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Transient versus sustained biophysical responses to dam removal

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Dams fragment the longitudinal flux of sediment and obstruct fish passage. To help remediate these impacts, dam removal has become an important tool in the river restoration toolkit. Scientifically, these removals also provide an important experimental design, fixed in time and space, to quantify geomorphic and ecological responses to removal of a disturbance. Using the removal of a 6 m high dam in Massachusetts (USA), we quantify the immediate and subsequent channel and ecological recovery to test whether the immediate ecological/geomorphic responses were sustained or transient. Initial geomorphic adjustments have been generally sustained since removal, especially for bed sediment size, where initial fining and reduction in bed caliber size has been maintained over the course of the study. Sampling of transported passive integrated transponder (PIT) tagged clasts indicates that the median of bedload grain sizes now corresponds to surface median grain sizes below the former dam. Channel cross-sectional area varied irregularly downstream initially but is now spatially uniform. Pool filling, however, has been a transient response as initial aggradation shifted to sediment evacuation. Ecologically, upstream establishment of resident fish species previously restricted to below-dam locations occurred in the first year after removal. Upstream expansion increased upstream species richness and has been maintained throughout the study period, in spite of the variability in presence and abundance of rare and migratory species such as the anadromous Sea lamprey (*Petromyzon marinus*). In contrast, a reduction in abundance of resident species in dam proximal sites in 2012 appears to be a transient response to abrupt and intense bed movement associated with removal of the dam, as numbers recovered and, in some cases, exceeded pre-dam removal levels. Overall, we found that immediate (within the first 1–2 yr), sustained effects on geomorphology and ecology dominated the response to dam removal in this system, a finding that may be generally applicable to small dam removals in upland catchments.

1. Introduction

Human impacts on river systems over the past decades have profoundly disturbed fluvial and ecological systems (Gregory, 2006; Downs and Piégay, 2019; Macklin and Lewin, 2019; Grill et al., 2019) driven by the multiple stressors of damming, hydrological change, introduction of non-native species, urbanization, and sediment mining (Best, 2019). To help combat these anthropogenic effects, scientists and watershed managers have developed various approaches to restore rivers, but many scientists fear that the science remains somewhat uncertain and that the practice of river restoration may be outpacing the scientific knowledge (Wohl et al., 2005; Wohl, 2005; MacVicar et al., 2015; Rubin et al., 2017; England and Wilkes, 2018). Part of the scientific uncertainty results from the lack of biophysical monitoring that plagues river restoration assessments. In a national compilation across a range of restoration activities (e.g., bank stabilization, channel reconfiguration, etc.), Bernhardt et al. (2005, 2007) document that less than 10% of the >37,000 projects in their river restoration database had any monitoring of any kind. This lack of monitoring is equally evident with dam removals, where over 1700 dams have been removed nationally over the past several decades (O'Connor et al., 2015; American Rivers, 2021), yet with minimal post-removal assessments. Only 139 of these removals had any ecological or geomorphic monitoring, and fewer than half of those included before- and after-removal studies, with only 35 having combined geomorphic and ecological assessments (Bellmore et al., 2016). More importantly, only ~35% of these post-removal studies extended beyond the second year (Bellmore et al., 2016).

This lack of monitoring has major implications for watershed management. Dam removals represent large-scale experiments offering a rare opportunity to understand the dynamics of fluvial systems beyond

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the reach or plot scale typical of most studies (Magilligan et al., 2016a). Moreover, understanding the ecological and geomorphic responses to dam removal can establish the necessary protocols and strategies for pending dam removals and can serve to coordinate management efforts to meet desired conservation and restoration goals. Biophysical responses to removal may be complex (Sawaske and Freyberg, 2012; Grant and Lewis, 2015) and may generate unanticipated effects (Sethi et al., 2004), and the uncertainty about correctly predicting potential outcomes clouds the decision-making process (Tullos et al., 2016; Magilligan et al., 2017; Bellmore et al., 2019), underscoring the need for post-removal monitoring. Sustained monitoring is particularly important because immediate post-removal responses may not represent long-term outcomes, as the decay of the dam-removal signal may occur over timescales of years (Major et al., 2017, 2019).

In many ways, the science of dam removal should be relatively straightforward geomorphologically: the impoundment is removed, gravity and flow hydrodynamics take over ultimately releasing stored water and sediment from the former reservoir, and the channel begins establishing a new equilibrium – perhaps even to its pre-dam condition. Although first principles control the resulting geomorphic processes, considerable uncertainty orbits around the magnitude and timing of released sediment, the extent and rate by which the former reservoir will be evacuated, the thickness, bed texture, and spatial extent of sediment aggradation downstream, and the associated changes in turbidity (Pizzuto, 2002; Doyle et al., 2002, 2003; Sawaske and Freyberg, 2012; Grant and Lewis, 2015; Tullos et al., 2016; Collins et al., 2017; Cashman et al., 2021). Post-removal assessments suggest that sediment evacuation from the former reservoir can be rapid and robust with upwards of 50% of the previously stored sediment being evacuated within the first year even in the absence of large post-removal flow events (Sawaske and Freyberg, 2012; Major et al., 2012; Grant and Lewis, 2015; Major et al., 2017; Ritchie et al., 2018). The rate and extent of knickpoint migration varies depending on grain size, gradient, and extant reach boundary conditions (Major et al., 2008; Gartner et al., 2015), therefore, predicting the spatial extent of downstream sediment pulses remains poorly documented or constrained (Grant and Lewis, 2015; Bellmore et al., 2016; Cashman et al., 2021).

Understanding post-removal sediment dynamics is critically important geomorphologically as sediment flux controls a suite of morphologic properties, but it can also be a first order control on ecological attributes as sediment size and supply can determine fish habitat suitability (e.g., for nesting materials, cover, and shelter) (Beechie and Sibley, 1997; Pasternack et al., 2008; Peters et al., 2017), the structure and function of benthic invertebrate assemblages (Jowett, 2003; Morley et al., 2020), hyporheic flows (Packman et al., 2004), and other biogeochemical properties (Lake et al., 2000). Complex and time-dependent mechanisms are also characteristic of ecological responses to dam removal. Like some of the geomorphic responses described previously, and in many cases closely linked to them, ecological effects span a range of time scales. At one extreme, resident fish have been observed to move upstream of dam locations rapidly, sometimes within days (Watson et al., 2018; Bellmore et al., 2019). In contrast, changes in habitat quantity or quality in response to dam removal may have substantial lag times, given the time necessary for habitat features (for example, sinuous planforms and associated spawning gravel deposits, scour pools, and floodplain surfaces) to develop, and additional time may be needed for these positive effects to be manifest in terms of population vital rates (growth, survival and recruitment) of target species (Minns et al., 1996). Ecological responses may in some cases not just take time to develop, but can change direction, thereby representing a source of process uncertainty. For example, the major and rapid changes in sediment supply following dam removal can result in substantial streambed movement and instability. In the long-term, this reconnection of sediment supply and adjustment of the stream planform can have beneficial effects on habitats and ecosystems (Peters et al., 2017). In the short-term, however, intensive bed reorganization and movement can disrupt ecologic processes and negatively influence populations via catastrophic displacement and mortality (Nislow et al., 2002; Sethi et al., 2004; Magilligan et al., 2016b; Morley et al., 2020), or via rapid infilling of interstitial spaces in gravel-bedded streams and rivers, which are critical habitat for benthic fishes and invertebrates, as well as for gravel-nesting species such as trout and salmon. Conversely, while fish may rapidly recolonize above the site of the removed dam, changes in upstream community composition can result in novel species interactions (involving competition, predation, parasitism) whose long-term effects are difficult to predict (Peterson et al., 2008; Kornis et al., 2014).

In addition to these sources of process uncertainty, challenges in detecting time-dependent responses can also result from observation uncertainty. For example, high levels of inter-annual variability in the population vital rates of stream fishes and invertebrates substantially reduces statistical power to detect the effects of dam removal via short-term monitoring (Dauwalter et al., 2009). This is particularly the case for anadromous fish species that are frequently a major focus of dam removal, where variability in both marine and freshwater environments can result in poor return years and may not provide enough individuals to move and be observed upstream of removed dams, even when there is ready access (Pess et al., 2012). In addition, observation uncertainty in ecological targets can be the result of imperfect detection, where changes may indeed have occurred but are not observed (Benoit et al., 2018). This is particularly the case for rare or cryptic species, as well as other processes and ecological targets. Longer-term monitoring, by increasing sample size and statistical power, is therefore essential, particularly in the case of complex and time-dependent dynamics.

The goal of this paper is to add an important longer-term perspective on geomorphic and ecological responses to dam removal. In this way we are contributing a much needed longer time post-removal assessment – a significant limitation of post-project restoration studies (Bellmore et al., 2016). Moreover, the continued post-removal sampling also provides an opportunity to evaluate how well initial adjustments are progressively sustained, manifest as a transient response, or whether the new boundary conditions engender a fundamentally different "state change" of fluvial properties (Phillips, 2009, 2014; Lisenby et al., 2018). Recent attempts to conceptualize the immediate and long-term geomorphic trajectory following dam removal often allude to the "two-phased" model initially developed by Pizzuto (2002) in which he separated an immediate process-driven phase from potentially longer-term changes driven by post-removal events. His conceptual model has been validated in a range of geomorphic settings from small dam removals throughout the eastern USA (Pearson et al., 2011; Collins et al., 2017) and to large dam removals, especially the removal of the Elwha and Glines Canyon dams on the Olympic Peninsula (East et al., 2015, 2018; Ritchie et al., 2018). The two-phase model, and its mathematical articulation, provides an important characterization for geomorphic responses singularly in the former impoundment, but we prefer instead the conceptualization presented by Foley et al. (2017) that extends the spatial scope of potential geomorphic effects and that further considers potential temporal shifts in the direction of response domains (Fig. 1). Knickpoint migration and channel evolution in the former impoundment is only one of the many responses, but is generally spatially fixed to dam proximal locations. The conceptual models by Foley et al. (2017) and Bellmore et al. (2019), however, capture a suite of other geomorphic responses with many of them distal to the former dam and perhaps linked by both positive and negative feedbacks, but more importantly, frames these outcomes as either being a sustained or a transient response (Fig. 1). Thus, our specific research objectives are: (a) to quantify progressive changes in geomorphic and ecological responses; (b) to document whether channel and ecological properties change in magnitude or direction over time; (3) and, lastly, to use the dam removal as an experiment to evaluate whether the system has attained geomorphic equilibrium relative to the re-connected sediment supply.

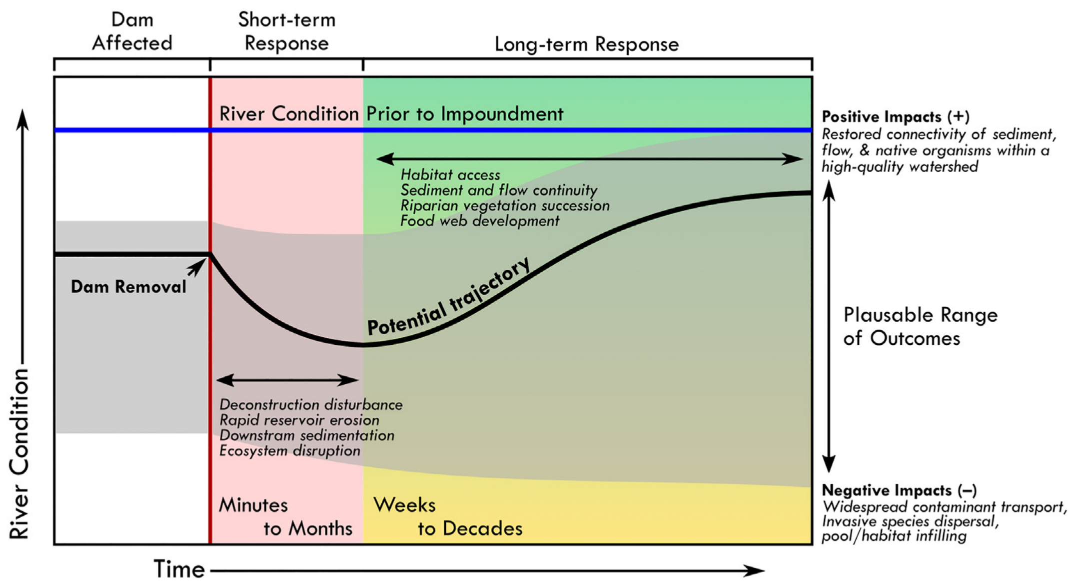

Fig. 1. Conceptual river response to dam removal indicating that the initial responses may be sustained over time or instead may be a transient response. Moreover, the range of outcomes may be positive or negative (see Grant, 2001) and for the positive responses, may change direction over time perhaps even approaching pre-dam conditions. Reprinted from Foley et al. (2017) and used with permission of the American Geophysical Union.

1.1. Background

The ca. 1820 Bartlett Rod Company Dam, a 6 m high stone block structure more commonly known as the Pelham Dam, was removed in the Fall of 2012 in part to mitigate dam safety concerns but also to achieve greater watershed connectivity. The dam site is located in the headwaters of Amethyst Brook, a tributary of the Fort River that subsequently joins the mainstem Connecticut River near Hadley, Massachusetts (MA). In preparation for the removal, the contracted consulting firm estimated ~3000 m^3 of mobile impounded sediment within the impoundment; final plans called for onsite storage of 2700 m^3 of sediment in the floodplain to be removed naturally by the channel over time (Magilligan et al., 2016b). Because headwater systems like Amethyst Brook offer important spawning habitat for diadromous fish such as Atlantic salmon (*Salmo salar*), Sea lamprey (*Petromyzon marinus*), and American Eel (*Anguilla rostrata*), as well as within-river migratory species that use both upper and lower river habitats, there is considerable regional interest in restoration efforts such as dam removal (Pess et al., 2014; Magilligan et al., 2016a) especially because only one large hydropower dam (Holyoke Dam) separates these headwater spawning habitats from Long Island Sound (Fig. 2). More than 180 dams have been removed in New England over the past several decades (Magilligan et al., 2016a; American Rivers, 2021), with Massachusetts accelerating its removal efforts since the near collapse of the Whittendon Dam on the Taunton River in 2005 (Magilligan et al., 2017) with >50 dams having been removed or slated for removal across the state since then.

Amethyst Brook is a steep (~1%) gravel-bedded stream draining 26 km^2 at the site of the former dam with an estimated 2-yr discharge of 9.8 m^3/s (water.usgs.gov/osw/streamstats/). We initiated pre-removal sampling in the summer and fall of 2012 and focused our monitoring efforts at reaches ~300 upstream of the former dam, within the former reservoir/impoundment, and ~800 m downstream of the former dam (Fig. 2). Within several months of its removal, knickpoint migration exhumed an older 2 m high wooden crib dam from the late eighteenth century that was further eroded during an intense storm in June of 2013 that generated an estimated 5–10 yr recurrence interval flood (Magilligan et al., 2016b). Although dilapidated, the crib dam (~140 m upstream of the former dam) still acted as a grade control structure limiting headwater extension of the initial knickpoint (Magilligan et al., 2016b). Because of its historical significance, it could not be removed until January 2016 until local archaeologists and historians could collect and document its structural design and components. In this way, our analyses capture a two-phase response to dam removal: from 2013 to 2015 when the Pelham Dam was removed but the wooden crib dam still remained, and post-2015 when the entire 1.1 km reach was dam free.

In our initial analysis of the responses to dam removal, we documented the geomorphic and ecological responses that occurred in 2013 following the fall 2012 removal (Magilligan et al., 2016b). As background to this longer-term monitoring presented herein, we documented significant bed fining below the former dam with 50–75% reduction in the median grain size following removal such that the post-removal downstream bed textures now correspond to upstream control reaches. At dam proximal locations, aggradation ranged from 0.3 to >1 m but gradually attenuated to negligible deposition at distal cross sections ~750 m below the former dam, with a mean depth of deposition of ~0.20 m over the downstream reach. Because of erosion to the resistant bedrock, knickpoint migration was limited and only progressed ~25 m upstream of the former impoundment. Post-removal fish surveys identified four species of fish, including Sea lamprey (*Petromyzon marinus*), which were not present above the dam prior to removal. We also documented lamprey spawning activity at sites immediately below the dam, which had previously been unsuitable owing to the pre-removal coarse and armored riverbed. We continued to monitor the site through 2016 for geomorphic adjustments and through 2017 for ecological responses following the same field and modeling protocols established previously (Magilligan et al., 2016b) to maintain consistency.

2. Materials and methods

2.1. Geomorphic methods

Because we focused on monitoring progressive changes along the reach, we re-sampled monumented sites (e.g., channel cross sections, longitudinal profiles, pebble counts, etc.) initially established in 2012 using either a robotic total station or auto level for cross-section surveys and the longitudinal profiles. Pebble counts were done using the Wolman method (Wolman, 1954) at each cross-section sampling

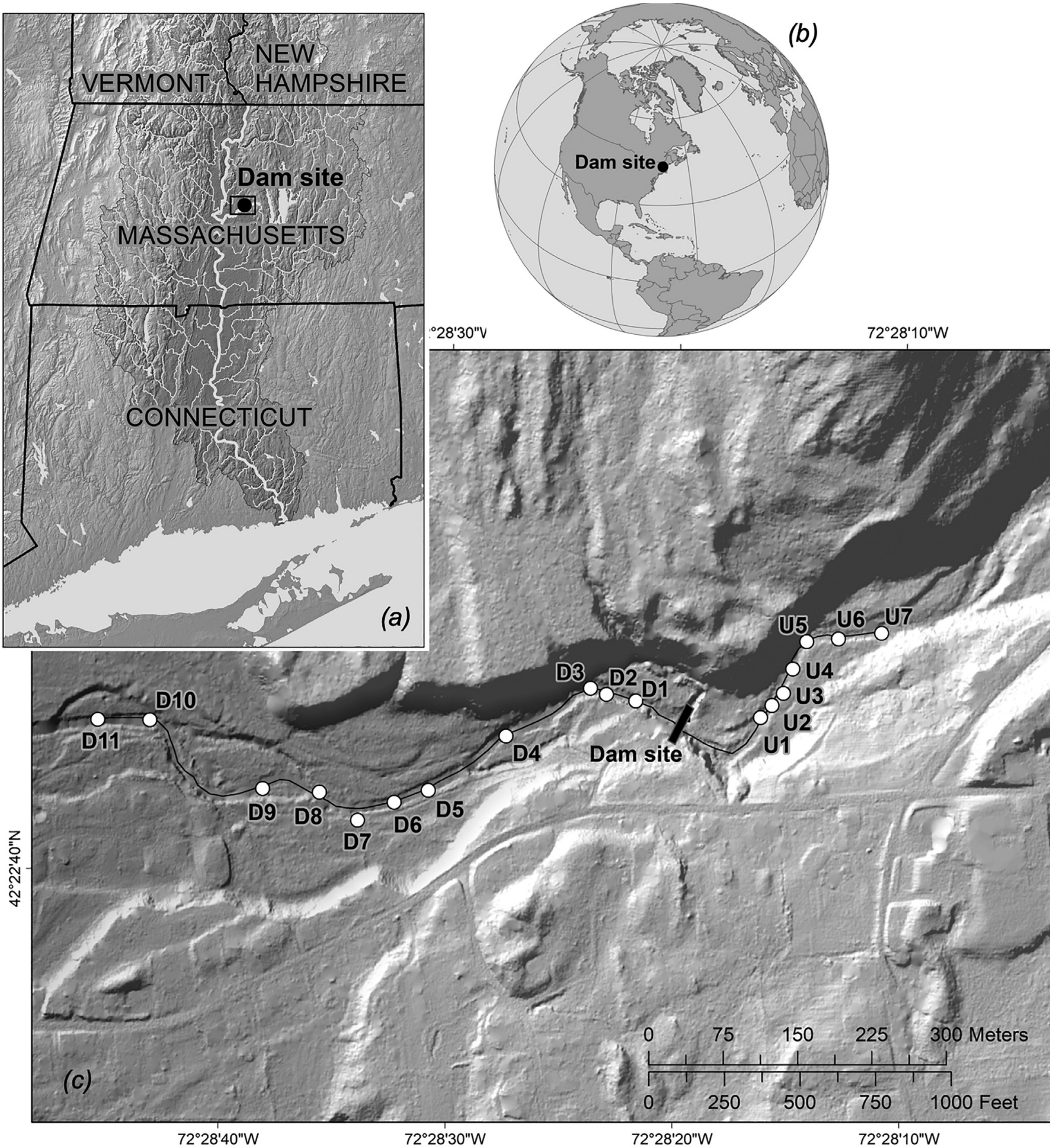

Fig. 2. Map of lower Connecticut River and location of Pelham Dam. Larger hillshade map shows the location of cross sections upstream (U) and downstream (D) of former dam.

~100 clasts per cross section, yielding ~1100 clasts per year. To better capture progressive geomorphic adjustments following the immediate Year 1 response, in subsequent years (2014–2016) we augmented initial channel surveys with high resolution topographic lidar surveys using a Riegl VZ 1000 Terrestrial Laser Scanner (TLS) concentrating sampling efforts in dam proximal reaches both upstream and downstream of the former dam, and we installed a pressure transducer in late 2015 to continuously monitor post-removal streamflow stage. In addition, we augmented topographic change detection at the wooden crib dam site with UAS (unmanned aerial system) photogrammetric surveys using a DJI Inspire 1. Because of the thick forest cover in reaches downstream of the former Pelham Dam, these UAS flights could only be conducted in the more open spaces within and directly above the former reservoir.

To maintain consistency across years, we re-occupied all eleven monumented cross sections downstream of the dam during the post-removal summers of 2013–2016 maintaining the original site identification (cross-section numbering starts as #1 near the dam and numbering increases with distance both upstream, US#1–#7, and downstream, DS#1–#11, of dam). Year 1 (2013) post-removal results indicated that the wooden crib dam's presence limited geomorphic adjustments above the former reservoir, thus the seven upstream cross sections were only re-surveyed again in 2015 and topographic measurements shifted to lidar and UAV sampling. Cross sections were surveyed, orthogonal to streamflow, with either a TOPCON Auto Level or a PENTAX Total Station. As in 2012 and 2013, we surveyed the channel bed longitudinal profile with either a TOPCON Robotic Total Station or a Topcon HiperLite RTK-GPS, sampling every 2–3 m. Downstream longitudinal profiles were resurveyed every post-removal summer (2013–2016) while the upstream profiles were only re-surveyed in 2013, 2015, and 2017.

Topographic change detection was initiated in 2014 for TLS sampling and in late 2015 for UAS measurements. All of our TLS scans were conducted in a relative coordinate system using the same tie points from year to year so they could be registered together. In the downstream reach, we used nine scan positions and seven scan positions in the upstream reach. These data were collected and the initial processing was completed in RiScan Pro. Subsequent processing was done in CloudCompare (Girardeau-Montaut, 2017). We used an affine coordinate transformation to register the different scan years together and the built-in version of M3C2 (Lague et al., 2013) to compute the geomorphic change between the different scans.

Our UAS flights were flown before the wooden crib dam was removed in early January 2016 and was re-flown repeatedly in 2016. Our flights were conducted to capture aerial photography for Structure-from-Motion (SfM) multi-view stereo photogrammetry. The photographs were captured at multiple altitudes (10–30 m) done in a radial (convergent) pattern, centered on the crib dam site. Ground control for the SfM models was established with 30 cm checkerboard targets surveyed with a Topcon Hyper-lite RTK-GPS. SfM processing was done in Agisoft Metashape Pro (v1.5) using high quality settings for all steps in the processing workflow. To calculate change between the SfM point clouds we again used the M3C2 tool (Lague et al., 2013) in CloudCompare.

Following the initial Year 1 (2013) results that revealed significant bed mobility following the re-connected sediment flux, we therefore monitored gravel transport travel distances within and downstream of the former reservoir using Radio Frequency Identification (RFID) PIT (passive integrated transponder) tagged gravels deployed in December 2015 before the crib dam was removed and sampled repeatedly in 2016 and into 2017. Because of the greater ease of detection – relative to painted rocks or other tracer methods – RFID tags are finding increased use used in geomorphic assessments (Schneider et al., 2010; Olinde and Johnson, 2015; Chapuis et al., 2015; Papangelakis and Hassan, 2016; Cassel et al., 2017; Mao et al., 2017; Galia et al., 2021). For each clast, we measured and recorded the long, intermediate, and short axis (in mm) and sliced a thin groove into each clast with a rock saw. Depending on the size of the clast, we placed either a 12 mm, 23 mm, or 32 mm long, 433 MHz half-duplex (HDX) RFID PIT tag into the groove and sealed in the tag with an exterior-grade silicone sealant. We distributed 337 clasts (see Fig. 3) at multiple locations both upstream and downstream of the former dam, including an upstream control site (XS#U7) far removed from any headcutting; in the knickpoint immediately upstream of the former wooden crib dam and the cross section immediately above the knickpoint; within the channel of the former reservoir; and along two cross sections and a bedrock-controlled scour pool downstream of the former Pelham Dam. Using a high performance LF HDX RFID backpack reader (Oregon RFID) and pole antennae we sampled after each storm or snowmelt event. To more precisely locate clasts, beginning in September 2016, we used a Trimble Geo7X GPS that, with post-processing, generated an horizontal uncertainty of <1 m. Prior to utilizing the GPS we measured distances from known control points, which was less accurate; to account for this discrepancy, we consider "movement" significant if the distance traveled was greater than bankfull width (~8 m).

To better represent the combined geomorphic and sedimentological post-removal trajectory, we used the Shields parameter (θ), which is the ratio of bed shear stress, τ, to the submerged weight of a characteristic grain size, usually D_{50}, such that:

$$\theta = \frac{\tau}{\left(\rho_s - \rho_f\right)gD} = \frac{\rho_f gSh}{\left(\rho_s - \rho_f\right)gD} = \frac{hS}{DR} \quad (1)$$

where τ is the shear stress acting on the channel bed, ρ_s is the density of the sediment (assumed to be 2.65 g/cm^3), ρ_f is the density of water, g is the gravitational acceleration, D is the characteristic grain size of the bed surface material, S is slope, and R is the relative excess density ($(\rho_s - \rho_f)/\rho_f$). Slope and depth were calculated for the bankfull discharge using HEC-RAS, a 1-D flow model developed by the Corps of Engineers that iterates to a best fit solution of hydraulic variables based upon input variables of slope, discharge, roughness, and valley and channel morphology. We measured discharge at our installed gage site to derive an initial input value for the Manning's roughness coefficient. We used the modeled output parameters slope and τ generated for each cross section for quantifying the Shields parameter. To test whether the post-removal channel is in equilibrium for mobilizing bed material, using Eq. (1), we calculate the grain size that should be mobilized at a critical Shields value. The critical Shields parameter (θ_{cr}) varies between ~0.03–0.07 (Buffington and Montgomery, 1997), and Dade and Friend (1998) documented that gravel-bed rivers are adjusted for sediment mobilization at $\theta_{cr} = 0.05$. Substituting a critical Shields parameter value of 0.05 in Eq. (1) generates the grain size that should be mobilized by a channel that has developed the requisite channel parameters and slope to entrain the median grain size mantling the bed. Lastly, in order to identify the ways in which the channels have adjusted, we examine the covariant channel adjustments over time. In an approach similar to evaluating covariant geomorphic changes to flow regulation (Schmidt and Wilcock, 2008; Curtis et al., 2010; Dade et al., 2011), we compare evolving changes in grain size, width and slope post-removal to ascertain which parameters account for most of the mutual adjustments.

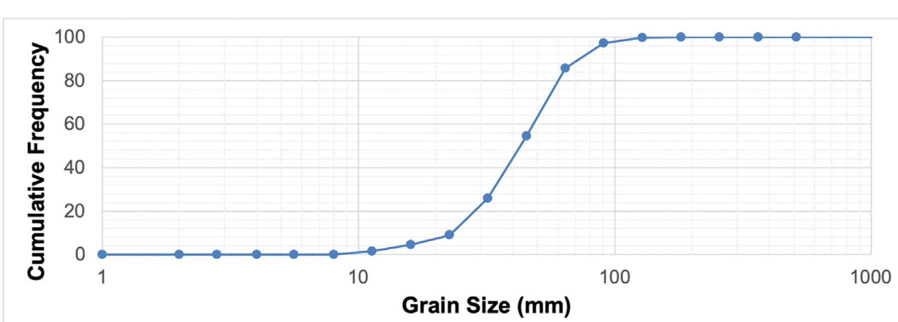

Fig. 3. Cumulative frequency plot of RFID gravel clasts deployed ($n = 337$).

2.2. Ecological methods

Fish assemblages were sampled once each year (during the second and third weeks of July) using multiple-pass electrofishing (Smith-Root Backpack Electroshocker set at 500 V Direct Current) from 2012 to 2017. Sample sections were 30 m long and situated at key points along the study reach above and below Pelham dam, as well as in spatial reference sites in neighboring tributaries of the Fort River watershed (Magilligan et al., 2016b). Of these sites, five were maintained consistently across the six years of the study and are the basis of the longer-term analyses of fish distribution and abundance. Four of these sites corresponded to geomorphic cross sections distributed across the length of the study reach and one was located in a neighboring tributary of the Fort River system.

During sampling, upstream and downstream block nets were used to prevent movement in and out of the section between electrofishing passes and fish captured during each pass were held in live wells for processing, where they were identified, weighed and measured (fork length). Abundance and density (number or biomass/sample area) of individual species was calculated using the removal method (Carle and Strub, 1978) where N (population size) and the associated confidence interval (C.I.) is a function of the number of fish captured and the rate at which the number captured declines (the depletion curve) with sequential passes. In cases where the estimator failed (generally because of inadequate depletion), we represented abundance and density based on total catch per unit effort of sampling (CPUE). For Sea lamprey (*Petromyzon marinus*) presence/absence and abundance was evaluated using standard visual nest surveys, where a single trained observer covered (on foot) all of the potential nesting habitat in Amethyst Brook, neighboring tributaries, and downstream on the mainstem of the Fort River (~3 river km).

Fish assemblage electrofishing samples approximated a Before-After Control-Impact (BACI) design (Stewart-Oaten et al., 1986). Comparisons were made between 2012 (pre-dam) vs. 2013–2017 (post-dam) samples in Impacted (dam proximal upstream and downstream) and Control (distant upstream and downstream, neighboring tributary) sites (see Magilligan et al., 2016b). For Sea Lamprey presence/absence and nest abundance, nest counts post-removal (2013–2017) were compared nest surveys conducted in 2009, 2011, and 2012 (Nislow and Kynard, 2009) in the Fort River system including Amethyst Brook.

3. Results

3.1. Geomorphic adjustments

Progressive geomorphic and ecological sampling indicates that many of the Year 1 results (Magilligan et al., 2016b) were generally sustained following the initial removal of the Pelham Dam and were not significantly affected by the removal of the wooden crib that was not removed until January 2016. Prior to the fall 2012 removal of Pelham Dam, the reach below the dam was heavily winnowed and armored, especially in dam proximal locations where median grain sizes in the first three downstream cross sections were 150 mm, 110 mm, and 120 mm, respectively, with a reach averaged D_{50} = 110 mm. Grain sizes decreased significantly immediately following removal (Magilligan et al., 2016b) with 2013 reach averaged median grain sizes of 51 mm (Fig. 4) with some coarsening and increased variability occurring after the first post-removal year, but with all sites remaining significantly finer than pre-removal particle distributions (Fig. 4).

Similarly, morphologic parameters at cross section and reach scales also changed minimally in the downstream reach following the first year's initial response to removal (Fig. 5). The progressive changes in channel cross sectional area further reveal the spatial and temporal adjustments following dam removal (Fig. 6). Major deposition in dam proximal locations, in part controlled by channel spanning large woody debris (LWD) at cross section DS#3, and a conspicuous sediment wedge ~400 m downstream by cross section DS#7 (see Fig. 14 in Magilligan et al., 2016b). At cross section DS#1, the most dam proximal location, the initial aggradational phase was subsequently followed by some incision but then channel bed filling back to the Year 1 channel bed elevation (Fig. 5) in response to the re-connected sediment supply. Subsequent years (2013–2016) reveal a progressive reduction in erosional and depositional processes, the natural removal of the LWD and its associated bar at cross section DS#3, and the erosion, probably by

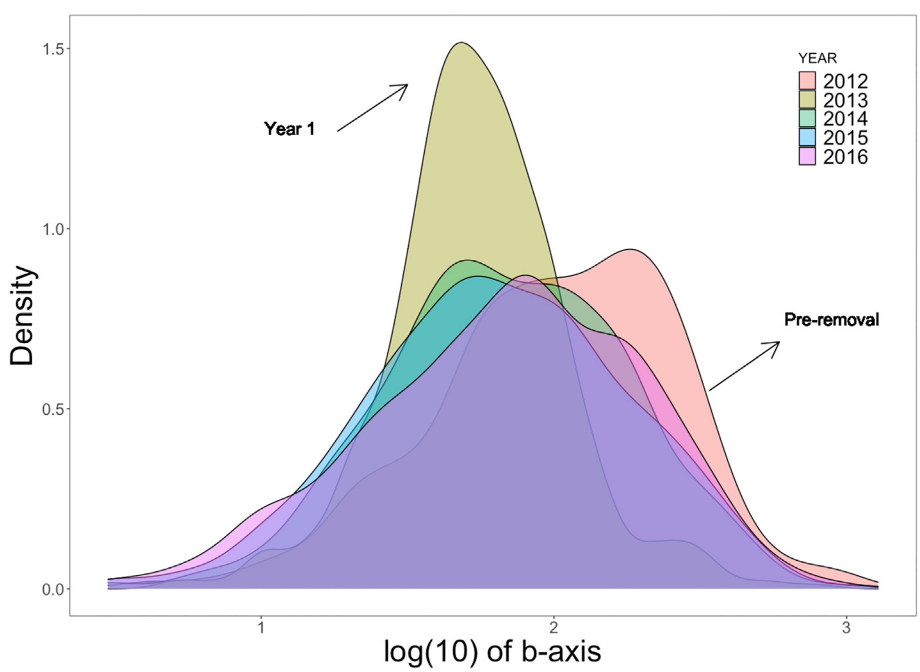

Fig. 4. Gaussian kernel density plots for the pre-removal pebble counts and for the post-removal years below the former dam. For 2012 (pre-removal), the reach-averaged median grain size was 110 mm which declined to 51 mm in 2013, the first year following removal. Grain sizes increased slightly in subsequent years (D_{50} = 68 mm in 2014, D_{50} = 62 mm in 2015, and D_{50} = 70 mm in 2016) and are generally similar (i.e., curves are indistinguishable) but remain consistently and significantly lower than the pre-removal grain size distribution.

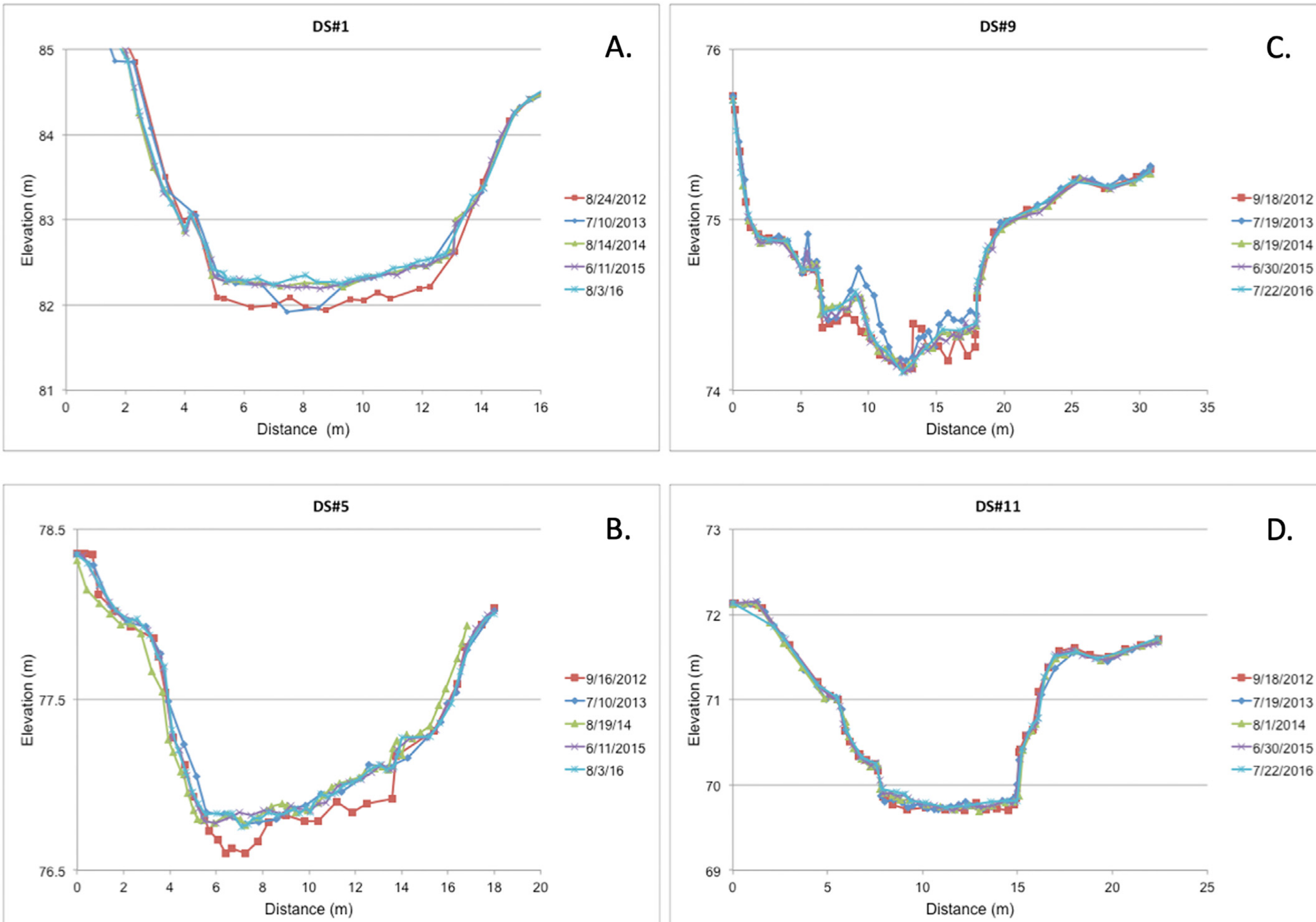

Fig. 5. Surveyed channel cross sections for select cross sections below the former dam for the pre-dam period (2012) and each subsequent year until 2016.

translation, of the sediment wedge by cross sections DS#6–DS#8 (Figs. 6 and 7). The most distal cross sections (e.g., DS#11) aggraded minimally immediately post-removal and also in subsequent years (Fig. 5D) suggesting that the sediment wedge has not translated to these most distal reaches. This sustained trend of decreased channel morphologic adjustments is more evident in the 2015–2016 interval where erosional and depositional changes have essentially abated (Fig. 6).

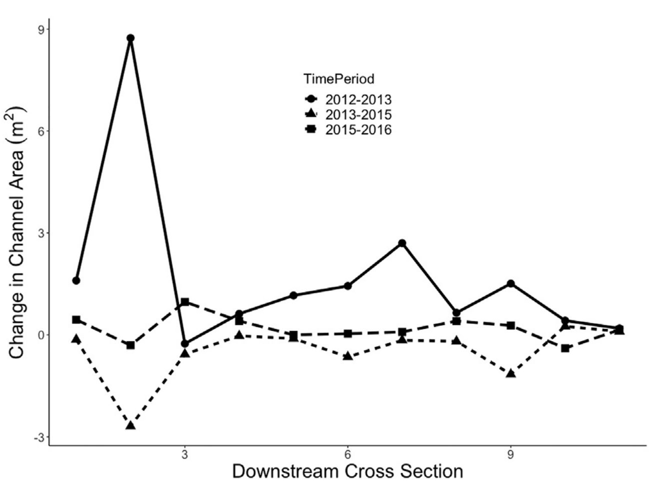

Fig. 6. Channel change (net area) over time: pre-dam (2012) to post-dam (2013); 2013–2015; 2015–2016.

We observed subtle changes in channel shape post-removal, with width-depth (W/D) ratios increasing from reach averaged median ratios of 26.8 pre-removal to 35.84 in 2015 (Fig. 7A). The variation across the reach is less generalizable as no major pattern exists other than a general increase of W/D ratios in the reach between cross sections DS#5–DS#11 (Fig. 7B). The increase in W/D ratios reflects the progressive pool-filling and channel aggradation that has made many of the downstream cross sections more symmetrical over time (e.g., cross sections DS#1 and DS#5 in Fig. 5).

Similarly, changes along the longitudinal profile further reveal minimal-to-no changes post-removal along the ~800 m downstream reach (Fig. 8). Some pools have been filled-in post removal, but the effect has been irregular over the sampling period. As part of the RFID PIT tag clast experiment, we deployed seventeen clasts (mean b-axis = 54 mm) in the deep bedrock-controlled long pool below cross section DS#3. Although bankfull flows rarely occurred post-deployment, all of the of clasts were evacuated from the pool, with two clasts (b-axis of 45 and 46 mm, respectively) transported ~75 m from their initial deployment indicating that the initial pool in-filling was a transient response. The most discernible change along the 800 m reach is the ~10 cm of incision below cross section DS#6 (~500 m downstream) that removed the initial 2013 post-removal sediment pulse (Fig. 8). This incisional phase began in 2014 and has since stabilized with bed elevations remaining relatively constant over the next two years. The post-removal re-organization of the bed further manifests in the nascent development of alternate bars in the downstream reach between cross section DS#4 and cross section DS#8 (Figs. 9 and 10). During the pre-dam removal sediment starved phase, downstream reaches generally lacked lateral bars and/or the bed lacked fines (Fig. 9A). Following removal, the re-connected sediment

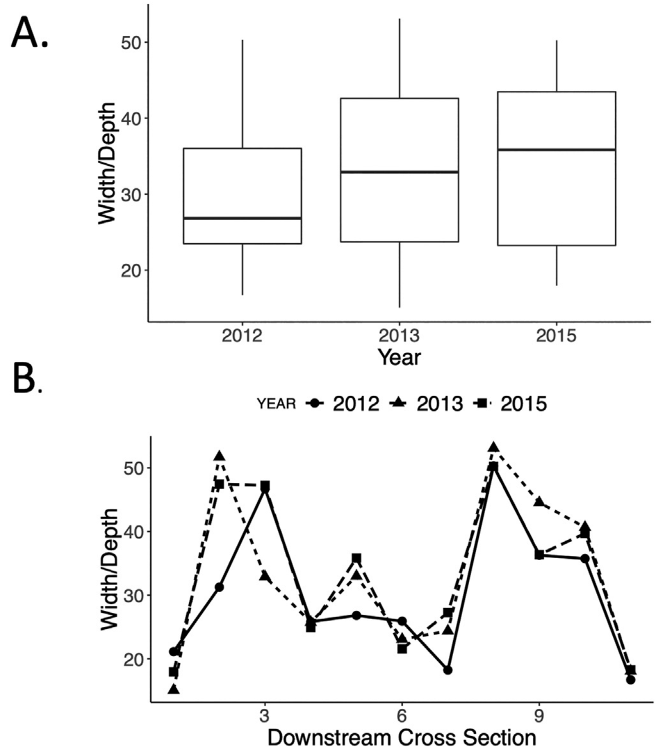

Fig. 7. Width-to-depth (W/D) ratios for cross sections below the former dam. (A) Box and whisker plots over time (2012 is pre-removal). (B) is W/D ratios for individual cross sections plotted by year.

supply has provided the necessary sediment supply and grain sizes to generate alternate bar formation (Fig. 9B), which has been sustained through 2017 (Fig. 9B).

Geomorphic changes upstream of the former dam were conditioned by the presence of the wooden crib until winter 2015–16 and its subsequent removal in early January 2016. Prior to its removal, the plunge pool directly below the dam continued to deepen to ~2 m but was immediately filled in following the removal of the wooden crib dam (Figs. 11 and 12). The removal process that extracted upstream sediment to exhume the dam left a steep riffle immediately above the crib dam. The initial slope of the riffle was 8.6% extending 14 m upstream of the dam (Fig. 12). The step nature of the riffle initiated a small knickpoint that began to headcut but has now ultimately led to a relaxation of the riffle that extends 50 m upstream of the former crib dam and now has a slope of 3.7%. Examining the CloudCompare M3C2 change maps from the initial UAV survey in January 2016, the change

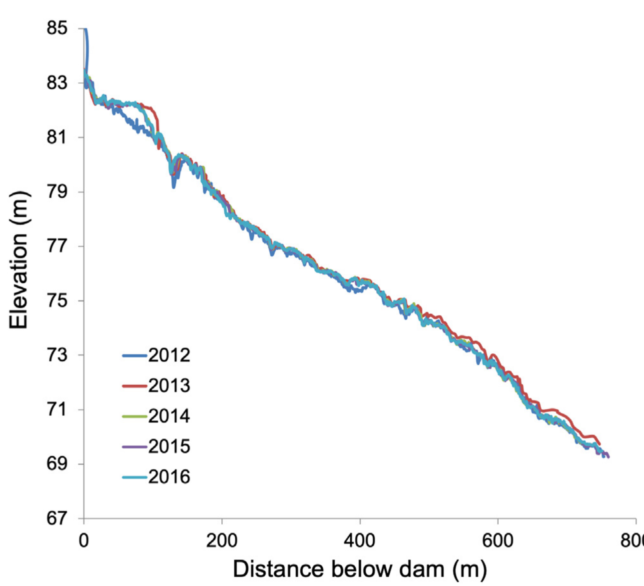

Fig. 8. Time series of the longitudinal profile downstream of former dam pre-removal (2012) and in subsequent years.

Fig. 9. View looking upstream (from cross section DS#6) during typical summer lowflow conditions. Upper photo (A) shows the winnowed and armored pre-dam (2012) bed conditions. Lower photo (B) shows the post-dam removal greater supply of fine gravels and the beginning of alternate bar formation (photo taken 2016).

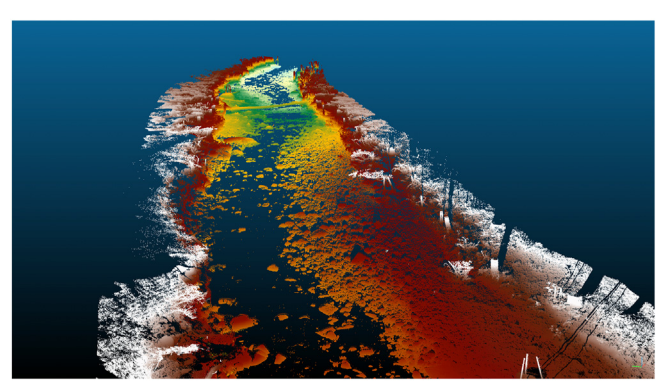

Fig. 10. Terrestrial laser scan (TLS) looking downstream towards cross section DS#6. Note incipient alternate bar formation on river right and farther downstream on river left.

Fig. 11. Photo of wooden crib dam over time. Pelham Dam was removed in fall of 2012 and the upstream knickpoint migration exhumed the previously unknown undated (ca. 1780?) wooden crib dam. Middle photo (2015) shows deep plunge pool that remained until subsequent removal of wooden crib in December 2016.

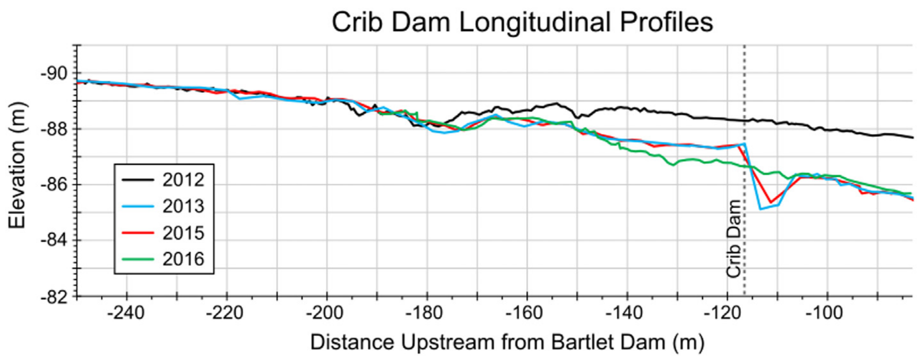

Fig. 12. Longitudinal profile above former dams.

in the first two months (January–March) was dramatic (Fig. 13). The stream widened by 6.9–10.5 m just upstream of the crib dam and the relaxation of the riffle slope (4.2% extending 33.5 m upstream) corresponded with an average erosion on the upstream side of 35 cm and average deposition of 34 cm at the crib dam.

Repeat PIT tag surveys showed the significant sediment mobility throughout most of the reaches within the first year and a half of deployment despite the lack of a significant bankfull flows (Fig. 14) through most of the sampling period with the summer/fall of 2016 being one of the driest on record for most of New England greatly limiting sediment transport. From the time of initial deployment to November 2016, 131 clasts moved significantly while 134 remained in place or had not moved beyond our detection accuracy (Fig. 15). Most of the transported clasts were in either in the 40–50 mm range or 60–70 mm bin (Fig. 15A). By July 2017, 172 clasts had moved since the November 2016 survey (Fig. 15B) including 71 that had not been previously mobilized (Fig. 15C). The predominant bin size for mobilized clasts for this period is 60–70 mm (for context, the D_{50} for the 1100 gravels counted in the 11 downstream cross sections in 2016 is 70 mm (Fig. 4)). Travel distances ranged between no movement (especially at the control site, US#7, at the most upstream deployed cross section) and a maximum of 125 m (Fig. 16). Grains larger than 100 mm never traveled farther than 10 m, yet grain size had minimal effect on travel distances as there is tremendous scatter in the relationship between grain size and travel distance (Fig. 16). Importantly, several clasts moved from above the old dam to reaches below the removed dam signaling the re-connected post-removal sediment supply.

3.2. Ecological adjustments

Over the six years of sampling, >7000 individual fish representing 16 species were collected from the five study sites, 12 of which are native to the Connecticut River basin. The relatively high diversity reflects the occurrence of fishes' characteristic of a range of habitats (cold, cool,

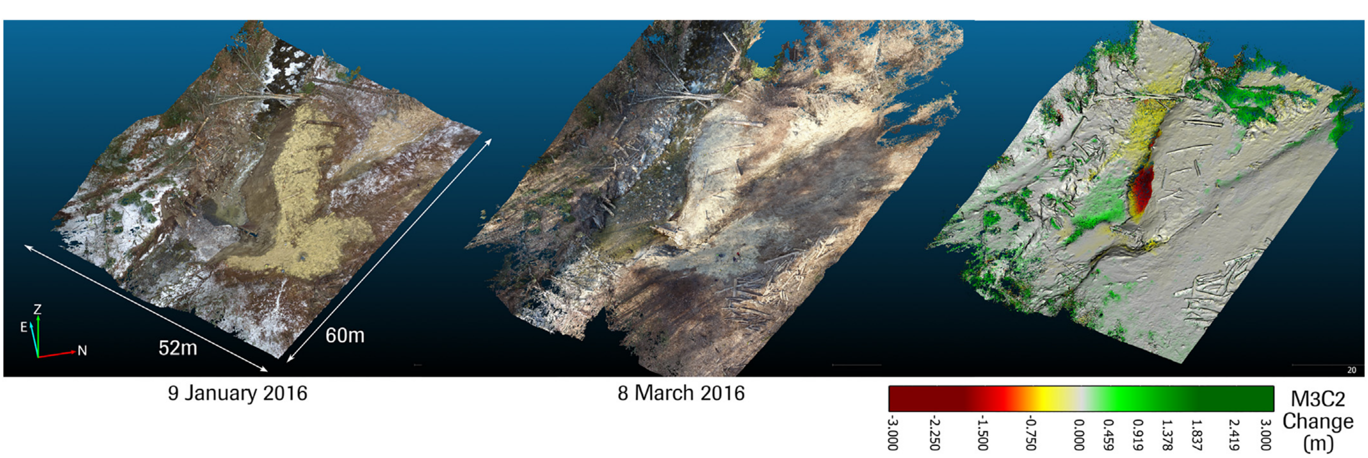

Fig. 13. Drone imagery of crib dam. (A) is RGB image and (B) is change detection within first month following removal of wooden crib dam.

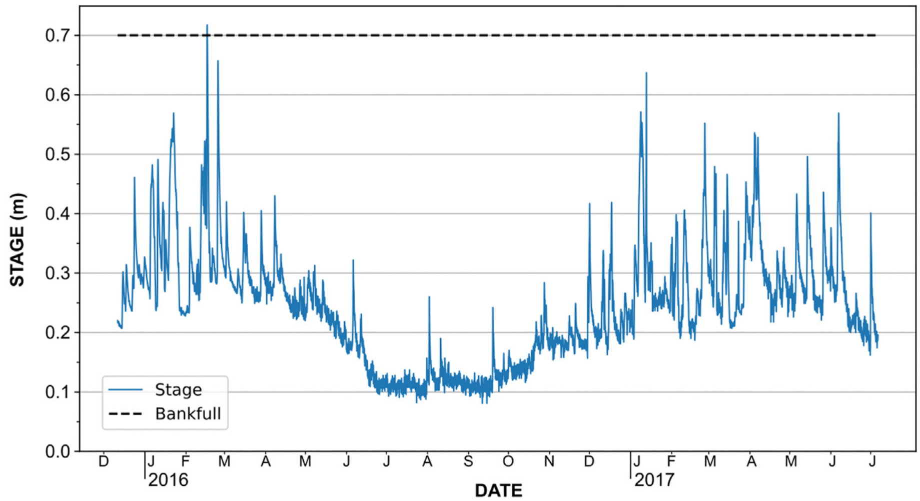

Fig. 14. Time series of river stage recorder by upstream cross section (US#6). Dash line shows bankfull stage.

and warmwater) including both resident and migratory species. Blacknose dace (*Rhinichthys atratulus*) and Slimy sculpin (*Cottus cognatus*) were the most common species, representing 53% and 23% of total numerical abundance, respectively, while several species were rarely encountered (<10 individuals over the entire seven-year interval).

Concordant with geomorphic responses, several key immediate (first year following dam removal) ecological adjustments were sustained over the course of the study. An increase in species richness upstream of the dam following removal is one of these consistent effects (Table 1). Prior to dam removal, only three species (Brook trout, Brown trout, and Blacknose dace) were found in the two sample sites upstream of the dam. Species richness in these sites increased substantially (approximately doubled) in the year following removal as several species that were originally observed only below the dam site were now found upstream. These included two abundant stream-resident species, slimy sculpin (*Cottus cognatus*) and longnose dace (*Rhinichthys cataractae*). Both species were found in low numbers in upstream sites in 2013, and observed in each subsequent year (Table 1, Fig. 17) and their consistent occurrence ensured that species richness remained elevated above pre-removal levels. Abundance of both species in the upstream sections increased over the course of the study, to the point that by 2017 abundances were generally equivalent to downstream sections (Table 1). Several other, less common resident species found only in downstream sections prior in 2012 also were observed upstream of the former dam site after removal. These included several important migratory species. Juvenile Atlantic salmon stocked as fry in Amethyst Brook downstream of the dam as part of the Connecticut River salmon restoration program were found in above-dam sites in 2013 and 2014 but not in subsequent years as the restoration program was discontinued. Sea lamprey nests were observed in downstream (but not upstream) adjacent sections in 2013, observed upstream in 2014, but not observed in any of the study sections in 2015. White sucker (*Catostomus commersoni*) a partially in-river migratory species, was not observed in either of the dam-proximal locations in 2013 but was consistently observed both upstream and downstream in 2014 and in subsequent years. Other species such as tessellated darter, common shiner and American eel, were also only found above the dam after removal, but overall numbers were very low (<20 individuals over the entire duration of the study).

In contrast to effects on species richness, abundances of most species (including both species of resident salmonids) in the dam proximal sites (and to a lesser extent the farthest downstream site), were sharply lower in 2013 (Table 1, Fig. 17) compared to the pre-removal year (2012). This reduction in abundance was not observed in the most upstream site on Amethyst Brook, nor in the control sample section in the

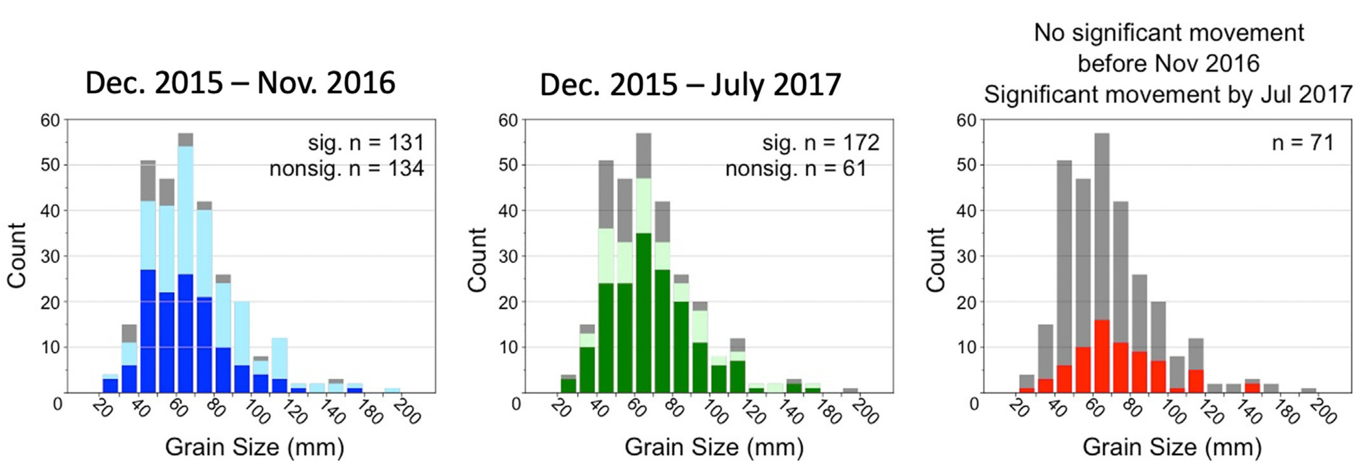

Fig. 15. Results of RFID pit-tagged clasts experiment. In each panel, the dark gray area is the number of clasts in each bin size. The darker color is number of clasts exhibiting significant movement (>8 m from initial deployment) and lighter color bars show the number of clasts recovered but that lacked significant movement (0–8 m from initial deployment).

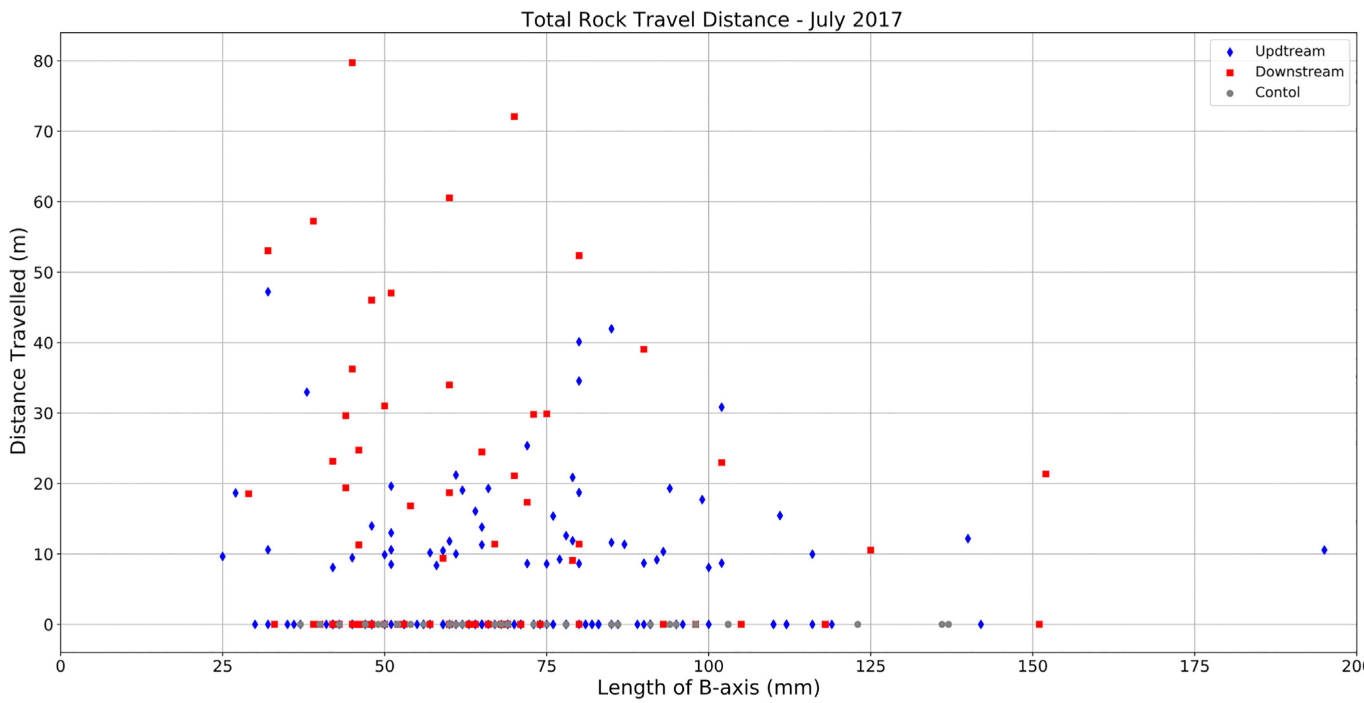

Fig. 16. Distance moved (m) by RFID PIT-tagged clasts plotted against median grain size for clasts deployed upstream and downstream of Pelham Dam.

neighboring tributary (Table 1, Fig. 17). However, from 2014 to 2017 these sections had equivalent or greater abundance compared to 2012, suggesting that the reduction in abundance was a transient effect.

Responses of Sea lamprey, the focal anadromous species in the study, were concordant in some aspects to those observed for freshwater resident species. Likely in response to observed bed fining downstream of the dam and establishment of upstream access, lamprey redds were observed in dam proximal downstream and immediate upstream sections for the first time in ~10 yrs of surveys (Fig. 18). In contrast to the resident and river migratory species, however, presence of lamprey redds in the study section and throughout Amethyst Brook since 2013 has been highly variable, with no redds observed in several post-removal years. The highest number of redds throughout Amethyst Brook occurred in 2014; most were in the lower portions of the study reach or downstream of the study reach although a few redds were located in dam proximal locations. The number of redds increased to their second highest post-removal levels in 2017, with a larger fraction of redds occurring in the lower section of the study reach and in dam proximal locations including the largest number of redds above the former dam (Fig. 18).

4. Discussion

4.1. Timeframes and legacy of adjustments

These detailed results cover five years of channel and ecological response and document significant adjustments within the first year following dam removal but generally muted adjustments in subsequent years, especially geomorphologically. In a similar fashion, changes in species spatial distribution and associated increases in overall species richness established in the first year following removal were sustained throughout the course of the study, although the response of migratory and/or rare species was less consistent. However, immediate changes in abundance, likely associated with

Table 1
Fish species presence (P) and absence (A) by study year and site position (D = downstream/U = upstream/R = reference site in neighboring tributary) along with the total number of individuals encountered during the study period. Sea lamprey presence/absence was determined by a combination of the presence of larvae or the presence of nests and did not yield a total number of individuals. The lower row, species richness, is the sum of all the presences for that year.

	2012 (D/U/R)	2013 (D/U/R)	2014 (D/U/R)	2015 (D/U/R)	2016 (D/U/R)	2017 (D/U/R)	Total number
Sea lamprey (*Petromyzon marinus*)	A/A/NA	P/A/NA	P/P/NA	A/A/NA	A/A/P	A/A/P	–
Blacknose dace (*Rhinichthys atratulus*)	P/P/P	P/P/P	P/P/P	P/P/P	P/P/P	P/P/P	3786
Slimy sculpin (*Cottus cognatus*)	P/A/P	P/P/P	P/P/P	P/P/P	P/P/P	P/P/P	1531
Brown trout (*Salmo trutta*)	P/P/P	P/P/P	P/P/P	P/P/P	P/P/P	P/P/P	608
Brook trout (*Salvelinus fontinalis*)	P/P/P	P/P/P	P/P/P	P/P/P	P/P/P	P/P/P	507
Longnose dace (*Rhinichthys cataractae*)	P/A/P	P/P/P	P/P/P	P/P/P	P/P/P	P/P/P	429
White sucker (*Catostomus commersoni*)	P/A/A	P/A/A	P/P/A	P/P/A	P/P/A	P/P/A	112
Atlantic salmon (*Salmo salar*)	P/A/P	P/P/P	P/P/P	A/A/A	A/A/A	A/A/A	75
Common shiner (*Luxilus cornutus*)	A/A/A	A/A/A	A/A/A	P/P/A	P/P/A	P/P/A	8
Fallfish (*Semotilus corporalis*)	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	P/P/A	7
Tessellated darter (*Etheostoma olmstedi*)	A/A/A	A/A/A	A/A/A	A/A/A	A/A/A	P/A/P	6
American eel (*Anguilla rostrata*)	A/A/A	A/P/A	A/A/A	A/P/A	A/A/A	A/P/A	3
Creek chub (*Semotilus atromaculatus*)	P/A/A	P/A/A	P/A/A	P/A/A	P/A/A	P/A/A	2
Central mudminnow (*Umbra limi*)	A/A/A	A/A/A	A/A/A	P/A/P	A/A/A	A/A/A	2
Yellow bullhead (*Ameiurus natalis*)	P/A/A	A/A/A	A/A/A	A/A/A	A/A/A	A/P/A	2
Chain pickerel (*Esox niger*)	A/A/A	A/A/A	A/A/A	A/A/A	A/P/A	A/A/A	1
Species richness	9/3/6	8/7/6	9/7/6	9/8/6	8/7/5	10/10/6	

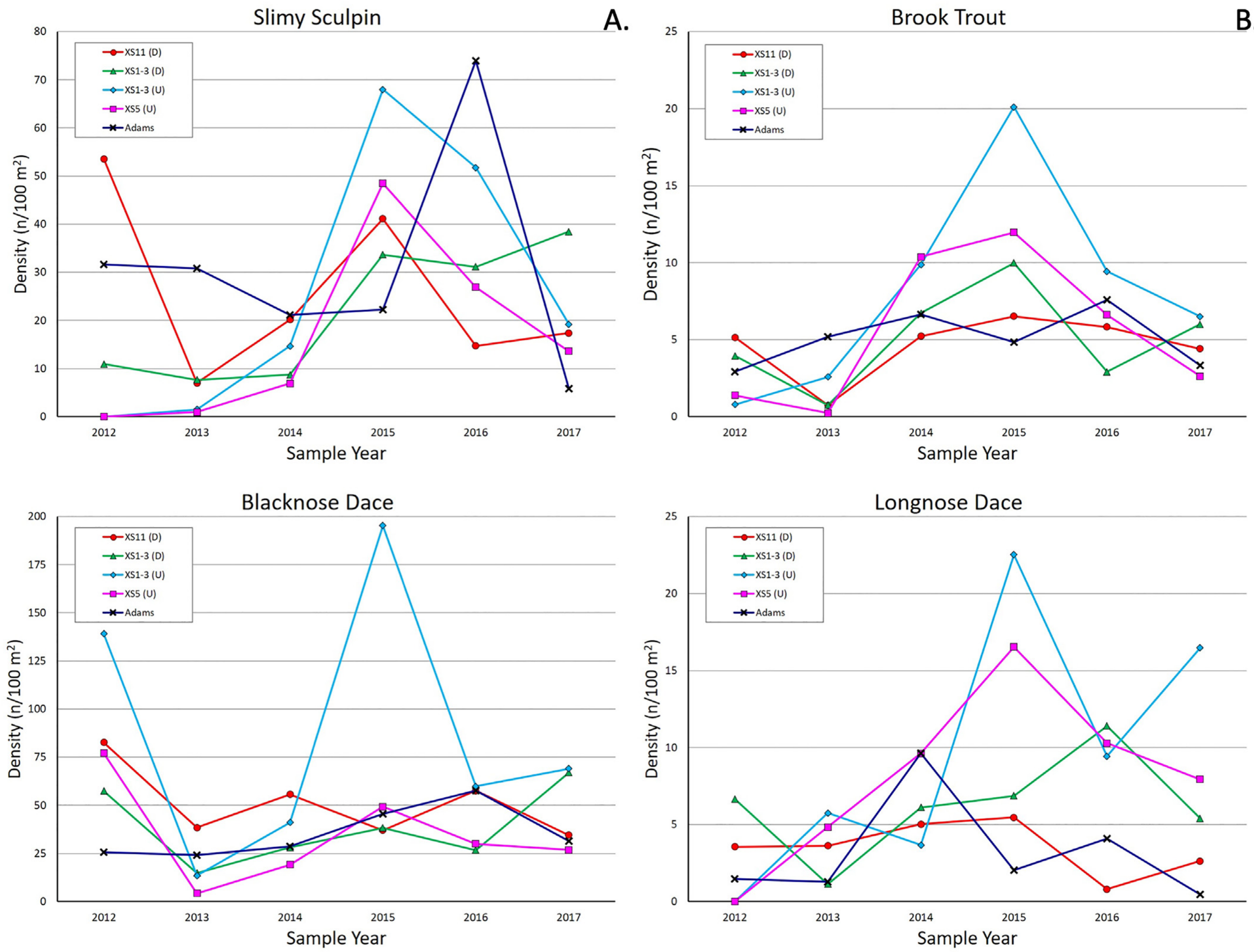

Fig. 17. Time series of fish densities for Slimy sculpin (A), Brook trout (B), Blacknose dace (C), and Longnose dace (D).

the immediate and intense geomorphic adjustment, appeared to be transient, and were not apparent by the end of the study period. Overall our results fit well into the general framework and time-scales of response to dam removal outlined in recent reviews and working groups (Foley et al., 2017), and provide one of the first examples of the use of empirical data to test the hypotheses generated by these reviews. At the same time, our findings suggest ways that management expectations about how and when fluvial systems respond to dams and dam removal can be informed by multi-year and multidimensional assessments, and that this information can help support and communicate dam removal goals (Bellmore et al., 2019).

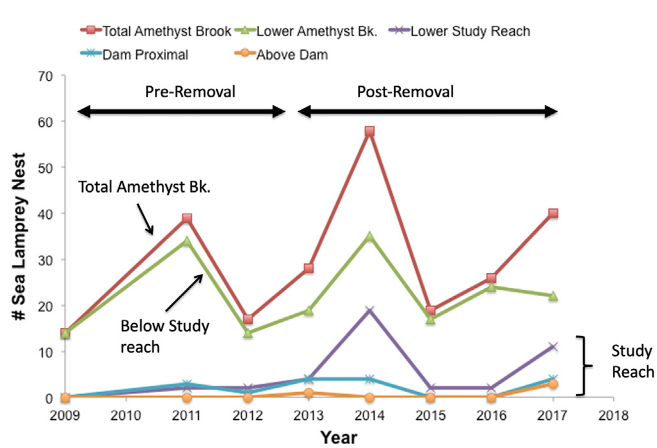

Fig. 18. Sea lamprey nests over time. Nest surveys were sampled along the entire length of Amethyst Brook including a reach below the study reach. Dam proximal locations correspond to XS#1–#3DS and lower reach corresponds to XS#4–#11DS.

4.1.1. Transient and sustained geomorphic adjustments

The attenuation of knickpoint retreat, which when assembled with other limited changes in the former reservoir (minimal lateral migration or channel bed incision), shows that pronounced sediment evacuation of the former reservoir may be a transient response of the fluvial system. Early conceptual models predicting fluvial responses to dam removal suggested that either "process-based" (e.g., base level changes) or "event-based" controls could drive the intensity of erosion (Pizzuto, 2002), and our results suggest that process-based controls predominate, and that the effect is an ephemeral, transient response. Aggregate data are limited, but recent syntheses suggest that most (>50%) of the erosion occurs within the initial post-removal year even in the absence of large flows (Sawaske and Freyberg, 2012; Grant and Lewis, 2015; Major et al., 2017; Foley et al., 2017; Warrick et al., 2015; Ritchie et al., 2018) again suggesting a transient response. The lack of sustained erosion characterized by these multiple studies may cause a reconsideration of the applicability of channel evolution models (Simon and Hupp, 1986) in predicting the progressive and sustained response of reservoir erosion (Doyle et al., 2002). These models, based on channel development in incised channels, have been suggested as an analogue for reservoir erosion that present an evolutionary sequence of four stages corresponding to a major period of incision ultimately leading to a stable, meandering channel inset into an unconfined valley fill composed of former reservoir sediment (Doyle et al., 2002). This model may be less applicable where steeper, coarser streams exist and where physical constraints may diminish erosional intensity (Gartner et al., 2015), thus suggesting that reservoir erosion may be a more transient response.

Other geomorphic adjustments suggest a muted but more sustained long-term response. Yearly sampling along the downstream reach reveals that the initial bed fining following removal has remained relatively consistent both spatially and temporally (Fig. 4). This trend is clearly evident in channel area (Fig. 6) where net change, especially in the most recent survey (Fig. 6), is consistently limited spatially over time. The channel appears to have developed an equilibrium shape relatively quickly and is generally maintaining that bankfull channel area. Channel shape, as evidenced by width to depth ratios, is still adjusting in part to the pool filling at some cross sections and some alternate bar formation, but those adjustments are not occurring at all cross sections and are sub-reach dependent.

4.2. Establishment of geomorphic equilibrium

In many ways dams and dam removal represent one of the few large-scale geomorphic experiments as the disturbance is fixed in time and space. Results from this long-term monitoring effort can provide an important lens into the processes and timeframes of the joint ecological and geomorphic post-removal adjustments that are fundamental attributes for process-based river restoration (Woolsey et al., 2007; Wohl et al., 2005; Beechie et al., 2010; Palmer et al., 2014; Wohl et al., 2015). Where sediment trapping is significant, previous research has shown the profound effects of dams (Magilligan et al., 2013) and the persistent channel disequilibrium below the dam (Graf, 2001; Kondolf, 1997; Gaeuman et al., 2005; Curtis et al., 2010), although inconsistent responses may occur (Williams and Wolman, 1984; Schmidt and Wilcock, 2008; Magilligan et al., 2008). As Mackin (1948) pointed out, a stream will attempt to establish equilibrium relative to the upstream sediment supply through the mutual adjustments of slope and channel characteristics to provide the necessary energy for sediment transport. For dam removals, the re-connected sediment supply should engender channel responses as the channel needs to either

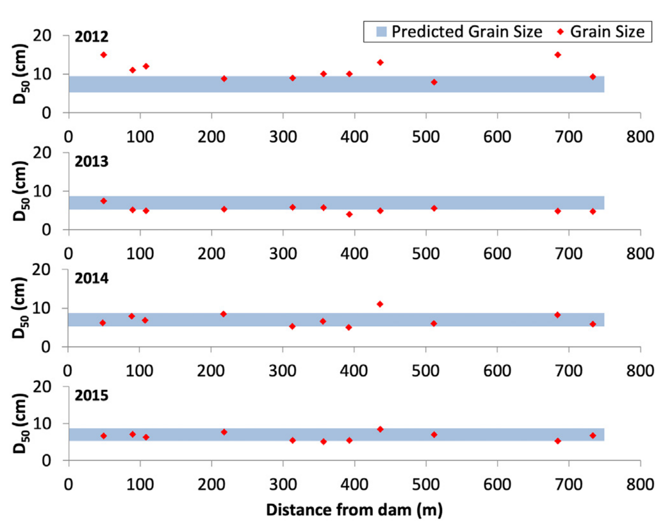

Fig. 19. Time series of calculated median grain sizes associated with $\theta_{cr} = 0.05$ (see Eq. (1)) for each cross section. Shaded area is reached averaged range (±1 standard deviation) of predicted b-axes.

store or transport the newly connected sediment flux in order to re-establish equilibrium (Wohl et al., 2019). Our assessments suggest that the return to equilibrium happens quickly and has been sustained for several years (Fig. 19). For the pre-removal cross sections, the Shields parameter values (Eq. (1)) reflect the dis-equilibrium with most cross sections having coarser material mantling the bed that can be transported at a critical Shields parameter value of 0.05 (see Eq. (1)). Within the first year following removal, despite the increased re-connected sediment flux, the channels have adjusted sufficiently to transport the load being delivered from above. This adjustment is further revealed in the progressive dampening of changes in cross-sectional area downstream (Fig. 6) and the limited subsequent channel aggradation spatially over time (Fig. 5).

Lastly, in order to identify the ways in which the channels have adjusted, we examine the covariant channel adjustments over time. As Hey and Thorne (1986) outlined, gravel-bedded rivers have seven degrees of freedom of adjustment (bankfull width (or wetted perimeter), mean depth, maximum depth, slope, velocity, sinuosity and meander arc length), but for rivers having experienced disconnected sediment supply, another mode of adjustment is changes in grain size. For Amethyst Brook, the predominant post-removal mode of adjustment has been changes in grain size below the former dam with minimal changes in either width or slope over time (Fig. 20) and that shift happened immediately and has been sustained during the monitoring period (Figs. 5 and 20). We adduce the minimal changes in slope to the decreased caliber of the material being delivered. Normally the increased flux from the re-connected sediment delivery would necessitate a greater slope, but with the smaller size of bedload material the channel does not need as large a slope to transport the greater volume of material.

4.3. Linked geomorphic and ecological responses to removal

Ecological adjustments to the removal of the Pelham Dam showed interesting parallels to the geomorphic responses described above. Upstream establishment of resident species previously not present above the former dam was in most cases immediate (year after dam removal) sustained over the duration of the study, and the presence of these species resulted in a sustained increase in species richness and diversity. Rapid upstream establishment of barrier-restricted species has been observed repeatedly (Pess et al., 2014; Hogg et al., 2015; Magilligan et al., 2016b; Ding et al., 2019), but few studies have assessed the duration and consistency of these changes in longitudinal distribution (cf. Pess et al., 2012). Part of the reason for the sustained and consistent pattern in our system may be that the resident fish assemblage in Amethyst Brook, like most small streams in the Connecticut River Basin and similar Atlantic coastal drainages, consists of relatively few, relatively abundant species that are easily detected by standard sampling methods. In systems such as Amethyst Brook, there is generally a reliable source of

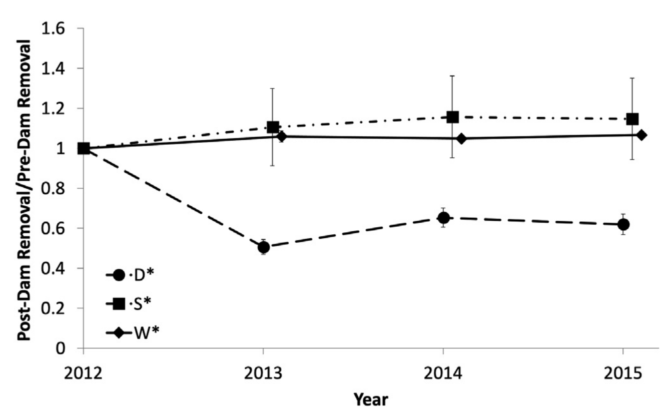

Fig. 20. Covariant plots of width (W), median grain size (D) and slope (S). The asterisk (*) refers to the ratio of the pre-removal data to the post-removal data.

upstream migrants, and distributional changes are readily detected. By contrast, in streams and rivers with diverse assemblages including many rare (or dispersal-limited), difficult to detect species, observed changes in species distribution and assemblage characteristics may be more variable, and consequently more difficult to detect in any given year. These considerations are illustrated to some extent in our study by the observed response of Sea lamprey to dam removal. While an upstream expansion of redd distribution was observed in the first year following dam removal, redds were not present in dam proximal or upstream locations in some subsequent years. Unlike the abundant resident species, there is considerable variation in the availability of upstream migrants, as the number of adults returning to the mainstem Connecticut River from the sea fluctuates greatly from year to year (Nislow and Kynard, 2009). This high local inter-annual variation is generally characteristic of diadromous fishes, and may influence results and conclusions of monitoring studies in a wide range of situations (Pess et al., 2014). In addition, dam removal may foster the development of life history diversity at both interspecific (because of increases in migratory species) and intraspecific (because of increases in movement and migratory life-history expression) levels. Monitoring changes in life history diversity therefore can and should be an important additional dimension for dam removal studies (Pess et al., 2014).

In contrast to changes in distribution and presence-absence, changes in fish abundance following dam removal exhibited a more complex pattern. Abundances of most resident fish species decreased markedly in the year following removal, particularly in dam proximal locations. Over the course of the study, however, abundances rebounded to levels within and in some cases exceeding the range of the pre-dam year samples. Reductions in abundance following bed-mobilizing disturbances in streams are frequently transient as long as there is a source of and access to recolonists (Roghair et al., 2002). Our results support this general paradigm. However, concerns about potential population losses associated with dam removal still factor into decision-making, and clear demonstration that these impacts are transient helps to manage expectations and allay these concerns. Further, following the first year post-removal, when only a few individuals of these recolonizing resident species were observed upstream of the dam site, abundances were largely similar upstream and downstream, consistent with re-establishment of population connectivity (Nislow et al., 2011).

5. Conclusion

Dam removal can be viewed not only as a restoration tool but as an opportunity to evaluate the processes and timeframes of geomorphic adjustments to the removal of a disturbance. Understanding or predicting the trajectory of change is not only fundamentally important from a management prospectus (Tullos et al., 2016), but remains a key scientific issue as well for dam removal (Foley et al., 2017; Bellmore et al., 2019). The recovery trajectory from dam removal can be an important proxy for an array of other geomorphic settings where the channel is adjusting to the removal or attenuation of a chronic (e.g., land-use change) or an acute (e.g., flood, wildfire, etc.) disturbance (Magilligan and Stamp, 1997; Pitlick, 1993; DeLong et al., 2018). We observed similar dynamics in ecological response. Immediate (within the first year) responses involving restoration of key system attributes (aquatic organism passage, available of suitable spawning habitat) were sustained over the duration of the study, while responses that were more characteristic of episodic disturbance (such as reductions in abundance) appeared to be transient.

Although five years is a small window to evaluate recovery, our results point to the strong influence of rapid and sustained adjustments to the removal of a prolonged disturbance, such as a dam. Some features, such as large scale planform change, may require decades or longer to manifest, but other geomorphic properties have adjusted quickly and have been sustained over the five year window (Table 2).

Table 2
Transient versus sustained biophysical responses to dam removal.

	Transient/variable	Sustained/consistent
Immediate	Geomorphic - Evacuation of reservoir sediment - Rapid aggradation and degradation - Pool filling Ecological - Reduced abundance and biomass associated with bed movement - Occurrence and abundance of rare or migratory species	Geomorphic - Reduced bed caliber downstream - Re-establishment of sediment continuity Ecological - Increased species richness upstream of removed dam - Upstream extension of distributions of common species
Delayed	Geomorphic - Pool sediment evacuation - Stable channel area Ecological - Occurrence and abundance of rare or migratory species	Geomorphic - Bar formation and re-establishment of low flow downstream sinuosity Ecological - Habitat-associated impacts on abundance and population dynamics - Novel species interactions

Interestingly, within a larger watershed context, the contemporary landscape differs considerably from when the dam was built ca. 1820 and certainly different from pre-historical conditions, yet even with these different boundary conditions, the channel has quickly “recovered” to the new extant boundary conditions. Similarly, in terms of ecological considerations, while the faunal composition of streams and rivers in the New England region has changed considerably over the last two centuries because of a combination of species extirpations and introductions (Kanno and Vokoun, 2008), fish assemblages upstream quickly achieved a new and relatively stable species composition. This is likely to be more applicable for stream-resident fishes, as changes in ocean and mainstem river conditions will continue to generate variation in the occurrence of migratory species in upstream tributaries such as Amethyst Brook. In a similar way, the consistent availability of suitable spawning gravels (Fig. 4) to previously sediment-starved downstream sections will provide a sustained level of habitat quality for species such as Sea lamprey. This sustained change in species composition and habitat raises questions about the longer-term impacts of dam removal that are beyond the scope of the present study. For example, the establishment of formerly downstream-restricted species in upstream locations raises the possibility of changes in species interactions that can have important impacts on population dynamics and persistence, but that will likely involve long time-scales to be fully manifest (Fausch et al., 2009). In the case of negative species interactions (species displacement of competitive exclusion, hybridization) long-term studies generally show that multiple years and multiple generations are required before these effects to become evident (Fausch et al., 2009). In terms of physical habitat and sediment dynamics, any downstream geomorphic impacts such as re-establishment of bars and meanders will involve considerable time lags (decades or longer?) both in terms of effects on habitat structure and concordant influences on fish population dynamics.

In contrast to the immediate and sustained influence on habitat and species composition, effects on abundance and population dynamics were variable, and in some cases transient. Removal of dams and other barriers to movement has been suggested to increase stream fish population resilience due to metapopulation dynamics (Letcher et al., 2007) and as a function of portfolio effects (Schindler et al., 2010). Detecting these effects, however, given the large amount of inter-annual variation inherent in stream fish populations (Schlosser, 1985) usually requires extremely intensive studies of populations or broad-scale studies that allow substitution of space for time (Nislow et al., 2011) or that consider age- and stage-specific responses

(Liermann et al., 2017). Depending on whether the emphasis is on the effectiveness of a specific dam removal on ecological targets, or on general principles, different approaches can be brought together to answer these challenging questions. When dam removal was progressively becoming a major restoration effort, because of the inherent complexity of geomorphic systems and the poorly documented boundary conditions, Grant (2001) rightfully queried whether dam removal would be a panacea or Pandora's box. Our results suggest that if they manifest at all, the negative effects (e.g., pool in-filling, knickpoint migration, etc.) are more of an ephemeral, transient response and that the positive attributes of removal happen quickly and can be sustained as observed elsewhere (Foley et al., 2017; Collins et al., 2017; East et al., 2018; Bellmore et al., 2019).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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