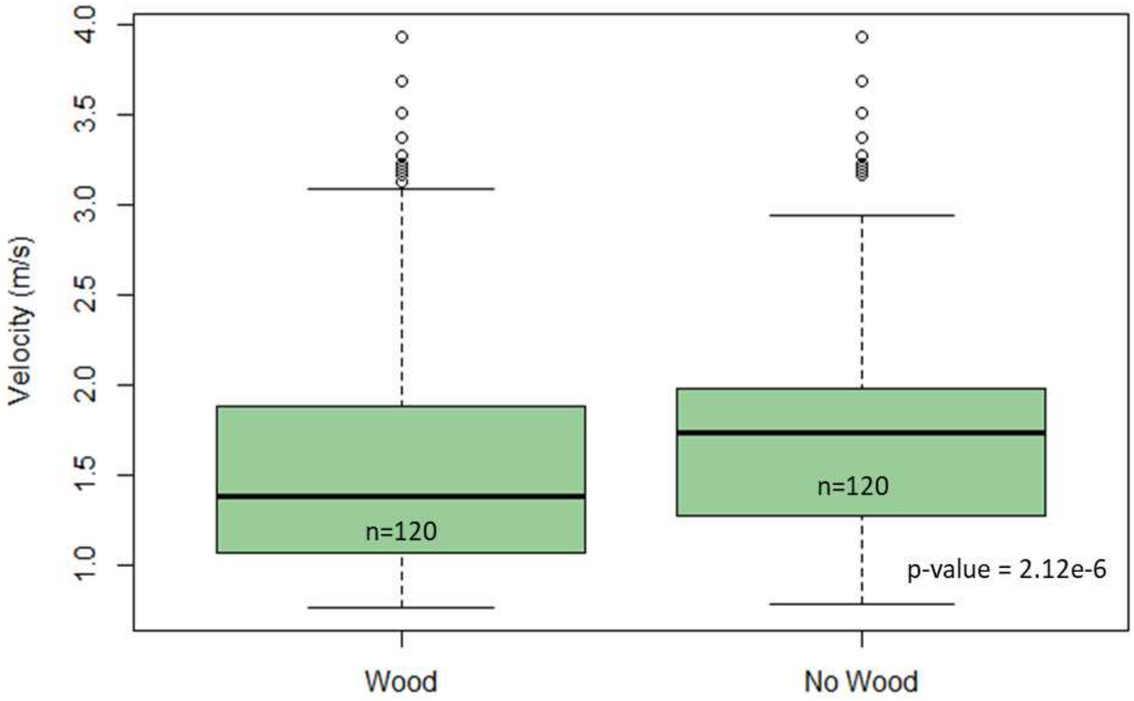


Figure 15. T-tests of velocity within 20 m upstream of the 6 major log jams show a significant difference in velocity between cross sections upstream of wood and the same cross sections modeled with wood virtually removed.

Valley geometry also creates localized effects, such as the backwater effect and a loss of transport capacity at canyon outlets. In Figure 17, I show localized sections in alluvial reaches, specifically 20 m upstream and downstream of transitions to and from bedrock, in comparison with all velocities and alluvial velocities. To determine whether alluvial velocities differ statistically upstream and downstream of bedrock reaches, I compared velocities 20 m upstream and 20 m downstream of boundaries with bedrock reaches. Figure 18 shows there is sufficient evidence to suggest that modeled velocities are lower downstream of bedrock reaches by 0.07-0.25 m/s.

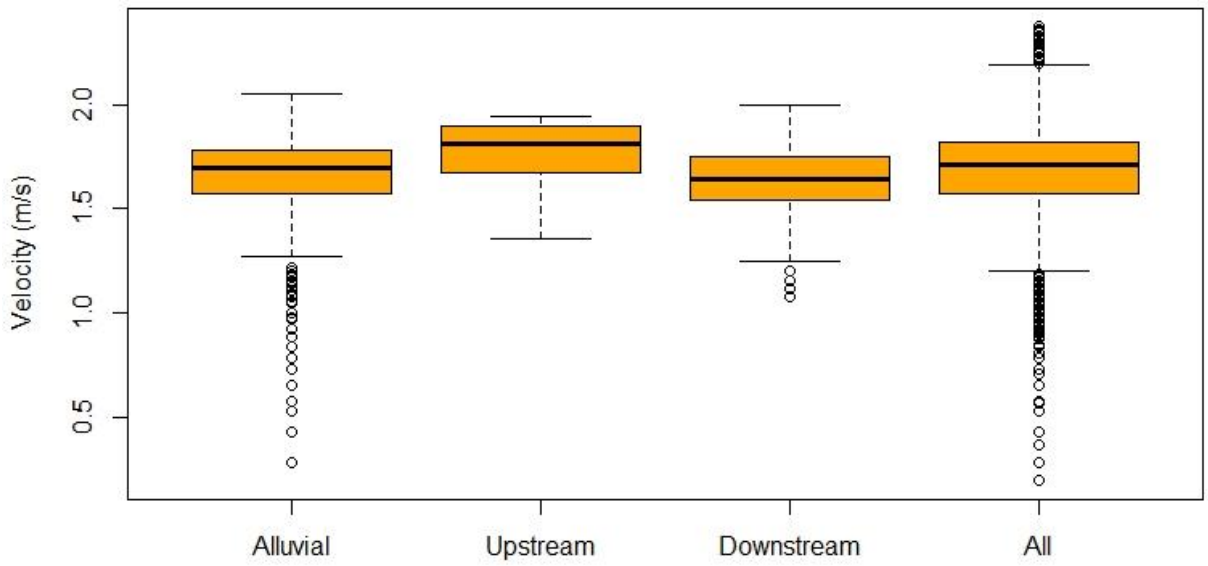


Figure 17. Alluvial velocities, localized velocities 20 m upstream and downstream of bedrock, and all velocities including bedrock.

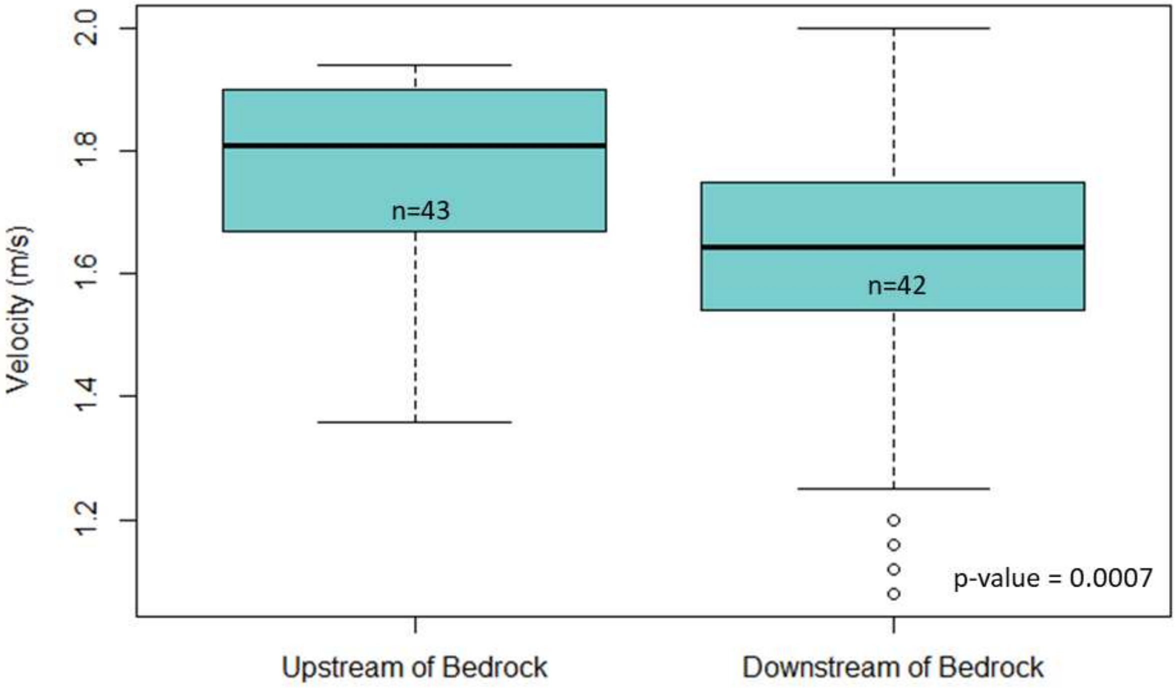
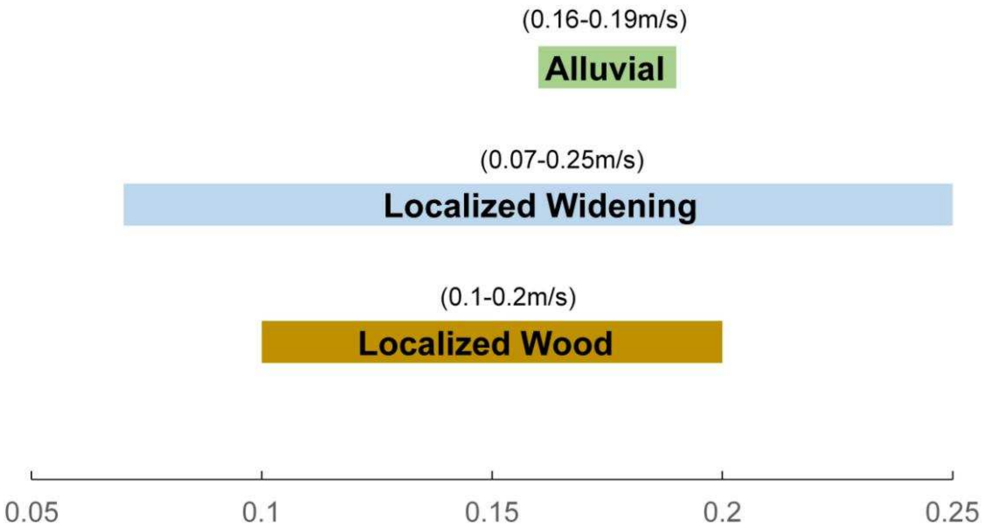


Figure 18. Velocities were compared in alluvial reaches upstream and downstream of the transition to bedrock reaches. Upstream represents the backwater effect, and downstream represents localized widening. There is a significant difference in modeled velocities, indicating that velocities are slower at bedrock outlets.



Decrease in mean velocity (m/s)

Figure 19. Confidence intervals for the decrease in velocity associated with alluvial vs. bedrock reaches (t-test 1), backwater vs. downstream widening (t-test 4), and upstream of wood vs. upstream of removed wood (t-test 3). All values are positive, which indicates that there is a velocity decrease associated with substrate, widening, and wood. Bedrock outlets to alluvial reaches, or localized widening, have potential to have the largest decrease in velocity at the upper bound of the confidence interval.

Three of the four tests produced significant results at the 90% confidence level, suggesting that substrate, backwater from wood, and transition to alluvial at bedrock reach outlets can all decrease velocity in Biscuit Brook. Confidence intervals of the mean difference in velocity from each test are shown in Figure 19. Alluvial versus bedrock reaches have the highest sample size and the narrowest confidence interval, showing a decrease in velocity from 0.16-0.19 m/s. Localized widening, at the upper boundary of the confidence interval, has the potential to cause the largest decrease in velocity. Localized effects of wood on velocity have a wider interval, but the interval includes the same range of decrease in velocity that is related to alluvial versus bedrock reaches.

DISCUSSION

Results from linear regression, multiple linear regression, and hydraulic modeling suggest that valley geometry, including channel characteristics like slope and confinement, has a stronger influence on sediment storage and grain size distribution than wood. Wood complements this influence by further enhancing potential for sediment retention. Wood and valley geometry are closely linked in forested watersheds, and their influences on sediment should be utilized in combination for stream restoration. Valley geometry is often geologically controlled and thus cannot often be adjusted by humans in the context of stream restoration. Cases where geometry can be altered may require relocation of infrastructure. These complications lead to difficulties in the modification of valley geometry for stream restoration. However, in climates where wood is naturally found in streams, the possibility for introduction of wood to a stream reach may be much more practical.

Erosional and depositional zones from 2009-2013 indicate a sediment pulse is currently stored in the A4d and A4e subreaches. A4a and A4b contain the most bedrock out of all the subreaches in A4 because they were scoured to bedrock during Hurricane Irene, contributing material to the sediment pulse. A4d has the most gradual slope and the finest sediment distribution of all the subreaches because of the geomorphic response to wood in A4e. Wood recruitment to A4e from hillslopes, the forested floodplain, and upstream reaches during Hurricane Irene culminated in several large, channel-spanning jams in A4e. These jams caused significant aggradation in subsequent years after the hurricane and have influenced the grain size distribution both up and downstream by causing fining and coarsening, respectively. Storage of fine material that otherwise would have been transported downstream in A4e produces detectable changes in grain size distribution between reaches, and longitudinal trends in sediment data.

Episodic wood recruitment from storms, as opposed to low levels of continuous wood recruitment over time, interact with valley geometry to create hot spots of sediment storage (Czuba and Foufoula-Georgiou 2015)~~.~~ My field observations, wood data, sediment data, and the hydrologic record suggest that the large volume of wood in subreach A4e was emplaced by Hurricane Irene and is now serving as a sediment storage hot spot. Wood in A4e prevents the sediment pulse from moving downstream to the confluence with the Neversink River, and thus even farther downstream to the Neversink Reservoir.

A4e also lies immediately upstream from several distinct changes in valley geometry including lower confinement (effective valley width, valley confinement, valley bottom confinement) and more gradual slope. Constriction of the valley in A4e compared to downstream reaches may have provided the necessary conditions for maximized wood accumulation. Thus, wood directly influences sediment distribution surrounding A4e, but underlying controls for wood in A4e wood and sediment storage may be related to the geologically controlled valley geometry.

Wide, alluvial reaches alternating longitudinally with bedrock reaches in Biscuit Brook can be conceptualized as river beads between river strings (Stanford et al. 1996). The functionality of beads versus strings is primarily controlled by valley geometry. Within beads, there is enhanced sediment and organic matter retention, and increased lateral mobility of the channel. The number of channels, the single variable most strongly correlated with grain size, represents lateral channel mobility. Abundant lateral mobility of channel branches not only decreases slope along the length of the channel, but also accumulates more wood by creating a greater total length along which bank erosion can recruit wood from the forested floodplain. In this sense, valley geometry provides the underlying control, or template, for sediment distribution. However, wood is known to block flow, force side channels, and facilitate anastomosing planforms (Wohl 2011, Collins et al. 2012). Although there is no significant correlation between wood volume and number of channel branches in Biscuit Brook, wood-forced avulsions could potentially increase the number of active channels within a particular reach, and therefore further enhance sediment retention.

Correlation analyses of singular predictor variables also provide evidence that the inclusion of wood within log jams is highly important for sediment distribution and storage. The significant correlation of jam proportion with finer, more uniform sediment distributions, and the absence of a significant correlation between grain size and wood volume alone, indicate that wood has a much greater influence on sediment retention when the wood is included in a jam.

High proportion of bedrock in the channel and high channel gradient are indicators of transport processes dominating over storage. Reaches with more bedrock will have greater stream power and lower hydraulic roughness, facilitating sediment transport. High active valley proportion is associated with grain size fining, indicating that highly incised valleys are likely to have coarser sediment and higher energy. When streams are heavily incised, concentration of energy within the narrow, incised channel leads to higher probability of sediment transport (e.g., O'Connor et al. 1986, Wohl 1992).

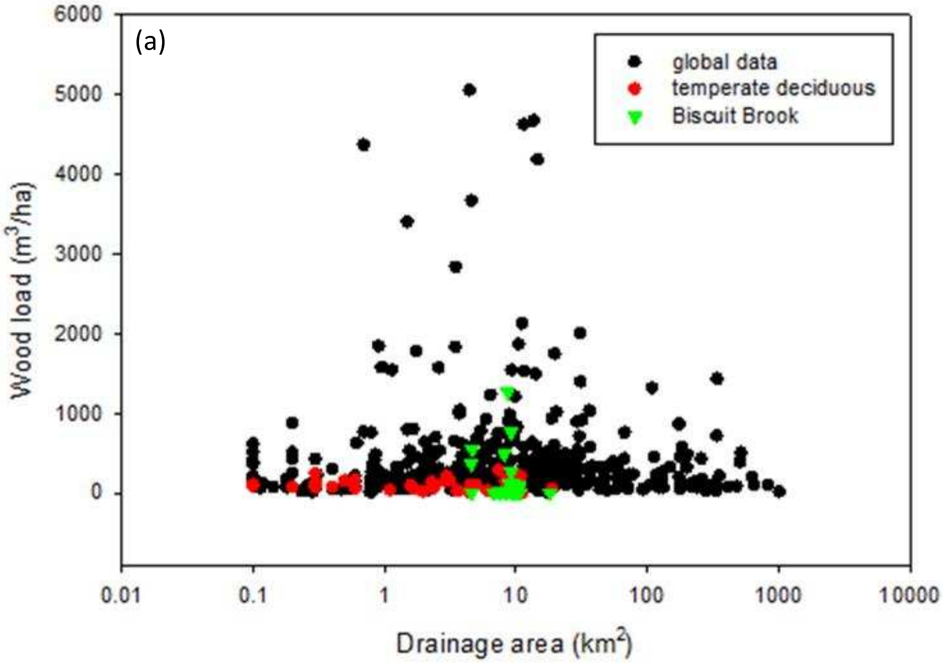
A multiple linear regression to investigate the combined influence of valley geometry and wood on sediment distribution shows a strongly correlated, significant estimation of median grain size. Although the equation cannot be used for direct grain size prediction, it shows that valley geometry and wood interact to influence sediment dynamics in Biscuit Brook. Because slope and bedrock proportion, both components of valley geometry, have the strongest influence within the predictive equation, I infer that valley geometry more strongly influences broad-scale grain size trends than wood.

Decreases in flow velocity create the potential for sediment storage. Modeled velocities in Biscuit Brook show that wood and valley geometry can result in localized decreases in velocity, but only valley geometry has a statistically significant velocity decrease when averaged over entire reaches. The localized velocity decrease caused by valley geometry occurs at the transitions from bedrock to alluvial reaches. At these locations, there can be increases in valley width and decreases in stream power. These are sites where there is no longer enough flow energy to imbricate and transport sediment. The localized effect of wood on velocity occurs upstream of jams or pieces, where pools can form and local slope decreases. Storage zones upstream of wood occur either from direct blockage of sediment downstream movement or from the local velocity reduction.

Relative influences of valley geometry and wood can be considered at varying scales. Through an entire river, valley geometry, along with sediment supply and hydrologic regime, controls sediment distribution and storage. At the reach scale, either wood or valley geometry can govern whether sediment is stored or transported. For example, wood in A4e controls the accompanying aggradational wedge. However, the numerous bedrock reaches in Biscuit Brook facilitate rapid sediment transport. Closer examination suggests that the competing processes of transport and storage do not have to be mutually exclusive in one cross sectional sample of a river. Wood provides the ability for a channel to have transport and storage in close lateral proximity. Valley geometry controls sediment distribution and storage at coarse spatial scales and can also facilitate the presence or absence of wood.

Wood Loads in Biscuit Brook Compared to Other Regions

Wood data from Biscuit Brook can be evaluated in a larger context by comparison to global datasets. Figure 20a shows Biscuit Brook wood load per reach grouped with global and temperate deciduous wood loads from several studies (Wohl et al. 2017). The global data include sites in the humid tropics, semiarid regions, temperate rainforest (the US Pacific Northwest), and subarctic regions of North and South America. Biscuit Brook shows the highest values for temperate deciduous wood loads. Considering the high proportion of bedrock channel in Biscuit Brook, it is possible that wood loads are more highly concentrated in the alluvial reaches because there is a high level of transport elsewhere. When compared with other sites from the northeastern and southeastern US (Fig. 20b), Biscuit Brook reaches have high wood loads for the middle range of drainage areas. As noted above, this may reflect the locally high transport capacity in the bedrock portions of Biscuit Brook, as well as the lack of management history (e.g., removal of large wood from the river corridor).



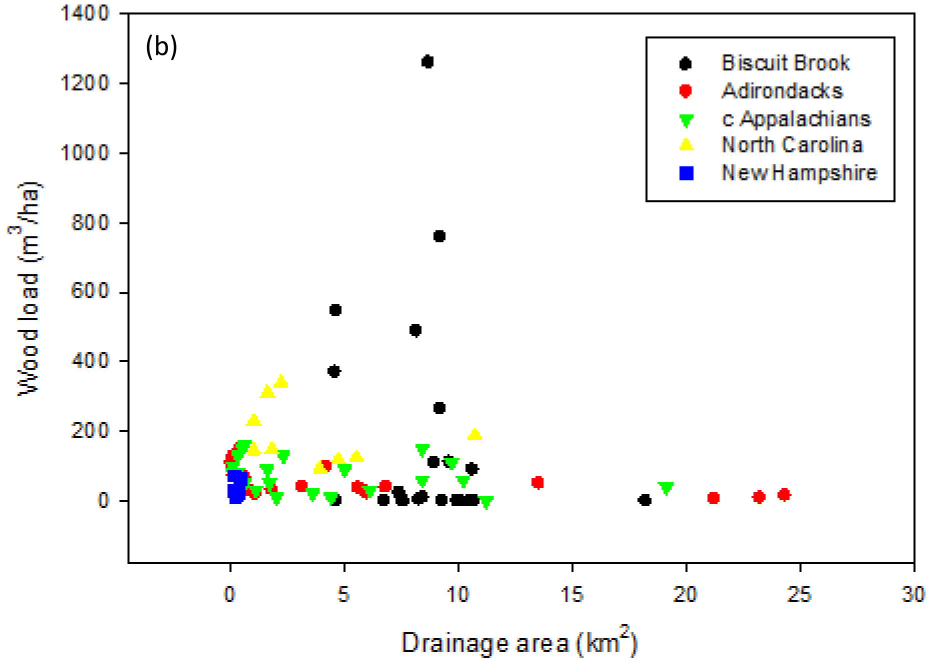


Figure 20. (a) Biscuit Brook data added to a plot of global and temperate deciduous wood loads across a range of drainage areas. Biscuit Brook is at the upper bound of drainage area for temperate deciduous data and shows higher variability in wood load than other temperate deciduous sites. (b) Biscuit Brook has a high wood load compared to other sites in the northeastern and southeastern US.

CONCLUSIONS

Valley geometry provides an overall template for grain size distribution and sediment storage. Wood locally maintains sediment storage potential and grain size distribution over shorter timescales as wood is continuously or episodically recruited and removed. This study shows that valley geometry and wood metrics such as slope, bedrock proportion, jam proportion and number of active channels are all significantly correlated to grain size distribution. In a multiple linear regression, valley geometry variables exert a stronger influence on sediment distribution, but both valley geometry and wood are included in the model. Modeling of velocity as a proxy for sediment storage shows that valley geometry always shows a significant relationship to velocity and wood exerts a significant localized influence.

In the growing field of stream management, where sediment storage is desired, stream restoration designs should consider existing valley geometry and include wood rather than removing it. Valley geometry and wood should be used in conjunction to maximize the efficiency of projects and accomplish restoration goals when resources are limited. When sediment storage is an objective of restoration, wood can be strategically placed to supplement the naturally high storage potential of localized valley widening. Alternately, wood can be placed near the downstream end of river beads, or storage zones, to slow velocity and store sediment upstream of naturally occurring, high energy transport zones.

Future Directions

Data from Biscuit Brook provide insight into the relationships between wood, valley geometry, and sediment distribution. Although the multiple linear regressions are intended for qualitative use, the multi-regression of grain size could be even more useful if it is evaluated in neighboring catchments in the Neversink watershed, and even in other Catskill watersheds, such as the Esopus, where there is a high concentration of stream restoration projects managed by the NYCDEP. Porosity of log jams was visually estimated during wood mapping. Including porosity as factor in HECRAS may increase the reliability of modeled velocity estimates.

The use of a hydraulic model to examine the effects of wood on flow velocity and sediment storage potential highlights the need for better representation of wood in modeling software. Substitution of a geometric block for wood accumulation in the channel is highly simplified and does not incorporate aspects of in-stream wood such as porosity, decay, and mobility at high flows. Decades of research indicate that wood can improve habitat quality, and wood thus is a growing feature of restorative treatment to streams. With the increasing use of wood in stream restoration practices, tools should be developed to more accurately depict wood in streams for management planning purposes. Follow-ups to this study will likely include experimental use of model features that allow through-flow such as bridges, weirs, and culverts to more closely capture dynamics of wood in channels.

The next iteration of modeling should include a range of flows to illuminate any thresholds and show how velocity can vary through different hydrologic scenarios. In the field, I took photos of the A4b, A4e, and A4g reaches for the future production of DEM with Structure from Motion. With DEMs of the current landscape, a difference map can show how Biscuit Brook sediment and wood have adjusted since 2013. Another useful study could compare my results with watersheds of varying sizes. Because Biscuit Brook has extreme longitudinal variation between alluvial and bedrock reaches, the influences of valley geometry are particularly evident. However, a larger river with more subtle transitions may show different patterns in sediment storage vs. transport. In these cases, wood may have an even more significant influence, and the development of a relationship between watershed size and the relative roles of wood and valley geometry can be initiated. I have developed a valuable dataset of wood and valley geometry variables throughout Biscuit Brook and would be happy to contribute these data to interested parties in order to advance knowledge of how wood and valley geometry interact to store and transport sediment.

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Appendix A: Summary of Variables by Reach

Table A1. Wood Variables

Reach	Wood Volume (m^3)	Wood Volume/ Reach Length (m^3/m)	Wood Volume/ Area (m^3/ha)	# Mapped Wood[a]	# Jams	Wood Volume/ # Wood	Jam Proportion (Jam Volume/Total Volume)
A1	77	0.61	370	2	2	39	1
B1	0	0	0	0	0	0	0
A2	32	0.58	546	1	1	32	1
B2	0	0	0	0	0	0	0
A3	10	0.05	23	4	2	3	0.48
B3	0	0	0	0	0	0	0
A4a	0	0	0	0	0	0	0
A4b	98	1.48	487	6	4	16	0.80
A4c	0.96	0.01	4	1	0	1	0
A4d	2.75	0.02	9	2	1	1	0.97
A4e	1097	5.74	1261	10	8	110	0.99
A4f	105	0.83	108	4	2	26	0.98
A4g	494	5.43	760	3	3	165	1
A4h	166	1.36	264	9	6	18	0.63
B4	0	0	0	0	0	0	0
A5	64	0.30	111	6	6	11	1
B5	0	0.00	0	0	0	0	0
A6	0	0	0	0	0	0	0
B6	0	0	0	0	0	0	0
A7	46	0.35	90	2	2	23	1
A8	0	0	0	0	0	0	0
B7	0	0	0	0	0	0	0
B8	0	0	0	0	0	0	0

[a] # Mapped wood represents both pieces and jams. Jams and individual pieces are each referred to as single mapped units of wood.

Table A2. Valley Geometry Variables

Reach	Reach Length (m)	Geologic Valley Width (m)	Effective Valley Width (m)	Constriction Ratio	Expansion Ratio	Active Valley Proportion
A1	126	17	17	N/A	1.33	1.00
B1	126	14	12	0.75	1.17	0.88
A2	55	32	11	0.86	0.83	0.34
B2	104	29	13	1.20	0.65	0.44
A3	227	51	20	1.55	1.22	0.39
B3	80	62	16	0.82	0.66	0.26
A4a	82	72	25	1.52	0.81	0.34
A4b	66	80	30	1.24	1.32	0.38
A4c	96	57	23	0.76	0.87	0.40
A4d	111	45	27	1.15	0.58	0.59
A4e	191	46	46	1.71	0.59	0.98
A4f	126	79	77	1.70	1.08	0.97
A4g	91	73	71	0.93	1.39	0.99
A4h	122	55	52	0.72	3.15	0.94
B4	27	46	16	0.32	0.61	0.36
A5	215	34	27	1.64	1.59	0.79
B5	315	26	17	0.63	0.50	0.64
A6	137	45	34	2.02	2.41	0.75
B6	498	40	14	0.42	0.37	0.36
A7	133	42	39	2.72	2.26	0.91
A8	47	18	17	0.44	1.06	0.96
B7	21	19	16	0.94	0.66	0.86
B8	54	25	24	1.51	N/A	0.97

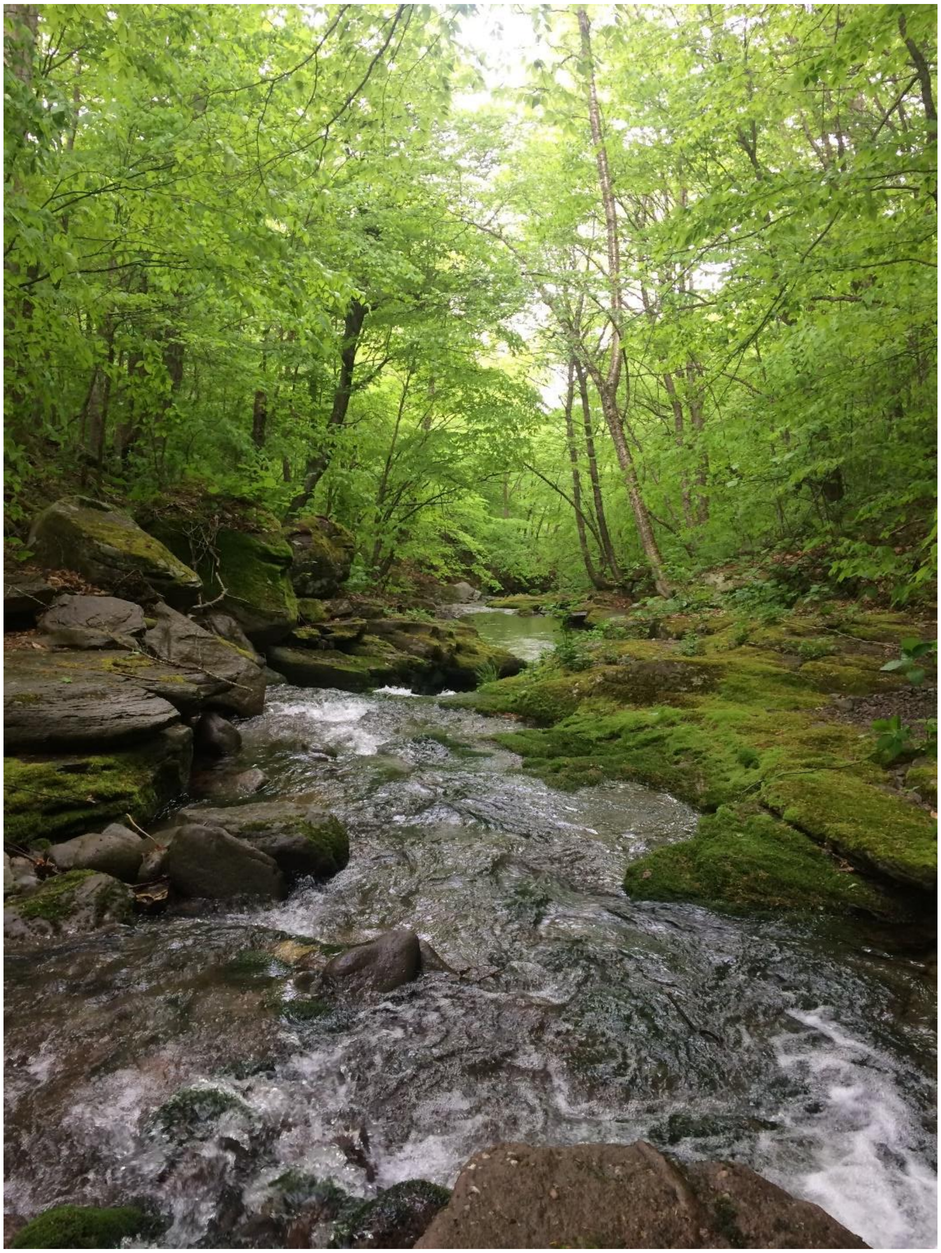
Table A3. Valley Geometry Variables, continued

Reach	Slope	Sinuosity	Average elevation change (m) 2013-2009	Average modeled velocity (m/s) Q=4.53m^3/s
A1	0.03	1.08	-0.09	2.48
B1	0.06	1.02	-0.22	2.82
A2	0.05	1.00	-0.12	3.05
B2	0.05	1.02	-0.35	2.70
A3	0.03	1.03	-0.42	2.41
B3	0.05	1.03	-0.96	3.10
A4a	0.04	1.05	-1.19	1.84
A4b	0.04	1.00	-0.84	2.39
A4c	0.03	1.04	-0.04	2.17
A4d	0.02	1.03	0.58	1.98
A4e	0.04	1.04	0.55	2.28
A4f	0.03	1.15	0.04	2.16
A4g	0.03	1.06	0.14	1.18
A4h	0.04	1.26	-0.17	2.21
B4	0.03	1.08	-0.43	2.43
A5	0.02	1.02	0.09	1.96
B5	0.03	1.04	-0.32	2.65
A6	0.05	1.11	-0.11	2.28
B6	0.03	1.03	-0.20	2.25
A7	0.04	1.08	0.12	2.25
A8	0.03	1.02	-0.01	1.96
B7	0.02	1.00	-0.15	1.92
B8	0.02	1.06	0.07	1.86

Appendix B: Reach Photos

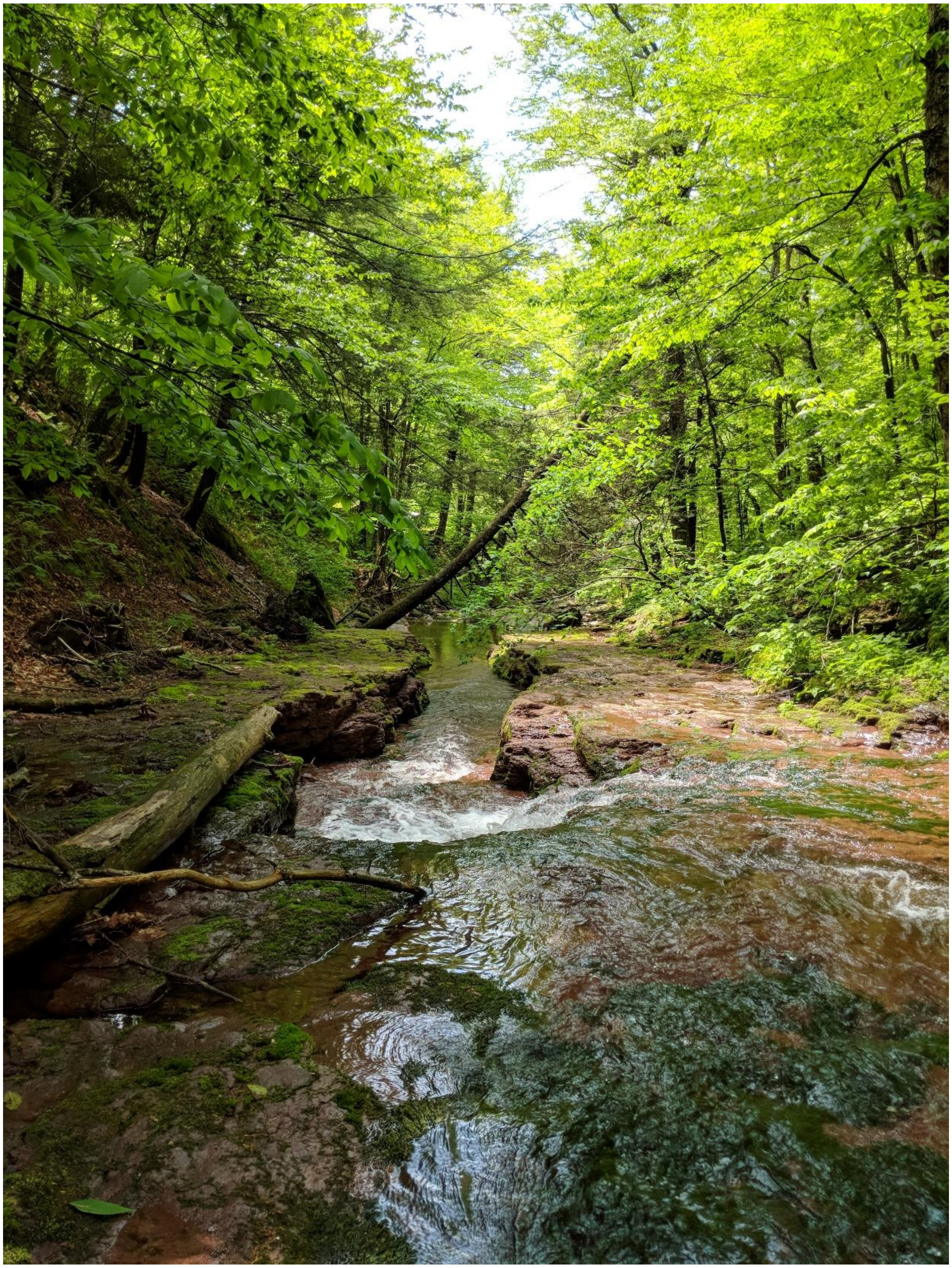
The following photos are of reaches delineated in Biscuit Brook for this study. Reaches A6-B8 are not pictured because they are on private property.

Downstream view of reach A1.



Downstream view of B1.

Downstream view of A2.



Downstream view of B2.

Downstream view of A3.

Downstream view of B3.

Downstream view of A4a.

Downstream view of A4a. A4b begins at log jam.

Downstream view of A4b. Flags were removed after photo was taken.

Downstream view of A4c.

Downstream view of A4d.

Downstream view of A4e.

Downstream view of jam in A4e.

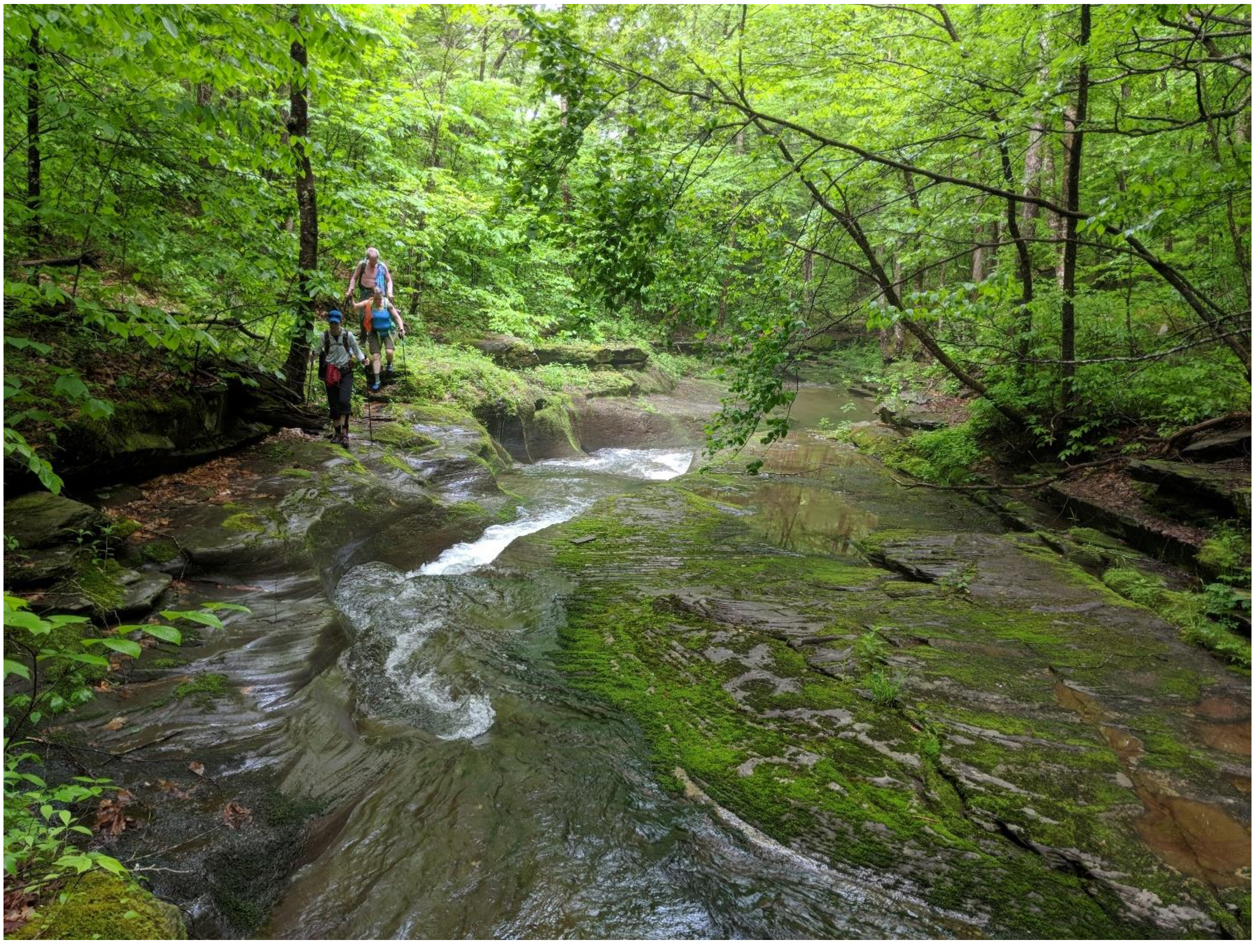
Downstream view of A4f.

Downstream view of A4g.

Downstream views of left (top) and right (bottom) branches of A4h.

Downstream view of B4.

Downstream view of A5.



Downstream view of B5.