GEOMORPHIC VARIABILITY OF THE UPPER WATAUGA RIVER: PROVIDING A REFERENCE FOR IMPACT ASSESSMENT OF THE WARD MILL DAM REMOVAL

A Thesis
by
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Abstract

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This study aims to provide pre-removal reference data on the geomorphology of the Watauga River prior to the removal of Ward's Mill Dam. Field data was collected from May 2020 to May 2021 and analyzed to ascertain the variability of bed grain materials and channel geometry. Data were collected at six sites, with at least three cross-sections measured at each site, and 47 collected during the year of study. These collections spanned across a range of flowrates, representing a variety of possible events which could modify the channel. Dendrochronological analysis of American Sycamore (PLOC, *Platanus occidentalis*) and Butternut (JGCI, *Juglans cineria*) was conducted to explore the potential for elongating geomorphic records through ecological response to landform and hydrologic change. Changes in stand composition may indicate ongoing shifts in flooding. Variability of both channel geometry and bed material was minimal within sites, suggesting a quasi-stable geomorphic regime to the contemporary erosion and sediment inputs. Ranges of variability differed between sites, which is expected given each site represented

slightly different geomorphic settings. Given these findings, we believe that changes observed in these measurements after removal can be reasonably interpreted as causal to the dam removal.

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I would also like to thank the Ward family for their support of this project and allowance of the use of their land for data collection, as well as Andy, the Watauga Riverkeeper. I would also like to thank Dr. Song Shu for his help in acquiring the imagery used in some of the site-specific figures. Last but certainly not least, I would like to thank Josh Platt, Caty Parham, and Tatiana Magee for their help in data collection on this project and the many days spent wading in the cold waters of the Watauga River.

Dedication

I would like to dedicate this thesis to my friends and family. Particularly Brenda and Dan for being loving parents, Mary and Carol, and also to the memories of Jim and Harold.

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Foreword

This thesis was prepared in a non-traditional format and is intended for publication in The Southeastern Geographer. This is a regional journal distributed by the University of North Carolina Press. Formatting is in the Annals of the American Association of Geographers style. It is intended to be submitted in April – May of 2022 for review and publication.

Introduction

While dam removals are increasing in the United States, relatively few have been studied for their impacts on the environment. One of the dams removed in 2021 was the Ward's Mill Dam on the Watauga River near Sugar Grove, North Carolina. Dam removals still tend to be both politically and socially controversial. However, the rate of removal in the United States is increasing over time, with 69 dams being removed across the country in 2020 (American Rivers 2021). Ongoing dialogue largely centers around the use of dams as generators for hydroelectric power in the ongoing push to transition to mitigate carbon emissions. Proponents of removal cite the numerous impacts that dams have on natural systems such as altering erosion, deposition, temperature, nutrient balance, biology, and both form and velocity of rivers (Poff and Hart 2002). Often, however, local residents are reluctant to support removal efforts for a number of factors regarding personal memory, nostalgia, and perceived or actual benefit (Fox, Magilligan, and Sneddon 2016; Diessner et al. 2020). Dam removal has also garnered bipartisan political support in areas within the United States (American Rivers 2021). These political pressures for removal may additionally conflict with a personal or local opinion which can lead to differing levels of support for these projects. Ward's Mill Dam is no different, as during the extent of this project both we and other researchers were approached multiple times with concerns.

While much is known about the impacts imparted by dam construction and operation, removals have been seldom studied relative to the number conducted and typically have limited pre-removal observations (Bellmore et al. 2017). This is of concern due to the large number of dams present in the United States, with estimates ranging in excess of 2 million structures (Graf 1993). This differs from the numbers mentioned by the United States Army

Corps of Engineers (USACE) National Inventory of Dams (92,075) as the USACE only count those dams which fall under their jurisdiction and monitoring (USACE 2020). The few removals that have been studied, however, indicate that post-removal ecosystem recovery trajectories vary widely. This variability supports the need for further study to understand how dams interact with rivers over time and during their eventual removal (Grant 2001; Foley et al. 2017), and highlights the need for detailed pre-removal observations.. Similar to the national trend, 32 dams have been removed in North Carolina as of 2017, however only 9 of these removals involved detailed study (Bellmore et al. 2017). Of the studies conducted, pre-removal observations are quite limited, even though they suggest that pre-existing conditions are the primary driver of recovery trajectories (Foley et al. 2017).

The objectives of this study were to assess one year of geomorphic variability of the Watauga River prior to the removal of Ward's Mill Dam in order to provide an adequate reference of pre-existing geomorphic conditions, and to assess our pre-removal data collection initiative relative to other dam removal studies. Between 3 and 4 repeat observations were conducted of stream channel geometry, slope, riverbed grain size distribution, and ecological disturbance. These metrics will allow us to quantify the pre-existing system variability, which will be critically necessary for understanding post-removal system recovery. Additionally, I investigate the application of tree-ring analysis as a viable method for extending our record of geomorphic change. While I don't expect annual geomorphic variability to be high, I expect that conducting multiple (more than two) repeat surveys will provide the survey resolution necessary to accurately characterize the pre-removal channel regime.

Study Area

Ward's Mill Dam is located in the headwaters region of the Watauga River with a watershed area of 239.33 km^2 (Figure 1) feeding into the 6.1 meter tall structure which has operated in a run-of-river mode since its initial construction in 1890 (Staff Report 2021, Figure 2). These characteristics would establish the region of the Watauga River watershed above the dam as a small river according to Sheldon, Barnett, and Anderson (2015). The Watauga River is part of the Mississippi River watershed and drains into it via the Tennessee River. Monitoring sites were selected in areas of geomorphic interest, such as immediately downstream of the dam (Figure 3).Flowrate statistics are provided by a USGS river gauge located at the upper boundary of the Ward's Mill Dam impoundment (gauge 03479000) with a mean annual discharge of 9.14634 $m^3 s^{-1}$ based on 81 water years of record (USGS 2020, Figure 4).

The dam was reconstructed during 1963-1964 from its original timber crib construction to the concrete-rock conglomerate form it retained until removal in the summer of 2021 (Wigginton 1980). The dam is intertwined with the local cultural geography as it brought electricity to the area prior to expansion of the Watauga County grid and the impoundment provided an area where locals frequently fished. Due to this, dams impacts on local cultural geography should be accounted for through evaluations similar to Section 106 of the National Historic Preservation Act (General Services Administration 2022). Ward's Mill Dam's removal was postponed from June of 2020 to June of 2021 in part due to review for compliance with the Act (Bartos 2020). This allowed for both State and Federal authorities to determine the most appropriate way to proceed regarding both environmental, cultural, and historical impacts.

This research took place at 6 sites along the Watauga River. Sites were chosen based on a combination of factors including their location relative to the dam, as well as ease of access. Control locations (US1, US2) were selected upstream of the dam impoundment, with one immediately above the reservoir, 1 river km above the dam, and the furthest upstream being located approximately 5.6 river km above the dam to assure that it would be outside of any potential backwatering effects. Four sites were located downstream of the dam with the first (DS1) located immediately downstream of the dam, the second (DS2) approximately 1 river km downstream of the dam, and the third and fourth (DS3, DS4) located approximately 1.5 river km downstream (Figure 1).

Methods

Overview

Both channel geometry and bed material composition were measured using a suite of field methods over the course of the study. Geomorphic assessment was based on measurements common to fluvial geomorphology described by Rosgen and Silvey (1996). These general methods were then modified to follow those used in other projects regarding geomorphic impacts of dam removal such as the removal of the Merrimack Dam on the Souhegan River, New Hampshire and Brownsville Dam on the Calapooia River, Oregon (Kibler, Tullos, and Kondolf 2011; Pearson, Snyder, and Collins 2011). These included cross-sectional and longitudinal profile surveys as well as Wolman Pebble counts (1954).

Then, in order to explore new techniques for gauging ecological response to geomorphic change, I conducted a study of tree growth of *Platinus occidentalis* (PLOC, American Sycamore), and *Juglans cineria* (JGCI, Butternut) present on a mid-channel bar immediately downstream of the dam. While the use of tree ages has been used in similar projects (Walter and Merritts 2008), the methods used were primarily visual estimation of age inferred by diameter at breast height (DBH). This can be problematic as DBH must first be established as a good estimator of age through dendrochronological methods. Due to limitations of PLOC and JGCI, chronological reconstruction of geomorphic change was not possible at this location. However, the determination of individual tree establishment with a high degree of confidence was possible with multiple individuals above a level of critical significance. This is important for further studies as it suggests that while caution must be exercised in collection, processing, and analysis, ring diffuse tree species as well as more ideal ring porous species provide important historical data to be considered in dam removal assessments even though few studies consider this data at present (Leopold, Wolman, and Miller 1964).

All fieldwork was conducted between 5/15/2020 and 5/11/2021. A total of 47 cross-sections were surveyed along with 8 longitudinal profiles. In addition to surveys of the channel geometry, 8 pebble counts were conducted at each cross-section with 20 pebbles collected in each of these cross sections. In total, 2,520 pebbles were collected across all sites Tree ring cores were collected from 22 trees which were located on a mid-channel bar which was in the DS1 site. Included below are the specific data collection and data analysis procedures for each component.

Pebble Counts

Pebble count surveys were conducted following a modified Wolman (1954) method at each cross-section in four approximately equidistant parallel transects of the river (Figure 3). Each transect contained 20 samples roughly equally spaced apart where possible. If cross-sections were too narrow to facilitate the full sample depth without concern of samples being too close together, as close to 20 as possible were collected. Each pebble was either passed through an aluminum diameter template or measured on the intermediate axis. Sediment passing the smallest (2mm) hole was assessed either visually or by feel as either sand or fines with a size value of 0.2mm for sands and 0.032mm for fines. Immobile boulders and those greater than 4m at minor axis were noted as 4000mm. Size class values were then adjusted by $\log_2$ following Krumbein's (1934) methods for large sediment. Sorting was calculated using ψ values as input for each site and cross-section due to a strong positive skew (Equation 1, Folk and Ward 1957).

$$\Psi = \log_2 D$$

$$Sorting = \frac{\Psi_{16} + \Psi_{84}}{4} + \frac{\Psi_{95} - \Psi_5}{6.6}$$

Equation 1

Statistical analysis was conducted using Wilcoxon Rank Sum two-sided tests between each reach upstream (UP), downstream (DN), pre bridge (PRE), and post bridge (POST). A Kruskal-Wallis test was performed on the size class by reach and a Dunn test with Bonferroni correction was applied to reduce pairwise errors. Wilcoxon and K-W tests were completed using the R base statistical package (R Core Team 2020), with K-W Multiple Comparisons conducted using the pgirmess (Giraudoux 2018) package, and Dunn Tests with the dunn.test package (Dinno 2017). These tests have been used in previous studies for the purpose of gauging variability in sediment size classes across reaches (Skalak, Pizzuto, and Hart 2009). Quantiles were calculated for the 5% (D05), 16% (D16), 50% (D50), 84% (D84), and 95% (D95) levels of population to assess spatial variation.

Topographic Channel Surveys

Cross Sectional Geometry

Cross-sectional surveys were conducted to discern channel profile variability as well as to establish a baseline of geomorphic variability over one year prior to removal. Measurements were conducted at six sites, with one (DS4) being added several months after surveying began in order to account for potential backwatering impacts from the Hubert Thomas Road low-water bridge (Hence PRE and POST in the statistical analysis above). At each site, at least three cross-sections were collected except for DS1, where four were collected (Figure 3). We chose to select diagnostic sites as opposed to surveying at regular intervals (Pearson et al. 2011) due to the greater length of the study reach. Sites were selected in areas with features of geomorphic interest, such as DS1, which was chosen to cross a channel bar immediately downstream of the dam. Surveys were conducted with an automatic level, 100-meter tape, and a surveyor's rod graduated in centimeter and meter increments. All measurements were taken in SI units and to a precision of 0.01 meters. Each elevation station measurement was taken at an interval no greater than 2 meters in spacing. Measurements were recorded in a field notebook and digitized into Microsoft Excel for analysis and graphing. Station height measurements were then inverted and backsighted to the absolute reference of the stakes. This process converts the reference station of the stake as the coordinate (0,0), with prior or subsequent stations being converted to be relative so that all repeated surveys share the same origin. These methods allow for relatively simple and low-cost instrumentation to be used.

Longitudinal Profiles

Scouring, deposition, and channel slope can be determined from longitudinal profiles. These are critical through the period of sediment release from dam removals as pre-removal measurements provide a 1-year geomorphic baseline. The longitudinal profile is expected to be affected as the sediment slug released during dam removal migrates downstream post-removal, particularly the in-filling of residual pools along with channel slope, residual pool depths were extracted from the longitudinal profiles, and where repeat profiles were collected, the variability of residual pool depths was also determined.

Dendrochronological Analysis

Dendrochronological data was collected at channel bar features immediately downstream of the dam in the fall of 2021. Sampling all trees of with a diameter greater than 10 cm was conducted on a mid-channel bar located at DS1. Increment cores were taken with an 5.15 mm bore from American Sycamore (*Platanus occidentalis,* PLOC) and Butternut

(*Juglans cineria*, JGCI). Trees were cored below 30cm height perpendicular to any lean, all of which were perpendicular to the flow of the river and leaning downstream. This inclination suggested that trees were exposed to external stresses resulting in changes to their inclination, the most likely of which would be high flows corresponding to inundation levels higher than the bankfull gage height which was inferred to be the top of the bar. Second cores were taken if significant visible debris scars were present to provide dates of injuries. Diameter at breast height (DBH) was recorded along with species and additional notes. Samples were processed according to methods of Stokes and Smiley (1996) by drying, mounting, and sanding with progressively finer sandpaper grits from 80 – 600 and selectively sanded to 1000 grit if needed for clarity in visible identification. After sanding, samples were manually counted, marked and noted as either wide or narrow rings to produce a visual cross-dating estimation (Yamaguchi 1991). Samples were then scanned on an Epson 12000XL at 1200 dpi resolution, measured in Cybis Coorecorder (2020), and converted to Tucson measurement format in CDendro (Cybis 2020a). Measurement files were then read into R using the dplR package (Bunn 2008) for statistical analysis of disturbance patterns using the Nowacki and Abrams (1997) Radial Growth Averaging method in the R package TRADER (Altman et al. 2014). Choice of these methods for growth disturbance analysis were based on prior work done by Kaiser (2019). The length of disturbance was selected to be three years, a two to three year recurrence interval is that which is expected to most closely correspond to a water elevation which would fill to bankfull levels, with the top of the bar corresponding to this same elevation (Wolman and Miller 1960).

Results

Surveys

Cross-Sectional Geometry

As expected, The cross-sectional area was minimally variable in all of the sites with repeat surveys. The surveys represent the middle cross-sections of each site which had the greatest number (min. 3) of repeat surveys (Figure 3, 5). The channel at most cross-sections was dominantly large cobble to boulder-sized rock. The Watauga River is largely transport limited for many of the larger-sized clasts which typified the study reaches. A notable exception was DS3, which had significantly smaller sediments across all quartiles than other reaches, but also displayed minimal variability. During the time in which the study took place, there were six events with discharges of greater than 28.31 $m^3 s^{-1}$ (1000 $ft^3 s^{-1}$), or approximately three times average flow (USGS 2020), this amount closely corresponds to the average surveyed bankfull area, which was 33.30499 m^2. There were also two flooding events which were around 169.9011 $m^3 s^{-1}$ (6000 $ft^3 s^{-1}$), which is 20 times greater than average and more than five times greater than that expected at bankfull flow. The presence of these high flow events coupled with minimal change in the cross-sectional profiles, even after these events, supports that the reaches measured were in a semi-stable regime (no indication of aggradation or degradation) during the course of the study.

Bed and Water Slope

The slope of both the bed and water surface varied across sites as well as between repeated surveys. This is likely due to higher variability in flow conditions due to environmental variables such as runoff in the high gradient environment of the Appalachian region and due to the proximity to the headwaters of the Watauga. Bed slope varied from -1.65 – 1.34% slope, and water surface slope varied from -1.03 – -0.03% slope. Average slope of the bed profiles was a 0.1325% slope and the water surface averaged a -0.37875% slope. The average slope of the water surface falls within the definition of a Moderate-Low Gradient (Sheldon, Barnett, and Anderson 2015). The bed gradient was positive, which falls outside of the range of classification schema due to surveying a mixture of pools and riffles. Depending on where the profile started and ended, this can result in a slope that rises as the distance downstream increases. DS3 had the most positive slope and DS4 had the most negative slope. The smaller sediment sizes found at DS3 suggest that the presence of the Hubert Thomas low-water bridge is impacting deposition, resulting in the formation of a sediment wedge immediately upstream of its location, which covers DS3.

Residual Pool Depths

Residual pool depth was delineated for each longitudinal profile where possible. Only DS4 was not possible due to positive bed slope caused by a sediment wedge present upstream of the Hubert Thomas Bridge. The largest pool was the plunge pool formation from cascading water impacting the bed, with a depth of 2.44 meters (Figure 6). Upstream pools (0.25 – 1.06 m) were generally deeper than those downstream of the dam (0.13 – 0.5 m) other than the plunge pool.

Pebble Counts

As the channel profile varied minimally within each site, pebble counts similarly had minimal variability within each site. Kruskal-Wallis tests showed significant differences between the upstream and pre-bridge downstream sites, with no significant difference between upstream and post-bridge downstream sites (Table 1). Changes in pebble size characteristics were best observed in the D16 quartile (Table 3) which can be observed both across the entire US to DS reaches, but also from US1 and US2 to DS1 – DS3. Size of D16 class returned to US levels at DS4 though D84 sizes were smaller.

Sorting was extremely poor throughout all sites, which is typical of areas close to the sediment source, though some appeared to be immobile and were covered in vegetation. Visual assessments of pebbles were that most shapes were irregular and jagged with minimal weathering, which further suggests that many grains >D16 are either not experiencing weathering or are carried downstream in flows that would cause such morphological changes. Large quantities of colluvial boulders were present throughout all sites other than DS3. These are unlikely to be mobilized even during the highest flood stages and flowrates, and many are covered in thick layers of aquatic vegetation, further suggesting that they have been immobile for long enough periods for this vegetative mat to have established. Qualitative signs of mobility such as vegetation establishment provide important context and evidence to support hypotheses of bed stability in the Watauga River.

Tree Ring Analysis

The use of tree-ring records provided a linkage to these qualitative observations to the more quantitative measurements of stream variability. Preliminary crossdating of the nine cores in COFECHA had an interseries correlation of 0.369, mean sensitivity of 0.349, and critical value of 0.4226. Establishment dates were graphed in relation to decade, and DBH was graphed in comparison to both age and species (Figure 7, 8). Establishment year was also graphed in comparison to peak flood stage per year (Figure 9). The ring-width measurements (mm) of the cores were used in the Radial Growth Averaging (RGA) analysis for samples with the highest interseries correlation (Figure 10). Moderate release events were observed in 1985 and 1999. Minor release events were found between 1960 and 2018.

An additional RGA analysis was run on all (22) non-scar samples to compare to the results of the highest autocorrelated trees (Figure 11).

Graphing of tree ages to diameter showed a positive association between age and diameter in PLOC, with no discernable pattern in JGCI (Figure 6). Datapoints were separated by species with the three JGCI trees established in 1971, 1995, and 2008. The establishment dates of each species were graphed in comparison to USGS peak streamflow data collected at USGS gauge 03479000 "Watauga River Near Sugar Grove, NC" located approximately 300 meters upstream of the dam and 400 meters upstream of the bar where tree-ring samples were collected (Figure 9). Visual inspection revealed that there may be a relationship between maximum stream depth per year and species establishment patterns. This is indicative that PLOC establishes during years when flooding may help reduce competition with other less flood-tolerant species, whereas years where floods do not cover the bar allow for JGCI to establish.

National Comparison

Methods used in this study were derived from a variety of other dam removal studies and chosen for the site-specific characteristics of the Watauga River. Choosing between multiple studies is more appropriate in this case due to the differences in many rivers and dams. A sample of 10 other studies of the impacts of dams and dam removals on river geomorphology was reviewed to compare methods. A higher frequency of sampling was chosen to capture sub-annual variability, which a sample of national studies that possess pre-removal measurements may lack (Table 1). This higher temporal resolution of our study allows for better quantification of channel form response to a variety of individual discharge events. Pebble counts were conducted at greater sample depth than provided by most of the sample studies, allowing for a higher degree of significance to be held in statistical tests.

Discussion

Survey variability

Human factors may influence both pebble counts and cross-section surveys through several biases. In this study, water temperature, level, and velocity are of primary concern due to influencing human safety and dexterity, which are necessary for surveying. Other noted differences occurred due to differences in the level of detail included in cross-sectional surveys. As such, sediments equal to or greater than a size class associated with immobility during bankfull discharge would most appropriately be considered part of the stable channel profile at the time of the survey.

While other studies have collected pre-removal data, in this study, four repeat surveys were collected within the year prior to removal, which we believe provides adequate pre-removal context for post-removal comparison. During this pre-removal monitoring period a multitude of discharge events occurred between each survey. Given this multitude of flow events and the extremely minimal variability in channel cross section geometry and bed sediment conditions, we are comfortable in assuming that the channel represents a condition that is relatively equilibrated to the presence of the dam and current sediment inputs. Therefore, when post-removal monitoring occurs, any changes that occur outside of the range of variability documented in this study may reasonably be assumed to be the result of the dam removal and the resultant changes to the sediment load.

Additionally, a reasonable knowledge of the pre-removal sediment/geomorphic regime should dictate the temporal resolution of pre-removal monitoring surveys. While the variability of the channel profile was relatively low in this study, this may not be the case in other rivers. River channels with a higher degree of geomorphic change may require a higher frequency of surveying data to capture change on different temporal scales.

Minimum spacing of station measurements also appears to be of importance to measurement of geometric variability which was found in this study. In the first cross-section measurement at several sites, the spacing was greater than subsequent measures, and these larger measurements led to differences caused by either including or excluding boulders in the channel profile (Figure 4). In several cross-sections, repeat measures had significant differences in volume; however, it is not possible to tell if the changes in profile geometry were due to survey errors or geomorphic change. Given that there were few areas where such errors were observed with the majority of repeat measures showing minimal variability, it is likely that these errors are caused by survey operators. Future studies should closely consider how methodological variability and level of detail may impact the results of analyses. Using stratified station spacing may help avoid these issues in future studies.

Pebble Counts

While no significant difference in median particle size variability was found between the upstream and post-bridge downstream site, the box and density graphs (Figure 12, 13) show that the amplitude of the pebble population is decreased as the distance downstream increases. There were significant differences between the upstream and pre-bridge sites caused by the Hubert Thomas bridge. A high level of sorting of fine sediments immediately upstream of the bridge suggests it enacts a sieve-like action on finer particles in a backwatering effect. This filtering effect is the likely cause of the return to D16 values similar to those found in upstream sites.

Tree rings

Dendrochronological methods have not been used to analyze the effects of dam removal. While studies of tree rings recovered from timber cribs have been conducted (van de Gevel et al. 2009), they were conducted for purposes other than gauging geomorphic change of the river channel. This study shows the possibility to integrate tree-ring measurements and analysis into future dam removal studies to extend the pre-removal record, or even reconstruct records prior to either the observational record, or dam installation. However, the ability to reconstruct these records may be limited by tree species and tree age.

Tree establishment dates and tree inventory recording complimented the geomorphology methods. In this study, the presence of JGCI on a mid-channel bar is significant because this species is flood intolerant and has high drought tolerance (Crystal and Jacobs 2014; Brennan et al. 2020). Conversely, PLOC is a drought intolerant but highly flood-tolerant species and may survive extended periods of flooding of weeks to months in length (Nesom and USDA NRCS 2003; Jerin 2020). Though not sampled, two *Salix spp.* were observed on the downstream bank of the channel bar. Further observation of species decline may be a useful indicator of a receding baseline water level (Scott et al. 1996). Additional JGCI trees were also observed but were smaller than the 10cm DBH cutoff. Future studies should consider using bars as forest plots and survey the composition of species at each river bar.

While PLOC has been subject to several dendrochronological studies and is used in geomorphic studies, the use of JGCI is not used in tree-ring studies and is therefore not available on the International Tree-Ring Data Bank (NCEI 2022). Our study suggests that JGCI may be of greater importance than the literature may suggest if present in riparian ecosystems due to the indication of a receding or lower water level compared to what may be suggested by geomorphic features. The limitation to using JCCI as a species is the difficulty in distinguishing annual tree-ring boundaries and wood anatomy.

The addition of tree-ring dating to geomorphic studies is of great importance to studies where the pre-disturbance collection may no longer be possible or is limited in time by a dam removal date. These baseline data collections are of utmost importance in all aspects of quantifying geomorphic change due to dam removal and are many times insufficient in length due to the brevity of the planning process for removal (Kibler, Tullos, and Kondolf 2011). These studies may also allow for researchers to extend observations of ecological disturbance and geomorphic change past the initial installation of dams which is a baseline that has eluded practically all previous studies. Furthermore, while many studies have suggested the use of dendrochronology in geomorphic studies and for tracking the impacts of both dam installation and removal, we found no studies that have applied dendrochronology to study the geomorphic change associated with dam removals. Tree-ring studies may purposefully avoid sampling in dam impacted reaches due to potential masking of climate signals due to the streamflow mediation that are produced. We want to expand on this emerging body of literature is critical to establishing the use of dendrochronology in geomorphic assessment of dam impacts on river systems.

Conclusion

The size and disposition of sediment in the studied reaches of the Watauga River appear to be largely immobile in periods of bankfull flooding. This is likely the reason for the minimal degradation or widening of the channel profile observed during the duration of this study. We believe that it is appropriate to assume that any post-removal changes in channel profile or sediment distribution will be a result of the removal and not fluctuations present in otherwise natural variability of either erosional or depositional process.

While the tree-ring dating and study of the channel bar immediately downstream of the dam is unable to establish a definitive date of bar establishment, it does allow us to confidently date the bar to at least 1956, indicating potential disturbance or hydro-geomorphic regime change at that time. Additionally, while PLOC, a more flood-tolerant species has declining establishment over time, JGCI continued to establish and persist to maturity since 1971. Using JGCI as indicator species of changes in flood elevation may be a critical tool for floodplain managers and offer linkage of stream power through the discharge-gage height relationships to ecological communities.

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Appendix

Figures

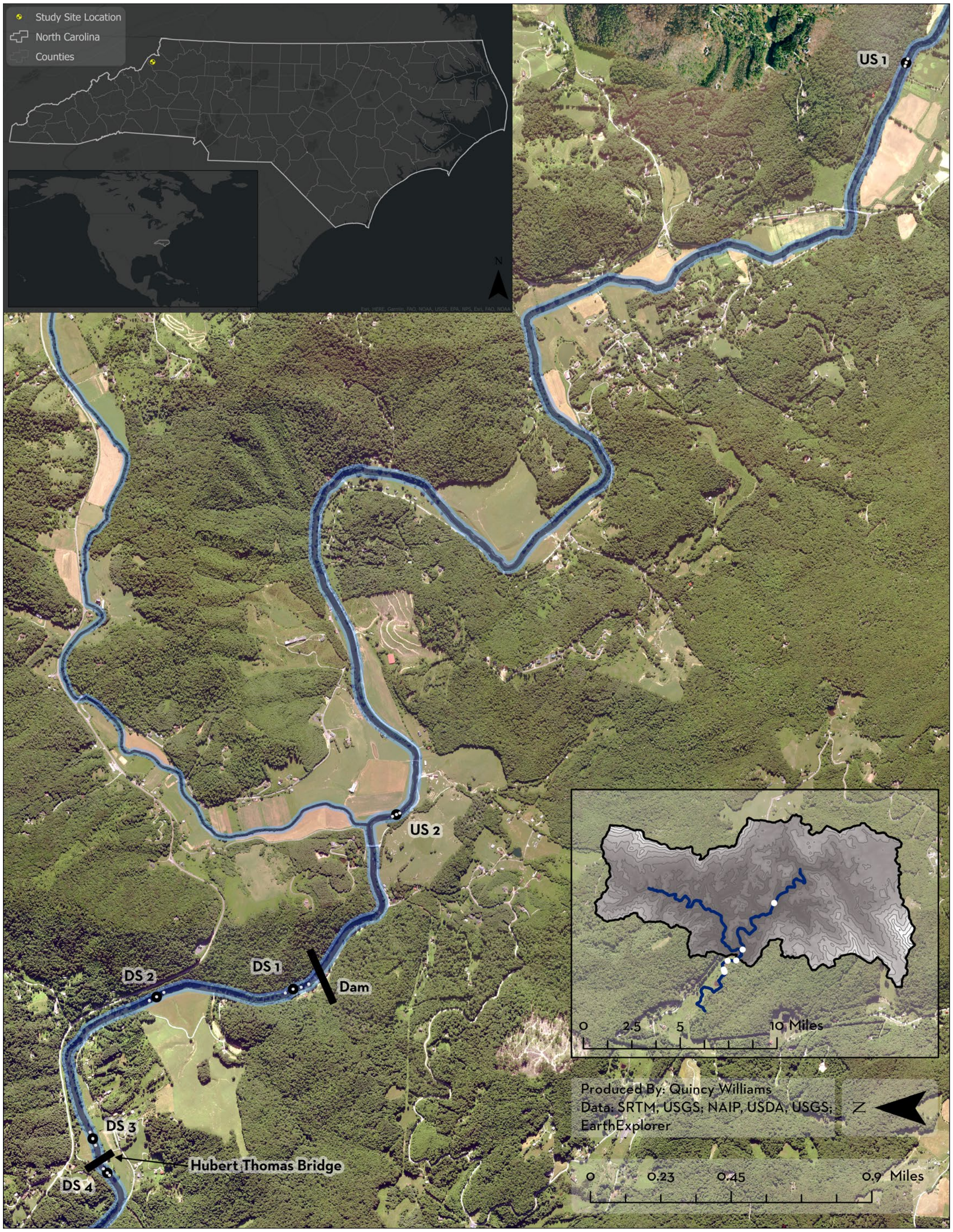
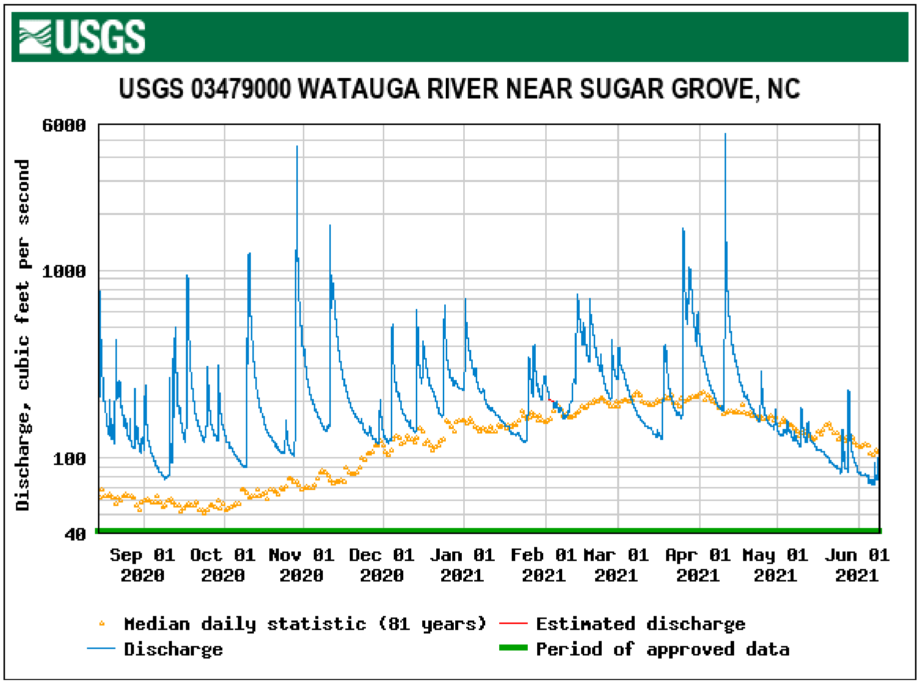


Figure 1: Site map of the study reach

Figure 2: Image of Ward's Mill Dam prior to removal. Taken from DS1 XS1 by Quincy Williams.

Figure 3: Sampling schema for pebble counts (a), cross-sections, and longitudinal profiles (b). Images provided by Dr. Song Shu.

A



B

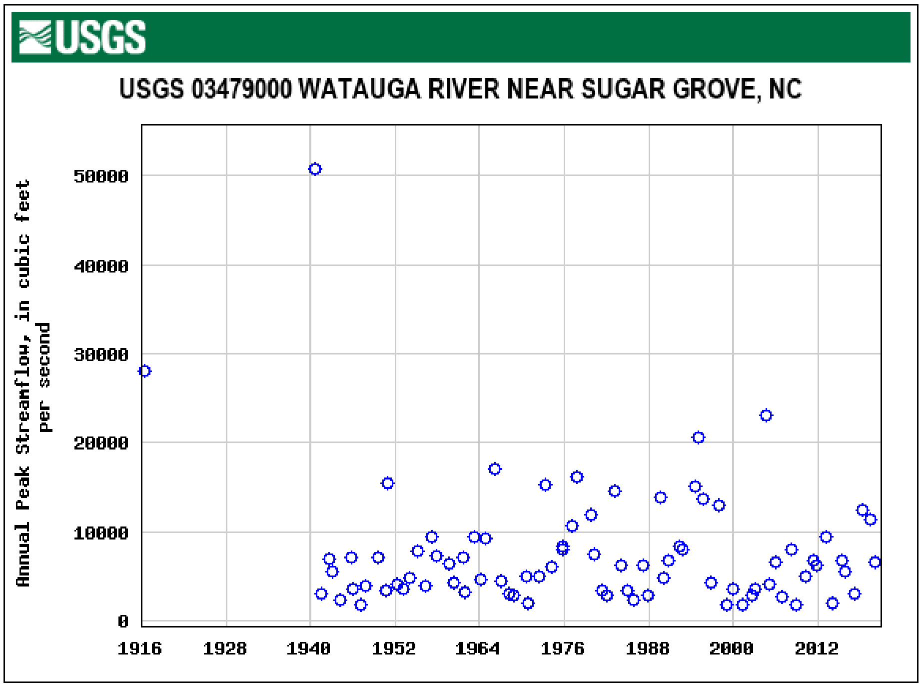


Figure 4: Discharge during study period (a) and peak streamflow per water year during the monitoring period (b).

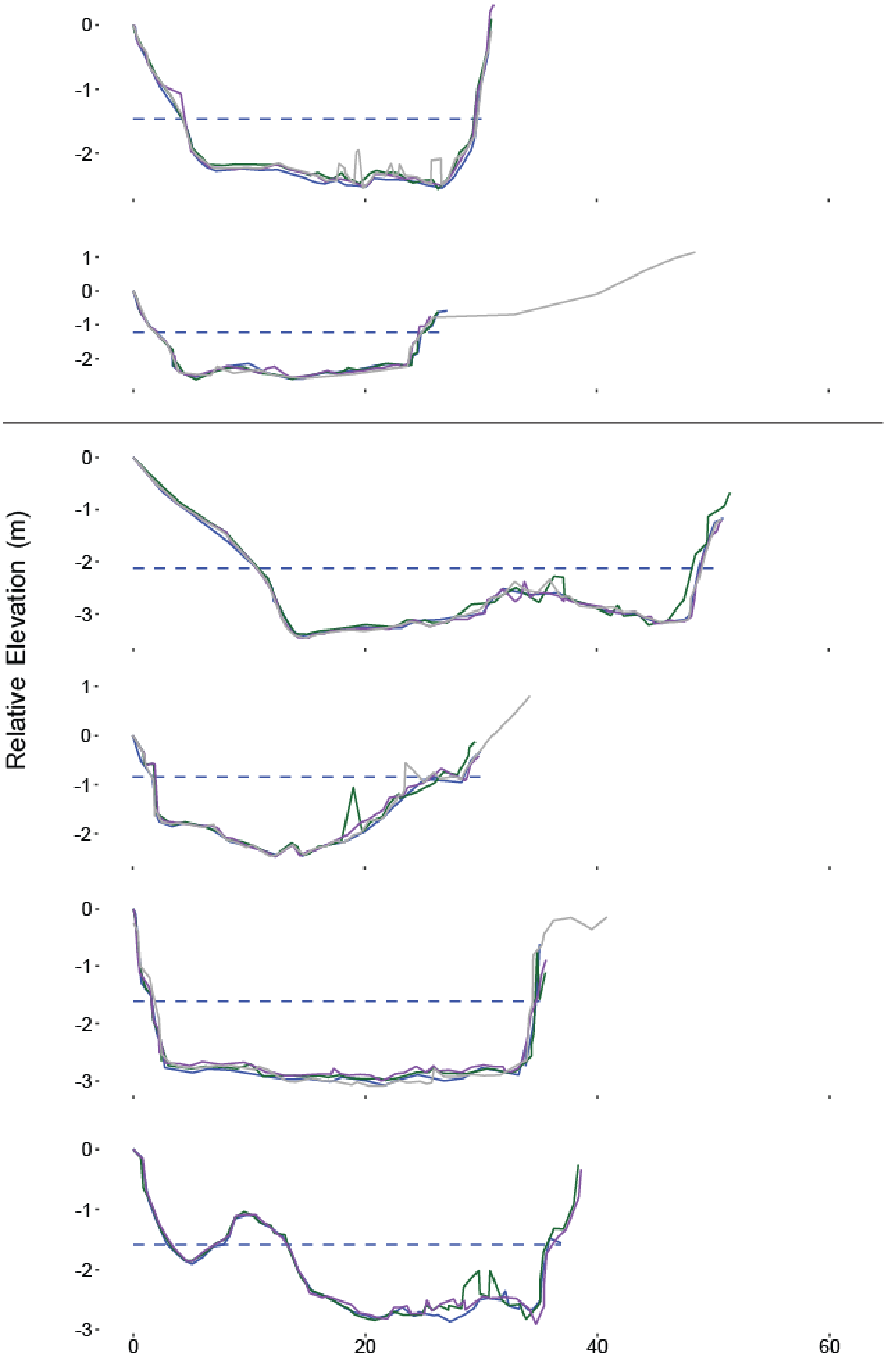


Figure 5: Cross-section geometry of study reaches. Depth and horizontal distance are relative to survey pin. Cross sections are in order from upstream (top) to downstream (bottom) with the black line representing the location of the dam.

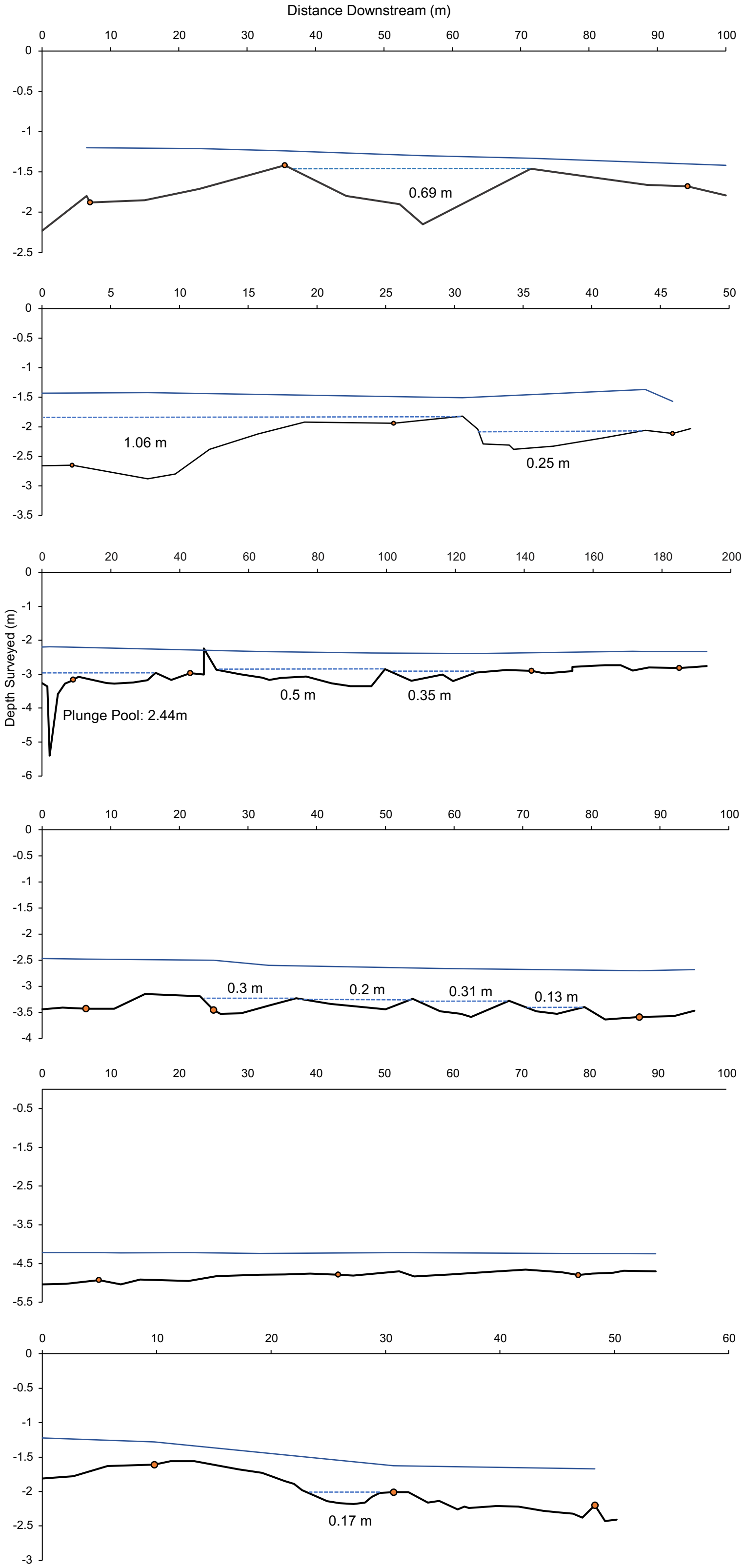


Figure 6: Longitudinal profile geometry of study reaches. Depths are relative to autolevel location and distances are relative to cross-section location (dots). Residual pool depths are noted and water surface depicted by solid blue line.

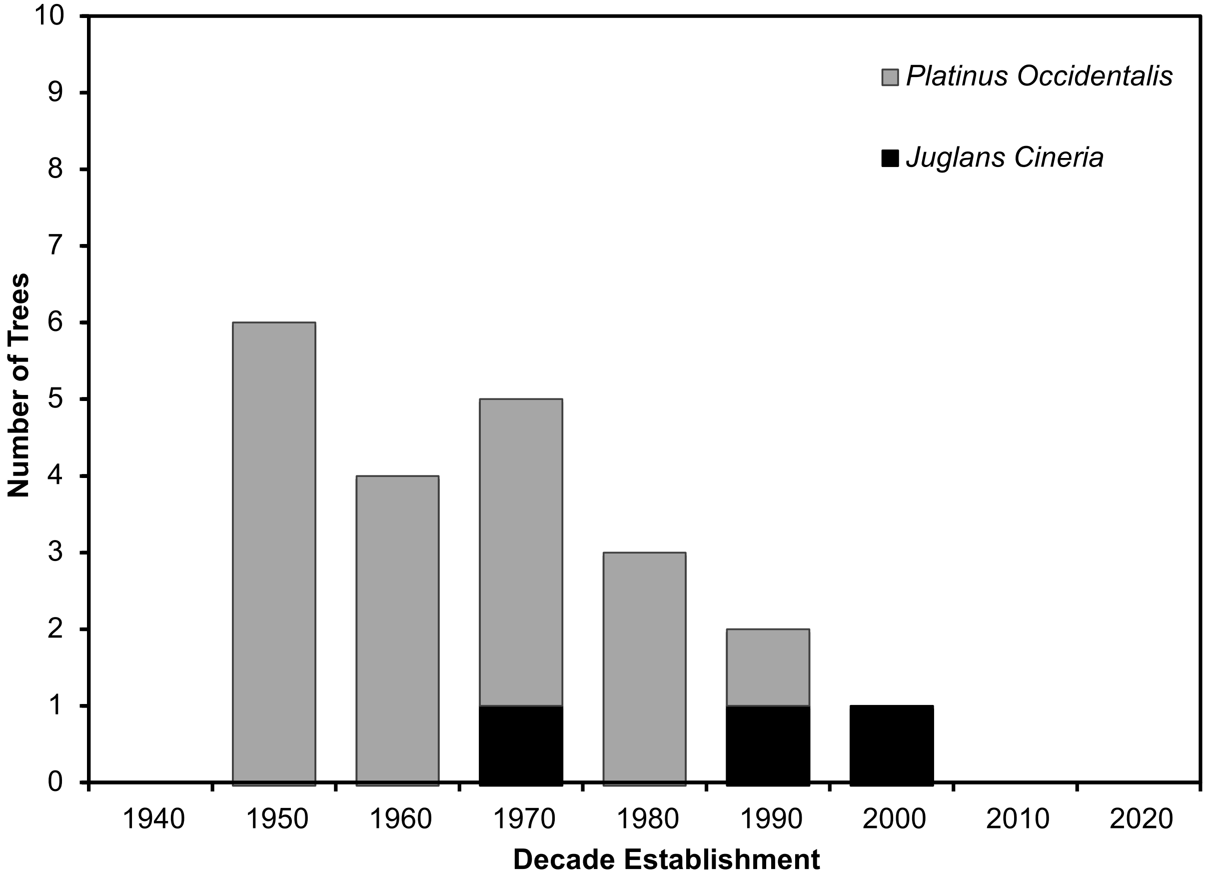


Figure 7: Decade of establishment for 21 sampled trees.

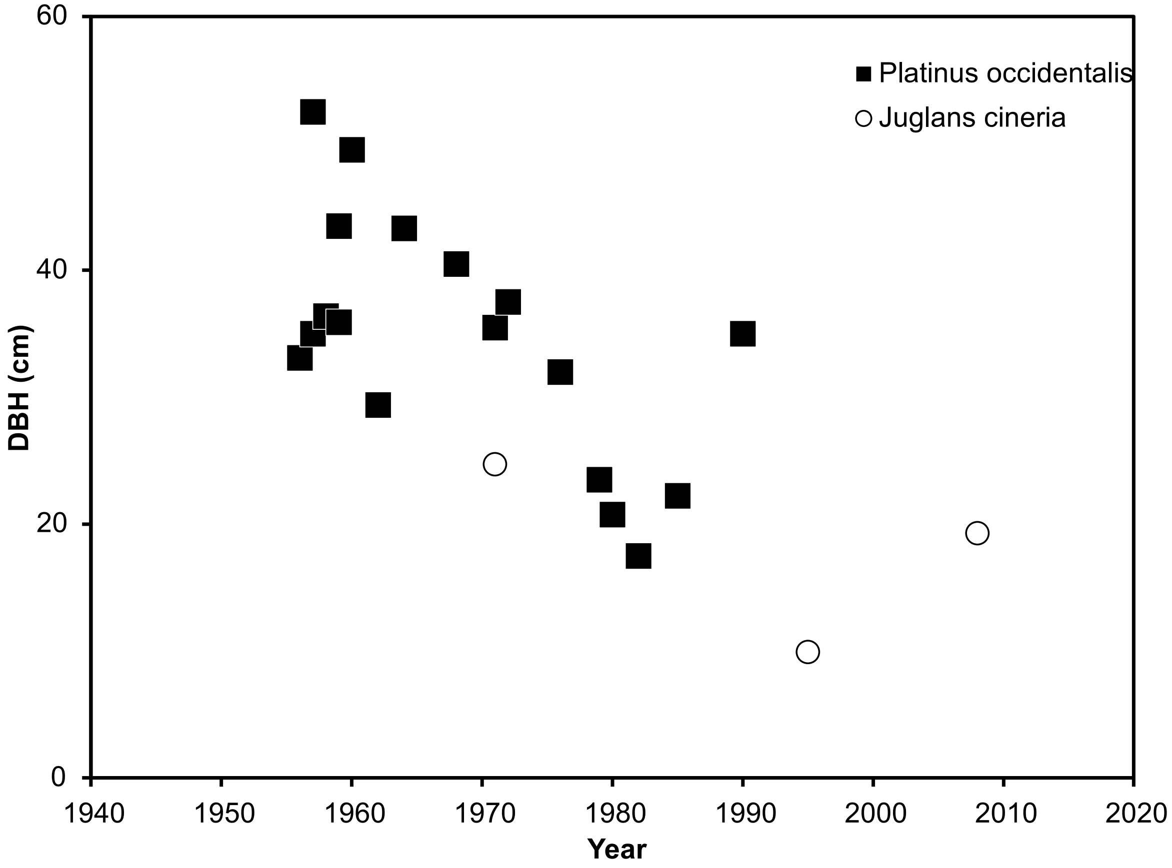


Figure 8: Age-diameter relationship for 3 JGCI and 18 PLOC samples.

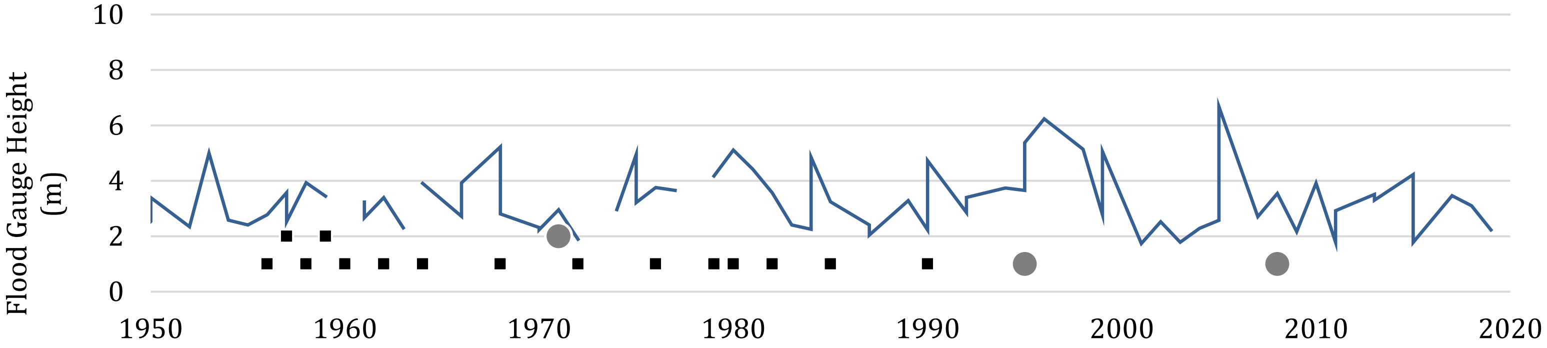


Figure 9: Relationship of annual peak streamflow to tree establishment year. Black squares represent PLOC, with grey circles representing JGCI. Blue line is measured peak flood height per water year at the USGS gauge at the top of the impoundment.

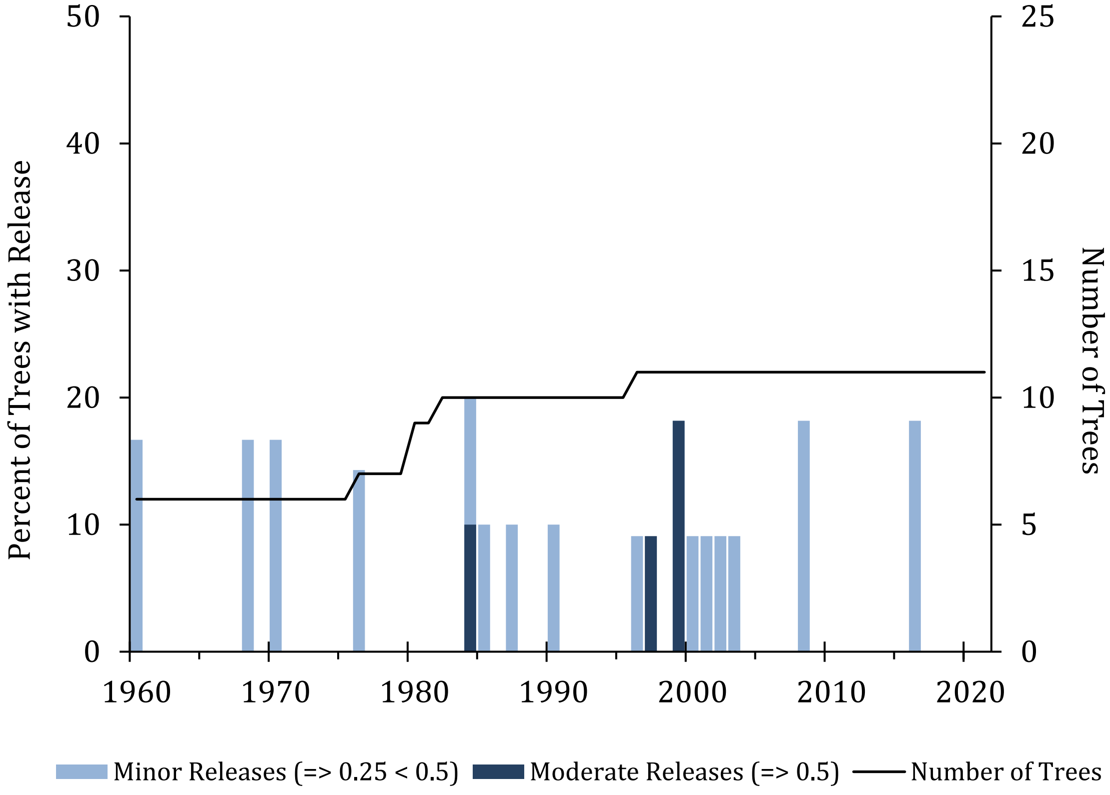


Figure 10: Radial growth averaging for most ideal samples.

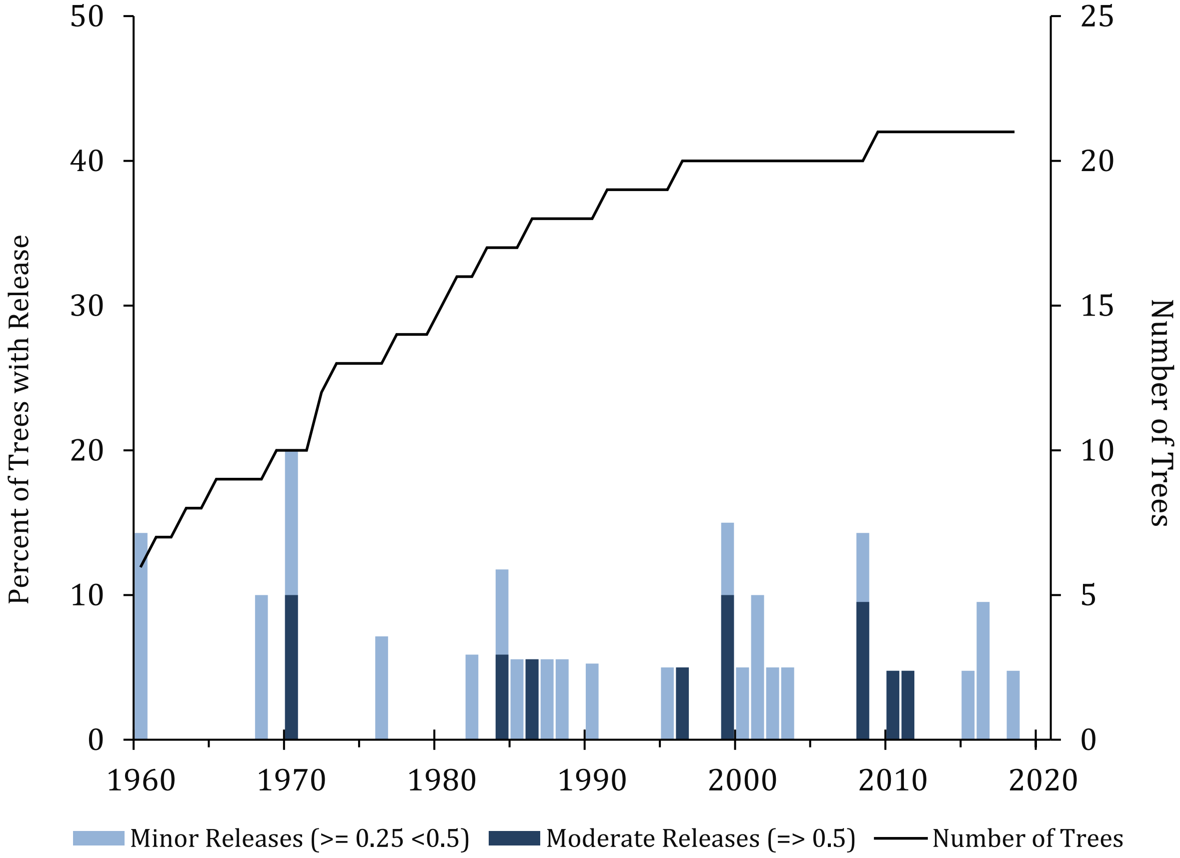


Figure 11: Radial growth averaging for all tree ring samples. There were no stand-wide release events, though individuals experienced minor to moderate disturbances throughout the record.

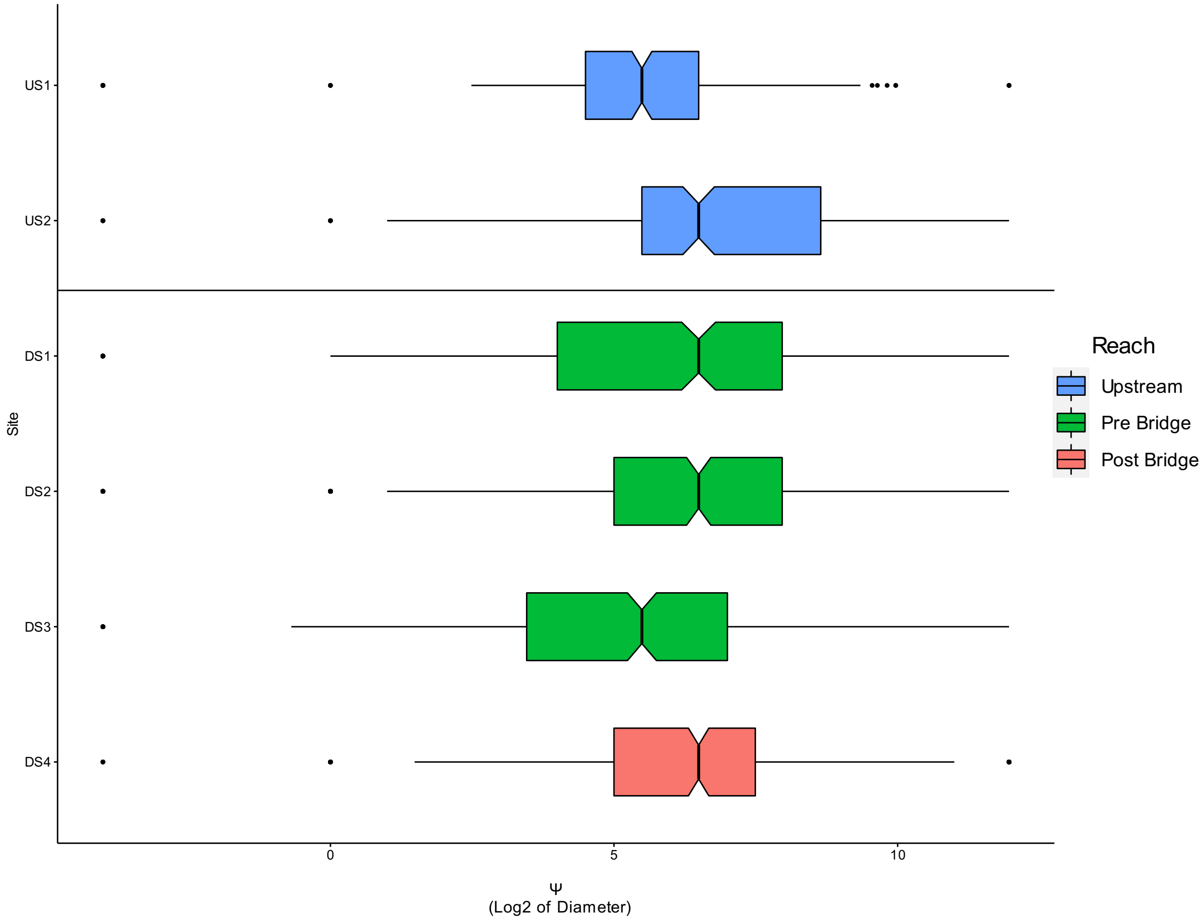


Figure 12: Pebble size distribution for each site. Upstream and downstream samples are divided by the horizontal black line.

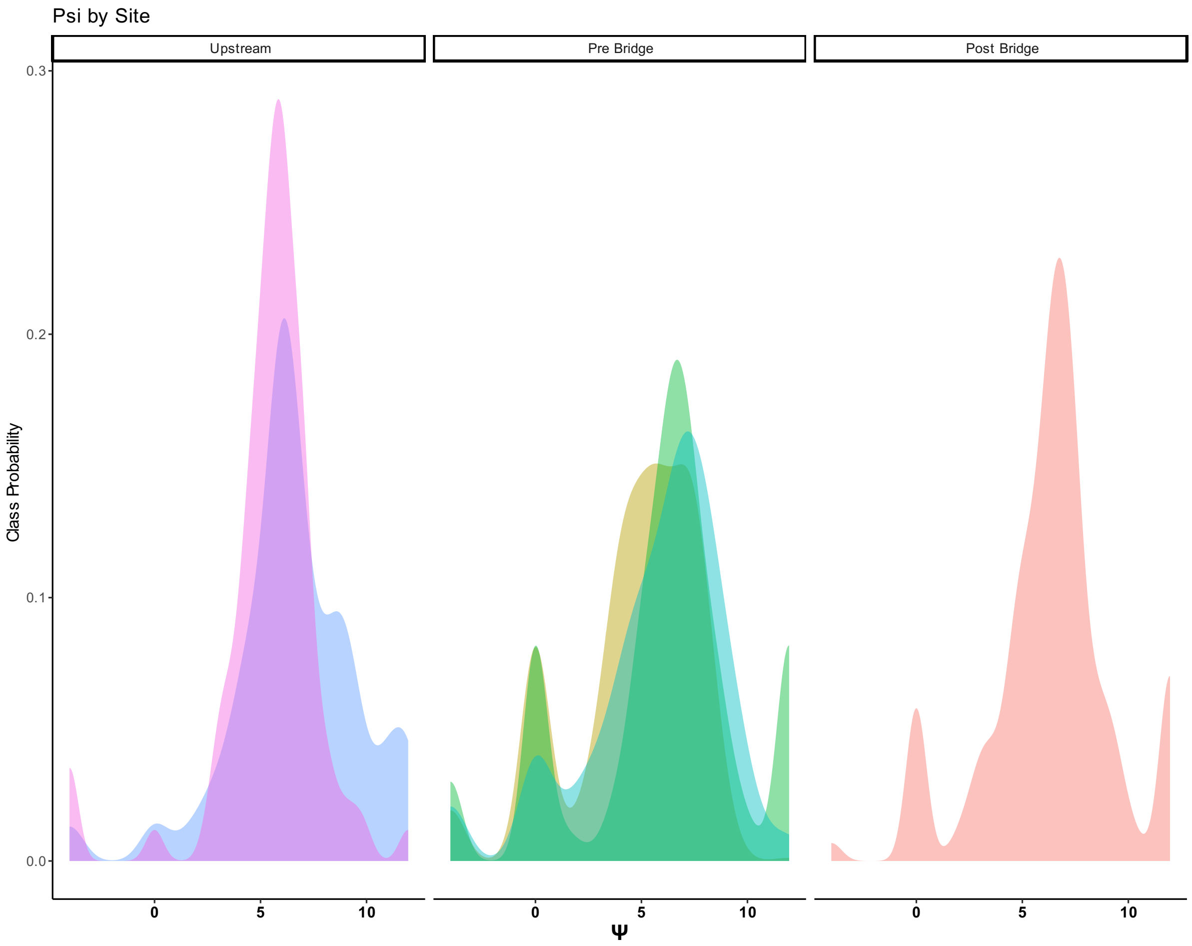


Figure 13: Pebble size-density plot normalized by Log2

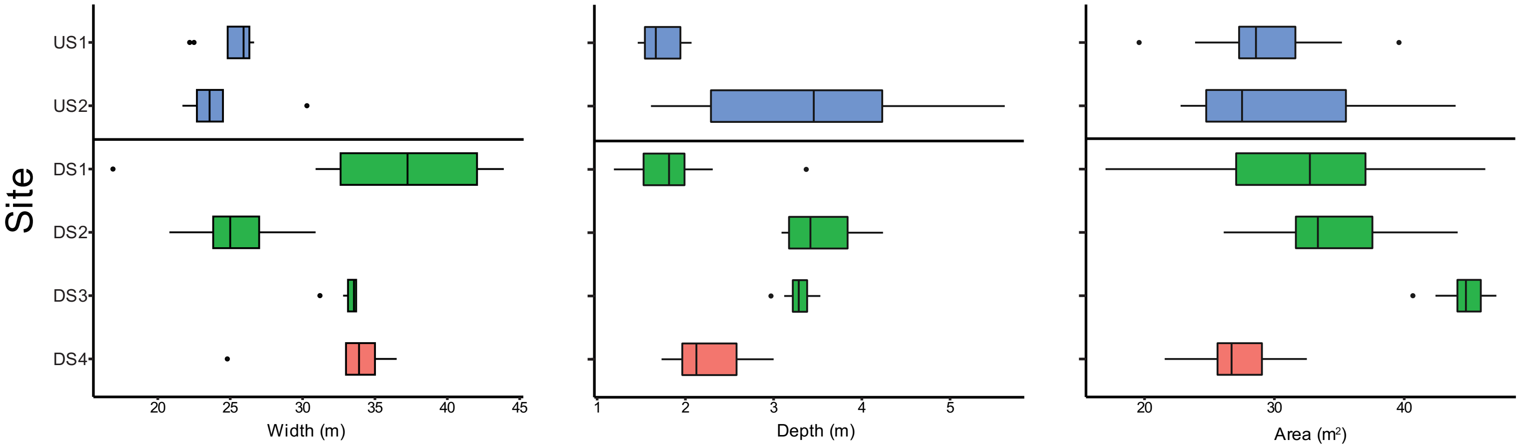


Figure 14: Distribution of channel geometry measurements of wetted width, thalweg depth relative to bankfull elevation relative to pin, and cross-sectional area.

Tables

Table 1: Sample of 10 studies of dam impacts on river geomporphology across the continental United States.

Studies	Location	Pre-Removal Baseline?	# of survey cross-sections	# of longitudinal profile surveys	Temporal Resolution	Bed Material Sampling
Burroughs et al. 2009	Pine River, MI	Yes	31 (10 added later)	N/A Done on river scale and not sites	2 pre-removal (1 per year)	Wolman 100 particle
Csiki 2014	4 sites across IL	Not a removal response study	Variable per site, 3 reference and at least 7 DS	1 per site	None, single surveys, dams not removed	Grab sampling supplemented with Wolman
East et al. 2015	Elwha River, WA	Yes	4 subreaches	2	1 pre-removal	Wolman 100 particle
Epstein 2009	Blackfoot River, MT	Yes	13	Derived from cross-sections	1 pre-removal	Wolman 100 particle
Kibler, Tullos, and Kondolf 2011	Calapooia River, OR	Yes	103	Yes, # not clear	1 pre-removal	Bulk Density Wolman
Magilligan et al. 2016	Amethyst Brook, MA	Yes	18	1 upstream 1 downstream	1 pre-removal	Interstitial Space
Pearson, Snyder, and Collins 2011	Souhegan River, NH	Yes	12 (1 monument lost due to flood)	1 across all sites	2 pre-removal (1 per year)	Bulk Density Wolman 100 particle
Rumschlag and Peck 2007	Middle Cuyahoga River, OH	Yes	7 (5 added post-removal)	Derived from cross-sections	1 pre-removal	Folk and Ward Sieving
Skalak, Pizzuto, and Hart 2009	15 sites in MD and PA	Not a removal response study	10 per site	1 per site Water surface slope	Not a removal response study	Wolman 200 particle
Tullos, Finn, and Walter 2014	Caloopia and Rogue River, OR	Yes	None pre-removal	1 per river	1 pre-removal (longitudinal)	Wolman 100 particle

Table 2: Channel geometry measurements of wetted area, thalweg depth, and water surface width at bankfull flow. Sites are divided by single lines, and upstream and downstream reaches by the double line.

Cross-Section	Repeat	Area (m^2)	Width (m)	Depth (m)
US1XS1	1	28.41329	26.3	2.07
US1XS1	2	28.6291	26.65	1.955
US1XS2	1	35.20025	25.65	1.53
US1XS2	2	28.5331	26.4	1.545
US1XS2	3	30.42294	25.6	1.94
US1XS2	4	39.59717	26.2	1.59
US1XS3	1	23.89215	22.2	1.74
US1XS3	2	19.58344	22.5	1.46
US2XS1	1	35.38361	22.7	4.03
US2XS1	2	43.95947	30.3	4.145
US2XS2	1	28.61207	24.3	1.61
US2XS2	2	22.77628	24.5	1.69
US2XS2	3	24.81874	21.7	2.49
US2XS2	4	35.88667	24.5	5.62
US2XS3	1	26.40788	22.7	2.88
US2XS3	2	24.54035	22.85	4.49
DS1XS1	1	16.99509	16.9	2.31
DS1XS2	1	27.04048	31.2	1.88
DS1XS2	2	32.692	30.9	1.71
DS1XS3	1	32.77419	37.3	1.75
DS1XS3	2	40.9193	36.9	1.19
DS1XS3	3	27.1045	37.7	1.465
DS1XS3	4	22.55339	37.2	1.205
DS1XS4	1	46.2445	43.5	2
DS1XS4	2	38.12918	43.5	1.96
DS1XS4	3	33.67543	43.9	3.37
DS2XS1	1	33.99017	24	4.18
DS2XS1	2	35.95697	25.3	4.24
DS2XS2	1	26.09805	23.3	3.415
DS2XS2	2	31.66604	26.4	3.725
DS2XS2	3	31.62209	24.7	3.42
DS2XS2	4	32.70815	20.8	3.13
DS2XS3	1	44.11607	28.8	3.09
DS2XS3	2	42.3222	30.9	3.19
DS3XS1	1	46.68853	33.7	3.53
DS3XS1	2	42.40688	33.6	3.12
DS3XS2	1	44.76565	33.25	3.25
DS3XS2	2	44.73789	33.5	3.35
DS3XS2	3	44.65734	33.7	3.47
DS3XS2	4	47.09548	32.8	3.25
DS3XS3	1	40.6651	31.2	2.97
DS3XS3	2	45.63478	33.7	3.32
DS4XS1	1	32.50111	36.5	2.125
DS4XS2	1	21.55225	33	2.58
DS4XS2	2	29.04064	33.9	1.73
DS4XS2	3	25.62027	35	1.965
DS4XS3	1	26.70449	24.8	3

Table 3: Water surface and bed slope profiles. Upstream and downstream sites are divided by the double line.

Site	**Repeat**	**Bed % Slope**	**Water % Slope**
US1	1	0.24	-0.24
US2	1	1.3	-0.13
DS1	1	0.33	-0.08
DS2	1	-0.07	-0.35
DS2	2	-0.77	-1.01
DS3	1	0.34	-0.03
DS3	2	1.34	-0.16
DS4	1	-1.65	-1.03

Table 4: Pebble size classes and population sizes (a) and sorting coefficients (b).

a

Site	N	5%	16%	50%	84%	95%
US 1	320	5	16	45	128	305
US 2	320	3	23	90	600	4000
DS 1	440	1	6	90	300	853
DS 2	480	1	2	90	500	4000
DS 3	480	1	1	45	180	300
DS 4	480	1	16	90	400	4000

b

Site	Sorting (Ψ)
Watauga	3.005344
US Total	2.464759
DS Total	3.248846
US1	1.632991
US2	2.770575
DS1	2.910932
DS2	3.87602
DS3	3.119754
DS4	2.973962

Table 5: Results from statistical tests on raw pebble counts. Wilcoxon Rank-Sums between reaches (a), Kruskal-Wallis test of size variation by both reach and individual cross-sections (b), post-hoc Kruskal-Wallis test for Multiple Comparisons between reaches (c), and post-hoc Dunn's Test with Bonferroni correction between reaches (d).

a

Wilcoxon Rank Sum	**W**	**p-value**	**H_0**
Upstream – Downstream	598518	8.460×10^{-1}	reject
PRE – POST	293390	3.166×10^{-5}	reject
UP – PRE	467616	1.113×10^{-1}	reject
UP – POST	137055	1.943×10^{-3}	reject

b

Kruskal-Wallis	**χ^2**	**df**	**p-value**	**H_0**
Size by Reach	19.127	2	7.026×10^{-5}	reject
Size by Cross-Section	114.55	5	$< 2.2 \times 10^{-16}$	reject

c

Kruskal-Wallis Multiple Comparisons (p = 0.05)	**Observed Difference**	**Critical Difference**	**Difference**
PRE – POST	49.28562	83.11466	False
UP – POST	118.46771	105.17559	True
UP – PRE	167.75333	92.13207	True

d

Dunn's Test with Bonferroni Correction (alpha = 0.05)	**Z**	**Adjusted p-value (* = significant values)**
PRE – POST	4.369088	**1.871495×10^{-5}***
UP – POST	2.702810	**1.031340×10^{-2}***
UP – PRE	-1.422895	**2.321495×10^{-1}***

Vita

Quincy Williams was born in Ann Arbor, Michigan to Brenda and Daniel Williams. He subsequently moved to and grew up in Madison, Wisconsin where he attended both East and Memorial High Schools, earning a diploma from Memorial in the spring of 2016. Quincy attended the University of Wisconsin – Platteville where he was awarded a Bachelor of Science in Geography with a minor in Geographic Information Systems in the spring of 2020. In the fall of 2020, Quincy began attending Appalachian State University with a GRAM award to work with Dr. Derek Martin. In May 2022 he is graduating with a Master of Arts in Geography.