GEOMORPHIC RESPONSE TO THE REMOVAL OF THE WARD'S MILL DAM ON THE WATAUGA RIVER, WESTERN NORTH CAROLINA

A Thesis
by
JOSH RYAN PLATT

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Abstract

GEOMORPHIC RESPONSE TO THE REMOVAL OF THE WARD'S MILL DAM ON THE WATAUGA RIVER, WESTERN NORTH CAROLINA

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Dam removals are a growing trend in the United States with an average of 90 per year in the past decade. Current removal studies largely indicate that ecological benefits of river re-connectivity outweigh the economic benefits and the costs of maintaining aging infrastructure. However, there is a lack of comprehensive studies in certain regions of the United States, including Southern Appalachia. In May of 2021 the Ward's Mill Dam, a 6 m high run-of-river dam located on the Watauga River in Western North Carolina, was removed. We used this removal as an opportunity to study geomorphic impacts to such removals in this understudied region with the objective of (1) identifying changes in channel form, (2) analyzing bed sediment characteristics, and (3) quantifying rates of volumetric evacuation and deposition. To capture geomorphic change repeated pre- and post-removal cross-sectional surveys, longitudinal profiles, and in-situ particle size sampling was conducted in upstream and downstream reaches. Field collections the

day after removal show significant deposition of gravel sized particles immediately downstream of the dam (≤200m) and shifted the channel slope to -1.11% grade. Channel bed texture remains significantly finer across the 2km downstream study reach 506 days following removal. Erosion rates of the impoundment during the deconstruction period (May 13-17) were on average 860 m^3/day and decreased to 75.5m^3/day by day 74. Below average mean daily flows during this process-driven phase were able to evacuate ~72% of impounded sediment. Tropical Storm Fred introduced a 2-year recurrence interval flow that remained elevated above baseline flow for 8 days and subsequently evacuated 33% of remaining reservoir sediment, helping to transition the river to an event-driven recovery trajectory.

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The Ward family for allowing access to their land for data collection, and Andy Hill (Watauga Riverkeeper) for facilitating discussions about land access. My advisor, Dr. Derek Martin, for the advice and guidance with field methods. Dr. William Armstrong and Dr. Mayfield for agreeing to join the committee. Many thanks to the field work crew, Quincy Williams, Tatiana McGee, and Caty Parham, as well as those who volunteered their time to spend an afternoon in the Watauga River Mac McMahan, Lauren Andersen, Rich Gibbs, Danielle Nunnery, and Sophie Ryan.

Dedication

My parents, Billy and Darlene, for always supporting my endeavors throughout life. My partner, Danielle Nunnery, for not freaking out when I needed a career change and listening to me blabber about "floating mud" during this process.

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Foreword

This thesis was constructed in a non-traditional format with the intention of submitting to *Geomorphology*, a peer-reviewed journal published by Elsevier; it has been organized according to the style guide for submission and formatted in accordance with the Association of American Geographers citation guidelines.

Geomorphic response to the removal of the Ward's Mill Dam on the Watauga River, North Carolina

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1.Introduction

Dam removals are an increasingly used method for restoring riverine ecosystems as the ecological benefits of a removal outweigh the ecological costs and those of maintaining an aging infrastructure. Since the year 2000, nearly 700 dams have been removed in the United States. Each year, the number being removed is higher than the previous (Bellmore et al. 2017). This increased rate of dam removals has demanded more studies to fully understand the geomorphic and biological responses. The reason for the rise in removals stem from the relicensing regulations that require managers of dams to adhere to new fish regulations and hazard assessments. Although dam managers possess increased awareness of the impact of dams on the fluvial environment, local citizens are more reluctant to support removal efforts for numerous reasons (Diessner et al. 2020). Economic projections suggest the removal of dams would cost 44% percent less than rehabilitation (Grabowski et al. 2018). Given the monetary costs of rehabilitation, managers are increasingly opting for removal. Especially since the majority of dams in the country are older than their intended lifespan (ASCE, 2009). From the current *Infrastructure and Jobs Act* bill recently passed in Congress, $2.4 billion will be spent on the removal or rehabilitation of dams and an additional $21.1 billion in funding is possible, providing for the passing of the *21st Century Dams Act*. Currently, less than 10% of dam removals in the U.S. are scientifically studied, with most having a limited duration of pre- and post- removal monitoring. Additionally, very few studies incorporate an interdisciplinary approach (Bellmore et al. 2017). However, a longer duration of detailed pre- and post-removal monitoring (particularly pre-removal) would provide critical information for understanding the trajectories of recovery, and would thus provide improved guidance for policy

makers, science advisors, and politicians to ensure the best outcomes for our rivers and their ecosystems. That being said, the limited number of removals studied thus far have provided valuable information.

Following a dam removal, the initial increase in velocity scours the upstream reservoir and introduces years to even centuries worth of stored sediment and other pollutants to the downstream reach. The loss of sediment in the reservoir and the deposition downstream cause environmental and ecological change, the majority of which is highly beneficial in the long run, such as river connectivity for migrating fish to spawn and restoring natural flow and temperature variations. However, some studies show a temporary decline in species richness and complete loss of certain species in that region altogether (Poulos et al. 2014). For example, Poulos et al. (2014) observed an absence of atlantic salmon and sea lamprey in the river following dam removal while observing an increase in darter species that favor sediment regimes in geomorphic transitional periods. Any negative impacts to habitat and spawning grounds are likely correlated with embeddedness. This adds to the need for more high frequency and longer duration studies regarding the geomorphic characteristics of the channel beds. Typical geomorphic response includes: (1) a decrease in water levels in the former impoundment, (2) degradation of the channel upstream of the former dam (Granata et al. 2008), (3) increased sediment deposition downstream via increased velocity rates (Tullos et al. 2014), (4) and changes in channel bed composition (Ferrer-Boix et al. 2014). These changes have been observed to occur rapidly within the first few months following removal. However, the inherent variability of river systems in different physiographic settings makes each dam removal, and its impacts, unique. Our understanding of

the rates of these responses is limited due to the temporal scale of available dam removal literature, which typically end after two years post-removal (Hart et al. 2002, Bellmore et al. 2017).

Further temporal data collection gaps exist during and immediately following a removal. Most dam removal studies start with post-removal particle size data collections 6 months after the dam removal is completed, except for a select few (Granata et al. 2008, Kibler et al. 2011). Quasi-stabilization of downstream particle sizes typically occurs between 1- and 2-years following removal but continues to remain significantly finer than pre-removal particle distributions (Magilligan et al. 2021). Conversely, one study noticed geomorphic disturbance from the pulse lasting beyond 2 years (Tullos et al. 2014), while others report geomorphic and biologic responses are still in transition 4 years later (East et al. 2015, Poulos et al. 2014). Our study implements high temporal resolution data collection both during the removal process and immediately following.

Additionally, there exists a spatial gap in scientific studies of dam removal (Bellmore et al. 2019, Hart et al. 2002, Grabowski et al. 2018). The variables that contribute to the ever-changing nature of river systems also make each dam removal unique. Using one removal as a guide for how an ecosystem will respond following a future removal is currently not possible due to the limited number of academic studies. Spatial gaps in these studies are evident in the Great Plains as well as Southern Appalachia (Fig. 1), especially when compared to the number of dams within these regions. The removal of the Ward's Mill Dam is relevant for study for many reasons, one of which is that it is in one of these identified regions and can address the need for high temporal data collection. Any results from this study would add to existing literature regarding removals as a whole and within this underrepresented region.

1.1. *Background*

The privately owned Ward's Mill Dam was located on the Watauga River in Sugar Grove, NC, impounding an area spanning approximately 800 meters upstream just below the confluence with Cove Creek. The dam, in various forms, impounded the Watauga River for 123 years. The most current iteration of the dam was constructed in 1964 to a height of ~6m and consisted of concrete and stone (Wigginton, 1980). The cultural impact the dam had is undeniable as it brought industry and electricity to the surrounding community and presents a unique intersection of human and physical geography. However, the dam had not been used for its intended purpose of electricity for wood milling since 1970. In 2018, the Ward family, owners and operators of the dam since its original construction, chose to not renew the Federal Energy Regulatory Commission permit for the dam and agreed on its removal from the Watauga River. The removal was encouraged by the Watauga Riverkeeper and MountainTrue, a regional conservation non-profit organization, after the dam was determined a "tier one, priority one" removal by the Southeast Aquatic Resource Partnership's Aquatic Barrier Prioritization Tool (Southeast Aquatic Resources Partnership 2022).

Prior to removal, the Ward's Mill Dam underwent a Tier 1 sediment study in 2020 to evaluate environmental risks to sediment recruitment within a 1-mile radius of the dam (Wildlands Engineering, Inc 2020). An estimated 19,000-21,000 cubic yards (14,526-16,055m^3) of sediment were estimated to be impounded by the dam. The release of this sediment constitutes the largest change to morphology in the impounded area and immediately downstream through the transport of the eroded sediment wedge, exposing new features upstream and creating new geomorphic

features and promoting lateral and upstream migration of existing features downstream via deposition (Major et al. 2017).

This study presents the geomorphic response of the removal of the Ward's Mill Dam which has various under-represented characteristics, including its location in the Blue Ridge ecoregion and high average watershed slope. Geomorphic response rates are quantified within the reservoir and downstream reach following the removal of the dam on the Watauga River. The objectives were to (1) capture ongoing geomorphic change through repeated surveying of cross sections and longitudinal profiles, (2) analyze changes in bed texture with the introduction of sand to gravel sized particles, and (3) estimate the volumetric rates of sediment evacuated from the reservoir following removal.

1.2. Study Area

The site of the Ward's Mill Dam, 14.5 km west of Boone, NC, is located within the Beech Creek subwatershed (HUC 060101030305) which drains an area of approximately 103 km^2 with an average terrain slope of 16%. The Watauga River continues into the Watauga Basin (HUC 06010103) and is a tributary to the Holston and Tennessee Rivers. The study reach extends 5km upstream of the dam to the furthest most control site while the downstream reach continues 2km below the dam (Fig. 2). A gravel road (Watauga River Road) extends the length of the study area associated with the removal and the surrounding floodplain consists of mainly agricultural land use. Cove Creek, the upper Watauga's largest tributary, is a significant source of sediment due to predominantly agricultural land use. During our study period, development and stream

restoration projects along the creek were an added sediment source, particularly in suspended loads.

A total of 6 study sites were established along this section of the Watauga River: 2 upstream control sites, and 4 downstream sites, with one additional site added within the reservoir following the removal of the dam. The first downstream site (DS1) is located immediately downstream of the dam and center cross sections at DS2, DS3, and DS4 are located approximately 880m, 1800m, and 2000m downstream of the dam respectively (Table 1). Previous observations have shown that most of the sediment deposition following a dam removal occurs within the first 2 km below the breach (Doyle, 2002). The sizes of the dams and rivers in these studies are larger than the Ward's Mill dam but suggests the spatial range of our downstream collection sites are appropriate to adequately capture the sediment transport as a result of the removal.

Large colluvial boulders are present on the banks at all upstream and downstream sites except for DS3 which consists of high (2.5 – 3m) and steep vegetated banks. A predominant site of deposition exists ~145m downstream of the dam in the form of a mid-channel bar that extends through the plane of DS1XS3 and DS1XS4 (Fig. 3).

A USGS gaging station (0379000) is conveniently located immediately at the upstream end of the former impoundment. The station has been in operation for 81 years and indicates the highest seasonal flows occur during the spring and the lowest in the late fall/early winter with a mean annual peak flow of 210.27 m^3/s and mean annual discharge of 5.12 m^3/s (180.81 ft^3/s). Field collections were thoughtfully timed after it was concluded that safe, wadable working conditions were only possible at or below 2.83 m^3/s (100 ft^3/s), which is nearly half the mean

annual flow. Convective rainfall, extra-tropical cyclones, and snowmelt (albeit rarely) contribute to flows that top bankfull height, which is consistent to approximately a 2-year recurrence interval (RI) or 174 m^3/s.

2. Methods

2.1. *Quantifying Changes in Channel Geometry*

Nineteen semi-permanent cross-sections, split between 6 sites, were established 18 months prior to the dam removal to capture pre- and post-removal changes to channel geometry and bedform (Fig. 2). A seventh site, consisting of 3 cross sections, was established within the lower reservoir following removal to capture the erosion of the impounded sediment wedge. Repeat surveys at downstream sites were conducted weekly for the first 3 weeks following removal and continued bi-monthly until December of 2021. Surveys resumed in April of 2022 to capture an approximately one-year response post-removal. The repeated cross-sectional surveys across the 22 established cross-sections provide sufficient spatial and temporal resolution to capture geomorphic response. Survey points were taken across the cross section at frequent, but not regular, intervals. However, following the first round of surveys, point location measurements were taken at an interval no greater than 2 meters in spacing. Point locations were based on visual changes in slope, geomorphic surface, and the bankfull channel elevation was surveyed and noted where it was clearly identifiable. Coupled with corresponding pebble counts (described in next section), these surveys will help quantify the rates and patterns of post-removal incision, aggradation, and bank erosion. It will also provide evidence of any channel widening or narrowing in response to the removal. This is crucial to not only help in understanding geomorphic responses following a

removal, but also for assisting biological responses related to aquatic habitats and spawning grounds.

Longitudinal surveys were performed using a standard rod and level surveying technique and followed the thalweg of the channel through each site's corresponding cross-sections, providing insight into changes in channel slope and the infilling of pools and riffles. In the case of the reservoir and DS-1, these surveys connect to create a longitudinal profile through the plane of the former dam. Analysis with corresponding cross-sectional surveys aids in estimating sediment volumes as the sediment pulse migrates downstream.

To estimate volumetric changes in the channel bed, cross-section area changes were extrapolated over their representative upstream and downstream distance (Collins et al. 2017). This distance was bound by transect 1 and 8 of the cross-section's pebble count schema (described in 2.2) and was calculated between surveying points where cross-sections intersected the longitudinal profile. Changes in net erosion in the reservoir and deposition downstream between survey intervals were then summed to estimate volume changes through time.

2.2. Quantifying Changes in Bed Sediment Characteristics

At all sites, particle size surveys were conducted across 8 transects at each cross section using a variation of the Wolman (1954) pebble count method (Fig. 3). In-situ measurements utilize a gravelometer to pass pebbles through standardized square holes that correspond with particle size classes. A maximum class size of 4000mm and a minimum of 0.062mm was used to follow the classification used by Wildlands Engineering (2020). For particles larger than 180mm the rule on the side of the gravelometer was used to estimate the intermediate axis. If both sides of

the intermediate axis could not be determined (i.e. – buried in the bed), then the particle was determined bedrock and assigned to the 4000mm class. Sediments smaller than the 2mm slot on the gravelometer was assessed either visually or by feel as either sand or fines with a size value of 0.2mm for sands and 0.062mm for fines. A systematic random sampling technique was used at every cross-section, but instead of collecting 100 pebbles sizes over a reach of 100 meters, 160 pebbles were measured across eight transects (Fig. 3), a total of 480-660 potential pebbles measured across each site (~90-200m). This increase in number of particle size measurements gives a more accurate representation of particle size distribution and minimizes biases (Olsen et al. 2019). Following the removal of the dam, only particles from the middle cross-section(s) at each site were measured for the sake of increasing our overall temporal collections throughout the study area. Temporal sampling followed the schedule mentioned for cross-sectional surveys.

A total of 2,520 pebbles were measured across all sites during the pre-removal study period. Currently, 3,992 pebbles have been measured post-removal. A Kruskal Wallis test followed by a Dunn post-hoc test aggregated by site and cross-section was used to determine significant differences in particle distribution from pre-removal baseline and each subsequent collection. Kruskal-Wallis tests were completed using the R base statistical package (R Core Team 2020) and the dunn.test package (Dinno 2017). Quantiles were calculated for the 16% (D_{16}), 50% (D_{50}), and 84% (D_{84}) quantiles for each collection to assess spatio-temporal variation.

3. Results

3.1. Changes in Channel Morphology

3.1.1. Pre-Removal

Cross-sectional surveys in the pre-removal period were conducted to establish a baseline of geomorphic variability of the channel width, cross-sectional area, and thalweg depth over a one-year period (Table 1, Fig. 4). Pre-removal variability across all sites was minimal with percent change of cross -sectional area ranging from -13% to 26% when excluding sites where survey pins had to be re-established. After establishing point location measurements be taken at an interval no greater than 2 meters in spacing, cross-sectional variability decreased by 18% to a range of -13% to 19%. Any post-removal changes outside of the range of pre-removal variability can be assumed the result of the dam removal and subsequent aggradation or deposition of materials.

Bed slope varied from -1.53 to + 0.19% slope, and water surface slope varied from -1.38 to -0.03%. Average slope of the bed profiles was 0.1325% and water surface elevations averaged a -0.37875%. The average slope of the water surface falls within the definition of a Moderate-Low Gradient stream (Sheldon et al. 2015) but the average bed gradient was positive, falling outside of the range of classification. This is potentially due to surveying short longitudinal reaches with a mixture of pools and riffles.

3.1.2. Post-Removal

Deconstruction of the Ward's Mill Dam began on May 13th, 2021 and the dam was fully removed to the channel bed elevation on May 16th. Excavators were left in the channel and removed by 0900 hours on May 17th. Post-removal surveys began at the Downstream 1 site immediately after.

Within a week following removal, a substantial amount of deposition occurred at DS1 that aggraded the channel bed by as much as 1.5 m and decreased channel area to, on average, 20.57 m^2

(Fig. 5, Table 2). Aggradation continued through 38 days where cumulative deposition onto the mid-channel bar increased to above bankfull elevation. For instance, using pre-removal bankfull depth as a datum, DS1-XS3 went from an average cross-sectional area of 17.9m^2 in its pre-removal state to 0.5m^2 immediately following removal and -1.07m^2 one month later (negative represents a greater area of deposition on the mid channel bar than area of water in the channel). The initial deposition of sediment infilled the plunge pool formation, created by cascading water from the dammed state, and aggraded enough within the first 100km of DS1 to create a bed and water slope of -1.11% and -.59% respectively (Fig. 6). Water and bed slope decreased at the head of the mid-channel bar which provides storage for sediment transport. DS2 experienced the largest decrease in channel cross sectional area at XS3 (-66.3%) which helped transition the channel from a negative to a positive slope within 23 days.

Within a week post-removal, the lower impounded sediment quickly incised to near the base of the dam as indicated by the first RES surveys on May 24th (Fig. 6). The longitudinal survey continues through the plane of the former dam and into DS1, where the scour pool below the former dam was completely infilled. Incision was slower in the upper impoundment but was mostly complete by August 26th, 2021, our final survey of the site. Incision exposed a series of rapids across the representative distance of RES-XS1, hindering further field collections using current methods (Fig. 9). Further erosion of the impoundment channel and banks are evident in the plots of cross-sectional area changes (Fig. 5).

Erosion rates were substantial during from the first day of deconstruction to the first survey in the post-removal period, averaging ~860 m^3/day (Fig. 7). Rates decreased throughout

the next 74 days following removal where an estimated total of 9,814.92 m^3 eroded from RES and deposited within downstream reaches. Ninety-five days following removal, Tropical Storm Fred increased discharge to 185m^3, just above a 2-year recurrence interval flow, on August 18th, 2021. Eight days later the total evacuated sediment increased to 11,160.63 m^3 as a result.

Throughout the post-removal study period, both upstream sites, DS3, and DS4 indicate cross-sectional area, channel slope, and channel width experienced minimal change and fell within the range of pre-removal variability and excluded from volume calculations. However, DS3 did experience significant accumulation of fine sand and silt (explained in 3.2). Cross-sectional surveys within the 1-year post-removal monitoring period suggests no permanent change to bankfull width or bank erosion across the upstream or downstream study reaches, with the exception of RES. However, during the most recent pebble count collection (October 5th, 2022), recent bank erosion was observed at DS1-XS3, ~170m from the former dam.

3.2. Changes in Bed Sediment

3.2.1. Pre-Removal

Particle size distribution showed minimal spatial variability during the pre-removal period. D_{50} consisted of cobble across the study reach and only varied at DS3, 1600m from the former dam, where D_{16} was also considerably finer than other sites. A low water bridge separates DS3 and DS4 where large wood (LW) is typically prevented passage. The longitudinal profile of DS3 also has the greatest positive slope, +0.55%, within the downstream study reach. Characteristics of the site suggest finer materials are deposited in the lower reach of DS3 via suspension in a backwater effect from the low water bridge.

3.2.2. Post-Removal

Within a week of dam removal, downstream channel bed texture experienced a fining downstream of the Ward's Mill Dam site where the cobble beds at DS1 and DS2 were aggraded with predominately medium gravel sized sediments, while DS3 experienced significant deposition of fine sand and silt (Fig. 8, Table 3). DS4 pebble counts indicate an initial decrease in D_{50} to medium gravel, but particle size distribution was back to its pre-removal state within 6 months. The 2-year event associated with Tropical Storm Fred increased D_{50} across DS1 and DS3 while DS2 experienced a fining of bed materials to very fine gravel, or 4mm. As of our last bed sample, 506 days since removal, particle sizes remain significantly lower than pre-removal surveys across DS1, DS2, and DS3. As expected, no change in particle size distribution was detected at US1 and US2.

Only one pebble count was conducted in the impoundment area, where D_{50} was 32mm, or medium sized gravel. Due to the exposed rapids and an increase in water depth and velocity, further collections were not possible. However, with a prior survey and qualitative observations, it is evident the reservoir bed grain size coarsened as material was eroded from the former impoundment.

4. Discussion

The high temporal, repeated field collections within 6 weeks following the removal allowed us to capture immediate channel responses of a dam removal. The ensuring period of elevated flows during the drawdown period allowed for rapid erosion of impounded sediment. During the process driven period, the transport of impounded particles redistributed throughout

the 2km downstream study reach, with particle sizes decreasing with distance, resulting in a significant net decrease in cross-section area at DS1/DS2 and decreases within the pre-removal variability range for DS3/DS4. Fine gravel to coarse gravel was the dominate particle size deposited within DS1 due to sediment trapping at the pre-existing mid channel bar, which experienced a lateral and upstream migration during the first week and throughout the 1-year post-removal period. Prior research has suggested the introduction of impounded sediment translates as waves through the downstream reach (Madej and Ozaki 1996). This appears to be the case within the first 200km downstream and potentially could have translated further downstream in the absence of the mid-channel bar 145m from the dam. During the process driven phase, prior to Tropical Storm Fred, the sediment regime past DS1 follows a dispersive pattern. Significant sediment accumulation occured at the mid-channel bar where the upstream pulse was temporarily trapped, allowing degradation to occur slowly from the crest of the pulse (Lisle et al. 2001). Pizzuto (2002) highlights the ecological impacts of both processes, with dispersion having greater temporal impact albeit much smaller spatial impact within a particular location.

After 506 days, bed texture remained significantly finer with D_{50} decreasing with distance from the dam. Egan (2001) observed similar impacts of downstream deposition where former cobble beds remained buried under a mixture of sand through gravel sized particles after 11 months of monitoring. Sediment storage was also documented in backwater areas (Gerrits 1994). In the case of the Watauga River, the storage of fine and sand size particles at DS3 were present in the pre-removal period where a low-water bridge created a backwater effect into DS3's positive channel slope. Below the low-water bridge, DS4 did not experience enough of an increase in D_{16}

to suggest deposition of sand sized particles and particle distribution swiftly transitioned back to a pre-removal state. Many studies show impacts of bed texture dissipating with distance downstream, particularly within the first 2km (Major et al 2012). The presence of the low-water bridge presents a lingering impact on DS3 through 506 days post-removal.

In the first 74 days after removal, the river rapidly eroded the stored sediment at discharge levels in the range of ~3 to 30 m^3/s (Fig. 4), evacuating an estimated 71.3% of the impounded materials. This is indicative of a dominantly process-driven adjustment phase with rates similar to recent studies (Pearson et al. 2011, Collins et al. 2017, Magilligan et al. 2016). During this time, degradation of the bedform and channel banks (both consisting of gravel) were so rapid they were visibly eroded and transported downstream. Note in particular the below mean daily average discharge during the first survey interval (May 17, 2021) which corresponds to the most rapid erosion rate of the study.

Tropical Storm Fred delivered a 2-year event 60 days after the removal. Between survey periods (day 74 and 103), process-driven erosion and the 2-year flow aided in evacuating ~34% of the remaining reservoir sediment. In the period between Fred and our last cross-sectional survey (August 26, 2021 - April 22, 2022), DS1 cross sectional area increased only within our range of pre-removal variability. The occurrence of the event was able to disperse a substantial portion of sediment from RES and DS1 and was enough to transition the movement of material from process to event driven, meaning high flow events are now required to transport a substantial portion of the remaining sediment immobilized in the upper downstream reach.

Volume estimates do not account for any suspended loads during the study period. However, total suspended sediment (TSS) samples were collected and analysed during the pre- and post-removal period as well as high resolution samples during the period of deconstructions of the dam. Further analysis on TSS will be conducted in the future to determine the rates and quantities transported as a result of removal. TSS collections, along with pebble counts and cross section and longitudinal surveys are still ongoing to determine change within a greater temporal period.

With the number of dam removals increasing every year in varying geographic regions, so are opportunities to study its effects on channel form and bed sediment characteristics within unrepresented watersheds. Understanding the rates and patterns of particle size as they transport and deposit downstream will lend to removal management strategies in the future, particularly as it relates to biological communities. For instance, if it is known that a certain species of concern spawns within pools of a certain particle size at a certain time of the year, understanding various rates of deposition and transport of individual sediment sizes could help in determining the best period to remove a dam to minimize the impacts on that species.

5. Conclusion

Dam removals with uncontrolled sediment releases are valuable opportunities to investigate channel response to increased bed load materials. This study documents the geomorphic response rates of downstream reaches after the introduction of impounded sand to coarse gravel sized sediments (1-63mm). The high temporal resolution was adequate to capture (1) the translation of the sediment pulse to within 200km where the mid-channel bar aided in the

dispersion of sediment downstream as opposed to a wave and (2) calculate erosion rates during the process-driven phase of sediment transport.

Given the limited number of studies across unique watersheds, any dam removal case study offers valuable insight in understanding how a river system may respond to such an event. While this study may contribute to the existing literature, it is obvious the sediment transport is still in flux and channel geometry is still in transition to a quasi-stable state. Thus, the continuation of our field methods is necessary to continue capturing the downstream migration of the sediment pulse of larger particle sizes and the continued geomorphic response of the Watauga River.

Declaration of Competing Interest

The authors declare they have no knowledge of competing interests or personal relationships that could have appeared to influence the work and results of this study.

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Figures

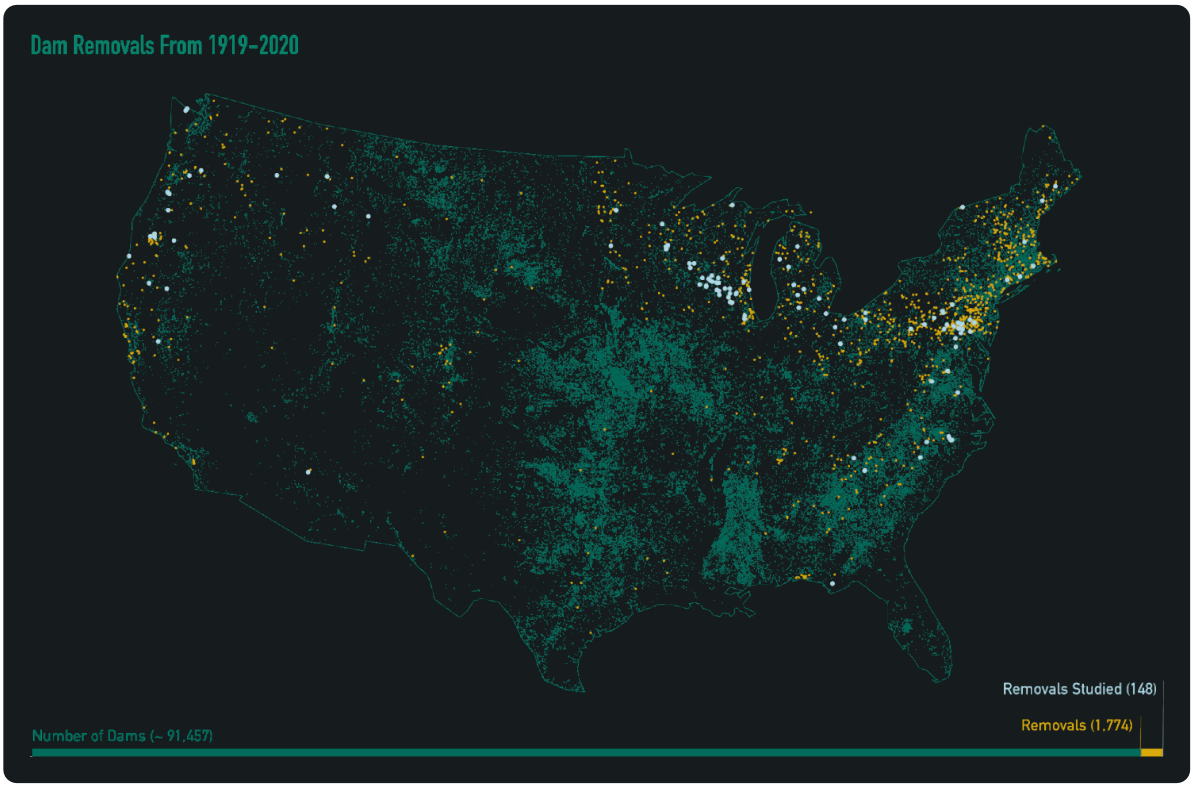

Figure 1. Dams (teal), dam removals (yellow), and dam removals with an academic study (light blue) at the start of our study period.

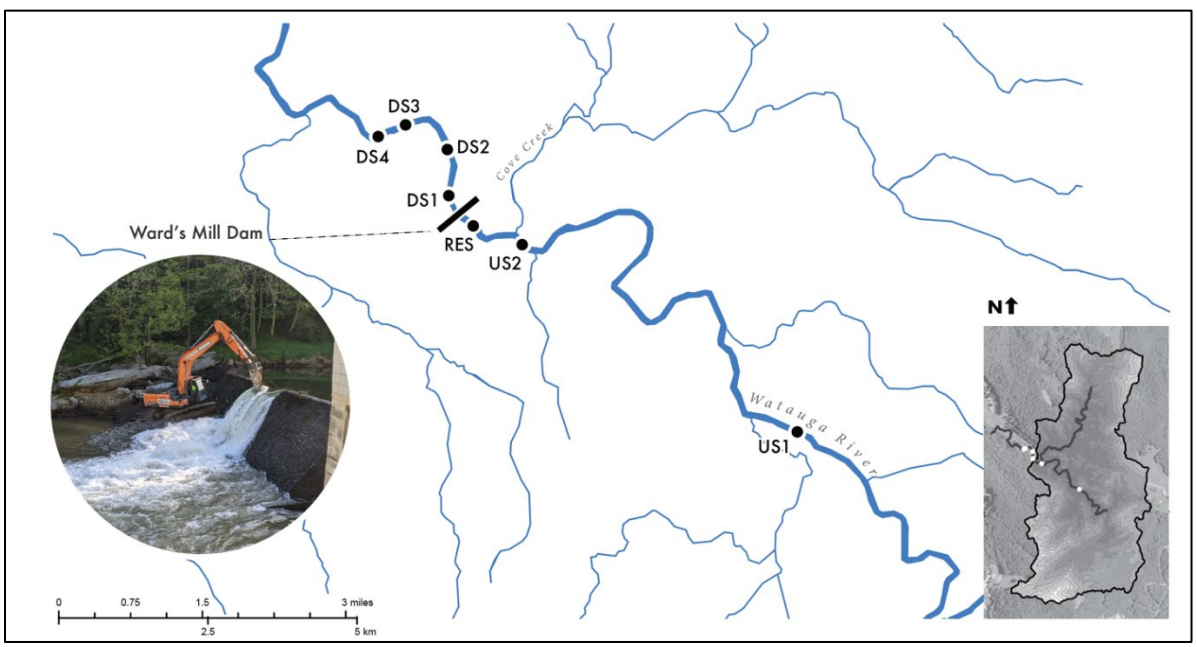

Figure 2. Map of dam and study reach. Each site contains 3 cross-sections (i.e. – US1, or upstream 1, has three cross-sections, or XS), except for DS1 which contains 4 cross-sections.

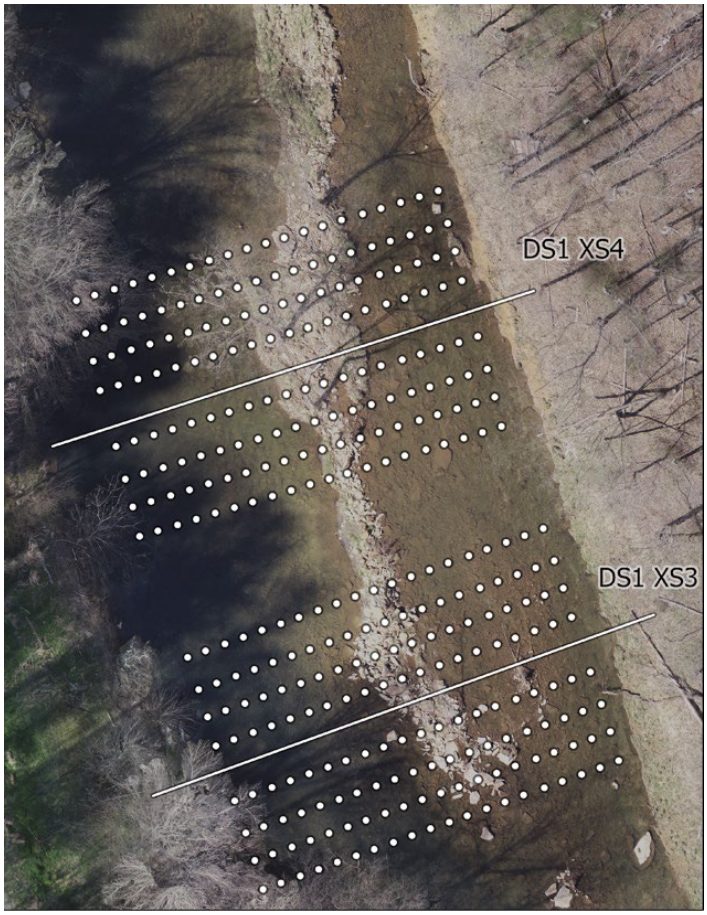

Figure 3. Sampling schema for pebble counts. Dotted lines represent transects of pebble counts, 8 per cross-section. Collections were taken within the wetted perimeter and mid-channel bar. *Photo: Dr. Song Shu.*

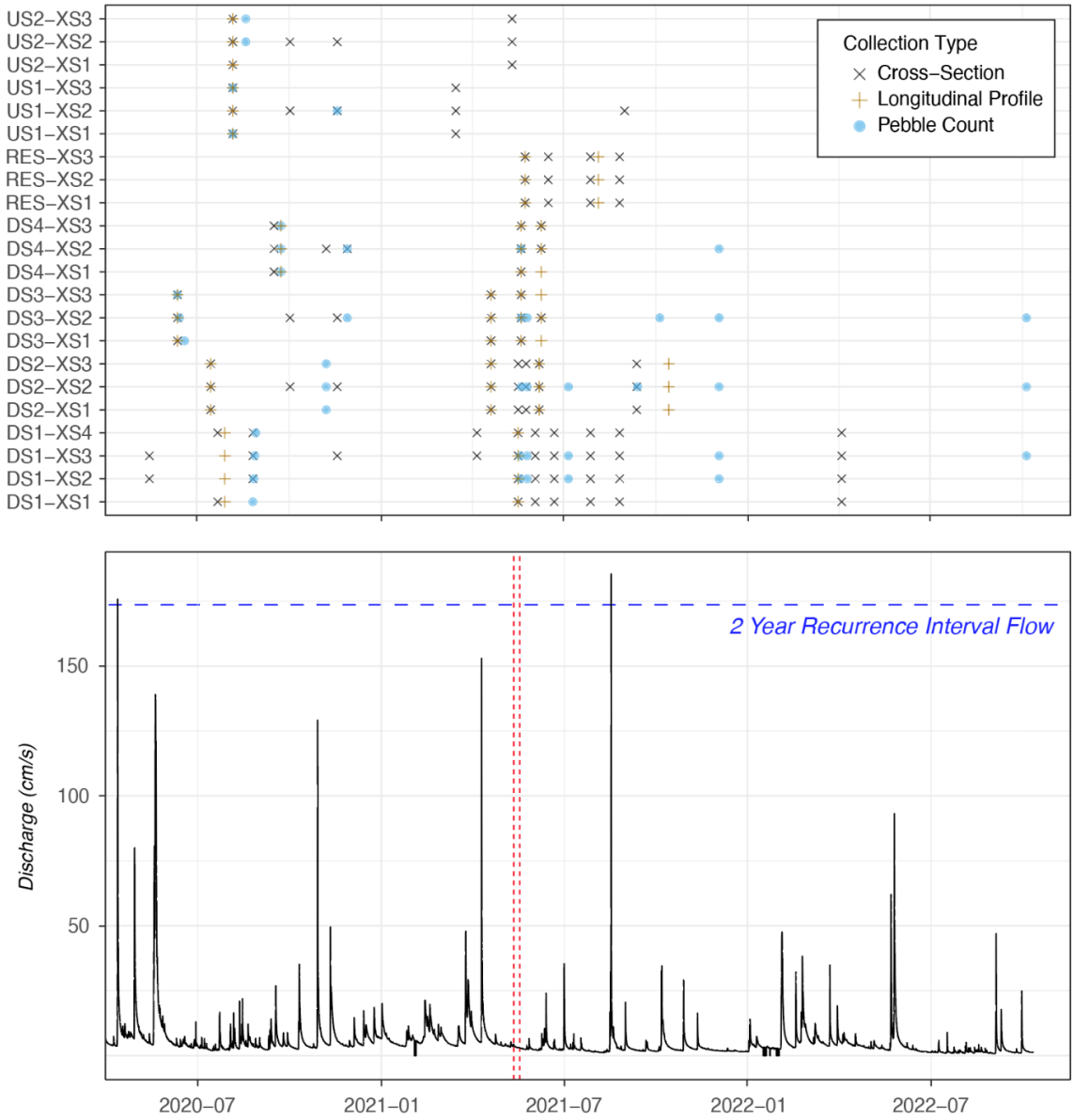

Figure 4. Times of field collections in correspondence with 15-min time series of USGS gage 03479000, 2-yr recurrence interval (horizontal dashed line), and dam deconstruction period (vertical dashed line).

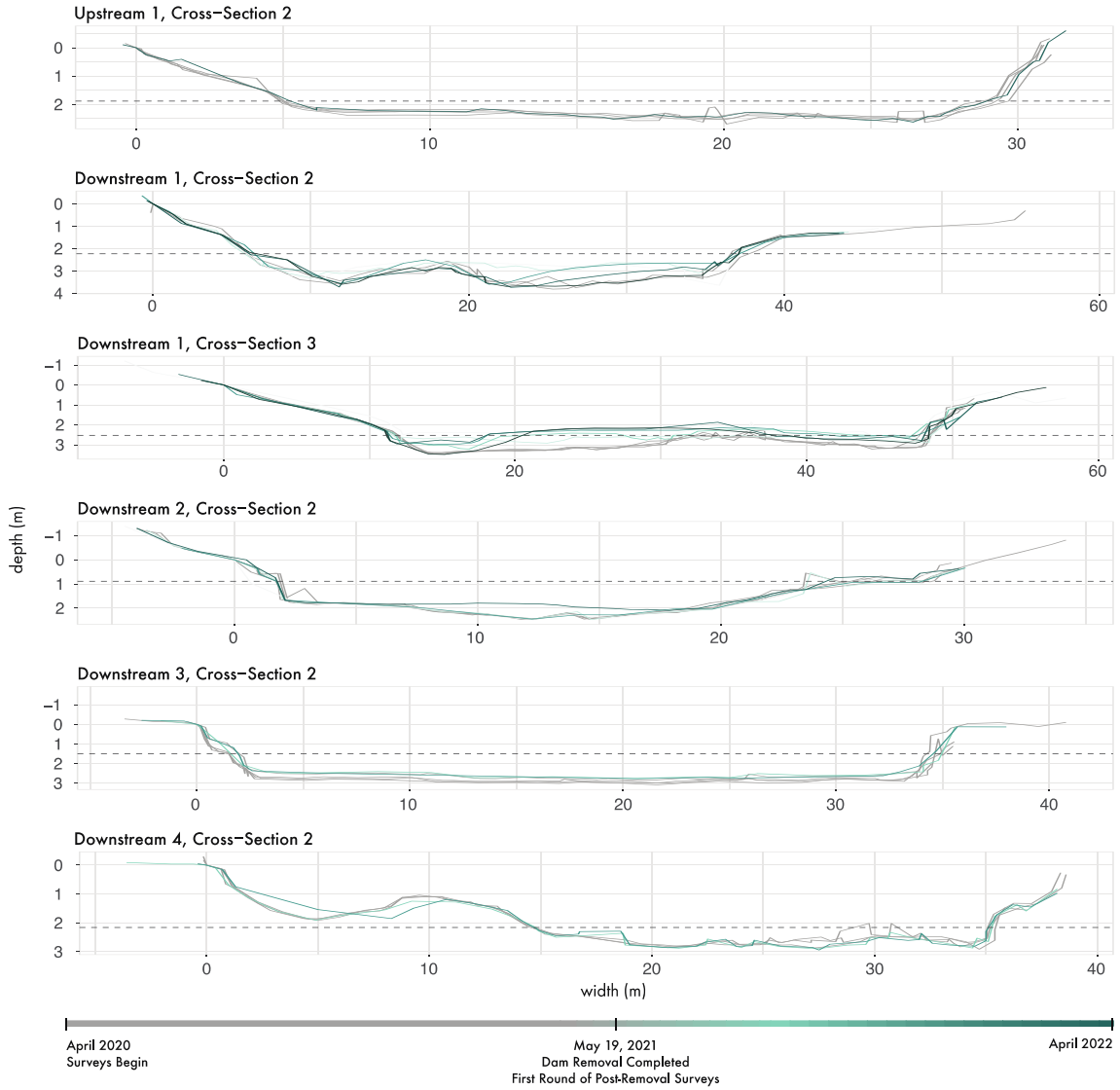

Figure 5. Time series of cross-sectional surveys for sites with most repeated surveys. Dotted line represents bankfull depth. Elevation and distance are relative to survey pin on the left bank.

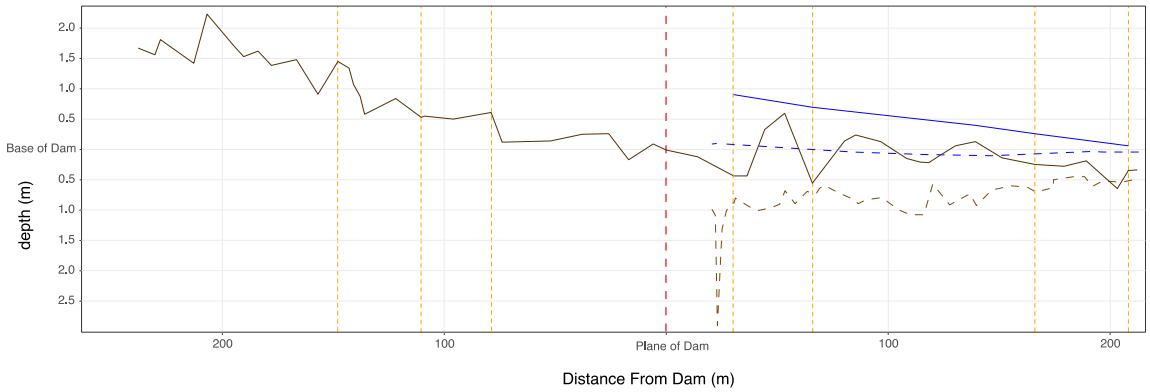

Figure 6. Post-removal longitudinal profile. Horizontal dotted lines represent pre-removal survey of DS1. Orange vertical dotted lines represent cross-sections from respective sites. Elevation is relative to the base of the dam structure which is visible follow removal. Distance is relative to the plane of the former dam.

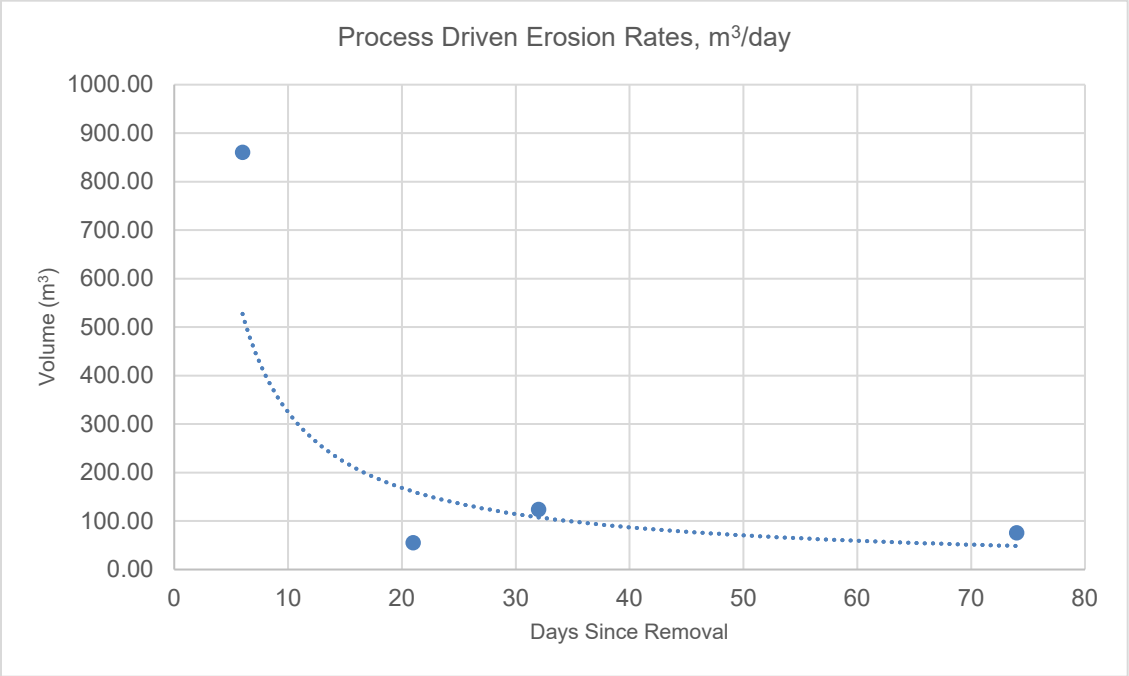

Figure 7. Process driven rates of erosion between day 1 of deconstruction and survey prior to Tropical Storm Fred.

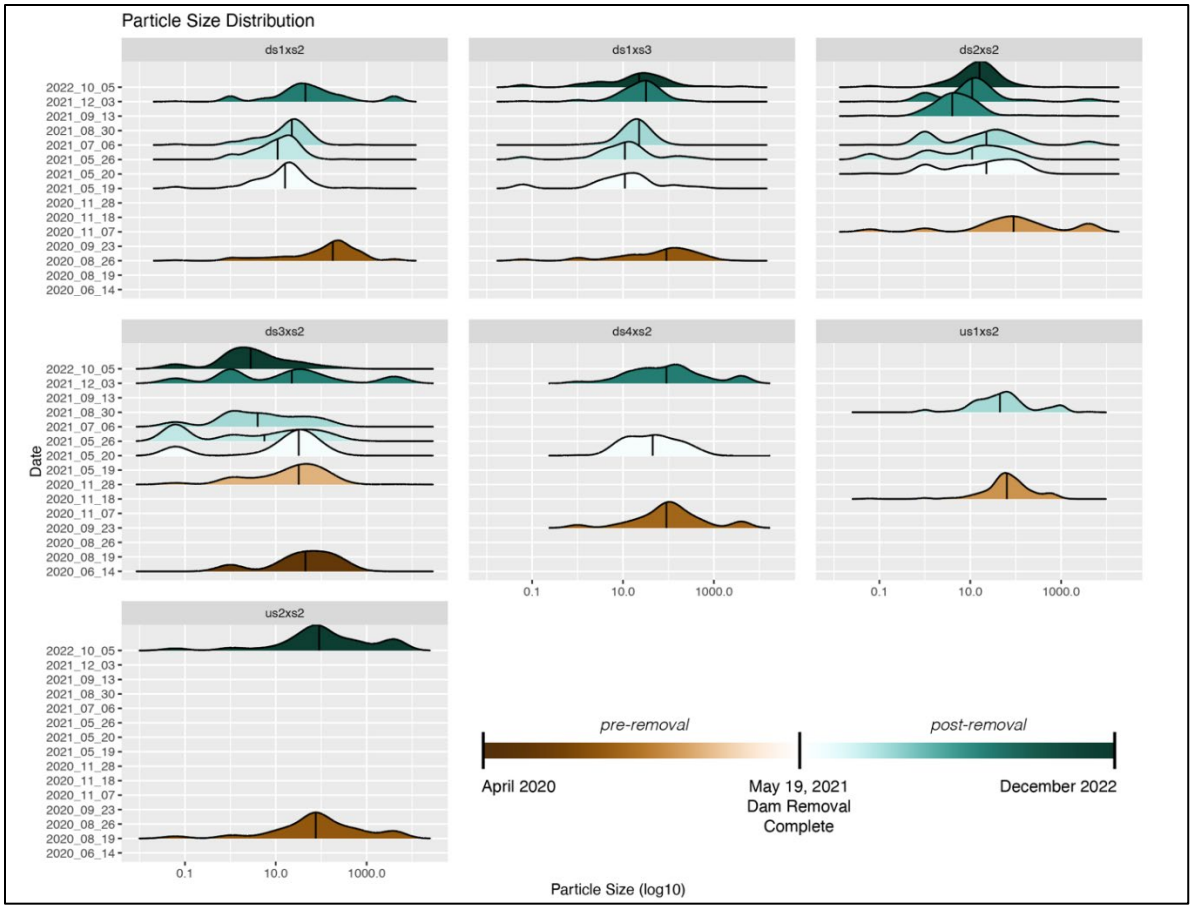

Figure 8. Particle size distribution of the middle cross-section(s) of each site where post-removal collections were possible. Aggregated by site, over time. Vertical black bar on each plot represents D_{50}.

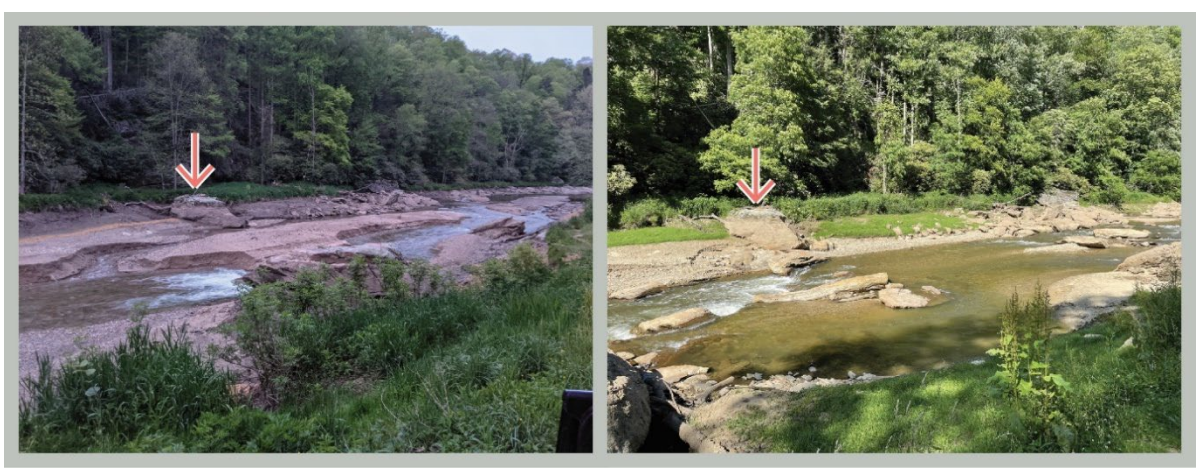

Figure 9. Upper end of sediment wedge at RES-XS1 (150m from dam) on May 17, 2021 (left) and June 16, 2021 (right) when rapids began to be exposed.

Tables

Site	Dist. From Dam (m)	Mean Bankfull Width (m)	Mean Bankfull Depth (m)	Slope	D16	D50	D86	Representative Distance (m)
US1	-5000	24.6	1.925	0.23	22.6	64	200	28, 43.7, 87.4
US2	-1000	24.3	0.73	1.26	16	90	2900	23.4, 32, 40.6
DS1	25 - 200	36.9	2.39	0.29	16	90	500	35, 66.05, 70, 42.9
DS2	840 - 940	25.3	1.2	-0.16	16	90	2000	24, 31, 38
DS3	1770 - 1860	33.1	1.82	0.55	11	45	180	35, 35, 35
DS4	1900 - 2000	33.9	1.79	-1.53	22.6	90	500	20.9, 19.25, 17.6
RES	-225 - 0	x	x	x	x	x	x	37.5, 34.5, 31.5

Table 1. Pre-removal site-averaged geomorphic characteristics. Distance from dam includes approximate range of study reach through digitizing with negative numbers reading as upstream from the dam. Cross section (XS) representative distance reads from left to right as XS1, XS2, XS3, and in the case of DS1, XS4.

Site	Date	Removal Status	XS Area (m2)		Absolute Change from Pre-Removal Avg	Relative Change from Pre-Removal Avg (%)
Downstream 1,	-	pre	33.84			
Cross-Section 1	5/17/21	post	19.07		-14.77	-43.64%
	6/3/21	post	1.32		-32.52	-96.10%
	6/22/21	post	-0.27	*	-34.11	-100.80%
	7/28/21	post	6.73		-27.11	-80.11%
	8/26/21	post	10.23		-23.61	-69.76%
	4/4/22	post	12.99		-20.85	-61.60%
Downstream 1,	-	pre	34.86			
Cross-Section 2	5/17/21	post	18.75		-16.11	-46.21%
	6/3/21	post	19.41		-15.45	-44.31%
	6/22/21	post	-0.06	*	-34.92	-100.18%
	7/28/21	post	21.20		-13.66	-39.19%
	8/26/21	post	25.03		-9.83	-28.21%
	4/4/22	post	30.19		-4.67	-13.39%
Downstream 1,	-	pre	17.99			
Cross-Section 3	5/17/21	post	0.49		-17.49	-97.26%
	6/3/21	post	5.27		-12.72	-70.70%
	6/22/21	post	-1.07	*	-19.05	-105.92%
	7/28/21	post	2.41		-15.58	-86.63%
	8/26/21	post	3.18		-14.81	-82.35%
	4/4/22	post	8.02		-9.97	-55.43%
Downstream 1,	-	pre	40.77			
Cross-Section 4	5/17/21	post	6.86		-33.91	-83.17%
	6/3/21	post	3.00		-37.77	-92.63%
	6/22/21	post	-2.25	*	-43.02	-105.51%
	7/28/21	post	1.16		-39.61	-97.14%
	8/26/21	post	0.85		-39.92	-97.92%
	4/4/22	post	4.49		-36.29	-89.00%
Downstream 2,	-	pre	16.76			
Cross-Section 1	5/17/21	post	14.97		-1.80	-10.73%
	5/25/21	post	14.25		-2.51	-14.98%
	6/7/21	post	14.60		-2.17	-12.93%
	9/12/21	post	4.89		-11.88	-70.86%
Downstream 2,	-	pre	24.22			
Cross-Section 2	5/17/21	post	25.25		1.03	4.26%
	5/25/21	post	24.60		0.38	1.56%
	6/7/21	post	22.37		-1.85	-7.64%
	9/12/21	post	20.11		-4.11	-16.97%
Downstream 2,	-	pre	24.86			
Cross-Section 3	5/17/21	post	25.01		0.16	0.63%
	5/25/21	post	3.48		-21.37	-85.98%
	9/12/21	post	16.75		-8.10	-32.60%
Downstream 3,	-	pre	42.41			
Cross-Section 1	5/20/21	post	43.19		0.79	1.86%
Downstream 3,	-	pre	36.34			
Cross-Section 2	5/20/21	post	35.14		-1.20	-3.30%
		post	35.57		-0.77	-2.12%
Downstream 3,	-	pre	6.46			
Cross-Section 3	5/20/21	post	6.37		-0.09	-1.45%
Downstream 4,	-	pre	18.94			
Cross-Section 1	5/20/21	post	17.37		-1.57	-8.28%
Downstream 4,	-	pre	8.99			
Cross-Section 2	5/20/21	post	10.36		1.37	15.28%
	6/9/21	post	9.91		0.92	10.25%
Downstream 4,	-	pre	13.59			

Cross-Section 3	5/20/21	post	13.14	-0.45	-3.35%
	6/9/21	post	13.27	-0.32	-2.39%
Upstream 1,	-	pre	18.25		
Cross-Section 2	8/31/21	post	18.14	-0.11	-0.59%
Upstream 2,	-	pre	17.81		
Cross-Section 2					
Reservoir,	5/24/21	post	27.98		
Cross-Section 1	6/16/21	post	51.89	23.91	85.47%
	7/28/21	post	56.09	28.12	100.50%
	8/26/21	post	59.87	31.89	113.99%
Reservoir,	5/24/21	post	7.19		
Cross-Section 2	6/16/21	post	15.24	8.04	111.77%
	7/28/21	post	22.09	14.89	207.04%
	8/26/21	post	71.01	63.82	887.04%
Reservoir,	5/24/21	post	97.46		
Cross-Section 3	6/16/21	post	98.65	1.19	1.22%
	7/28/21	post	125.66	28.20	28.94%
	8/26/21	post	110.31	12.85	13.19%

* area negative due to deposition above bankfull height

Table 2. Changes in cross-sectional area in the pre- and post-removal periods

Site	Date	n	D_{16}	D_{50}	D_{84}
US1-XS2	2020_11_18	160	22.6	64	200
US-1XS2	2021_08_30	160	16	45	180
US2-XS2	2020_08_19	160	16	90	700
US2-XS2	2022_10_05	160	22.6	90	2900
DS1-XS2	2020_08_26	120	16	180	500
DS1-XS2	2021_05_19	160	4	16	32
DS1-XS2	2021_05_26	160	2.8	11	22.6
DS1-XS2	2021_07_06	160	4	22.6	45
DS1-XS2	2021_12_03	155	11	45	256
DS1-XS3	2020_08_26	160	8	90	300
DS1-XS3	2021_05_19	160	2.8	11	32
DS1-XS3	2021_05_26	160	4	11	32
DS1-XS3	2021_07_06	160	11	22.6	32
DS1-XS3	2021_12_03	160	11	32	64
DS1-XS3	2022_10_05	160	2.8	22.6	90
DS2-XS2	2020_11_07	160	16	90	2000
DS2-XS2	2021_05_20	160	1	22.6	128
DS2-XS2	2021_05_26	160	1	11	64
DS2-XS2	2021_07_06	160	1	22.6	90
DS2-XS2	2021_09_13	160	2	4	11
DS2-XS2	2021_12_03	160	1	11	32
DS2-XS2	2022_10_05	160	5.6	16	32
DS3-XS2	2020_06_14	160	11	45	180
DS3-XS2	2020_11_28	160	2	32	90
DS3-XS2	2021_05_20	160	0.062	32	64
DS3-XS2	2021_05_26	160	0.062	5.6	90
DS3-XS2	2021_07_06	160	1	4	45
DS3-XS2	2021_12_03	160	1	22.6	180
DS3-XS2	2022_10_05	160	1	2.8	22.6
DS4-XS2	2020_09_23	160	22.6	90	478
DS4-XS2	2021_05_20	160	11	45	180
DS4-XS2	2021_12_03	156	15	90	600
US1-XS2	2020_11_18	160	22.6	64	200
US1-XS2	2021_08_30	160	16	45	180
US2-XS2	2020_08_19	160	16	90	700
US2-XS2	2022_10_05	160	22.6	90	2900

Table 3. D16, D50, D84 of sites with repeated pre- (grey rows) and post-removal collections.

Site	Removal Status	Date	*n*	Median	sign. (pre)	sign. (prior)
DS1-XS2	pre	8/26/20	120	180		
DS1-XS2	post	5/19/21	160	16	***	***
DS1-XS2	post	5/26/21	160	11	***	*
DS1-XS2	post	7/6/21	160	22.6	***	***
DS1-XS2	post	12/3/21	155	45		***
DS1-XS3	pre	8/26/20	160	90		
DS1-XS3	post	5/19/21	160	11	***	***
DS1-XS3	post	5/26/21	160	11	***	
DS1-XS3	post	7/6/21	160	22.6	***	*
DS1-XS3	post	12/3/21	160	32	**	
DS2-XS2	pre	11/7/20	160	90		
DS2-XS2	post	5/20/21	160	22.6	***	***
DS2-XS2	post	5/26/21	160	11	***	
DS2-XS2	post	7/6/21	160	22.6	***	
DS2-XS2	post	9/13/21	160	4	***	***
DS2-XS2	post	12/3/21	160	11	***	*
DS3-XS2	pre	6/14/20	160	45		
DS3-XS2	pre	11/28/20	160	32		
DS3-XS2	post	5/20/21	160	32	***	***
DS3-XS2	post	5/26/21	160	5.6	***	*
DS3-XS2	post	7/6/21	160	4	***	*
DS3-XS2	post	12/3/21	160	22.6	***	*
DS4-XS2	pre	9/23/20	160	90		
DS4-XS2	post	5/20/21	160	45	***	***
DS4-XS2	post	12/3/21	156	90		**
US1-XS2	pre	11/18/20	160	64		
US1-XS2	post	8/30/21	160	45		

Table 4. Results of the Dunn Test on D50. Significance values: **.01, **.001, ***.0001*

Vita

Josh Platt was born in Madison, NC to Darlene and Billy Platt. He graduated from Dalton L. McMichael High School in May 2004. That same year he started collegiate studies at the University of North Carolina at Greensboro. After a 10-year break from college to travel across North America playing drums in the punk band *Torch Runner*, he was accepted to Appalachian State University in the fall of 2019 and was awarded a Bachelor of Science degree in Geography in May 2021. Mr. Platt was accepted into the Geography Master of Arts program at Appalachian State in August 2021 to continue research on the Ward's Mill Dam Removal on the nearby Watauga River.

Mr. Platt resides in the High Country of North Carolina and works as the GIS Lab Supervisor for the Department of Geography and Planning at Appalachian State University where he is also an adjunct instructor.