Geomorphology 252 (2016) 158–170

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Immediate changes in stream channel geomorphology, aquatic habitat, and fish assemblages following dam removal in a small upland catchment

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ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form 14 July 2015
Accepted 16 July 2015
Available online 17 July 2015

Keywords:
Dam removal
River restoration
Channel recovery
Fish habitat
Fragmentation

ABSTRACT

Dam removal is becoming an increasingly important component of river restoration, with >1100 dams having been removed nationwide over the past three decades. Despite this recent progression of removals, the lack of pre- to post-removal monitoring and assessment limits our understanding of the magnitude, rate, and sequence of geomorphic and/or ecological recovery to dam removal. Taking advantage of the November 2012 removal of an old (~190 year-old) 6-m high, run-of-river industrial dam on Amethyst Brook (26 km^2) in central Massachusetts, we identify the immediate eco-geomorphic responses to removal. To capture the geomorphic responses to dam removal, we collected baseline data at multiple scales, both upstream (~300 m) and downstream (>750 m) of the dam, including monumented cross sections, detailed channel-bed longitudinal profiles, embeddedness surveys, and channel-bed grain size measurements, which were repeated during the summer of 2013. These geomorphic assessments were combined with detailed quantitative electrofishing surveys of stream fish richness and abundance above and below the dam site and throughout the watershed and visual surveys of native anadromous sea lamprey (*Petromyzon marinus*) nest sites. Post-removal assessments were complicated by two events: (1) upstream knickpoint migration exhumed an older (ca. late eighteenth century) intact wooden crib dam ~120 m upstream of the former stone dam, and (2) the occurrence of a 10–20 year RI flood 6 months after removal that caused further upstream incision and downstream aggradation. Now that the downstream reach has been reconnected to upstream sediment supply, the predominant geomorphic response was bed aggradation and associated fining (30–60% reduction). At dam proximal locations, aggradation ranged from 0.3 to >1 m where a large woody debris jam enhanced aggradation. Although less pronounced, distal locations still showed aggradation with a mean depth of deposition of ~0.20 m over the 750-m downstream reach. Post-removal, but pre-flood, bed surveys indicate ~2 m of incision had migrated 25 m upstream of the former reservoir before encountering the exhumed dam, which now acts as the new grade control, limiting progressive headcutting. Approximately 1000 m^3 of sediment was evacuated in the first year, with ~67% of the volume occurring by pre-flood, process-driven (e.g., changes in base level) controls. The combination of changes in channel-bed sedimentology, the occurrence of a large magnitude flood, and the emergence of the new crib dam that is a likely barrier to fish movement was associated with major reductions in abundance and richness in sites downstream and immediately upstream adjacent to the former dam in post-removal sampling. At the same time, we documented the presence of four species of fish, including sea lamprey, which were not present above the dam prior to removal, indicating that upstream passage has been achieved; and we also documented lamprey spawning activity at sites immediately below the dam, which had previously been unsuitable owing to an excessively coarse and armored riverbed. Our results point to the importance of interactions between dam removal and flood disturbance effects, with important implications for short- and long-term monitoring and assessment of dam impacts to river systems.

1. Introduction

Driven in part by the increasing number of aging dams needing pending repair and also by broader societal goals, dam removal is progressively becoming part of river manager's toolkit for river restoration

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http://dx.doi.org/10.1016/j.geomorph.2015.07.027
0169-555X/

(Shuman, 1995; Hart et al., 2002; Doyle et al., 2008; Doyle and Havlick, 2009; O'Connor et al., 2015). This national effort has led to the removal of over 1100 dams in the past several decades, averaging, at present, ~50 removed dams per year (Service, 2011). Because dam removal can minimize habitat fragmentation and reconnect riparian zones to fundamental hydrologic processes and channel-floodplain exchanges (Bednarek, 2001; Hart et al., 2002), many ecologists and environmental advocates embrace dam removal as a crucial element of river restoration. Recently, however, the scientific community has voiced some reluctance for indiscriminate endorsement of dam removal. Some scientists are concerned about the effect of released sediment on downstream geomorphic and ecological processes (Doyle et al., 2000, 2002, 2003; Grant, 2001; Pizzuto, 2002; Stanley and Doyle, 2003; Gangloff, 2013), especially as many of these previously stored sediments may be contaminated with pesticides, herbicides, and other byproducts of industrialization and mining such as mercury. The double-edged sword of ecological restoration associated with dam removal very much, thus, orbits around the geomorphic and biological impacts of sediment releases, including volume, flux, and sediment characteristics (size, sorting, etc.).

Research on dam removals has not kept pace with the currently brisk rate of removals. Despite the large number of removals over the past decades, there have been relatively few geomorphic or ecological assessments, especially detailed long-term monitoring or those linking the geomorphic adjustments specifically to the ecological (cf. Stanley et al., 2002; Stanley and Doyle, 2003; Pollard and Reed, 2004; East et al., 2015; Warrick et al., 2015). In an extensive compilation of dam removals in the U.S. and abroad, a recent USGS study (Bellmore et al., 2015) indicates that only ~130 dam removals have had any monitoring of any kind, with most lacking post-removal comparative assessments. The minimal documentation results in part from the frequent politicization and extended permitting process often limiting extensive pre-removal baseline data. Post-removal assessments are also commonly plagued by limited monitoring funds to document ecological and geomorphic recovery. Because of these limitations, dam removal research has evolved gradually from an initial phase that dealt with the conceptualization of potential impacts (Bednarek, 2001; Hart et al., 2002; Pizzuto, 2002; Poff and Hart, 2002; Shafroth et al., 2002; Stanley and Doyle, 2003) to progressively more field-based analyses of late that capture actual effects (Doyle et al., 2003, 2005; Cheng and Granata, 2007; Burroughs et al., 2009; Kibler et al., 2011; Pearson et al., 2011; Major et al., 2012; Draut and Ritchie, 2013; East et al., 2015; Harris and Evans, 2014; Magirl et al., 2015; Wilcox et al., 2014; Gartner et al., 2015; Randle et al., 2015; Warrick et al., 2015).

These case studies have documented specific changes in channel morphology and associated longitudinal effects, but no universal process-based model has been developed nor have these studies converged on universal responses. They have, though, documented the type and variability of responses and the fundamental importance of a spatial perspective in understanding the specific changes in fluvial systems following dam removal. The exact response depends on several factors including the volume, caliber, and cohesion of sediment stored in the reservoir; flow frequency; downstream channel dimensions (Pizzuto, 2002; Graf, 2003; Major et al., 2008; Sawaske and Freyberg, 2012; Bountry et al., 2013; MacBroom and Schiff, 2013); as well as dam function, size, and physiographic location (Poff and Hart, 2002; Graf, 2006). Some studies demonstrate a significant increase in sediment transport downstream (Burroughs et al., 2009), while other locations have little or no change in sediment transport downstream of the dam (Cheng and Granata, 2007). Downstream of a removed dam, bed sediment caliber typically initially decreases resulting from the release of finer sediments from the reservoir, which then increases in successive storms (Wohl and Cenderelli, 2000; Cheng and Granata, 2007; Pearson et al., 2011). Sediment routing downstream of the dam is also variable, with some streams exhibiting translation of a sediment wave and others an attenuated dispersive wave that gradually erodes (Wohl and Cenderelli, 2000; Doyle et al., 2002; Pizzuto, 2002).

These sedimentological effects are further complicated in the context of large flow events. Extreme flows acting immediately after a dam has been removed, when the channel is highly vulnerable to rapid and extreme adjustment (owing to the major change in hydraulic control) sets up the possibility for interactive effects on channels and river habitats that are difficult to anticipate. Recent research (Pearson et al., 2011; Major et al., 2012; Grant and Lewis, 2015) suggests that even in the absence of post-removal large flows, upward of 50% of the initial reservoir sediment volume can be evacuated within the first year—a conceptual model initially posited by Pizzuto (2002) where he distinguished between process-based erosion (e.g., knickpoint migration) and event-based erosion (e.g., large floods).

The ecological effects of dam removals are similarly complex, affecting different ecosystem components at a range of temporal and spatial scales (Stanley and Doyle, 2003). For stream fish populations and assemblages, barrier removal can result in rapid colonization of previously unoccupied upstream areas (Pess et al., 2014). This rapid upstream movement has often been observed, particularly with highly mobile diadromous species such as migratory salmonids (Pess et al., 2014). The role of barriers and barrier removal on the distribution and diversity of stream resident fishes has been less well appreciated, but several studies indicate that barriers to movement are associated with reduced richness and abundance (Nislow et al., 2011; Diebel et al., 2014). In addition to direct effects of reconnection and upstream access, dams and dam removal may also have a strong influence on physical habitat. Effects on habitat are driven in large part by the geomorphic processes described previously. As many of these processes are associated with large flows that occur infrequently, effects on habitat may not be fully manifest until years or decades following dam removal. However, in those cases where extreme flows occur in close association with dam removal, significant immediate change may occur given the potential for geomorphic instability and readjustment. In turn, these rapid adjustments may have indirect (via changes in habitat) and direct (via event-associated mortality) on populations and assemblages. Further, while large, high-profile dam removals have been well studied and monitored, we have considerably less information on the effects of removing small run-of-river dams in small upland catchments (Csiki and Rhoads, 2010). These structures are numerous and ubiquitous within the heavily-settled northeastern and north-central U.S. and are a major target of dam removal efforts.

Despite the recent spate of dam removal research, several important questions remain about the timing and spatial extent of geomorphic responses and the rate at which ecosystems respond to these transient adjustments. Dam removals, in many ways, are perhaps the closest analog in geomorphology to a controlled natural experiment: they represent the removal of a disturbance fixed in time and space with extant boundary and initial conditions. Therefore, rather than considering each dam removal as a unique case study, we suggest each dam removal represents an important boundary condition of reservoir sediment properties, dam removal style ('blow-n-go' vs. staged removal), dam trapping efficiency, valley confinement, and channel gradient. Using the staged removal of a 6-m-high, run-of-river dam that impounded a high gradient, coarse gravel-bedded stream, we elucidate the type, magnitude, and spatial variability of geomorphic adjustments immediately following its removal and further document the associated ecological responses. Thus, we have three major geomorphic research questions: (i) how does grain size change downstream of the former impoundment as the upstream to downstream sediment flux gets reestablished; (ii) what are the channel adjustments (bed elevation, planform, etc.) associated with the change in sediment flux; and (iii) what is the length scale of these geomorphic adjustments? Ecologically, our major questions are: (i) how does fish demography change following dam removal; (ii) how do changes in bed sediment composition enhance or diminish bed spawning habitat requirements; and (iii) are fish able to colonize new upstream territory now made available by dam removal?

2. Background

The Pelham dam (also known as the Bartlett Rod Shop Company dam; NID #MA01761) on Amethyst Brook was removed in Fall 2012. The masonry structure was in poor condition, stood ~6 m high and 50 m wide (Fig. 1), and in conjunction with large mainstem dams on the Connecticut River (e.g., Holyoke dam) significantly blocked upstream fish passage (Fig. 2). Originally constructed c. 1820, the dam supplied water power to the adjacent mill until the mid-twentieth century and then created a local swimming hole for several decades thereafter. The private dam owner was assisted in the dam removal process by a coalition of local, state, federal, and nongovernmental organizations with mutual interests in restoring fish passage (including diadromous species), improving sediment and organic matter transport for improved ecological conditions downstream, and eliminating risk and liabilities associated with the aging structure.

As with many dam removal projects, the management of impounded sediment was identified as a primary challenge during the design phase. Given the quality of the upstream watershed (heavily forested, protected for water supply) and coarse grain sizes observed in the impoundment, the planning focused on the volume of material and the rate of downstream movement rather than anthropogenic contaminants. The project design and regulatory approvals specified an approach to sediment management involving partial removal and partial downstream release. The habitat-forming benefits of sediment release were identified as an objective in the project, particularly given the observed winnowed bed in the reach immediately downstream of the dam. Approximately 3500 m^3 of sediment and organic matter (per contractor measurements) was physically removed and deposited on the adjacent floodplain with an expectation that future storm events would subsequently mobilize and transport additional material.

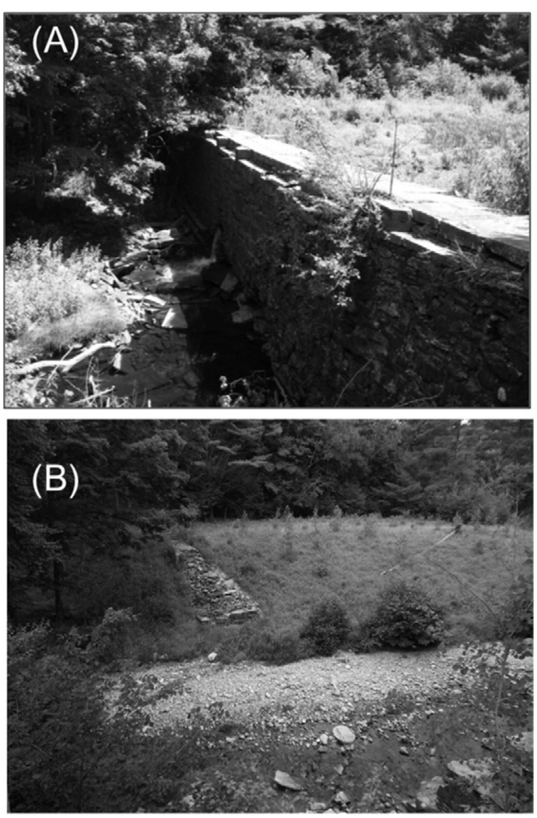

Fig. 1. View of Pelham dam pre- and post-removal. View in (A) is from below the dam on river left looking upstream. Note the level of sediment fill up to the dam crest. View in (B) is from river left to river right. Note the reconnected sediment flux through the former dam site.

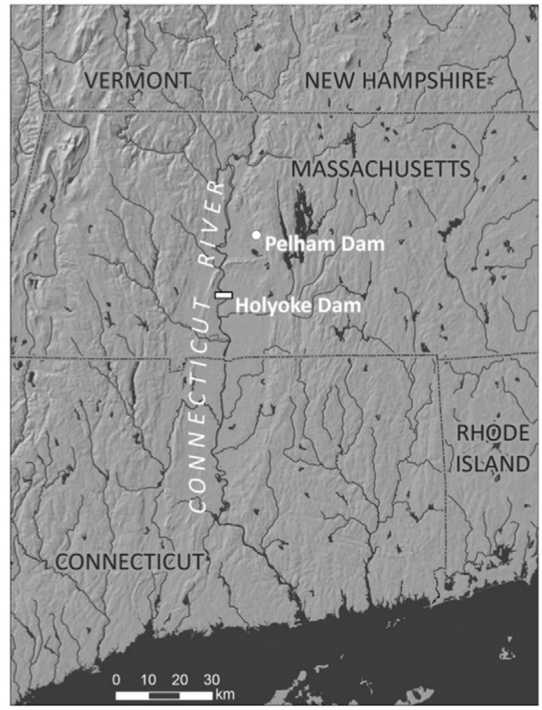

Fig. 2. Location map. Amethyst Brook with its position relative to Holyoke dam and the Long Island Sound.

As designed, the geometry of the initial channel in the former impoundment included a bottom width of 9.1 m and a 1–3 m wide low-flow channel, side-slopes set at 3:1 (horizontal:vertical), a longitudinal slope of 20:1 (H:V [5-percent]), and a length of ~100 m. No channel stabilization techniques were used upstream of the dam, and upon removal and deactivation of water controls, sediment mobilization and additional channel forming processes were initiated.

Amethyst Brook is a steep (1–2%) gravel-bedded stream with a watershed size of 26 km^2 at its confluence with the Fort River (a tributary to the Connecticut River). The study site is located several kilometers upstream of the confluence (Fig. 3). After a period of sustained period of land clearing for agriculture and grazing from settlement through the late nineteenth century, the basin is ~ 90% forested at present. Precipitation averages ~1200 mm y^{-1}. Mean monthly temperature ranges from a low of −5 °C (January) to a high of 22 °C (July). The past several years have been especially wet regionally (Armstrong et al., 2012), and the occurrence of large events factor prominently into the response of Amethyst Brook to dam removal. Prior to removal, the region experienced one of the largest floods on record as Tropical Storm Irene moved through the basin on 28 August 2011. Although no gages exist with the basin, adjacent watersheds recorded flood magnitudes >100-year recurrence interval (RI) floods. High water marks from Irene were clearly evident along the reach. More importantly, ~ 6 months after removal, after a wet June, a localized high intensity storm dropped considerable precipitation over the headwaters of the basin on 28 June 2013. Unfortunately, there are no rain gages in the basin. A nearby precipitation gage, though, in Northampton, MA, recorded ~64 mm in 24 h, which was ~ 50% of Irene totals. The 28 June 2013 storm had a much shorter duration (1–2 h) than Irene that occurred over an 18-h period. Local residents indicated anecdotally that streamflows were high following the June 28th microburst and in places approximated flows of Irene. Visual inspections 3 days later confirmed the high flows as fresh highwater marks could be seen below and even up to previous Irene levels. Channel erosion and sediment transport were pronounced following this localized event.

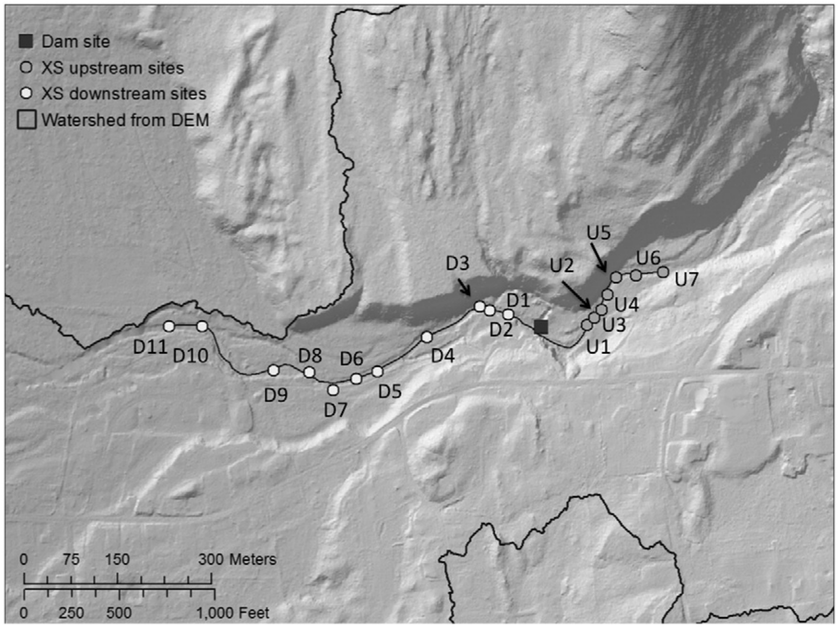

Fig. 3. Shaded DEM of Amethyst Brook, MA with location of Pelham dam and sampled cross sections along the study reach.

3. Methods

This research utilized a vast array of geomorphic, geospatial, and ecological approaches to capture the short-term, but spatially extensive, responses to dam removal. Field work began 1–2 years prior to removal, with post-removal assessments beginning ~6 months following removal and continuing over a 3–5 month summer–fall period during 2013.

3.1. Geomorphic methods

To capture the geomorphic responses to dam removal, we collected baseline data at multiple scales, both upstream and downstream of the dam site (Fig. 3). Because previous research has shown the dramatic changes in stream channel properties (e.g., widening, incision, etc.), we surveyed 11 cross sections over 750 m downstream of the dam, with an additional 7 cross sections spanning 300 m upstream of the former reservoir (cross section numbering starts as #1 near the dam and numbering increases with distance both upstream and downstream of dam). Spacing of cross sections increased with increasing distance from the dam resulting in a denser network of cross sections in dam proximal locations (Fig. 3). Cross sections were surveyed, orthogonal to streamflow, with either a TOPCON Auto Level or a PENTAX Total Station with the channel margins staked for subsequent re-occupation. To augment the channel cross sections, we surveyed the channel-bed longitudinal profile with a TOPCON Robot Total Station, sampling every 2–3 m along the ~1.1-km study reach. Pebble counts (Wolman, 1954) were conducted at each cross section. As bed grain-size distributions are skewed, data were logged (base 10) for subsequent difference of means test.

Because of the potential detrimental effects of fine sediment deposition (Stanley et al., 2002; Sethi et al., 2004; Gangloff, 2013), we sampled gravel embeddedness at multiple cross sections both upstream and downstream of the dam. Embeddedness techniques range from qualitative assessments to the more quantitative, but can still be fraught with measurement issues and inconsistencies (Sennatt et al., 2006; Descloux et al., 2010). Because we are dealing with impacts on spawning habitat and rearing, we used a method recently developed by Finstad et al. (2007) that uses a rubber tube (~5 cm long and 0.5 cm in diameter) to measure the number and extent of interstitial spaces within channel-bed gravels. Previous work in the region indicates that this approach represents broader patterns of bed aggradation (Kasprak et al., 2013). We recorded the total number of discrete spaces within 0.3-m^2 sampling quadrats, using three replicate quadrats randomly placed along transects.

Following removal, all channel cross sections were surveyed as well as the longitudinal profile (upstream and downstream) using the same pre-removal approaches and methods. The upstream longitudinal profile was measured twice: once several hours before the June 28 flood and also one month later which provided channel-bed profiles for the initial knickpoint erosion owing solely to the removed dam and also to post-removal and post-flood incision. Moreover, we established three new cross sections in the sub-reach of the former reservoir. Pebble counts and embeddedness measurements were resampled in previous locations.

Total volume of material eroded/deposited was approximated from the longitudinal profiles and from changes at measured cross sections. Each has its own merits and shortcomings: area changes at the cross section represent changes along the channel width but lack the resolution of detailed measurements afforded by detailed surveying along the longitudinal profile. Because distances between cross sections were not equally spaced, we used the percentage of the reach between successive cross sections to scale the cumulative erosion or aggradation along the entire downstream or upstream reach. Unlike the cross sections, the longitudinal profiles provide great detail at points along the channel but miss important lateral changes. We integrated the differences in depth along the profile and calculated sediment volumes from reach-averaged width measurements. Volume estimates from the cross sections and longitudinal profiles accorded well.

3.2. Fish sampling

We used two methods to sample fish species and assemblages above and below the dam site before and after dam removal. For sea lamprey (*Petromyzon marinus*), one of the three diadromous species present in the river, spatially-continuous visual redd surveys (redds are the distinctive raised gravel nests constructed by spawning lampreys) were conducted during the spawning period throughout the Fort River basin according to the protocols described in Nislow and Kynard (2009). In the dam-influenced reach, the locations of all redds were recorded with respect to distance and position from the removed and the newly exposed crib dam. For all other fishes, we used two-pass electrofishing removal in 30-m stream sections, in which all fish were weighed, measured (standard length), and identified to species before being returned to the stream. We sampled two sections downstream and two sections upstream of the removed dam and four sections within the basin as spatial references in 2012 (pre-removal) and 2013 (post-removal) years. We also sampled three sections within the basin, but outside the study area, as spatial references. Reference sections were placed on one site ~0.75 km upstream on Amethyst Brook ('Falls' site), a second site on a small tributary (catchment area 4.30 km^2; 'Tributary' site) with a confluence of ~0.25 km upstream of the Falls site, and a third site on Adams Brook an adjacent tributary of the Fort River with a similar drainage area as the Amethyst Brook study site (17.30 km^2; 'Adams' site). Upon exposure of the exhumed wooden crib dam following removal, we added two sections upstream of the exposed dam, which were sampled in 2013 only.

4. Results

4.1. Pre-removal baseline conditions

4.1.1. Geomorphic conditions

The study reach was significantly affected by the dam's longstanding presence, especially the downstream reach where the dam's sediment trapping led to significant bed coarsening and armoring, especially in dam proximal settings (Table 1). Median bed particle size (D_{50}) ranged between 79 and 150 mm with no evident downstream pattern (Fig. 4). The pre-removal downstream grain sizes are significantly coarser than the upstream sites (Table 1): pre-removal upstream sites ranged between 39 and 69 mm (Table 1). Bed coarsening/armoring continued to distal cross sections 750 m downstream. The armoring was further evident in embeddedness surveys (Table 2) that showed the lack of interstitial spaces pre-removal. In the immediate vicinity of the dam (downstream cross sections 1–4) and farther downstream, we found low availabilities of interstitial shelter spaces (3.56 ± 1.24 and 5.6 ± 1.02 spaces $* \ m^{-2}$, respectively), while at the furthest downstream cross sections (10 and 11) shelter space counts were at least twofold (12.67 ± 2.17 spaces $* \ m^{-2}$) (Table 2).

Upstream of the dam, the channel was graded to the elevation of the impoundment and former reservoir, with sandy-gravelly deltaic facies proximal to and into the former reservoir. Channels were generally symmetrical in shape, with width-to-depth (W:D) ratios on the order

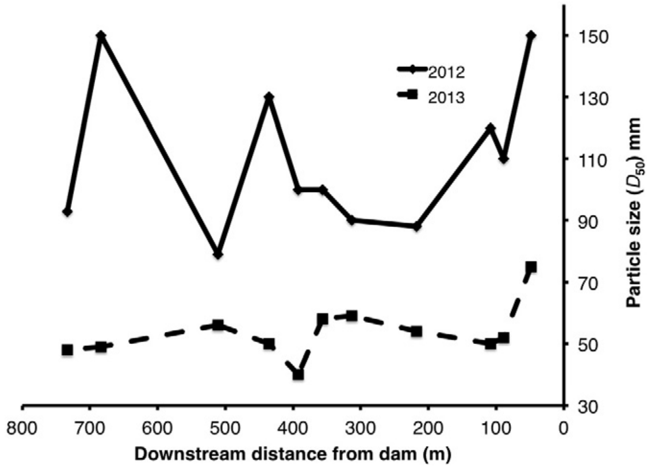

Fig. 4. Median bed particle size downstream of dam. Solid line is pre-dam and dashed line is post-dam.

of 8–12, with a bed profile slope of ~ 1.3%. Habitat units ranged evenly between riffles and glides, but deep pools occurred intermittently, especially at the large meander bend between cross sections 5 and 6 (Fig. 3) and where bedrock ledges controlled bed topography.

4.1.2. Fish assemblages

Fish assemblages in Amethyst Brook were characterized by a relatively diverse (11 species total) (Table 3) set of native and non-native cool- and cold-water freshwater resident (8 species) and diadromous species (3 species). Blacknose dace (*Rhinichthys atratulus*), a native, stream cool-water cyprinid was the most numerically abundant species. Blacknose dace, native brook trout (*Salvelinus fontinalis*), and non-native brown trout (*Salmo trutta*) (all freshwater resident) were the only species found above and below the removed dam prior to removal (Figs. 5–10). In contrast, four species that were abundant in below-dam samples were not encountered above the dam (Table 3). Similarly, sea lamprey redds were not found upstream, nor were they found immediately downstream of the dam, only occurring in association with the farthest downstream cross sections (Table 3). These patterns were reflected in a distinct threshold of species richness moving from downstream to upstream of the dam (Table 3; Fig. 5).

Table 1
Median (D_{50}) and mean bed particle size data for both upstream and downstream cross sections for pre-removal (2012) and post-removal (2013) surveys.

	Median bed particle size (mm)		Mean bed particle size (mm)[a]	
	2012	2013	2012	2013
I. Upstream cross sections				
U1	60	105	42.7	*84.1*
U2	52	55	41.2	50.2
U3	39	50	36.3	44.8
U4	61	74	48.1	*67.9*
U5	45	70	41.8	55.0
U6	45	77	48.4	57.5
U7	69	105	54.3	65.5
II. Downstream cross sections				
D1	150	75	129.7	*77.0*
D2	110	52	94.6	*58.0*
D3	120	50	109.6	*52.3*
D4	88	54	89.4	*65.6*
D5	90	59	84.3	*54.4*
D6	100	58	94.3	*54.5*
D7	100	40	106.7	*45.8*
D8	130	50	121.7	*55.0*
D9	79	56	70.7	*53.3*
D10	150	49	124.1	*46.3*
D11	93	48	104.4	*47.6*

[a] Note: Italics indicates significant difference ($p < 0.05$).

4.2. Post-removal impacts

4.2.1. Geomorphic changes

4.2.1.1. Upstream adjustments. Channel responses following removal reflect the effects of dam removal and partially the occurrence of the large flood 6 months after removal. We were only able to measure the upstream reach's longitudinal profile prior to the flood, with all other measurements being post-flood and post-removal. For the upstream reach, dramatic changes occurred within the first 6 months following removal (Fig. 11). Knickpoint migration exhumed an extensive buried wooden crib dam (Fig. 12) that now serves as an exposed grade control limiting continuous upstream headcutting. This crib dam was not identified during pre-removal field reconnaissance nor did it appear on any

Table 2
Results of interstitial space surveys (mean number of spaces $* \ m^{-2}$) downstream of the removed dam.

Downstream cross sections	Pre-removal mean	s.e.	Post-removal mean	s.e.
Cross sections 1–4	3.56	1.24	7.64	1.34
Cross sections 5–9	5.6	1.02	13.33	1.33
Cross sections 10–11	12.67	2.17	10.67	6.14

Table 3
Species encountered before (2012) and after (2013) dam removal (BKT = brook trout, BNT = brown trout, ATS = Atlantic salmon, BND = blacknose dace, LND = longnose dace, SS = slimy sculpin, WHS = white sucker, YBH = yellow bullhead, EEL = American eel, SL = sea lamprey). Those species that were only found below the removed dam prior to removal indicated in bold. See Fig. 3 for location of cross sections.

Site	Cross section	Removed dam	Exposed dam	2012	2013
Robert Frost Trail	D11	Downstream	Downstream	BKT, BNT, **ATS**, BND, LND, SS, **WHS**, **SL**	BKT, BNT, BND, LND, SS, SL
Below dam	D1–D3	Downstream	Downstream	BKT, BNT, **ATS**, BND, LND, SS, WHS, **YBH**	BKT, BNT, BND, LND, SS, WHS
Directly above removed dam	U1–U3	Upstream	Downstream	BKT, BND	BKT, BNT, **ATS**, BND, **LND**, **SS**, **SL**
Above dam treeline	U4	Upstream	Downstream	BKT, BNT, BND	BKT, BNT, **ATS**, BND, **LND**, **SS**, **SL**
Right above crib dam	U5	Upstream	Upstream	Did not sample	BNT, BND
150 m above crib dam	U7	Upstream	Upstream	Did not sample	BKT, BNT, BND, EEL
Below Buffam Falls	NA	NA	NA	BKT, BNT, **ATS**, BND	BKT, BNT, BND, **EEL**
Meetinghouse Rd Tributary	NA	NA	NA	BKT	BKT
Adams Brook	NA	NA	NA	BKT, BNT, ATS, BND, LND, SS	BKT, BNT, ATS, BND, LND, SS

historical records suggesting a very early historical age (older than the A.D. 1820 Pelham dam). Although unanticipated, exhumation of buried structures is not an uncommon phenomenon following dam removal (Harris and Evans, 2014; Wilcox et al., 2014; Zunka et al., 2015).

Post-removal channel incision and subsequent upstream migration evacuated significant volumes of sediment (Fig. 11). Between −70 and −104 m upstream of the former dam (Fig. 11), the channel incised 2–2.5 m following dam removal and the June 2013 flood (Fig. 13), evacuating a minimum of 650 m^3 of sediment between −125 m and into distal locations of the former reservoir (−70 m). A deep pool formed below the exhumed crib dam, but limited erosion occurred above it. In contrast to the significant incision below the crib dam, minimal difference exists in bed elevations pre- to post-removal for the upper 120 m of the reach (−290 to −170 m), with irregular bed elevation differences, including aggradation and degradation, between −170 m and the exhumed crib dam (Fig. 11).

Extensive erosion occurred in response to the June 2013 flood, magnifying the initial effects of the dam removal. Incision was pronounced again below the crib dam, with an additional incision of 0.4–0.8 m, including incision into the post-removal engineered channel-bed in the former reservoir (Fig. 11). The pool below the crib dam deepened following the flood, and some channel-bed erosion occurred upstream of the crib dam, due in part to some crib dam collapse during the flood (Fig. 11). Similar to the initial erosion prior to the flood, channel-bed incision and erosion was not translated into the upper reaches of the transect (−290 to −170 m). We estimate that an additional 450 m^3 of material was eroded post-flood along the entire transect (i.e., including the channel reach in the former reservoir).

Post-removal channel cross sections were not measured pre-flood, so they only represent the aggregate changes from the pre-removal to the combined post-flood and post-removal periods. Erosion was pronounced in reservoir proximal locations (cross sections 1–3) with 19 and 36 m^2 of channel erosion occurring within the first two upstream cross sections, respectively (Table 4). Total channel erosion attenuates rapidly upstream with imperceptible changes occurring in the three most upstream locations (cross sections 5–7) (Table 4). As is true of the longitudinal profile, translation of erosion and knickpoint migration occurs up to and above cross section 4 (at −140 m). The spatially averaged depth of incision from the cross section surveys indicate ~0.54 m of erosion along the upstream reach, which corresponds to ~1100 m^3 of erosion. Assuming a dry bulk density of 1500 kg/m^3 for the sand and gravel alluvium, this corresponds to ~$1.5 * 10^6$ kg of eroded sediment from the upstream reach. Integrating longitudinal profile depth differences along the upstream reach corresponds to 1000 m^3 of total erosion. Assuming the same dry bulk density of 1500 kg/m^3 of alluvial material, this corresponds to $1.6 * 10^6$ kg of evacuated sediment. The cross sectional volume estimates correspond well to the depth and volume differences, generating a standardized flux of 60,000 kg/km^2.

4.2.1.2. Downstream adjustments. Impacts downstream were less dramatic at the cross section scale but spatially more extensive along the longitudinal profile. For changes at cross sections and along the

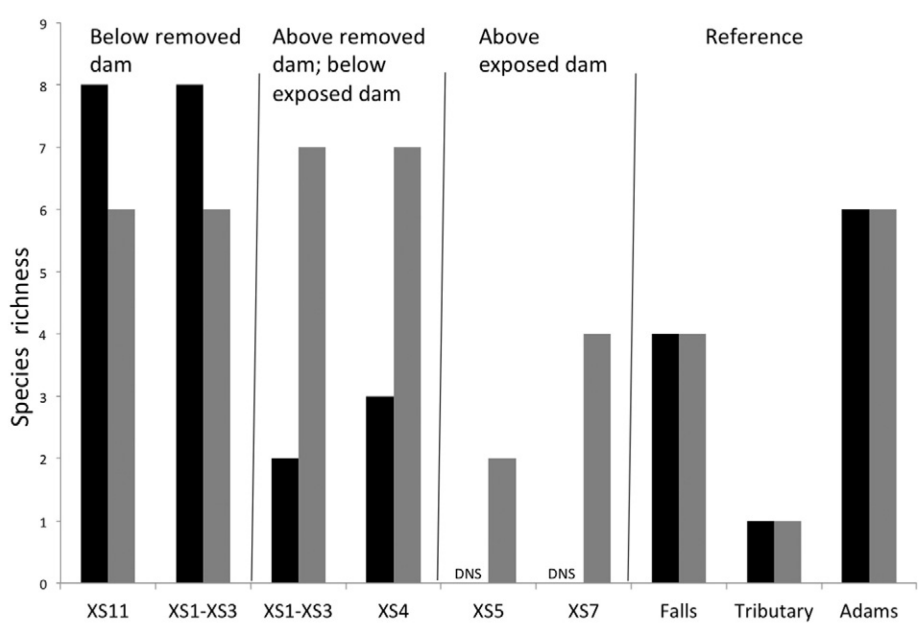

Fig. 5. Fish species richness (total number of species per sample). Black bars are before (July 2012) dam removal and gray bars are after (July 2013) dam removal.

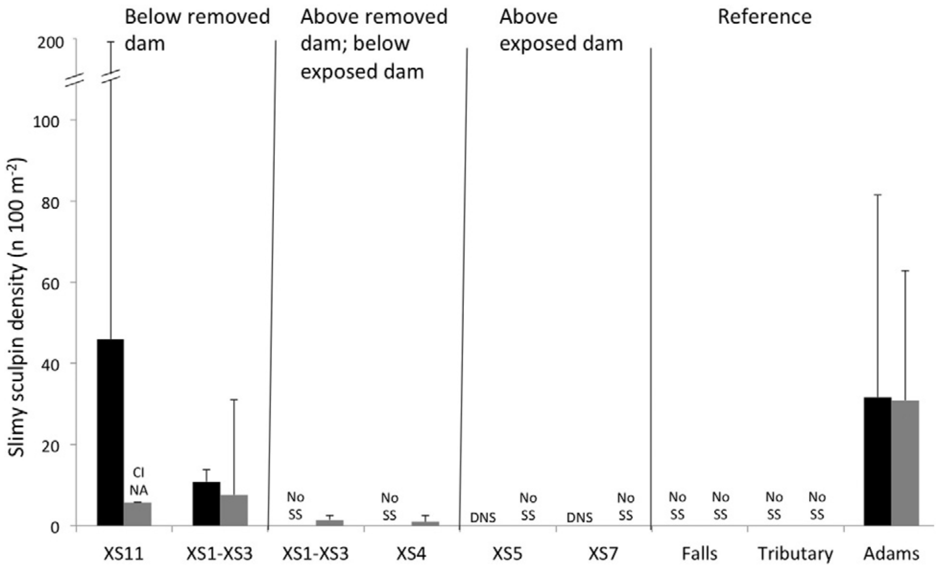

Fig. 6. Estimated slimy sculpin densities before (black bars, July 2012) and after (gray bars, July 2013) dam removal. Error bars represent 95% confidence intervals. CI NA = confidence interval not available because the number of individuals captured on second electrofishing pass equaling or exceeding captured on first electrofishing pass; in these cases density is calculated from total number of slimy sculpin captured during both passes. No SS = no slimy sculpin captured at this site. DNS = did not sample.

longitudinal profile, aggradation predominated, especially in dam proximal locations (Fig. 14). For the first two downstream cross sections, net deposition of 1.6 and 10 m^2 occurred, although the peak at cross section #2 was exacerbated by several pieces of large woody debris (LWD) on the left bank downstream of the cross section that created a backwater effect enhancing deposition. A second peak in aggradation occurs ~ 500 m downstream at cross section 7 (net deposition of 3 m^2) before thinning at the most downstream cross section 750 m downstream (Fig. 14). This peak suggests a wave of material translated downstream, especially as there are no major tributary inputs of sediment along the reach. Using the net changes occurring at each cross section and spatially averaging the distances along the profile generates ~858 m^3 of sediment deposition. Net aggradation is further revealed by the detailed longitudinal profile (Fig. 15). Integrating the net changes along the bed profile reveals ~1100 m^3 of deposition along the 750-m reach. Again, assuming a gravel-sand porosity of 1500 kg/m^3 generates $1.65 * 10^6$ kg of sediment, or 66,000 kg/km^2.

Post-removal pebble counts signal major fining in particle size downstream of the former dam and an irregular variation upstream (Table 1 and Fig. 4) where coarsening and fining both occurred. For the downstream reach, channel-bed fining was on the order of 30–50%, with all cross sections experiencing significant fining (Table 1). Prior to removal, there was no apparent systematic pattern in grain size downstream below the dam; whereas, following removal, there is a more consistent and coherent fining (Fig. 4). Results of embeddedness surveys coincide with these changes. Shelter space availability increased nearly twofold immediately downstream and nearly threefold toward the middle of the study section (Table 2), while the farthest

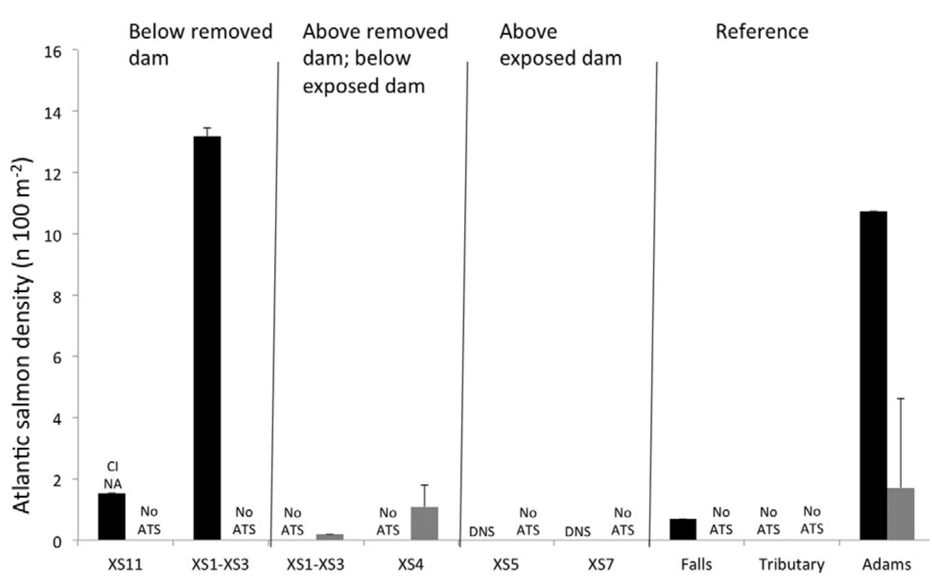

Fig. 7. Estimated Atlantic salmon densities before (black bars, July 2012) and after (gray bars, July 2013) dam removal. Error bars represent 95% confidence intervals. See Fig. 6 caption for confidence interval details. No ATS = no salmon captured at this site. DNS = did not sample.

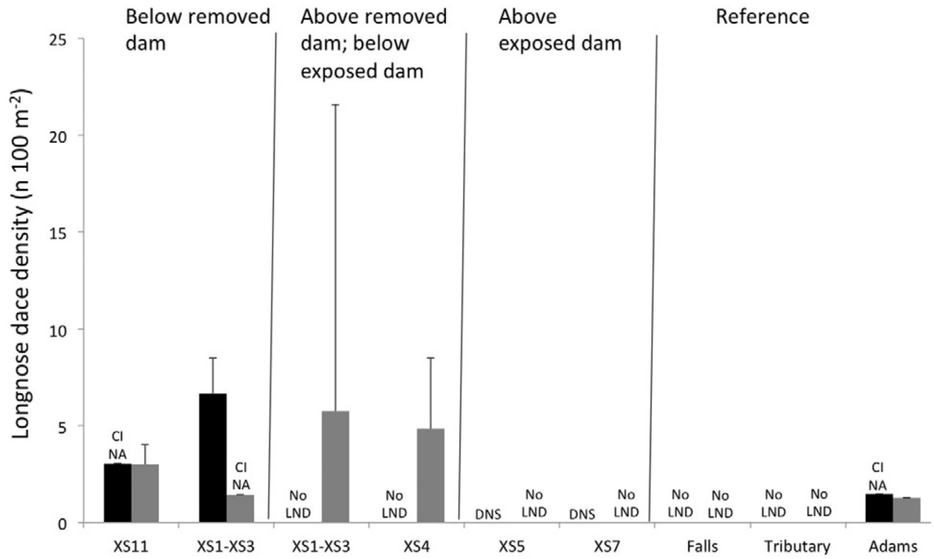

Fig. 8. Estimated longnose dace densities before (black bars, July 2012) and after (gray bars, July 2013) dam removal. Error bars represent 95% confidence intervals. See Fig. 6 caption for confidence interval details. No LND = no longnose dace captured at this site. DNS = did not sample.

downstream sections, which had the highest availability pre-removal, exhibited little change.

4.2.2. Fish assemblage changes

4.2.2.1. Upstream changes. In the post-removal samples, four species (Longnose dace (*Rhinichthys cataractae*), Slimy sculpin (*Cottus cognatus*), Atlantic salmon (*Salmo salar*), and sea lamprey (*P. marinus*) that were not found above the removed dam in the previous year were found in the two sections upstream in 2013, resulting in an approximate doubling of species richness in these sections (Table 3, Fig. 5). These species were not, however, found in the sections sampled immediately upstream of the exposed crib dam (Figs. 6–10). At the same time, overall fish abundance was greatly reduced in the two upstream sections in 2013 compared to 2012, due largely to a major reduction in the abundance of blacknose dace (Fig. 10), the most common species. Reference sections, well out of the influence zone of the dam removal, did not experience these reductions (Figs. 6–10).

4.2.2.2. Downstream changes. Overall, fish abundance decreased substantially in 2013 vs. 2012 in both downstream sample sections. Almost all, including the most common species, blacknose dace, showed decreases; and some species that were abundant in 2012 were completely absent from either one or both of the sample sections in 2013, resulting in lower species richness (Table 3 and Figs. 5–10). One notable exception was that sea lamprey redds, previously unobserved immediately downstream of the former dam, were found there for the first time in 2013.

5. Discussion

By combining pre- and post-quantitative geomorphic and ecological data, we were able to document complex, interactive immediate effects of a dam removal in a small upland catchment. The occurrence of an extreme flow event subsequent to removal resulted in a major readjustment of sediment and geomorphic regime, with aggradation and associated bed caliber fining extending downstream to the river's mainstem confluence. Evacuation of stored sediments upstream exposed a second,

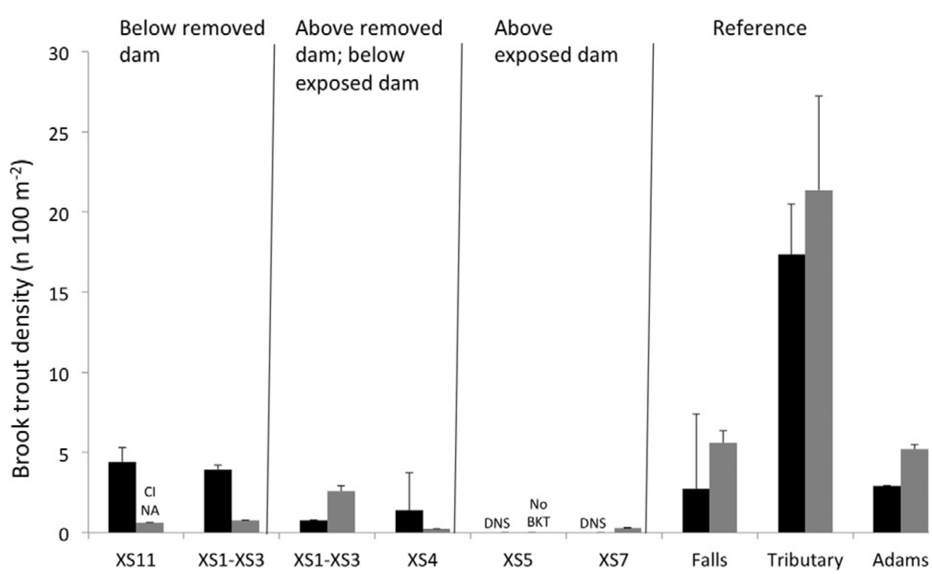

Fig. 9. Estimated brook trout densities before (black bars, July 2012) and after (gray bars, July 2013) dam removal. Error bars represent 95% confidence intervals. See Fig. 6 caption for confidence interval details. No ATS = no brook trout captured at this site. DNS = did not sample.

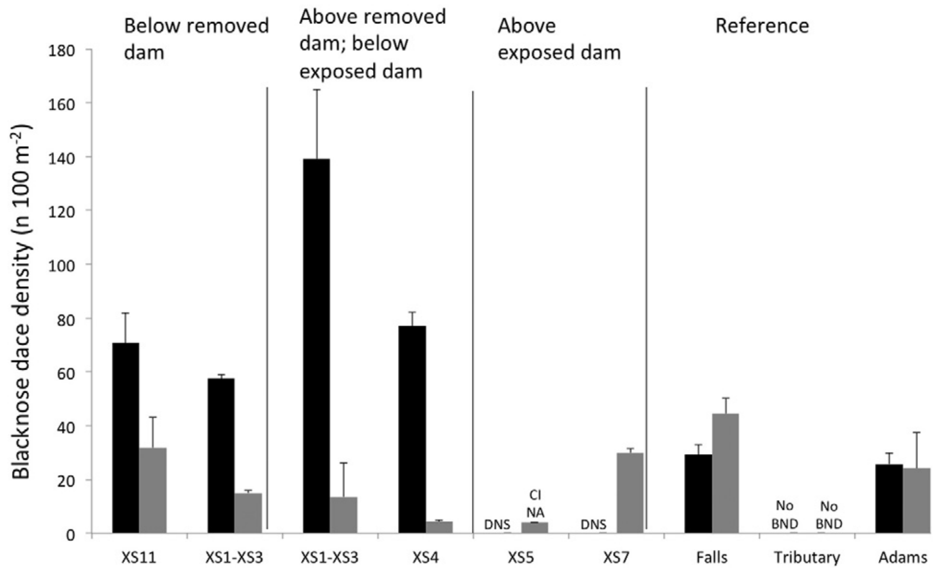

Fig. 10. Estimated blacknose dace densities before (black bars, July 2012) and after (gray bars, July 2013) dam removal. Error bars represent 95% confidence intervals. See Fig. 6 caption for confidence interval details. No ATS = no blacknose dace captured at this site. DNS = did not sample.

timber crib dam, which served as a hydraulic control limiting the extent of headcutting. These geomorphic effects were clearly reflected in changes in fish distribution and abundance. The occurrence of a bed-mobilizing event during a time period when many species were at vulnerable stages in their life cycle was associated with general reductions in overall abundance downstream and immediately upstream of the year following dam removal. At the same time, four species that were previously unobserved above the dam were found in post-removal samples, approximately doubling overall species richness. Further, the availability of appropriate spawning gravel following dam removal in downstream, sediment-starved sections was associated with successful spawning of native sea lamprey in areas where they were not previously observed. Finally the newly exposed crib dam, in addition to serving as a hydraulic control, also limited the spatial extent of upstream reestablishment of fish species. Our results indicated that a set of fairly routine geomorphic and ecological measurements effectively characterized important immediate effects of dam removal and could serve as a template for a generalized monitoring protocol. These results, while in some ways consistent with previous studies and general geomorphic and ecological understanding, also underscore the inherent unpredictability of the magnitude and direction of short-term responses. Effectively communicating that this uncertainty may be an essential component of constructive engagement with the wide range of stakeholders involved with, and affected by, dam removal.

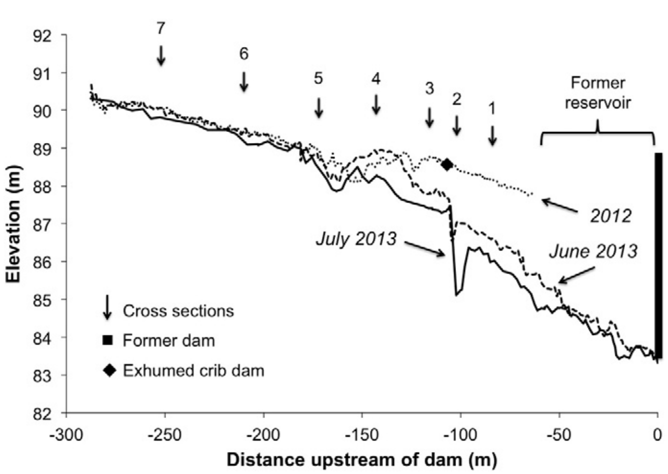

Fig. 11. Longitudinal profile for the upstream reach. Distances are shown as negative numbers indicating distance upstream of the former dam. The upper line is pre-dam removal. The middle line is post-removal but pre-flood. The lower line is post-flood. Numbers and arrows refer to sampled cross sections. Dam height is ~88.8 m.

5.1. Geomorphic adjustments

Results from this study provide new insights to the magnitude, style, and type of geomorphic adjustments to dam removal and help refine our general understanding of the tempo of change to the removal of a long-term disturbance and the associated spatial extent of geomorphic recovery. In particular, we document the important length scale of response, the role of event sequencing, and the geomorphic expression in coarse gravel streams. The magnitude and response rate was conditioned by both the geologic and geomorphic boundary conditions and removal strategies.

5.1.1. Length scale of impact

The type of removal, where the sediment was mechanically evacuated and stored on site with the dam removed in stages, prevented significant knickpoint headcutting through the impoundment. The upstream extent was further limited by the exhumation of an older wooden crib dam,

Fig. 12. Exhumed wooden crib dam. Photo taken soon following the 28 June 2013 flood.

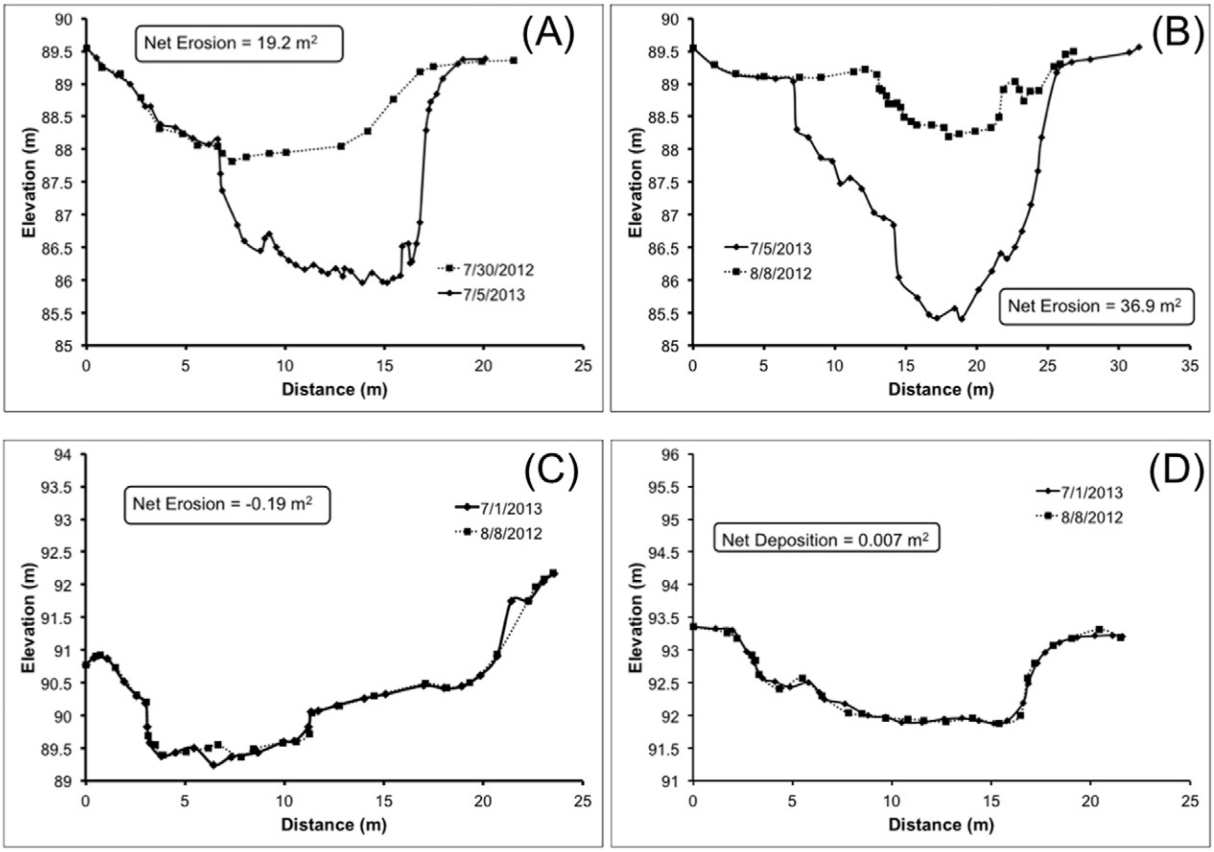

Fig. 13. Changes in representative cross sections upstream of the former dam. Cross sections 1 (A) and 2 (B) are below the exhumed crib dam. Cross sections 6 (C) and 7 (D) are at the beginning of the reach and are well above the crib dam (see Figs. 3 and 12 for location of cross sections).

but bed surveys revealed a bedrock ledge ~45 m upstream of the crib dam that would have arrested further upstream propagation. The limited spatial extent of headcutting seems to predominate in physiographic regions like New England where streams flow on resistant bedrock or where coarse Pleistocene deposits get exhumed and limit progressive headward propagation (Pearson et al., 2011; Gartner et al., 2015). For Amethyst Brook, the spatial extent of headcutting was on the order of ~4–5 bankfull widths above the former impoundment head (due to the crib dam) but would have only progressed to ~9–10 bankfull widths before encountering its first bedrock ledge.

The downstream impact was more extensive, both in terms of bed aggradation and bed sedimentological changes. Aggradation continued, but attenuated, throughout the entire downstream length of ~750 m, a distance of ~75 bankfull widths. Moreover, besides aggrading, the channel fined following removal—a response that typified the entire length scale. Unlike previous studies that document the general fining of the bed downstream of the removed dam due to material supplied from the former reservoir (Major et al., 2012), the progressive bed fining better reflects the re-connected sediment flux that has further led to channel-bed aggradation. In a recent assessment of large dam removals, Grant and Lewis (2015) document the post-removal downstream spatial extent of coarse and fine sediment and relate it to the amount (in tons or volume) of sediment exported from the impoundment relative to the annual sediment load (a metric they denote as E*). As to be expected, the fine fraction is exported the farthest, often twice the distance of the bedload, with sites with the highest E* ratios having the farthest travel distances. We lack regional sediment data to calculate E* so it is difficult to relate our results to their assessment, but for fines limited sites, typical of New England, and where sediment is removed and subsequently stored prior to dam removal, transport

Table 4
Pre-removal (2012) to post-removal (2013) changes in channel cross-sectional area for upstream locations[a]. See Fig. 3 for location of cross sections.

Cross section	Deposition (m^2)	Erosion (m^2)	Net change (m^2)	Distance from beginning of reach (m)
U1	0.30	−19.49	−19.19	219.59
U2	0.00	−36.85	−36.85	200.61
U3	0.56	−9.69	−9.13	185.80
U4	0.09	−5.70	−5.61	156.71
U5	0.63	−2.13	−1.49	126.99
U6	0.50	−0.69	−0.19	80.95
U7	0.36	−0.37	−0.01	37.78

[a] Note: Going from the downstream cross section (XS #U1) near the former dam to the most upstream cross section (XS #U7).

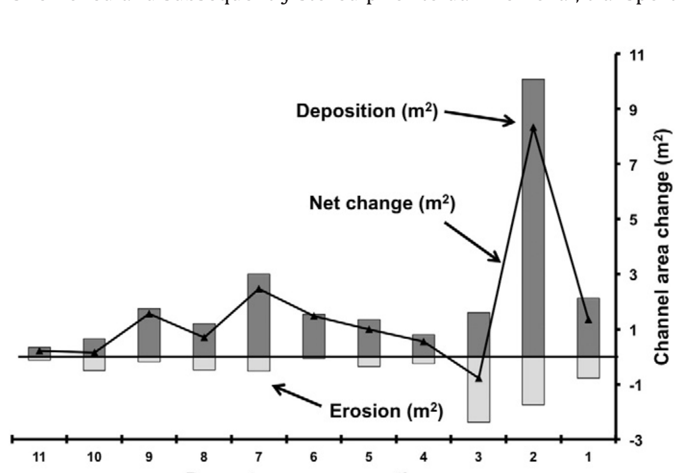

Fig. 14. Post-removal net deposition downstream of the former dam for channel cross sections. See Figs. 3 and 11 for location of cross sections.

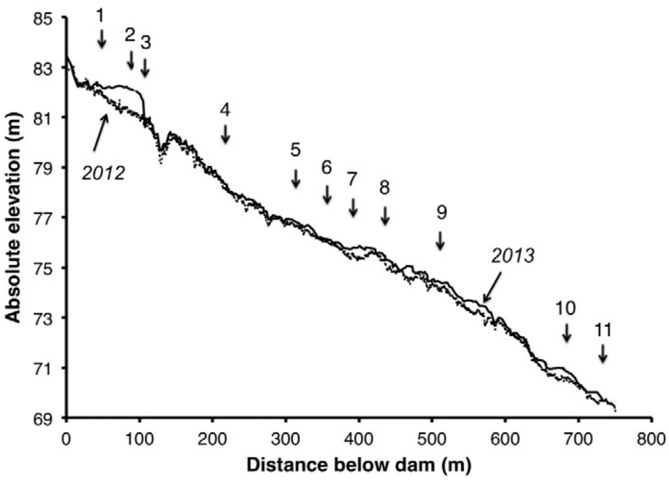

Fig. 15. Pre-removal (2012) and post-removal (2013) bed elevations along the longitudinal profile for the downstream reach.

distances may be less than estimated by Grant and Lewis (2015). Despite this caveat, the downstream fining and bed aggradation of the coarse fraction 750 m downstream of the dam within the first year corresponds well with dams of similar watershed size and sediment characteristics identified by Grant and Lewis (2015).

5.1.2. Event sequencing

Recent studies have identified the salient role of the initial processes driving upstream to downstream sediment delivery. Sawaske and Freyberg (2012) document that most of the erosion occurs quickly, generally within 1–2 years post-removal. However, when stratifying the Sawaske and Freyberg (2012) data set by impoundment sedimentology, Grant and Lewis (2015) show that the more rapid erosion occurs in sites where the impoundment sediments are primarily sandy (Major et al., 2012) or where mass movement occurs in saturated sediments (Wilcox et al., 2014). However, these assessments are usually aggregate data, and they lack a more mechanistic explanation. The timing and rate of sediment release can be governed by different driving forces, intrinsic or extrinsic to the system, similar to what Pizzuto (2002) conceptualized as process-driven erosion (often associated with falling base level, slope increases, and knickpoint migration) vs. event-driven erosion (large-flow dependent erosion and transport). The style of removal for Pelham dam represents one end member of a suite of styles: a staged removal combined with sediment evacuation and subsequent on-site storage prior to removal. The removal design limited material directly accessible by the stream. As the stream is at or near bedrock immediately upstream of the former dam, it will require progressive channel widening or lateral migration to access that material stored in the former impoundment—which has not yet happened, even during the large post-removal flood which was associated primarily with bed incision.

This is not to imply that process-driven responses have not occurred. Knickpoint migration was pronounced up to the former crib dam even before the June 2013 flood. Bed surveys pre- and post-removal along the reach where pre-flood data are available (Table 4 and Fig. 11) indicate that ~ 67% of the aggregate erosion happened before the major flood, suggesting that process-driven erosion predominated during the six post-removal months. Recent documentation of event sequencing (Pearson et al., 2011; Major et al., 2012; Grant and Lewis, 2015) indicates that process-driven erosion tends to predominate; and our results, which include an extremely large flood post-removal, also indicates that initial process-driven erosion may be the more important mechanism in the initial years post-removal.

The combined removal of ~1000 to 1110 m^3 of upstream sediment within the first year further corresponds with empirical relationships based on reservoir geometry. Sawaske and Freyberg (2012) suggest that the aspect ratio (width of reservoir to upstream channel width) represents a first-order control on the volume of sediment evacuation (where aspect ratio is high, less of the total sediment is removed in a given time period relative to a dam with a lower aspect ratio). Approximately 30% of the total volume of reservoir sediment was removed in the first year (assuming an estimated 3500 m^3 of reservoir fill—which is a minimum value as it is based on sediment volume excavated and stored on site) with a corresponding aspect ratio of 4.5. (assuming bankfull channel width is 9 m in the control section (Fig. 13) and an average reservoir width of 40 m). This percent volume evacuated in the first year (~30%) corresponds well with other removals of similar reservoir sedimentology (Grant and Lewis, 2015) and is generally in the region suggested by Sawaske and Freyberg (2012) for dams of similar reservoir geometry.

5.2. Ecological adjustments

Even given the limited time frame, the changes in fish distribution that we observed were in many ways consistent with our expectations and the results of previous studies. While stream fish populations and assemblages can exhibit marked interannual variation even in the absence of major floods and barrier removals, this general consistency with predictions and previous research, along with markedly lower between-year differences in reference sites, indicate that pre- and post-removal differences were likely influenced by the increased connectivity and geomorphic adjustments associated with dam removal. Several species that were not found below the dam in 2012 were found in sizeable numbers following dam removal. This finding is consistent with rapid colonization after the removal of barriers to movement observed in studies encompassing a wide range of dam types and environmental settings. While relatively few of these studies have been conducted in small upland catchments typical of the northeastern U.S., Gardner et al. (2013) found that three of the same species we observed extending their distributions upstream had the same response to small dam removal in a central Maine watershed. As two of these species (slimy sculpin and longnose dace) are widely distributed across the northeast, they may be an appropriate general effectiveness indicator for dam and barrier removal efforts. These distributional changes have particular importance for anadromous species. The ability of sea lamprey to spawn upstream immediately following dam removal has been observed previously in a small New England watershed (Hogg et al., 2013). Given the role of this species as a potential ecosystem engineer, influencing substrate composition (Hogg et al., 2013) and providing marine-derived nutrients (Nislow and Kynard, 2009), upstream reestablishment may have wide-ranging impacts on ecosystem function. Reinforcing the primary influence of barriers and barrier removal on the observed distributional changes, the four species that were found upstream of the removed dam did not move upstream past the newly-exposed dam. In addition to removing a barrier to upstream passage, our study is the first to demonstrate that reestablishment of appropriate spawning gravels in sediment-starved downstream locations could increase the number and distribution of lamprey spawners, although such effects have been demonstrated for migratory salmon, whose spawning gravel requirements broadly overlap those of sea lamprey (Saunders et al., 2006).

In spite of the positive changes in distribution, we did observe general reductions in abundance following the combination of dam removal and an extreme flood event. Although we cannot absolutely rule out that the flood alone was the cause of reduced abundance, two considerations suggest that an interaction between the flood and the geomorphic impacts of the dam removal was largely responsible. First, reference sections in the Amethyst Brook basin experiencing roughly similar rainfall intensities but unassociated with the dam did not exhibit similar reductions in fish abundance (Table 3 and Figs. 6–10). Second, a number of studies have found that direct mortality and reduction in stream fish abundance in response to floods is generally associated with bed movement (Nislow et al., 2002), which was strongly influenced by the removal of the dam. All of the fish species encountered in our study are widespread and relatively abundant in the basin; and large fluctuations in abundance, frequently associated with interannual variation in flow and temperature regimes, are often observed in northern stream fish populations (Xu et al., 2010). Therefore, the short-term decreases in abundance we observed are unlikely to persist or seriously threaten these populations. In fact, changes in physical habitat that we observed suggest that ultimate effects on fish abundance and diversity, even in downstream sections where we observed initial decreases, are likely to be positive. Availability of spawning gravel exerts a primary control on abundance for gravel nesters such as lampreys and salmonids (Opperman et al., 2005), and our results strongly indicate a substantial increase in availability for nearly a kilometer of downstream habitat. Replenishment of sediment in a previously sediment-starved reach also has implications for overall riparian and instream habitat diversity, as sediment will now be available to form bars, side channels, and other important habitat features. Finally, interstitial space appears to be an important habitat attribute for stream fishes, as a large percentage of the species that we observed use these spaces as shelters (Gries and Juanes, 1998) and the availability of shelters has been linked to increased growth and survival of stream salmonid fishes (Finstad et al., 2007). At the same time, the large-scale aggradation and sediment accumulation we observed underscores concerns raised by Sethi et al. (2004) about risks to rare, sedentary populations (such as freshwater mussels) with limited scope for recolonization and low compensatory scope to rebound from low population levels.

6. Conclusions

As Grant and Lewis (2015) indicate in their broad synthesis of 15 years of dam removal studies, our scientific understanding of how rivers respond to dam removal has dramatically improved. With the greater empirical coverage of dam types and styles of removal (Stewart and Grant, 2005; Sawaske and Freyberg, 2012; East et al., 2015; Grant and Lewis, 2015), the scientific community has moved well beyond early conceptual models based on geomorphic analogies (Doyle et al., 2002; Pizzuto, 2002). For the initial and extant boundary conditions outlined herein where a staged removal occurred in a coarse gravel-bedded stream and where the impoundment sediment was mechanically relocated, geomorphic adjustments have been robust, generating important ecological responses. The downstream bed fining was related more to the reconnected sediment supply rather than to the supply from the former impoundment. The decrease in bed caliber has provided greater interstitial spaces and has further generated the suitable bed texture for gravel-spawning species such as sea lamprey and salmonid fishes (trout and salmon).

The occurrence of a large flood within the first year of removal provided the opportunity to document the relative role of process vs. event-driven erosion and to quantify the resulting ecological effects due to the reconnected longitudinal connectivity following dam removal and associated impacts from a bed mobilizing event. With the timing of the large flood occurring at a vulnerable time of their life cycle, fish abundances tended to decline for most species downstream of the removed dam. As Nislow et al. (2002) documented, this effect is probably ephemeral and future monitoring will need to occur to capture the pace of population changes. The large flood did, however, help answer whether process-driven or event-driven erosion dominates. Although limited to a small reach upstream of the dam and its former impoundment, we were able to document that the 'normal' spring flows after the late fall dam removal, in combination with headward knickpoint migration (process-driven erosion), were adequate to achieve the bulk of sediment evacuation. The large flood accounted for only ~ 33% of upstream bed erosion; but despite its limited erosion relative to knickpoint migration, the flood probably contributed more importantly to downstream sediment dispersal. In this way, its occurrence may have been more significant at larger spatial scales as its effect on downstream transport may have been more pronounced. Future work should attempt to evaluate the role of event sequencing not just on upstream responses but also to the magnitude and spatial extent of downstream adjustments.

From a management perspective, this dam removal has provided important results and insights. It shows that ecological benefits can be achieved rapidly: (i) several species, which were never observed upstream of the former dam, have now made it upstream of the former barrier, and (ii) sea lamprey are constructing redds up to and beyond the former dam—all within the first year of removal. But success should not be limited to short-term changes in fish occurrence or abundance. We contend that the real measure of success is whether the coupled geomorphic and ecological response is occurring. The question should not merely be 'are the fish making it above the former impoundment?', but, rather it should be 'are fish demography, population viability, and species diversity responding to the new sets of geomorphic conditions resulting from the reconnected sediment regime and pre-dam natural flow?'. Our results highlight this coupled eco-geomorphic response and further show that it can happen quickly. From a regional perspective, our results support the recent emphasis on dam removal as an important tool for river restoration at reach and watershed scales. Given improvement in fish passage along the Connecticut River mainstem, our results clearly show that headwater spawning habitat can rapidly be made viable and available if small dams are removed. Stewart and Grant (2005) queried "What can we learn from the removal of little dinky dams?" We contend that you cannot only learn a lot, you can also achieve a lot.

Acknowledgments

This research was funded in part by the National Science Foundation (BCS: 1263519) and by the Rockefeller Center at Dartmouth College (Grant #061511). The authors would like to thank Eirik Buraas, John Gartner, Matt Pierce, Abby Franklin, Helen Doyle, Evan Dethier, Paul Damkot, Jason Coombs, and Keith Kantack for their help with field work. Jonathan Chipman provided great geospatial insights and fantastic cartography. This manuscript benefited from discussions held at the USGS Powell Center in Fort Collins, CO and from insightful comments and reviews by Noah Snyder and Bruce Rhoads. Lastly, FJM would like to thank Will Graf for his friendship, intellectual and professional guidance, and early and often mentoring. Will has pioneered several important research trajectories and all of us studying the impacts of dams and of dam removal on fluvial systems are in perpetual gratitude for his prescient foresight into these topics. Thanks Will.

References

Armstrong, W.H., Collins, M.J., Snyder, N.P., 2012. Increased frequency of low-magnitude floods in New England. J. Am. Water Resour. Assoc. 48, 306–320.

Bednarek, A.T., 2001. Undamming rivers: a review of the ecological impacts of dam removal. Environ. Manag. 27, 803–814.

Bellmore, J.R., Vittum, K.M., Duda, J.J., Greene, S., 2015. USGS Dam Removal Science Database URL: http://dx.doi.org/10.5066/F7K935KT.

Bountry, J.A., Lai, Y.G., Randle, T.J., 2013. Sediment impacts from the Savage Rapids Dam removal, Rogue River, Oregon. Rev. Eng. Geol. 21, 93–104.

Burroughs, B.A., Hayes, D.B., Klomp, K.D., Hansen, J.F., Mistak, J., 2009. Effects of Stronach Dam removal on fluvial geomorphology in the Pine River, Michigan, United States. Geomorphology 110, 96–107. http://dx.doi.org/10.1016/j.geomorph.2009.03.019.

Cheng, F., Granata, T., 2007. Sediment transport and channel adjustments associated with dam removal: Field observations: dam removal, sediment transport, and channel adjustment. Water Resour. Res. 43. http://dx.doi.org/10.1029/2005WR004271.

Csiki, S., Rhoads, B.L., 2010. Hydraulic and geomorphological effects of run-of-river dams. Prog. Phys. Geogr. 34, 755–780. http://dx.doi.org/10.1177/0309133310369435.

Descloux, S., Datry, T., Philippe, M., Marmonier, P., 2010. Comparison of different techniques to assess surface and subsurface streambed colmation with fine sediments. Int. Rev. Hydrobiol. 95, 520–540.

Diebel, M., Fedora, M., Cogswell, S., O'Hanley, J., 2014. Effects of road crossings on habitat connectivity for stream-resident fish. River Res. Appl. http://dx.doi.org/10.1002/rra.2822.

Doyle, M.W., Havlick, D.G., 2009. Infrastructure and the environment. Annu. Rev. Environ. Resour. 34, 349–373.

Doyle, M.W., Stanley, E.H., Luebke, M.A., Harbor, J.M., 2000. Dam removal: physical, biological, and societal considerations. American Society of Civil Engineers Joint Conference on Water Resources Engineering and Water Resources Planning and Management, Minneapolis, MN.

Doyle, M.W., Stanley, E.H., Harbor, J.M., 2002. Geomorphic analogies for assessing probable channel response to dam removal. J. Am. Water Resour. Assoc. 38, 1567–1579.

Doyle, M.W., Stanley, E.H., Harbor, J.M., 2003. Channel adjustments following two dam removals in Wisconsin. Water Resour. Res. 39, 1011.

Doyle, M.W., Stanley, E.H., Orr, C.H., Selle, A.R., Sethi, S.A., Harbor, J.M., 2005. Stream ecosystem response to small dam removal: lessons from the Heartland. Geomorphology 71, 227–244.

Doyle, M.W., Stanley, E.H., Havlick, D.G., Kaiser, M.J., Steinbach, G., Graf, W.L., Galloway, G.E., Riggsbee, J.A., 2008. Aging infrastructure and ecosystem restoration. Science 319, 286–287.

Draut, A.E., Ritchie, A.C., 2013. Sedimentology of new fluvial deposits on the Elwha River, Washington, USA, formed during large-scale dam removal: dam-removal fluvial deposits. River Res. Appl. http://dx.doi.org/10.1002/rra.2724.

East, A.E., Pess, G.R., Bountry, J.A., Magirl, C.S., Ritchie, A.C., Logan, J.B., Randle, T.J., Mastin, M.C., Minear, J.T., Duda, J.J., 2015. Large-scale dam removal on the Elwha River, Washington, USA: river channel and floodplain geomorphic change. Geomorphology 228, 765–786.

Finstad, A., Einum, S., Forseth, T., Ugedal, O., 2007. Shelter availability affects behaviour, size-dependent and mean growth of juvenile Atlantic salmon. Freshw. Biol. 52, 1710–1718.

Gangloff, M.M., 2013. Taxonomic and ecological tradeoffs associated with small dam removals: editorial. Aquat. Conserv. Mar. Freshwat. Ecosyst. 23, 475–480. http://dx.doi.org/10.1002/aqc.2383.

Gardner, C., Coghlan, S.M., Zydlewski, J., Saunders, R., 2013. Distribution and abundance of stream fishes in relation to barriers: implications for monitoring stream recovery after barrier removal: barrier removal effects on stream fishes. River Res. Appl. 29, 65–78. http://dx.doi.org/10.1002/rra.1572.

Gartner, J.D., Magilligan, F.J., Renshaw, C.E., 2015. Predicting the type, location and magnitude of geomorphic responses to dam removal: role of hydrologic and geomorphic constraints. Geomorphology 251, 20–30.

Graf, W.L., 2003. Dam removal research: status and prospects. The Heinz Center, Washington, DC.

Graf, W.L., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79, 336–360.

Grant, G., 2001. Dam removal: Panacea or Pandora for rivers? Invited commentary. Hydrol. Process. 15, 1531–1532.

Grant, G.E., Lewis, S.L., 2015. The remains of the dam: what have we learned from 15 years of US dam removals? Engineering Geology for Society and Territory vol. 3. Springer, pp. 31–35

Gries, G., Juanes, F., 1998. Microhabitat use by juvenile Atlantic salmon (Salmo salar) sheltering during the day in summer. Can. J. Zool. 76, 1441–1449.

Harris, N., Evans, J.E., 2014. Channel evolution of sandy reservoir sediments following low-head dam removal, Ottawa River, Northwestern Ohio, U.S.A. Open J. Mod. Hydrol. 04, 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., Charles, D.F., Kreeger, D.A., Velinsky, D.J., 2002. Dam removal: challenges and opportunities for ecological research and river restoration. Bioscience 52, 669–681.

Hogg, R., Coghlan Jr., S.M., Zydlewski, J., 2013. Anadromous sea lampreys recolonize a Maine coastal river tributary after dam removal. Trans. Am. Fish. Soc. 142, 1381–1394.

Kasprak, A., Magilligan, F.J., Nislow, K.H., Renshaw, C.E., Snyder, N.P., Dade, W.B., 2013. Differentiating the relative importance of land cover change and geomorphic processes on fine sediment sequestration in a logged watershed. Geomorphology 185, 67–77.

Kibler, K., Tullos, D., Kondolf, M., 2011. Evolving expectations of dam removal outcomes: downstream geomorphic effects following removal of a small, gravel-filled dam. J. Am. Water Resour. Assoc. 47, 408–423. http://dx.doi.org/10.1111/j.1752-1688.2011.00523.x.

MacBroom, J.G., Schiff, R., 2013. Sediment management at small dam removal sites. Rev. Eng. Geol. 21, 67–79.

Magirl, C.S., Hilldale, R.C., Curran, C.A., Duda, J.J., Straub, T.D., Domanski, M., Foreman, J.R., 2015. Large-scale dam removal on the Elwha River, Washington, USA: fluvial sediment load. Geomorphology 246, 669–686.

Major, J.J., Spicer, K.R., Rhode, A., O'Connor, J.E., Bragg, H.M., Tanner, D.Q., Anderson, C.W., Wallick, J.R., Grant, G.E., 2008. Initial fluvial response to the removal of Oregon's Marmot Dam. EOS Trans. Am. Geophys. Union 89, 241.

Major, J.J., O'Connor, J.E., Podolak, C.J., Keith, M.K., Grant, G.E., Spicer, K.R., Pittman, S., Bragg, H.M., Wallick, J.R., Tanner, D.Q., 2012. Geomorphic response of the Sandy River, Oregon, to removal of Marmot Dam. US Department of the Interior, US Geological Survey.

Nislow, K., Kynard, B.E., 2009. The role of anadromous sea lamprey in nutrient and material transport between marine and freshwater environments. Am. Fish. Soc. Symp. 69, 485–494.

Nislow, K.H., Magilligan, F.J., Folt, C.L., Kennedy, B.P., 2002. Within-basin variation in the short-term effects of a major flood on stream fishes and invertebrates. J. Freshw. Ecol. 17, 305–318.

Nislow, K.H., Hudy, M., Letcher, B.H., Smith, E.P., 2011. Variation in local abundance and species richness of stream fishes in relation to dispersal barriers: implications for management and conservation. Freshw. Biol. 56, 2135–2144.

O'Connor, J.E., Duda, J.J., Grant, G.E., 2015. 1000 dams down and counting. Science 348, 496–497. http://dx.doi.org/10.1126/science.aaa9204.

Opperman, J.J., Lohse, K.A., Brooks, C., Kelly, N.M., Merenlender, A.M., 2005. Influence of land use on fine sediment in salmonid spawning gravels within the Russian River Basin, California. Can. J. Fish. Aquat. Sci. 62, 2740–2751.

Pearson, A.J., Snyder, N.P., Collins, M.J., 2011. Rates and processes of channel response to dam removal with a sand-filled impoundment. Water Resour. Res. 47.

Pess, G.R., Quinn, T.P., Gephard, S.R., Saunders, R., 2014. Re-colonization of Atlantic and Pacific rivers by anadromous fishes: linkages between life history and the benefits of barrier removal. Rev. Fish Biol. Fish. 24, 881–900. http://dx.doi.org/10.1007/s11160-013-9339-1.

Pizzuto, J., 2002. Effects of dam removal on river form and process. Bioscience 52, 683–691.

Poff, N.L., Hart, D.D., 2002. How dams vary and why it matters for the emerging science of dam removal. Bioscience 52, 659–668.

Pollard, A.I., Reed, T., 2004. Benthic invertebrate assemblage change following dam removal in a Wisconsin stream. Hydrobiologia 513, 51–58.

Randle, T.J., Bountry, J.A., Ritchie, A., Wille, K., 2015. Large-scale dam removal on the Elwha River, Washington, USA: erosion of reservoir sediment. Geomorphology 246, 709–728.

Saunders, R., Hachey, M.A., Fay, C.W., 2006. Maine's diadromous fish community: past, present, and implications for Atlantic salmon recovery. Fisheries 31, 537–547.

Sawaske, S.R., Freyberg, D.L., 2012. A comparison of past small dam removals in highly sediment-impacted systems in the US. Geomorphology 151, 50–58.

Sennatt, K.M., Salant, N.L., Renshaw, C.E., Magilligan, F.J., 2006. Assessment of methods for measuring embeddedness: application to sedimentation in flow regulated streams. J. Am. Water Resour. Assoc. 42, 1671–1682.

Service, R.F., 2011. Will busting dams boost salmon? Science. 334 pp. 888–892.

Sethi, S.A., Selle, A.R., Doyle, M.W., Stanley, E.H., Kitchel, H.E., 2004. Response of unionid mussels to dam removal in Koshkonong Creek, Wisconsin (USA). Hydrobiologia 525, 157–165.

Shafroth, P.B., Friedman, J.M., Auble, G.T., Scott, M.L., Braatne, J.H., 2002. Potential responses of riparian vegetation to dam removal. Bioscience 52, 703–712.

Shuman, J.R., 1995. Environmental considerations for assessing dam removal alternatives for river restoration. Regul. Rivers Res. Manage. 11, 249–261.

Stanley, E.H., Doyle, M.W., 2003. Trading off: the ecological removal effects of dam. Front. Ecol. Environ. 1, 15–22.

Stanley, E.H., Luebke, M.A., Doyle, M.W., Marshall, D.W., 2002. Short-term changes in channel form and macro invertebrate communities following low-head dam removal. J. N. Am. Benthol. Soc. 21, 172–187.

Stewart, G., Grant, G., 2005. What can we learn from the removal of little dinky dams. In: Moglen, G.E. (Ed.), Managing Watersheds for Human and Natural Impacts. ASCE, Williamsburg, Virginia, USA.

Warrick, J.A., Bountry, J.A., East, A.E., Magirl, C.S., Randle, T.J., Gelfenbaum, G., Ritchie, A.C., Pess, G.R., Leung, V., Duda, J.J., 2015. Large-scale dam removal on the Elwha River, Washington, USA: source-to-sink sediment budget and synthesis. Geomorphology 246, 729–750.

Wilcox, A.C., O'Connor, J.E., Major, J.J., 2014. Rapid reservoir erosion, hyperconcentrated flow, and downstream deposition triggered by breaching of 38 m tall Condit Dam, White Salmon River, Washington. J. Geophys. Res. Earth Surf. 119, 1376–1394.

Wohl, E.E., Cenderelli, D.A., 2000. Sediment deposition and transport patterns following a reservoir sediment release. Water Resour. Res. 36, 319–333.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Trans. Am. Geophys. Union 35, 951–956.

Xu, C., Letcher, B.H., Nislow, K.H., 2010. Context-specific influence of water temperature on brook trout growth rates in the field. Freshw. Biol. 55, 2253–2264.

Zunka, J.P., Tullos, D.D., Lancaster, S.T., 2015. Effects of sediment pulses on bed relief in bar-pool channels. Earth Surf. Process. Landf. 40, 1017–1028.