Geomorphic Response to the Removal of the Ward's Mill Dam on the Watauga River, North Carolina

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Highlights

- We present a before-after/control-impact study of the geomorphic response of a dam removal within an understudied region, Southern Appalachia.
- Evacuation of gravel sized sediment required less time and lower flow rates than previously hypothesized.
- Eleven months post-removal, ~19-20 percent of former impounded sediment is stored within the first 200 m downstream.
- 506 days post-removal, previous bed textures of cobble remain buried by gravel within 1 km downstream.

ABSTRACT: *Though economic situations of individual dams vary, current dam removal studies largely indicate that ecological benefits of river re-connectivity may outweigh the costs of maintaining aging infrastructure. However, there is a lack of comprehensive studies in certain regions of the United States, including Southern Appalachia. We used the removal of the 6 m high Ward's Mill Dam on the Watauga River in North Carolina to conduct a before-after/control-impact study to monitor geomorphic impacts to such removals in this understudied region with the objective of identifying changes in channel form, analyzing bed sediment characteristics, and 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 (≤200 m). Channel bed texture remains significantly finer across the 2 km downstream study reach 506 days following removal. Erosion rates of the impoundment during the deconstruction period were on average ~860 m^3/day and decreased to 75.5 m^3/day by day 74. Below average mean daily flows during this period were able to exhume ~62.9 percent of impounded sediment.*

KEYWORDS: Dam Removal, Channel Morphology, Particle Size, Channel Bed Adjustments, Deposition

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 1912, 2,025 dams have been removed in the United States (American Rivers 2023). The accelerated rate of dam removals in the past century has necessitated more studies to fully understand the geomorphic and biological responses (Bellmore et al 2017, Major et al 2017). The reason for the rise in removals stems 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, including the potential loss of property values and preserving industrial history (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 Investment and Jobs Act* (P.L. 117-58) 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* (H.R. 4375). Currently, less than 10 percent 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.

The change in base level after a dam is removed increases stream power, which then scours the upstream reservoir to introduce years to even centuries worth of stored sediment and potential 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, several studies show a temporary decline in species richness and varying timescales for the transition from lentic to lotic fish assemblages (Poulos et al. 2014, Tullos et al. 2014, Magilligan et al. 2021). For example, the shift from lentic to lotic fish assemblage in the Eightmile River was still in transition four years following the removal of Zemko Dam. Yet an increase in species that favor sediment regimes in geomorphic transitional periods, such as the Tessellated darter, were observed (Poulus et al. 2014). Along with changes in temperature, water depth, and flow rates, the lack of optimal grain size due to the initial downstream deposition of fine sediment has a strong influence on habitat suitability and spawning grounds, thus affecting fish assemblage. This further supports the need for more high frequency and longer duration studies regarding the geomorphic characteristics of the channel beds and the transport rates and patterns of impounded material. Typical geomorphic response following dam removal includes: (1) a decrease in water levels in the former impoundment, (2) degradation of the channel upstream of the former dam through knickpoint erosion, (3) new deposition downstream through an increase in sediment supply, regardless of changes in flow velocity (Draut and Ritchie 2015), (4) and changes in channel bed composition. 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 most available dam removal literature, which typically end after two years post-removal (Hart et al. 2002, Bellmore et al. 2017). However, more and more studies are extending beyond 2-year post-removal monitoring (Collins et al. 2017, Magilligan et al. 2021, East et al. 2023) and even extending beyond 10 years (East et al. 2018).

Further temporal data collection gaps exist during and immediately following a removal. Most geomorphic studies start with post-removal particle size data collections around six months after the dam removal is completed, except for a select few (Kibler et al. 2011, Pearson et al. 2011, Major et al. 2012). Rivers respond rapidly to dam removal, but quasi-stabilization of the downstream channel varies. More and more studies document geomorphic responses as being mostly complete between one- and two-years following removal, with particle sizes remaining significantly finer than pre-removal distributions (East et al. 2018, Magilligan et al. 2021, East et al. 2023). Conversely, one study noticed geomorphic disturbance from the pulse lasting beyond two years (Tullos et al. 2014), while another reports geomorphic and biologic responses are still in transition four years later (Poulos et al. 2014). Our study implements high temporal resolution data collection in the pre-removal period, during the removal process, and in the 1-year post-removal period.

Additionally, there exists a spatial gap in scientific studies of dam removal (Hart et al. 2002, Major et al. 2017, Grabowski et al. 2018, Bellmore et al. 2019). 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 a river and its ecosystem will respond following a future removal is currently not possible due to the small number of academic studies in limited biogeographic and physiographic regions (Wieferich et al. 2021). Spatial gaps in academic studies are evident in the Great Plains as well as Southern Appalachia (Figure 1), especially when compared to the number of existing dams within these regions (ASCE 2009). The removal of the Ward's Mill Dam is relevant for study for many reasons, including its location within an underrepresented region in dam removal literature and our ability to 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.

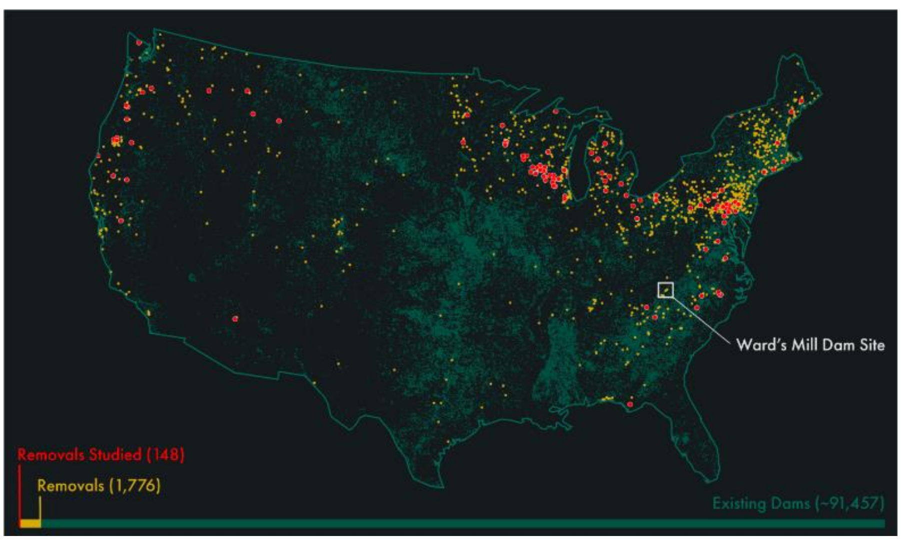

Figure 1. Dams (ASCE), dam removals (American Rivers), and dam removals with an academic study (USGS) from 1919-2020, ~5 months prior to the removal of the Ward's Mill Dam.

BACKGROUND

The privately owned Ward's Mill Dam was located on the Watauga River in Sugar Grove, North Carolina, impounding an area spanning approximately 800 m 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 ~6 m 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 survey in 2020 to evaluate environmental risks to sediment recruitment within a 1-mile radius of the dam (Wildlands Engineering, Inc 2020). The Tier 1 sediment survey also includes bathymetric survey within the reservoir where each measurement point included an elevation reading at the top of the sediment and at the depth of refusal using an extended soil probe. These measurements estimated 14,526 m^3 - 16,055 m^3 of sediment were available for mobilization following the dam's removal. After the removal the erosion and transport of the sediment wedge will be the largest contributor to geomorphic change. This release of the impoundment may change geomorphic form by exposing new features formerly covered by the sediment wedge and creating new features downstream with newly released sediment. It has been previously presented that pre-existing bar features may temporarily trap and store the increased sediment supply, promoting feature widening and upstream migration patterns (Major et al. 2017).

We conducted a before-after/control-impact (BACI) study to measure 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 reaches following the removal of the dam on the Watauga River. The goal of this study was to utilize several repeated field collections, from deconstruction through six months post-removal, to better understand the sediment pulse of a gravel dominant impoundment in a physiographic region new to dam removal research. The findings could further add to our understanding of the rates and patterns of initial reservoir exhumation and downstream deposition. In a similar impoundment, Major et al (2012) observed that erosion and downstream transport from a 50/50 sand/gravel sediment wedge was much swifter than previously anticipated (Pizzuto 2002). We hypothesize that within the first six months following removal, (1) the former reservoir will experience rapid incising, degradation, and bank erosion. (2) Downstream sites will experience fining of bed materials, moving from an armored bed to sand and gravel sized material. (3) The post-removal sediment regime will shift from process-driven to event-driven within the first year, allowing sand sized sediments to move past the study reach but prolonging the storage of gravel-sized particles downstream of the dam site.

STUDY AREA

The site of the Ward's Mill Dam, along with downstream survey sites, is located 14.5 km west of Boone, NC within the Beech Creek subwatershed (HUC 060101030305) which drains an area of 166.3 km^2 with an average watershed terrain slope of 16.4 percent. Upstream survey sites are located within the Dutch Creek subwatershed (HUC 060101030303) which has similar mean watershed terrain slope (16.2 percent) and drains an area of 77.4 km^2. The Watauga River continues through the Watauga Basin (HUC 06010103) and is a tributary to the Holston and Tennessee Rivers. The study reach extends 5 km upstream of the dam to the furthest most control site while the downstream reach continues 2 km below the dam (Figure 2). 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.

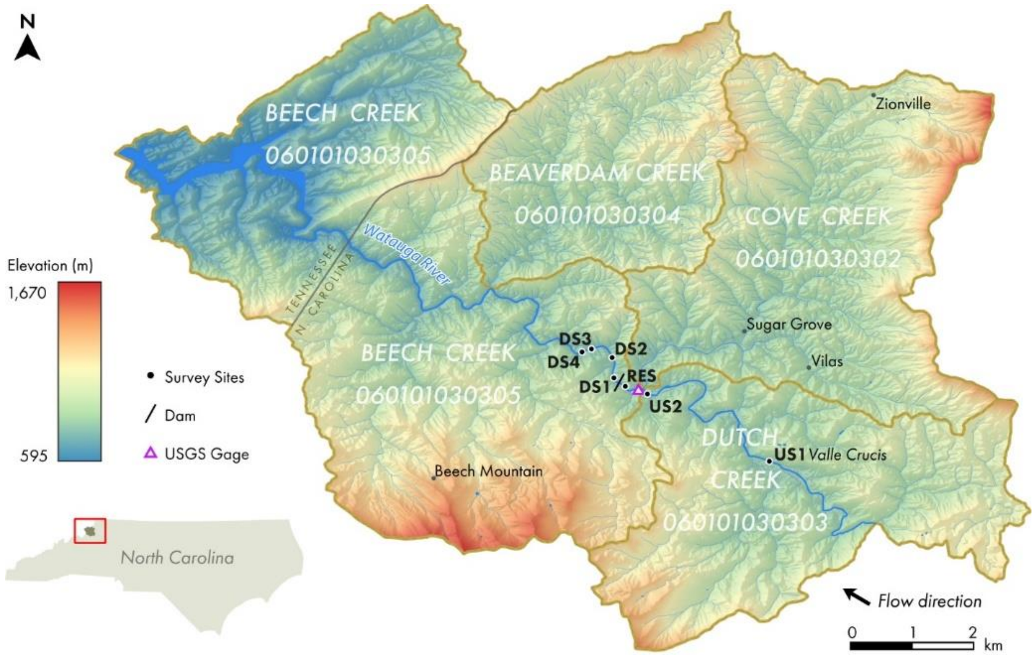

Figure 2. Map of study reach and surrounding HUC12 watersheds. Each site contains 3-4 cross-sections (e.g.–US1, or upstream 1, has three cross-sections labeled as US1-XS1, US1-XS2, US1-XS3).

A total of 6 study sites, each consisting of three or four cross-sections, 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 880 m, 1800 m, and 2000 m downstream of the dam respectively (Table 1). Previous observations have shown that the initial deposition of sediment, particularly gravel-size clasts, occurs within the first 2 km below the breach (Doyle 2002, Harris and Evans 2014, Tullos et al. 2014). 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 initial sediment transport and deposition 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 (2.5m – 3 m) and steep vegetated banks. A predominant site of potential deposition exists ~145 m downstream of the dam in the form of a vegetated mid-channel bar that extends through the plane of DS1-XS3 and DS1-XS4 (Figure 3).

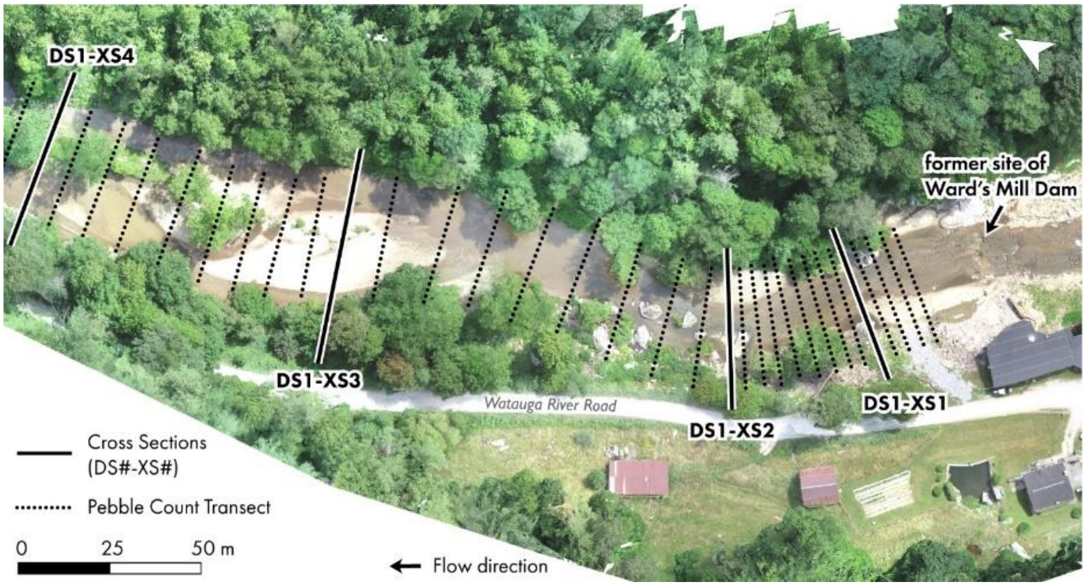

Figure 3. Example sampling schema at the Downstream 1 site (DS1). Solid lines represent cross-sections and dotted lines represent transects of pebble counts. There are 8 transects per cross-section, 4 upstream and 4 downstream. Collections were taken within the wetted perimeter and mid-channel bar. The distance between transect 1 (furthest most upstream) and transect 8 (furthest most downstream) of each cross-section is the representative distance, which when multiplied with cross-sectional area, is used for volume estimates. Photo: Dr. Song Shu.

A USGS gaging station (03479000) 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 210.3 m^3/s and mean annual discharge of 5.12 m^3/s (180.8 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 with approximately a 2-year recurrence interval (RI) or 174 m^3/s.

METHODS

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 as well as to establish a baseline of geomorphic variability in the 1-year pre-removal survey period (Figure 2). Each cross-section was monumented with a wooden stake driven into the top of the river left bank. Cross-sectional surveys were performed using an auto-level, stadia rod, and 100-meter tape. All measurements were recorded in a field book to a precision of 0.01 meters, digitized in Microsoft Excel, and analyzed using RStudio (R Core Team 2020). Each cross-sectional survey was backsighted to the absolute reference of their corresponding monumented stake to convert the location of the stake as coordinate 0,0 (x,y). All subsequent surveys were converted the same way so that all repeated surveys share the same origin. On May 17th, 2021, the four-day staged removal of the Ward's Mill Dam was completed. Post-removal surveys of downstream sites started on May 17th and were conducted weekly for the first 3 weeks and continued bi-monthly until December of 2021. Downstream surveys resumed in April of 2022 to capture an approximately one-year response post-removal. A seventh site, consisting of 3 cross sections within the lower reservoir was established after the removal to capture the erosion of the impounded sediment wedge. Post-removal reservoir surveys began on May 24th and ended on August 26th when unsafe working conditions were determined after incision exposed a series of rapids. 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 during the pre-removal period, 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 understanding biological responses related to aquatic habitats and spawning grounds.

Longitudinal surveys were performed at each site 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. The surveys spanned from just upstream of each site's first cross-section to just downstream of each site's last cross-section. In the case of the reservoir and DS-1, these surveys connect to create a longitudinal profile through the plane of the former dam. Slope of each longitudinal profile was calculated along the channel thalweg using a standard rise over run equation, with rise and run being the elevational change and distance, respectively, between each site's furthest most upstream and downstream cross-section. Analysis with corresponding cross-sectional surveys also aids in estimating sediment volumes as the sediment pulse migrates downstream.

To estimate volumetric changes in the channel bed, cross-section area changes were linearly extrapolated over their representative upstream and downstream distance (Table 1, Figure 3). This distance was bound by transect 1 and 8 of the cross-section's pebble count schema (described below) and was calculated between surveying points where cross-sections intersected the longitudinal profile. This method operates under the assumption that cross-sectional area does not change form nor shape throughout its representative distance. Changes in net erosion in the reservoir and changes in deposition downstream between survey intervals were then summed to estimate volume changes through time.

Table 1. Pre-removal site-averaged geomorphic characteristics. Negative 'Dist. from dam' numbers read as upstream from the dam. Cross-section (XS) representative distance is the along-channel distance bound by transect 1 and 8 of each XS's pebble count (Figure 3). Numbers read from left to right as representative distance of XS1, XS2, XS3, and in the case of DS1 a fourth cross-section is added, XS4.

Site	Dist. from dam (m)	Mean bankfull width (m)	Mean bankfull depth (m)	Slope	D16	D50	D86	Cross-Section Representative Distance (m)
US1	-5000	24.6	1.93	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
RES	-225 - 0	x	x	x	x	x	x	37.5, 34.5, 31.5
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

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 (Figure 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 4000 mm and a minimum of 0.062 mm was used to follow the classification used by Wildlands Engineering (2020). For particles larger than 180 mm 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 assigned to the 4000 mm class. Sediment smaller than the 2 mm slot on the gravelometer were assessed either visually or by feel as either sand or fines with a size value of 0.2 mm for sand and 0.062 mm 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 (Figure 3), a total of 480-660 potential pebbles measured across each site (~90-200 m). 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 clasts were measured across all sites during the pre-removal study period. Currently, 3,992 clasts 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 percent (D_{16}), 50 percent (D_{50}), and 84 percent (D_{84}) quantiles for each collection to assess spatio-temporal variation.

RESULTS

Pre-removal channel morphology

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, Figure 4). Pre-removal variability across all sites ranged from -13 percent to 26 percent (39 percentage points). After establishing point location measurements of bed elevation be taken at an interval no greater than 2 meters in spacing, cross-sectional variability decreased by 7 percentage points with a range of -13 percent to 19 percent (32 percentage points). Any post-removal cross-section area changes outside of the range of pre-removal variability can be assumed the result of the dam removal and subsequent aggradation or degradation of materials.

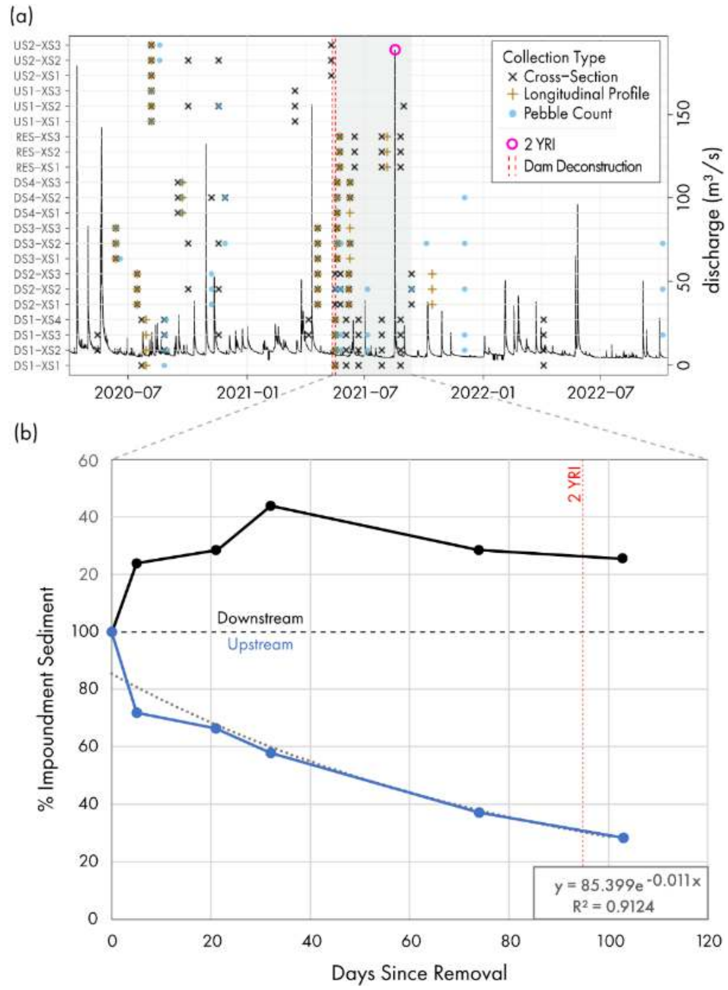

Figure 4. (a) Time series of field collections in correspondence with 15-min time series of USGS gage 03479000, 2-year recurrence interval (YRI) (hollow circle), and dam deconstruction period (vertical dashed lines). (b) The sediment budget for the reservoir (blue line) and downstream sections (black line) of the study area. A dashed exponential best-fit curve (R^2 = 0.91) is labeled for reservoir response. The dashed vertical line represents first significant flow event since removal (2-year recurrence interval).

Bed slope at each study site varied from -1.53 to + 0.19 percent, and water surface slope varied from -1.38 to -0.03 percent. Average slope of the bed profiles was +0.14 percent and water surface elevations averaged -0.38 percent. 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 (93 m - 214 m) with each consisting of one or more pools.

Post-removal channel morphology

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 cross-sectional area from an average of 31.9 m^2 to 20.6 m^2 (Figure 5, Figure 6). 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 17.9 m^2 in its pre-removal state to 0.5 m^2 immediately following removal and -1.07 m^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 100 km of DS1 to create a bed and water slope of -1.11 percent and -0.59 percent respectively. Water and bed slope decreased at the head of the mid-channel bar which provides storage for sediment transport. DS2 experienced its largest decrease in channel cross sectional area at XS3 (-66.3 percent) which transitioned the sites stream gradient from a negative to a positive slope within 23 days.

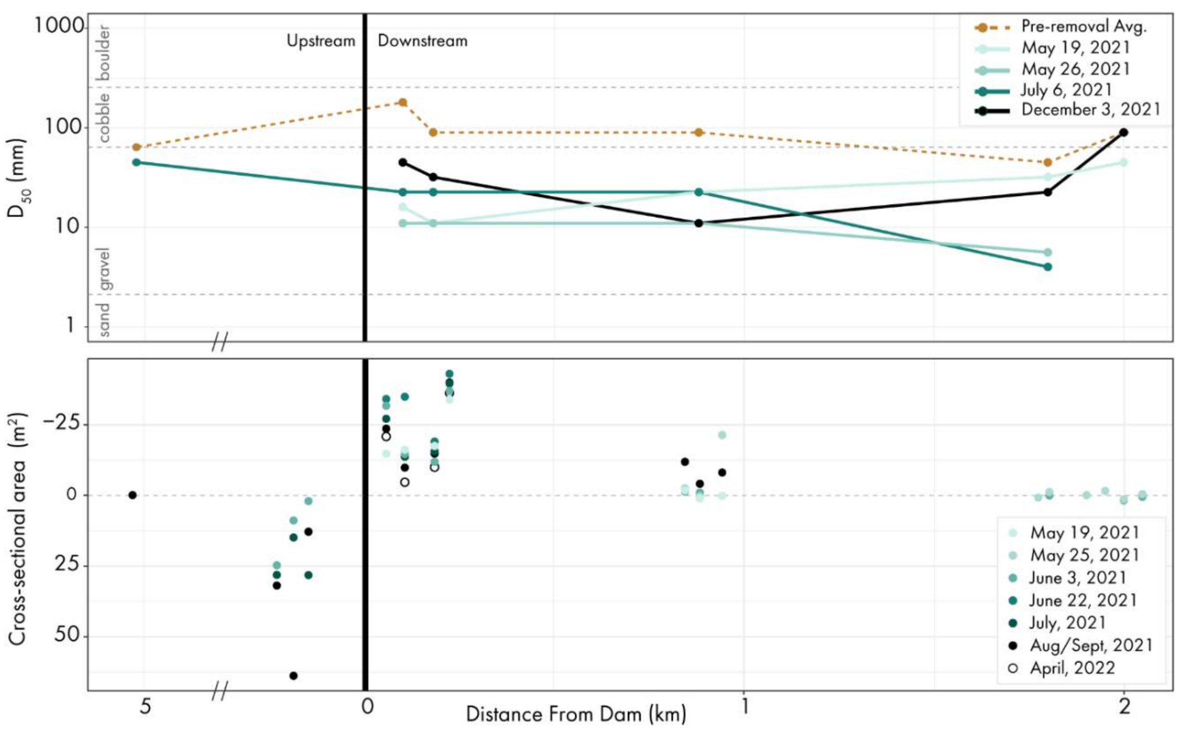

Figure 5. Post-removal evolution of (top) median grain size (D_{50}) and (bottom) cross-sectional area across the study area.

Within a week post-removal, the lower impounded sediment quickly incised to near the base of the dam as indicated by the first RES longitudinal profile survey on May 24th. Knickpoint erosion had advanced the sediment wedge 80 m upstream, or an average of 11.5 m per day. 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 advanced to

~140 m into the reservoir, exposing a series of rapids across the representative distance of RES-XS1. This hindered further field collections using current methods. Further erosion of the impoundment channel and banks downstream from RES-XS1 is evident in the plots of cross-sectional area changes (Figure 6).

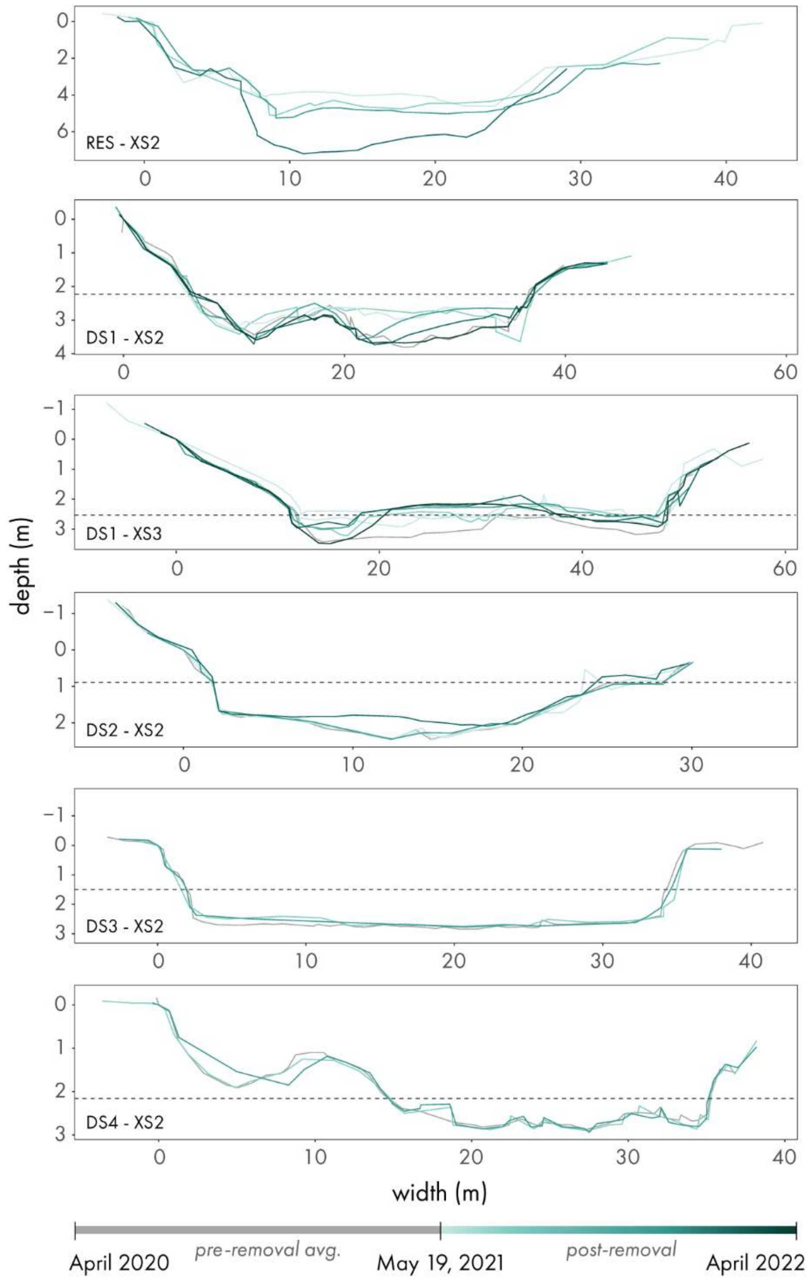

Figure 6. Example time series of selected cross-sectional surveys from our middle cross-section(s) from the reservoir and all downstream sites. Dotted horizontal line represents bankfull depth as measured pre-dam removal. Depth and width are relative to left bank survey pin.

Throughout the post-removal study period, our furthest upstream control site (US1) and both upstream sites (DS3 and DS4) show cross-sectional area, channel slope, and channel width experienced minimal change and fell within the range of pre-removal variability and thus excluded from volume calculations. However, when comparing cross-sectional survey to in-situ particle surveys, DS3 did experience accumulation of fine sand and silt in the river left portion of the channel (Figure 6, Figure 7). Cross-sectional surveys within the 1-year post-removal monitoring period did not indicate that downstream reaches had experienced a shift to a new equilibrium state. However, during the most recent pebble count collection (October 5th, 2022), recent bank erosion was observed at DS1-XS3, ~170m from the former dam.

Volumetric reservoir erosion estimates

Erosion rates were substantial from the first day of deconstruction to the first survey in the post-removal period, averaging ~860 m^3/day (± 138 m^3/day) (Table 2) and evacuating 5,151 m^3 (± 824 m^3) or 29.1 percent, of the estimated impounded sediment. Average daily rates decreased substantially throughout the next seventy-four days where discharge remained below the mean daily average except for two minor elevated flow events (Figure 4a). After seventy-four days an estimated total of 10,471 m^3 (± 1,675 m^3) eroded from RES and deposited within downstream reaches. Ninety-five days following removal, Tropical Storm Fred increased discharge to 185 m^3/sec, just above a 2-year recurrence interval flow, on August 18th, 2021. Eight days later the total evacuated sediment increased to 11,816 m^3 as a result.

Table 2. Sediment budget of Ward's Mill Dam reservoir during the post-removal period. Number in parenthesis represents percent of sediment stored within 200 meters downstream of former dam (DS1). 'Sediment Remaining' is based on the median of the range of estimated impounded sediment (14,526 m^3 - 16,055 m^3).

Days Since Removal	Average Erosion Rate (m^3/d)	Interval Sediment Evacuated (m^3)	Cumulative Sediment Evacuated (m^3)	Sediment Remaining (m^3)	% Sediment Remaining
5	860 (± 138)	4,299 (± 688)	5,151 (± 824)	10,991 (± 1,759)	71.9 (23.9)
21	53.3 (± 8.5)	852 (± 136)	6,004 (± 961)	10,139 (± 1,622)	66.3 (27.6)
32	117.8 (± 18.8)	1,296 (± 207)	7,300 (± 1,168)	8,843 (± 1,415)	57.8 (42.3)
74	75.5 (± 12.8)	3,171 (± 507)	10,471 (± 1,675)	5,672 (± 908)	37.1 (28.3)
103	46.4 (± 7.4)	1,346 (± 216)	11,816 (± 1,891)	4,327 (± 692)	28.3 (25.6)
322	x	x	x	x	x (19.7)

Pre-removal changes in bed sediment

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 percent, 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.

Post-removal changes in bed sediment

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 sediment, while DS3 experienced significant deposition of fine sand and silt (Figure 7, 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 4 mm. As of our last bed sample, 506 days since removal, particle sizes remain significantly finer than pre-removal surveys across DS1, DS2, and DS3. As expected, no significant change in particle size distribution or D_{50} was detected at US1 and US2 (Table 3).

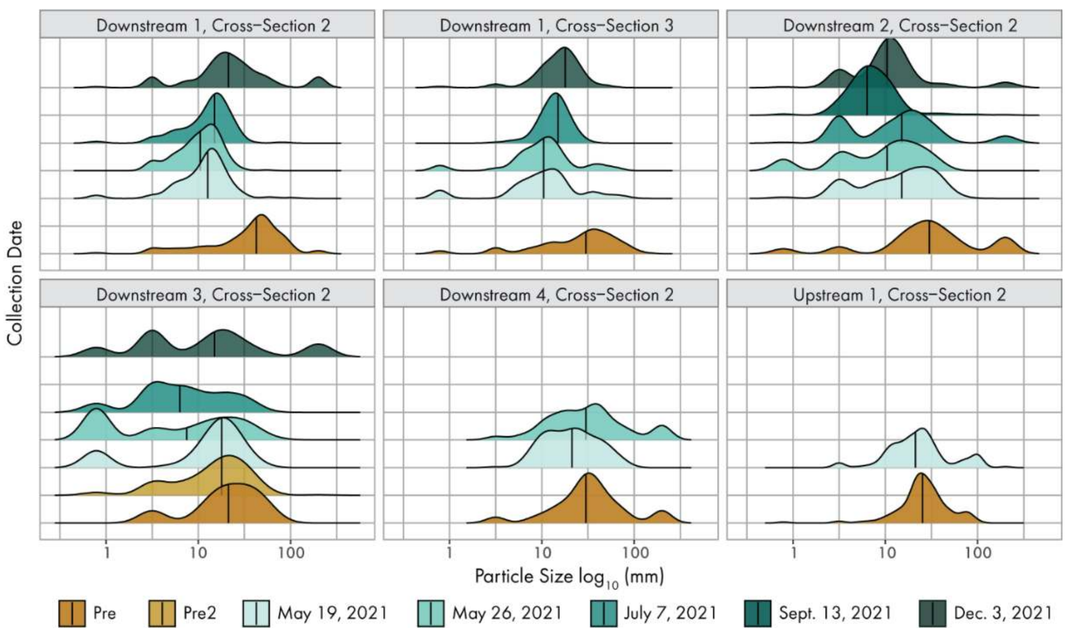

Figure 7. Particle size distribution density plots of the middle cross-section(s) of each site where post-removal collections were possible. Vertical black bar on each plot represents median particle size (D_{50}).

Only one pebble count was conducted in the impoundment area, where D_{50} was 32 mm, 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, exposing colluvial boulders and bedrock.

Table 3. D_{16}, D_{50}, and D_{84} of sites with repeated pre- (grey rows) and post-removal collections and results of the Dunn Test on particle distribution. 'Sign. Pre' meaning significant from pre-removal baseline and 'Sign. Prior' meaning significant from prior in-situ measurement.

Site	*Date*	*n*	*D_{16}*	*D_{50}*	*D_{84}*	*Sign. Pre*	*Sign. Prior*
US1-XS2	*2020_11_18*	*160*	*22.6*	*64*	*200*		
US-1XS2	*2021_08_30*	*160*	*16*	*45*	*180*	*0.151*	*0.151*
US2-XS2	*2020_08_19*	*160*	*16*	*90*	*700*		
US2-XS2	*2022_10_05*	*160*	*22.6*	*90*	*2900*	*0.144*	*0.144*
DS1-XS2	*2020_08_26*	*120*	*16*	*180*	*500*		
DS1-XS2	*2021_05_19*	*160*	*4*	*16*	*32*	*0.000*	*0.000*
DS1-XS2	*2021_05_26*	*160*	*2.8*	*11*	*22.6*	*0.000*	*0.776*
DS1-XS2	*2021_07_06*	*160*	*4*	*22.6*	*45*	*0.000*	*0.027*
DS1-XS2	*2021_12_03*	*155*	*11*	*45*	*256*	*0.023*	*0.000*
DS1-XS3	*2020_08_26*	*160*	*8*	*90*	*300*		
DS1-XS3	*2021_05_19*	*160*	*2.8*	*11*	*32*	*0.000*	*0.000*
DS1-XS3	*2021_05_26*	*160*	*4*	*11*	*32*	*0.000*	*0.690*
DS1-XS3	*2021_07_06*	*160*	*11*	*22.6*	*32*	*0.000*	*0.006*
DS1-XS3	*2021_12_03*	*160*	*11*	*32*	*64*	*0.000*	*0.108*
DS2-XS2	*2020_11_07*	*160*	*16*	*90*	*2000*		
DS2-XS2	*2021_05_20*	*160*	*1*	*22.6*	*128*	*0.000*	*0.000*
DS2-XS2	*2021_05_26*	*160*	*1*	*11*	*64*	*0.000*	*0.124*
DS2-XS2	*2021_07_06*	*160*	*1*	*22.6*	*90*	*0.000*	*0.138*
DS2-XS2	*2021_09_13*	*160*	*2*	*4*	*11*	*0.000*	*0.000*
DS2-XS2	*2021_12_03*	*160*	*1*	*11*	*32*	*0.000*	*0.002*
DS2-XS2	*2022_10_05*	*160*	*5.6*	*16*	*32*	*0.000*	*0.152*
DS3-XS2	*2020_06_14*	*160*	*11*	*45*	*180*		
DS3-XS2	*2020_11_28*	*160*	*2*	*32*	*90*	*0.037*	*0.037*
DS3-XS2	*2021_05_20*	*160*	*0.062*	*32*	*64*	*0.000*	*0.155*
DS3-XS2	*2021_05_26*	*160*	*0.062*	*5.6*	*90*	*0.000*	*0.000*
DS3-XS2	*2021_07_06*	*160*	*1*	*4*	*45*	*0.000*	*0.781*
DS3-XS2	*2021_12_03*	*160*	*1*	*22.6*	*180*	*0.000*	*0.018*
DS3-XS2	*2022_10_05*	*160*	*1*	*2.8*	*22.6*	*0.000*	*0.000*
DS4-XS2	*2020_09_23*	*160*	*22.6*	*90*	*478*		
DS4-XS2	*2021_05_20*	*160*	*11*	*45*	*180*	*0.000*	*0.000*
DS4-XS2	*2021_12_03*	*156*	*15*	*90*	*600*	*0.917*	*0.002*

DISCUSSION

Repeated field collections within the first six months following the removal of Ward's Mill Dam allowed us to capture immediate channel responses within the reservoir and downstream reaches. The ensuing period of elevated flows during the deconstruction period allowed for rapid erosion rates (860 m^3/day) and the evacuation of 29.1 percent of the estimated impounded sediment, with 23.9 percent trapped and stored within 200 m downstream (Figure 4b, Table 2). Degradation of the bedform and channel banks (both consisting of gravel) were so rapid they were visibly eroded and transported downstream. During the next survey interval (6-21 days post), erosion rates decreased substantially to 53.3 m^3/day with discharge levels in the range of ~3 to 30 m^3/s (Figure 4a, Table 2), but continued incision exposed the bedrock base level and the dam site and created a -1.93 percent channel gradient within the former reservoir. Pizzuto (2002) hypothesized that gravel dominated impoundments would only respond to high flow events ('event-driven'), while sand dominated impoundments will respond to the mechanism of incision and are not dependent on high flows ('process-driven'). Pearson et al (2011) and Collins et al (2017) tested the conceptual model proposed by Pizzuto and found that sand dominate impoundments respond as both process- and event-driven systems, with channel evolution rates much faster than hypothesized. Both studies show the transition from process- to event-driven erosion occurs after ~50% of impounded sediment is exhumed. East et al (2018) further tested, elaborated on, and supported the conceptual model from Collins et al (2017) using the Elwha River's response to the Glines Canyon and Elwha Dam removals. Our observations of the Watauga River's response to the removal of the Ward's Mill Dam give further evidence that a predominantly gravel impoundment will also respond as a process-driven system and will respond as such across a range of channel gradients and low flow rates (Kibler et al. 2011, Major et al. 2012). In addition, much of impoundment sediment erosion will occur soon after a dam is removed regardless of particle size, discharge rates, or physiographic region (Major et al. 2017, East et al. 2018). Note in particular the below mean daily average discharge during the first survey interval which corresponds to the most rapid erosion rate of the study (Figure 4a, 4b).

Albeit a higher dam and larger reservoir, Major et al. (2012) also documented rapid erosion during modest flows of a 50/50 gravel and sand impoundment stored above the 12 m high Marmot Dam in Oregon. Along with the Marmot Dam, other removals monitored for longer durations in varying physiographic provinces (Pearson et al. 2012, Collins et al. 2016, East et al. 2018, Magilligan et al. 2021), show that the rapid erosion experienced during an initial process-driven response will exponentially decline and transition to an event-drive adjustment phase. This means that as the energy from the headward erosion within the reservoir decreases, and as the downstream sediment pulse winnows, larger discharges become necessary to move distal sediment downstream.

Pearson et al. (2011) tested the two-phase model conceptualized by Pizzuto (2002) after noticing their observed reservoir erosion rates following the Merrimack Village Dam removal deviated substantially from a single-phase exponential model, specifically with much faster erosion rates of the first 52 percent of impounded sediment. A single-phase exponential model of the Ward's Mill erosion data suggests two possible trajectories; the transition to an event driven phase occurred (1) at 21 days or (2) after the flow-event associated with Tropical Storm Fred. The single-phase exponential curve only noticeably deviates from observations between the first two survey intervals (0 -5 d, 6-21 d), indicating a potentially different response than latter intervals (Figure 4b). However, Tropical Storm Fred delivered discharge rates (185 m^3/s) just over a two-year flood event (174 m^3/s) ninety-five days following the removal (Figure 4a). During this survey interval (75-103 d) impoundment erosion rates declined, and DS1 storage continued to decrease but cross-sectional area increased only within our range of pre-removal variability. If the response of the

Watauga River is in fact in an event-driven adjustment phase, this suggests discharges greater than a 2-year recurrence interval is needed for increased sediment transport. To definitively show whether the response of the Ward's Mill Dam could be explained by this two-phase model, observations over a larger temporal scale are necessary.

During the initial six-week post-removal period, the transport of impounded particles redistributed throughout the 2 km downstream study reach, with particle sizes and sediment volume decreasing with distance, resulting in a significant net decrease in cross-section area (aggrading) 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 flume and field research has suggested that a pulse of sediment on gravel-bed rivers translates as waves through the downstream reach (Madej & Ozaki 1996, Pryor et al. 2011). This appears to be the case within the first 200m downstream and potentially could have translated further downstream in the absence of the mid-channel bar ~145m from the dam. Significant sediment accumulation occurred at the mid-channel bar where the upstream pulse was temporarily trapped, allowing degradation to occur slowly from the crest of the pulse in a process called dispersion (Lisle et al. 2001). Downstream particle size and cross-sectional surveys suggests the sediment regime beyond the mid-channel bar follows this dispersive pattern with no evidence of a wave translation, even at elevated flows. Pizzuto (2002) states a combination of dispersion and wave translation are possible and highlights the ecological impacts of both, with dispersion having greater temporal impact albeit much smaller spatial impact within the study reach.

After 506 days, downstream bed texture has remained significantly finer with D_{50} decreasing with distance from the dam. Egan (2001) and Kibler et al (2011) observed similar impacts of downstream deposition where former cobble beds and hardpan remained buried under a mixture of sand through gravel sized particles after 11 months of monitoring. Several studies reflect our findings of the impacts of bed texture fining with distance downstream, particularly within the first 2 km (Kibler et al. 2011, Tullos et al. 2014). Although sediment volume decreased with distance, significant deposition of fine sediments was observed in backwater areas and interstitial spaces (Draut and Ritchie 2015). 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 the low-water bridge continued to create a backwater effect into DS3's positive channel slope. This storage was exaggerated due to the dam removal which increased loads of fines and sand sized particles. In contrast, downstream of 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 (Figure 7). The presence of the low-water bridge presents a lingering impact on DS3 through 506 days post-removal.

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 sediment is transported and deposited downstream will better support dam removal management strategies in the future, particularly those related 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.

CONCLUSION

Our BACI study provides valuable information for future planning and implementation of future dam removals on rivers of the Blue Ridge physiographic region. This study suggests that this style of dam removal, which involves no dredging of sand to coarse gravel sized reservoir sediments (1-63 mm) prior to removal, results in a fining of bed sediment at least within 2 km downstream of the dam, and an infilling of channel features within 1 km downstream of the dam over the course of at least one-year post-removal. Further, our high temporal resolution was adequate to (1) capture the translation of the sediment pulse to within 145 m where the mid-channel bar then aided in the dispersion of sediment; (2) calculate erosion rates of reservoir sediment transport and downstream deposition; and (3) determine the pre-removal cobble bed in the downstream reaches remain buried under formerly impounded gravel sized sediment 506 days into the post-removal period. Understanding the migration rate of the finer sediment wave (~16 m/day), and further monitoring of the dispersion rates of coarser sediment size classes, could be very important for planning the timing of future removals in the region in attempt to minimize the impact to certain habitats at specific times of the year. Overall, our findings are consistent with some of the most important findings from other dam removal studies. Our observations indicate that, following a dam removal, mobilization and transport of a predominantly gravel impoundment happens quickly under low discharge conditions and does not require flood events for reservoir exhumation.

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. This study is reporting the same geomorphic responses found in previous literature, albeit in a hydrologically and geographically different region than previously represented in BACI studies. While this study may contribute to the existing literature, it is obvious the sediment transport is still in flux. All sites downstream of the dam still currently show finer sediments than the pre-removal condition, however, the size distributions are on a trajectory toward pre-removal conditions. Channel geometries within 1 km of the dam on the other hand remain significantly changed, with no current sign of stabilization or a return to pre-removal geometry. Thus, our on-going monitoring is necessary to understand how these areas within 1 km downstream of the former impoundment will either (1) approach pre-dam conditions, or (2) establish a new equilibrium channel condition.

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REFERENCES CITED

American Rivers. 2023. Database of U.S. dam removals, https://figshare.com/articles/dataset/American_Rivers_Dam_Removal_Database/5234068. Accessed on 18 October 2023.

ASCE. 2009. 2009 Report Card for America's Infrastructure, Facts about Dams, p. 14-23. https://www.infrastructurereportcard.org/2009/sites/default/files/RC2009_dams.pdf

Bellmore, J., Duda, J.J., Craig, L.S., Greene, S.L., Torgersen, C.E., et al. 2017. Status and Trends of Dam Removal Research in the United States. *Wiley Interdisciplinary Reviews: Water* 4 (2): e1164. https://doi.org/10.1002/wat2.1164.

Bellmore, J., Pess, G.R., Duda, J.J., O'Connor, J.E., East, A.E., et al. 2019. Conceptualizing Ecological Responses to Dam Removal: If You Remove It, What's to Come? *BioScience* 69 (1): 12–14. https://doi.org/10.1093/biosci/biy152.

Collins, M.J., Snyder, N.P., Boardman, G., Banks, W.S.L., Andrews, M., et al. 2017. Channel Response to Sediment Release: Insights from a Paired Analysis of Dam Removal. *Earth Surface Processes and Landforms* 42 (11): 1636–51. https://doi.org/10.1002/esp.4108.

Draut, A.E., and Ritchie, A.C. 2015. Sedimentology of New Fluvial Deposits on the Elwha River, Washington, USA, Formed During Large-Scale Dam Removal**.** *River Research and Applications* 31 (1): 42-61. https://doi-org.proxy006.nclive.org/10.1002/rra.2724

Diessner, N.L., Ashcraft, C.M., Gardner, K.H., and Hamilton, L.C. 2020. I'll Be Dammed! Public Preferences Regarding Dam Removal in New Hampshire. *Elementa: Science of the Anthropocene* 8 (1): 003. https://doi.org/10.1525/elementa.003.

Dinno, A. 2017. dunn.test: Dunn's Test of Multiple Comparisons Using Rank Sums. https://CRAN.R-project.org/package=dunn.test.

East A.E., Pess G.R., Bountry J.A., Magirl C.S., Ritchie A.C., et al. 2015. Large-scale dam removal on the Elwha River, Washington, USA: river channel and floodplain geomorphic change. *Geomorphology* 228: 765–786. https://doi:10.1016/j.geomorph.2014.08.028.

East, A. E., Logan, J. B., Mastin, M. C., Ritchie, A. C., Bountry, J. A., et al. 2018. Geomorphic evolution of a gravel-bed river under sediment-starved versus sediment-rich conditions: river response to the world's largest dam removal. *Journal of Geophysical Research, Earth Surface*, 123, 3338–3369. https://doi.org/10.1029/2018JF004703.

East, A. E., Harrison, L. R., Smith, D. P., Logan, J. B., & Bond, R. M. 2023. Six years of fluvial response to a large dam removal on the Carmel River, California, USA. *Earth Surface Processes and Landforms* 48: 1487-1501. https://doi.org/10.1002/esp.5561.

Egan, J. 2001. Geomorphic effects of dam removal on the Manatawny Creek, Pottstown, PA. Master's thesis*.* Department of Geology, University of Delaware, Newark.

Grabowski, Z.J., Chang, H., and Granek, E.F. 2018. Fracturing Dams, Fractured Data: Empirical Trends and Characteristics of Existing and Removed Dams in the United States. *River Research and Applications* 34 (6): 526–37. https://doi.org/10.1002/rra.3283.

Harris, N and Evans, JE. 2014. Channel evolution of sandy reservoir sediments following low-head dam removal, Ottawa River, northwestern Ohio, U.S.A. *Open Journal of Modern Hydrology* 4: 44–56. http://dx.doi.org/10.4236/ojmh.2014.42004.

Hart, D.D., Johnson, T.E., Bushaw-Newton, K.L., Horwitz, R.J., Bednarek, A.T., et al. 2002. Dam Removal: Challenges and Opportunities for Ecological Research and River Restoration. *BioScience* 52 (8): 669–81. https://doi.org/10.1641/0006-3568(2002)052[0669:DRCAOF]2.0.CO;2.

Kibler, K., Tullos, D.D., and Kondolf, M. 2011. Evolving Expectations of Dam Removal Outcomes: Downstream Geomorphic Effects Following Removal of a Small, Gravel-Filled Dam. *Journal of the American Water Resources Association* 47 (2): 408–23. https://doi.org/10.1111/j.1752-1688.2011.00523.x.

Lisle, T.E., Cui, Y., Parker, G., Pizzuto, J.E., and Dodd, A.M. 2001. The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers. *Earth Surface Processes and Landforms*. 26: 1409-1420. https://doi-org.proxy006.nclive.org/10.1002/esp.300

Madej, M.A., and Ozaki, V. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California. *Earth Surface Processes and Landforms.* 21: 911-927.

Magilligan, F. J., Nislow, N.H., Kynard, B.E., and Hackman, A.M. 2016. Immediate Changes in Stream Channel Geomorphology, Aquatic Habitat, and Fish Assemblages Following Dam Removal in a Small Upland Catchment. *Geomorphology* 252: 158–70. https://doi.org/10.1016/j.geomorph.2015.07.027.

Magilligan, F. J., Nislow, K.H., Dietrich, J.T., Doyle, H., and Kynard, B.E. 2021. Transient versus Sustained Biophysical Responses to Dam Removal. *Geomorphology* 389: 107836. https://doi.org/10.1016/j.geomorph.2021.107836.

Major, J.J., East, A.E., O'Connor, J.E., Grant, G.E., Wilcox, A.C., et al. 2017. Geomorphic Responses to Dam Removal in the United States - a Two-Decade Perspective. *Gravel-Bed Rivers: Process and Disasters*, no. June: 355–83. https://doi.org/10.1002/9781118971437.ch13.

Major J.J., O'Connor J.E., Podolak C.J., Keith M.K., Grant G.E., et al. 2012. Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam. In US Geological Survey Professional Paper 1792. US Government Printing Office: Washington, DC; 64.

Pearson, A.J., Snyder, N.P., and Collins, M.J. 2011. Rates and Processes of Channel Response to Dam Removal with a Sand-Filled Impoundment. *Water Resources Research* 47 (8). https://doi.org/10.1029/2010WR009733.

Pizzuto, J.E. 2002. Effects of Dam Removal on River Form and Process. *BioScience* 52 (8): 683-691. https://doi.org/10.1641/0006-3568(2002)052[0683:EODROR]2.0.CO;2

Poulos, H.M., Miller, K.E., Kraczkowski, M.L., Welchel, A.W., Heineman, R., et al. 2014. Fish Assemblage Response to a Small Dam Removal in the Eightmile River System, Connecticut, USA. *Environmental Management* 54 (5): 1090–1101. https://doi.org/10.1007/s00267-014-0314-y.

Pryor, B.S., Lisle, T.E., Montoya, D.S., and Hilton, S 2011. Transport and storage of bed material in a gravel-bed channel during episodes of aggradation and degradation: a field and flume study. *Earth Surface Processes and Landforms* 36, 2028–2041. https://doi-org.proxy006.nclive.org/10.1002/esp.2224

R Core Team. 2020. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.r-project.org/.

Sheldon, A. O., Barnett, A., and Anderson, M.G. 2015. A Stream Classification for the Appalachian Region. The Nature Conservancy, Eastern Conservation Science, Eastern Regional Office:162.

Southeast Aquatic Resources Partnership. 2022. Aquatic Barrier Prioritization Tool. USA. https://connectivity.sarpdata.com/priority.

Tullos, D.D., Finn, D.S., and Walter, C. 2014. Geomorphic and Ecological Disturbance and Recovery from Two Small Dams and Their Removal. *PLoS ONE* 9 (9). https://doi.org/10.1371/journal.pone.0108091.

U.S. Congress. 2021. Infrastructure Investment and Jobs Act. Public Law 117-58, U.S. Statutes at Large 135. https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

U.S. Congress. 2021. Twenty-First Century Dams Act. H.R. 4375. 117th Cong., 1st sess. Introduced in House July 15th, 2021. https://www.congress.gov/bill/117th-congress/senate-bill/2356/actions.

Wieferich, D.J., Duda, J., Wright, J., Uribe, R., Beard J. 2021. drip-dashboard Version 2.3.2. U.S. Geological Survey software release. https://doi.org/10.5066/P9UNIWKF.

Wigginton, E. 1980. *Foxfire 6: Shoemaking, Gourd Banjos, and Songbows, One Hundred Toys and Games, Wooden Locks, a Water Powered Sawmill, and Other Affairs of Just Plain Living*. Anchor Press/Doubleday.

Wildlands Engineering, Inc. 2020. *Ward Mill Dam Removal Project: Tier 1 Sediment Evaluation*. US Fish and Wildlife Service.

Wolman, M. G. 1954. A method of sampling coarse river-bed material. *Eos, Transactions American Geophysical Union* 35 (6):951–956.

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