



# River restoration by dam removal: Enhancing connectivity at watershed scales

F.J. Magilligan<sup>1\*</sup> • B.E. Graber<sup>2</sup> • K.H. Nislow<sup>3</sup> • J.W. Chipman<sup>1</sup> • C.S. Sneddon<sup>4</sup> • C.A. Fox<sup>4</sup>

<sup>1</sup>Department of Geography, Dartmouth College, Hanover, New Hampshire, United States

<sup>2</sup>American Rivers, Northampton, Massachusetts, United States

<sup>3</sup>USDA Forest Service, Northern Research Station, Amherst, Massachusetts, United States

<sup>4</sup>Department of Geography and Department of Environmental Studies, Dartmouth College, Hanover, New Hampshire, United States

\*magilligan@dartmouth.edu

---

## Abstract

The prolonged history of industrialization, flood control, and hydropower production has led to the construction of 80,000 dams across the U.S. generating significant hydrologic, ecological, and social adjustments. With the increased ecological attention on re-establishing riverine connectivity, dam removal is becoming an important part of large-scale river restoration nationally, especially in New England, due to its early European settlement and history of waterpower-based industry. To capture the broader dimensions of dam removal, we constructed a GIS database of all inventoried dams in New England irrespective of size and reservoir volume to document the magnitude of fragmentation. We compared the characteristics of these existing dams to the attributes of all removed dams over the last ~25 years. Our results reveal that the National Inventory of Dams significantly underestimates the actual number of dams (4,000 compared to >14,000). To combat the effects of these ecological barriers, dam removal in New England has been robust with 127 dams having been removed between ca. 1990–2013. These removed dams range in size, with the largest number (30%) ranging between 2–4 m high, but 22% of the removed dams were between 4–6 m. They are not isolated to small drainage basins: most drained watersheds between 100–1,000 km<sup>2</sup>. Regionally, dam removal has re-connected ~3% (3,770 river km) of the regional river network although primarily through a few select dams where abundant barrier-free river lengths occur, suggesting that a more strategic removal approach has the opportunity to enhance the magnitude and rate of river re-connection. Given the regional-scale restoration of forest cover and water quality over the past century, dam removal offers a significant opportunity to capitalize on these efforts, providing watershed scale restoration and enhancing watershed resilience in the face of significant regional and global anthropogenic changes.

---

## Introduction

One of the pressing challenges facing biophysical scientists, policy makers, environmental managers, and environmental advocates is how to rehabilitate ecological systems that are increasingly characterized by long-term, significant, and complex anthropogenic changes. There is a growing consensus—representing fields as diverse as restoration ecology, conservation biology, sustainability science, political ecology, and a host of others—that research seeking to understand and enhance the sustainability of human-environment systems within the context of the Anthropocene must embrace trans-disciplinary perspectives (Jerneck et al., 2011; Steffen et al., 2011; Van Andel and Aronson, 2012; Seidl et al., 2013; Olsson et al., 2014) and think and act across multiple social-ecological scales from the local to the transboundary (Ogden et al., 2013). Nowhere are these challenges of the Anthropocene more important than in the case of efforts to understand, govern, and manage water systems (Sivapalan et al., 2014), wherein decades of human alteration through dams and other infrastructure have profoundly affected a host of hydrological and ecological processes.

**Domain Editor-in-Chief**

Anne R. Kapuscinski, Dartmouth

**Associate Editor**

Julian D. Olden, University of Washington

**Knowledge Domain**

Sustainability Transitions

**Article Type**

Research Article

Received: August 15, 2015

Accepted: April 12, 2016

Published: May 31, 2016

According to the U.S. Army Corps of Engineers National Inventory of Dams (NID), more than 80,000 dams exist in the US, with most of them occurring in the eastern US (Graf, 1999). This greatly understates the true number of dams, however, because NID's dam height and reservoir volume criteria fail to include the tens of thousands of historical mill dams scattered throughout the nation (cf. Smith et al., 2002; Walter and Merritts, 2008). This aging infrastructure, in combination with new environmental concerns regarding river and watershed restoration (Doyle et al., 2008; Doyle and Havlick, 2009), has prompted novel environmental, economic and social concerns surrounding their fate and led different stakeholders to argue for and against dam removal. Over the past several decades, more than 1,100 dams have been removed nationally (American Rivers, 2014; O'Connor et al., 2015) due to increasing public concern over their safety, an unwillingness to invest scarce resources in infrastructure repair, and a growing interest in restoring degraded ecosystems. Recent estimates indicate that more than 60 dams are being removed per year (Service, 2011a) with most of these being small run-of-river structures located primarily in Pennsylvania, Wisconsin, and Michigan (Pohl, 2002; Service, 2011a) – although large dams such as the Elwha (WA), Condit (MT) and Veazie (ME) have been recently removed (Wilcox et al., 2014; Pess et al., 2014; Magirl et al., 2015; East et al., 2015; Warrick et al., 2015; Randle et al., 2015).

Because dam removal can minimize habitat fragmentation and re-establish longitudinal and lateral connectivity (Bednarek, 2001; Hart et al., 2002), many ecologists and environmentalists embrace dam removal as a key component of river restoration. This perspective, however, encounters two broad challenges. First, recent thinking and research on the Anthropocene make it clear that restoration efforts are greatly complicated as watersheds and broader ecological assemblages are in effect “novel ecosystems” (Hobbs et al., 2009). Some argue that such novel ecosystems—because of the lack of any baseline ecological knowledge on which to peg restoration objectives—imply an approach termed “intervention ecology” that reflects a more thoughtful and experimental approach to the adaptive management of highly altered ecosystems (Hobbs et al., 2011). Dam removal may indeed be cast in this light. Second, this initial presentation of dam removal as a broad panacea of watershed restoration has encountered resistance from both the scientific and policy community, in part due to uncertainties regarding the effect of released sediment – some of which may be contaminated – on downstream geomorphic and ecological processes (Grant, 2001; Pizzuto, 2002; Doyle et al., 2003; Stanley and Doyle, 2003; Doyle et al., 2005). Despite the potential environmental costs, dam removal offers significant environmental benefits by re-connecting upstream-downstream sediment and geochemical fluxes, providing channel-floodplain exchanges, and allowing greater opportunity for fish passage (Bednarek, 2001; Bushaw-Newton et al., 2002; Doyle et al., 2005; Hogg et al., 2013; Pess et al., 2014; Vedachalam and Riha, 2014; Kornis et al., 2014; Hogg et al., 2015; Magilligan et al., 2016).

The impacts of dams in New England are especially acute as it possesses one of the highest densities of dams in the US (Graf, 1999), with the NID documenting more than 4,000 regional dams (Table 1), some of which have been in place for ca. two hundred years. Environmental organizations and state agencies in New England perceive dam removal as part of a broader integrated strategy to restore aquatic ecosystems and associated wetlands and riparian areas, and dam removal is increasingly becoming a crucial component of the river restoration toolkit (Nislow et al., 2010). These efforts are informed by: (1) the age and small size of many structures, (2) the associated risks and costs of safety and maintenance, and (3) the limited utility in terms of power generation and flood storage – thus allowing dam removal to achieve both conservation and human infrastructure benefits. The overall environmental context of the region also underscores the potential importance of dam removal as a conservation strategy. Native diadromous fishes (such as Atlantic salmon, river herring, sturgeon, and American eel) comprise a substantial proportion of historical native fish biodiversity (~30% of species in coastal rivers) and historically provided major economic and ecosystem benefits, but have experienced precipitous declines in distribution and abundance since European settlement (Saunders et al., 2006). Barriers to passage by dams are directly linked to loss of diadromous stocks, and restoration of fish passage has been a major justification for dam removal efforts. For freshwater resident fishes, effects of dams in New England may be less apparent, but a number of recent studies indicate the importance of within-river movements (Kanno et al., 2014; Letcher et al., 2007; Nislow et al., 2011) in allowing access to critical habitats, particularly in the context of the non-stationary thermal and flow regimes characteristic of the Anthropocene (Hodgkins et al., 2003; Isaak et al., 2012). Further, dams reduce the quality of fluvial habitat for both resident and migratory species via effects on sediment regimes and geomorphic processes (Kondolf and Wilcock, 1996). Finally, dam removal may be particularly valuable in the New England region given some of the major landscape-scale improvements in environmental quality over the last century. Forest cover, which had been substantially reduced following European settlement, has recovered in general to its pre-settlement extent throughout the region (Foster et al., 2010). This restoration, along with more recent regulation and mitigation of both point and non-point sources of water pollution, has resulted in major improvements in water quality (Mullaney, 2004). As a result, dam removal efforts are likely to yield access and connection to generally high-quality and resilient habitats.

Our primary goal in this analysis is to provide a regional assessment of dam removals in New England and to present the attendant ecological and hydrologic benefits at the watershed scale, especially the gain in fish passage associated with re-connecting free-flowing mainstem and tributary reaches. However, dam

removal does not occur within an institutional and social vacuum. For example, because dams are nested within watersheds, their removal may have effects extending well beyond the removal site (Grant and Lewis, 2015) or may generate unintended consequences (Doyle et al., 2005; Sethi et al., 2004). Dam removal – if done “right” – thus presumes a coordinated regulatory and institutional vision and/or an extremely well-organized and well-funded grassroots mobilization to meet desired aims. In contrast, removal may simply reflect an *ad hoc* process lacking formalized top-down or bottom-up structures (Fox et al., 2016). We are thus mindful of how the goals of restoration advocates are shaped and modified by the institutional structures for regulating the social and ecological use of watersheds. Our specific research questions address: (1) what is the spatial distribution of removed dams and how does this pattern relate to stated management goals of restoring critical habitat for native and diadromous fish; (2) what are the structural or management commonalities in dam types that have been removed; (3) what has been the incremental addition of free-flowing river length accomplished in terms of ecological changes; and (4) what policy or management lessons can be derived from the expected and unexpected biophysical benefits of dam removal? Our results present the ecological achievements at the watershed scale associated with dam removal as an on-going and future river restoration mechanism – a management option that may further serve to enhance the resilience of watersheds. Given recent discussions in the literature regarding watershed resilience (McCluney et al., 2014; Nemec et al., 2014; Waldman et al., 2016), our results point to the ancillary benefits of dam removal as a means of increasing the resilience of social-ecological systems (Walker et al., 2004).

## Methods

To best document the geomorphic, hydrologic, and potential ecological effects of dam removal at a regional level, we have compiled a database from state and federal agencies of all inventoried dams in each state in New England and compared the attributes of these existing dams to the population of removed dams compiled by NGOs (e.g. American Rivers) and state agencies, where available. Unlike the NID, there are minimal to no height or storage restrictions, and each state, whether for liability or environmental reasons, maintains a record of its dams, often including information about its type, function, and characteristics (e.g. height, length, etc.). For each existing and removed dam having geospatial information, we “snapped” its specific location directly to the river in ArcMap using the 1:100,000 hydrography layer. To ensure that we snapped correctly, we visually inspected the snapped location for each of the removed dams to be certain it was associated with the correct waterbody. Snapping thus permitted calculating watershed attributes such as basin size, distance to next upstream barrier, and number of free-flowing river km opened up by the removed dam. Most, if not all, of the removals lacked geomorphic attributes, such as sediment characteristics (bedload vs. suspended load, local or reach slope, etc.). To best represent these geomorphic parameters, we measured the distance and elevation change between the former dam and the headwater divide and used this basin-derived slope (also known as relief ratio) as a proxy of sediment type, based on established relationships between grain size and slope (Dade and Friend, 1998; Snyder et al., 2013).

For each removed dam we also calculated watershed attributes (e.g. percent of watershed developed, urbanized, or forested) using the National Land Cover Database (Jin et al., 2013). Moreover, the EPA ([https://www.epa.gov/wed/pages/ecoregions/na\\_eco.htm](https://www.epa.gov/wed/pages/ecoregions/na_eco.htm)) divides New England into five major ecoregions (Acadian Plains and Hills, Atlantic Coastal Pine Barrens, Eastern Great Lakes Lowlands, Northeastern Coastal Zone, and the Northeastern Highlands) differing in channel habitat, riparian and watershed vegetation, aquatic biodiversity and fish assemblages and potential for river restoration. Our GIS assessment groups the existing and removed dams occurring in each of the ecoregions. This linking to ecoregions provides an opportunity to ascertain which ecological types and settings are currently under- or overrepresented by dam removal efforts and the extent to which dam removal currently contributes to the ecological integrity of river systems at a regional scale. We also compare watershed and structural attributes of removed dams to the general population of dams, to ascertain the extent to which removals reflect the broad array of dam types and settings in the region. Our institutional analysis is based on the findings of an ongoing assessment of the social dimensions of dam removal in New England (Fox et al., 2016) consisting of semi-structured interviews with state and non-state stakeholders, participant observation at public meetings regarding dam removal, and textual analysis of hundreds of documents.

## Results

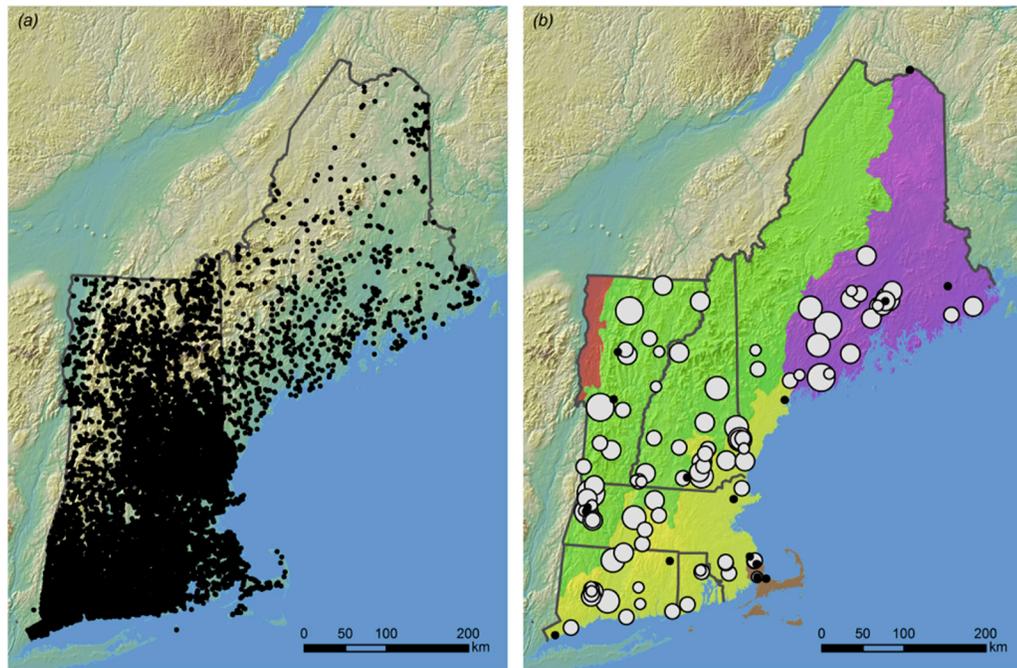
Our compilation from states agencies and NGOs indicate that the number of dams documented in New England by the NID (~4,000) significantly underestimates the actual number of dams as more than 14,000 inventoried dams are currently peppered throughout the New England landscape (Table 1; Figure 1A) generating a density of ~8 dams per 100 km<sup>2</sup>. Most of these inventoried dams are in Connecticut, Maine, Massachusetts and New Hampshire, with the fewest in Rhode Island and Vermont (Table 1). These existing structures obstruct an array of watershed types that possess orphaned mill dams, to small headwater water

**Table 1. Number of existing (in the National Inventory of Dams (NID) and in state records) and removed dams in each state in New England\***

| State        | # of Dams (NID) | # of Dams (all) | # of Removed Dams |
|--------------|-----------------|-----------------|-------------------|
| CT           | 734             | 3624            | 21                |
| ME           | 611             | 760             | 28                |
| MA           | 1490            | 3002            | 31                |
| NH           | 641             | 5076            | 26                |
| RI           | 236             | 668             | 4                 |
| VT           | 363             | 1027            | 17                |
| <i>Total</i> | 4075            | 14157           | 127               |

\*See Figure 1 for spatial distribution.  
doi: 10.12952/journal.elementa.000108.t001

supply dams, to larger hydropower facilities (Figure 2). Based on our detailed compilation, 127 dams have been removed in New England over the past several decades (up to 2013), presently averaging ~12 yr<sup>-1</sup>. Most of the removed dams were small with ~45% of them being less than 4 m in height (Figure 3); for comparison, across New England 35% all existing dams are less than 4 m (Figure 3). The frequency of removed small dams (< 4 m) is slightly larger than the binned values for existing dams; however, it is important to keep in mind the two orders of magnitude difference between the number of removed dams (10<sup>2</sup>) relative to the sheer number of existing dams (10<sup>4</sup>). For example, although the frequency of removed dams in the 6–8 m height category seems high (8.8%), this occurrence only corresponds to 8 dams, while there still remains more than 500 dams of this size regionally. Even with the prevalence of small dams among those eliminated, removals have not been exclusively restricted to small dams; over 40 dams > 4 m have been removed, including five > 8 m. These removed dams occurred widely across and within drainages. Moreover, despite the predominance of small dams among those removed, these dams were not restricted to headwater locations; most (38%) occurred in medium-sized watersheds having upstream drainage areas between 100–1,000 km<sup>2</sup> (Figure 4), with 8% formerly impounding watersheds between 1,000–10,000 km<sup>2</sup>.



**Figure 1**  
Location map of existing and removed dams.  
(A) All dams in New England,  
(B) Removed dams mapped by height and ecoregion.  
doi: 10.12952/journal.elementa.000108.f001



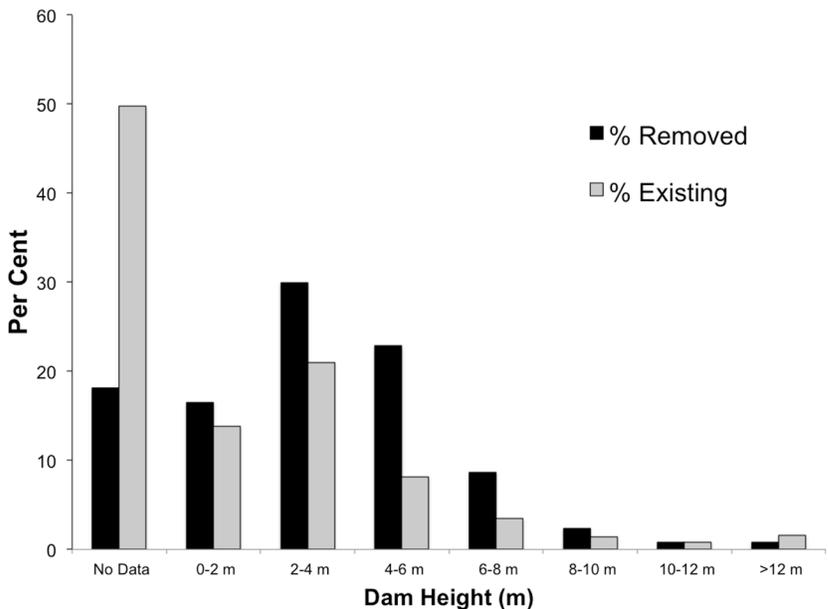


**Figure 2**  
Examples of removed dams.

(A) Kendrick Dam, VT; (B) Pelham Dam, MA; (C) Montsweag Dam, ME (photo courtesy of the Chewonki Foundation, Maine); and (D) Veazie Dam, ME.

doi: 10.12952/journal.elementa.000108.f002

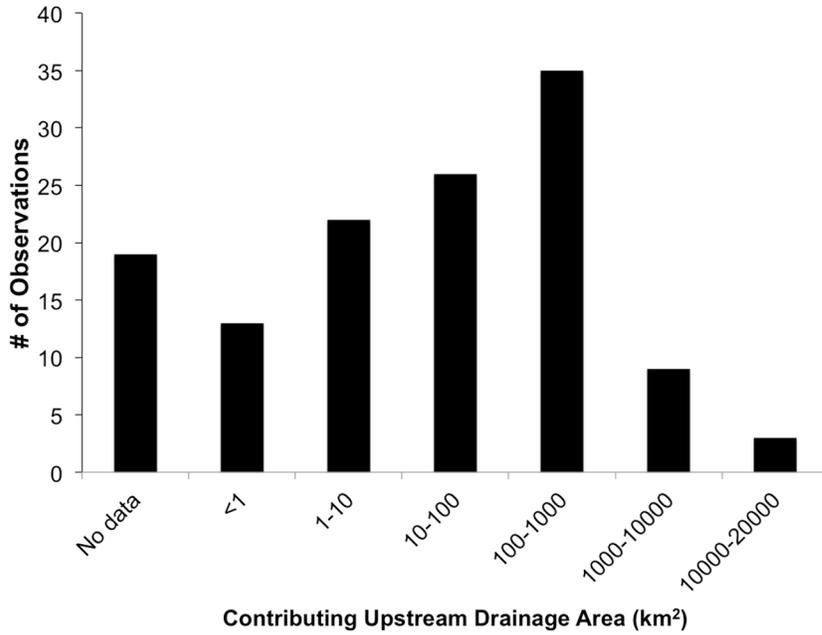
Within New England, most of the removed dams were located in Massachusetts (31) with Maine and New Hampshire accounting for 28 and 26 removed dams, respectively. Connecticut, which has over 3,600 documented dams, has only removed 21 dams and Rhode Island, an important coastal state, has only removed 4 dams. Vermont has removed 17 dams, many of them being very small run-of-river facilities. At the broader regional scale, the two dominant ecoregions of New England are the Northeastern Coastal Zone (NCZ) and the Northern Highlands, which account for 40% and 38% respectively of all dam removals in New England (Figure 1B). Yet, despite the NCZ having the most removals, most of the removed dams were generally far inland (Figure 1B), and this ecoregion also houses a large number of existing dams, with many of the removal sites possessing multiple dams downstream further fragmenting the watersheds and disconnecting them from the ocean. Most of the removed dams occurred at elevations below 100 m with a peak between



**Figure 3**  
Dam height.

Dam height (m) for existing and removed dams in New England.

doi: 10.12952/journal.elementa.000108.f003



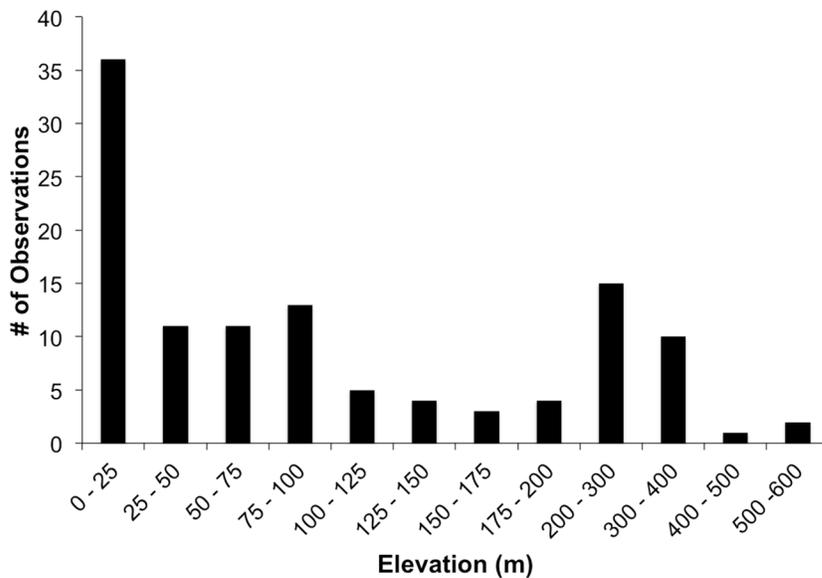
**Figure 4**  
Watershed area.

Watershed area (km<sup>2</sup>) upstream of all removed dams.

doi: 10.12952/journal.elementa.000108.f004

0 – 25 m (Figure 5) – suggesting a near coastal location – although 23% of the removals occurred in more upland (> 200 m) settings. Upstream basin slope clusters between 0.5 – 1.0%, although 21% occurred in low gradient sections (Figure 6).

The specific location of the dam within a watershed relative to the location of the next upstream barrier, in combination with upstream watershed structure (drainage density, number of tributaries, etc.), best represents the acquired benefit of dam removal in opening access to upstream river reach. Our comparison of the removed and existing dams databases shows that ~3,770 river km have been re-connected in New England waterways by dam removal (Figure 7). With New England possessing ~104,000 km of total river length, this liberated space of 3,770 km by dam removal represents 3.61% of all river lengths. Areas upstream of the former dams are well forested with little development or agriculture (Figure 8). Most of the liberated free-flowing river space has occurred in Maine. Removal of the Sandy River, Fort Halifax, Pleasant River and Bangor hydroelectric dams represent ~1500 km of the reconnected river lengths in Figure 7. With Maine accounting for the few viable remaining runs of the federally-endangered Atlantic salmon, these dam removals have provided significant access to upstream habitat (Hogg et al., 2013, 2015; Pess et al., 2014). The shape of the cumulative river length curve also reveals how most of the gain in reconnected river length is due to the removal of a small number of key barriers. However, even in instances where considerable re-connectivity

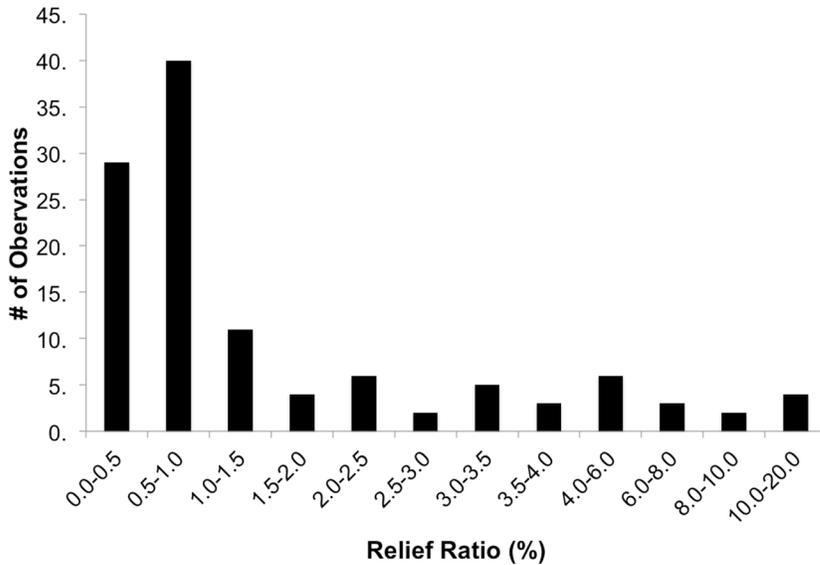


**Figure 5**  
Dam elevation.

Elevation (m) of locations of former dams.

doi: 10.12952/journal.elementa.000108.f005

River restoration by dam removal



**Figure 6**  
Watershed slope.

Relief ratio (i.e. watershed slope upstream of former dam) of sites of former dams.

doi: 10.12952/journal.elementa.000108.f006

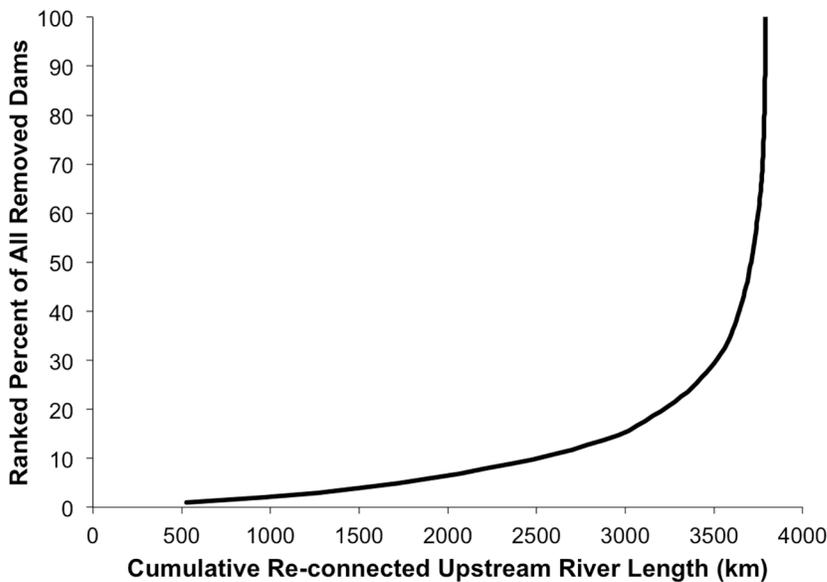
has occurred, as for example the gain of 130 river km during the removal of the Homestead Woolen Mills Dam on the Ashuelot River in NH, several large dams occur both upstream and downstream (Gartner et al., 2015), ultimately blocking diadromous fish from accessing this newly available habitat.

## Discussion

Besides documenting the general characteristics of removed dams at a regional assessment, our results provide, for the first time, the magnitude and extent of watershed scale re-connectivity resulting from dam removal. This, in turn, provides a basis for assessing how dam removal may enhance watershed resilience in the face of multi-scalar human impacts. As discussed below, we perceive dam removal as a potentially critical tool for not only re-establishing connectivity at watershed scales, but for enhancing the capacity of important upstream catchments to respond and adapt to regional and global anthropogenic changes (e.g., climate change) in ecologically desirable ways.

### *Regional benefits from dam removal*

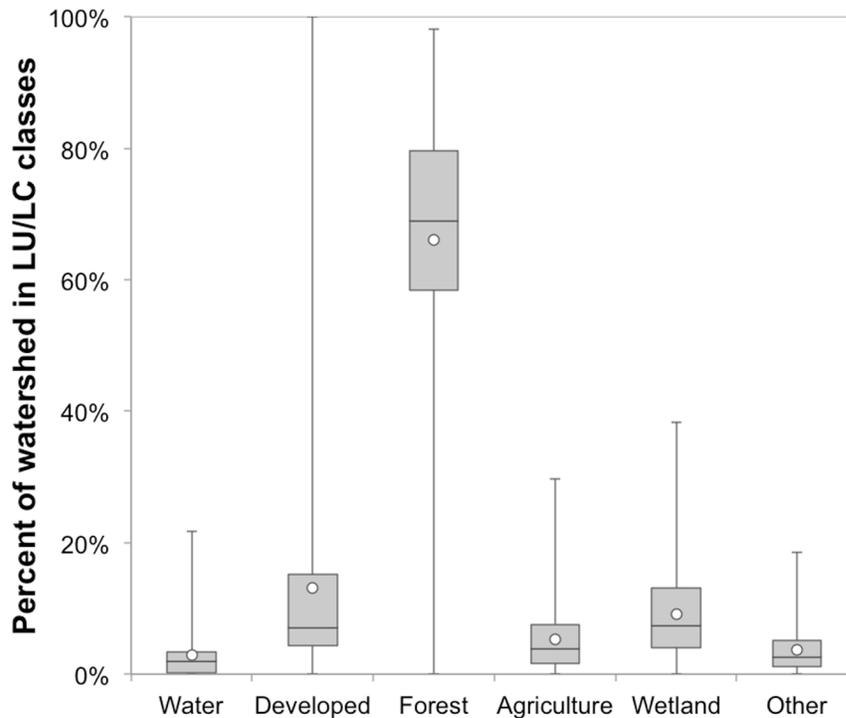
In terms of the general features of the removed dams, our data indicate that dam removal in the northeastern U.S. is not restricted to dams isolated in small headwater locations. Although well below the height of most flow regulation structures, most (30%) of the removed dams were between 2–4 m with 22% of them between



**Figure 7**  
Liberated river kilometers.

Cumulative length (km) made available by dam removal in New England.

doi: 10.12952/journal.elementa.000108.f007



**Figure 8**  
Watershed land use and land cover.

Box and whisker plots of land use and land cover types for portions of the watershed now made accessible by dam removal (from National Land Cover Database (Jin et al., 2013)). The solid line in the box is the 50<sup>th</sup> percentile while the box edges define the 25<sup>th</sup> and 75<sup>th</sup> percentiles. The circle is the mean and the whiskers identify the minimum and maximum values.

doi: 10.12952/journal.elementa.000108.f008

4–6 m – a height generally sufficient to meet the requirement to be registered in the NID. Additionally, they formerly dammed moderate size watersheds, generally between 100–1,000 km<sup>2</sup>, corresponding in size to a HUC-4 or HUC-5 USGS Hydrologic Unit Code. Moreover, the gain in longitudinal re-connectivity is further augmented by the associated quality of the now liberated upstream watershed. In a sense, dam removal will allow the region to capitalize on over a century of water quality improvements. These new liberated sections of the watershed are well forested with minimal development (Figure 8), thus providing access to high quality habitat. Besides providing important fish passage, these newly liberated watershed sections may thus serve to be important refugia as they are in some of the least disturbed watershed sections. The lack of development and broader forest cover may further serve to maintain the resilience of these ecosystems at a time of increasing concern of shifting freshwater thermal regimes regionally (Hayhoe et al., 2007). For example, distributions of native coldwater-dependent species (such as salmon and trout) are predicted to move upstream in response to downstream warming. Removing barriers such as dams is critical to this response, and in New England our analysis indicates that the high levels of forest cover and low development pressure of these upstream sites will increase the likelihood that they will serve as refugia (Kanno et al., 2014). Further, given that the scope for mitigating or ameliorating change via forest or water quality restoration may be limited (due to existing high quality and extensive cover), dam and barrier removal may be the most effective remaining adaptation strategy.

Although much of the public attention has been focused on large dam removal (Lovett, 2014; O'Connor et al., 2015; Service, 2011a, 2011b), our results elucidate the important singular and cumulative benefits of removing run-of-river dams. In their national assessment of river restoration projects Bernhardt et al. (2005) document the associated expense and limitations of the various approaches for restoration, and dam removal, on average, is cheaper than channel reconfiguration or other restoration measures. Not all of our removals provided firm costs for removal, but we estimate from our regional compilations that, in general, dam removal costs ~\$80k per vertical meter of dam height, corresponding to inflation-adjusted values reported by Born et al. (1998). This base removal cost, however, becomes progressively more expensive for any sediment remediation requirements. As dam removal becomes more prevalent in New England and other regions, such cost estimates provide an important additional consideration for environmental managers and other concerned actors. In addition, not only are restoration efforts (e.g. bank stabilization, channel reconfiguration, etc.) more costly, they often are site-specific generating, at best, reach scale improvements; whereas dam removal offers a greater spatial scale of watershed rehabilitation.

### *Geomorphic and ecological implications*

We were not able to assess any geomorphic adjustments or specific ecological benefits with each dam removal as post removal monitoring in New England, as elsewhere, has generally been absent. In fact, in a recent national assessment of dam removal monitoring, Bellmore et al. (2015) document that of the > 1,100 dams

removed nationally, only 139 had any monitoring whatsoever, and only 35 had both geomorphic and ecologic assessments. Detailed post-removal geomorphic assessments have been done on just a few rivers in New England (Pearson et al., 2011; Magilligan et al., 2016), and these studies show that most of the geomorphic adjustments occur within the first year driven primarily by the initial base level adjustment – a trend typical of dam removals elsewhere (Grant and Lewis, 2015; Sawaske and Freyberg, 2012). Because of the thin alluvial cover over bedrock in New England, upstream knickpoint migration is commonly limited to dam proximal reaches (Pearson et al., 2011; Gartner et al., 2015) suggesting that post-removal prolonged sediment production may not occur or impair downstream geomorphic and ecological stability. Although no published sediment data exist for these removals, the modal basin slope of 0.5 – 1% (Figure 6) corresponds generally to channel bed sedimentological environments typical of a sand to sandy gravelly matrix – typical of the coarse-grained Pleistocene deposits that mantle most of New England. The lack of fines regionally (Rainwater, 1962) and at the sites of removed dams further serves to assuage environmental concerns that pollutants sorbed to fine-grained sediment (silts and clays) may be flushed downstream following post-removal sediment evacuation. Although New England has experienced significant historical industrialization, downstream dispersal of contaminated sediments following dam removal has not been generally documented, in part due to the coarse (sand to gravel) nature of the released sediment where few binding sites – relative to finer grained material – exist for sorbing pollutants and because of the limited monitoring of these effects. Additionally, the length scale for sediment dispersal is grain size dependent; in a detailed analysis of downstream travel distance, Grant and Lewis (2015) document the spatially limited transport distances for the coarse fraction following dam removal. Contaminated sediment may potentially be a more significant issue in southern New England where lower slopes and finer-grained sediment exist.

From an ecological standpoint, the pattern revealed in Figure 1B depicts, perhaps, an operational disconnect between management goals to restore diadromous fish populations and the dam removal process. Although most of the dams have been removed in Massachusetts and in the Northeastern Coastal Zone, very few of them were along the most important reaches for marine-freshwater exchange – i.e. the most downstream watershed positions. Our analysis does not include efforts to restore fish passage (through ladders, lifts, and bypasses) at existing structures, which have been implemented widely throughout the region. However, in contrast to dam removal, the efficacy of these passage structures is highly variable across sites, years, and species (Haro and Castro-Santos, 2012), and even when they do facilitate adequate passage, they do not ameliorate the effects of dams on habitats and sediment regimes (Bunt et al., 2012). Further, the presence of downstream dams does not mean that dam removal has been an ineffective agent in the restoring aquatic ecosystems. Instead, with more than 3,770 river km now made accessible, resident fish and at-risk species have greater access to previously unavailable habitat, and re-establishing the continuity of sediment transport has likely facilitated the development of important fluvial habitats (bars, banks and floodplains) downstream.

### *Landscape of strategic opportunism*

From an environmental management and policy perspective, the pattern evident for dam removals in New England (Figure 1B) evokes a landscape of strategic opportunism more than a well-articulated management scenario planned out and implemented by local and regional stakeholders. This opportunistic strategy reflects the *ad hoc* nature of dam removals whereby NGOs and state agencies essentially react and respond to willing dam owners who – either by environmental awareness, business/personal foresight, FERC requirements, or economic liability – decide that removal may be the best economic or personal option. The lack of top-down or bottom-up driven processes may appear to be an effective strategy as it has generated over 125 removals (~10% of national removals), but the ecological/geomorphic effectiveness of removals as an intervention would almost certainly be enhanced by more programmatic approaches. There is an emerging literature engaging with various management scenarios, ranging from a “hit list” approach (Hoenke et al., 2014) to more market based strategies for prioritizing barrier removal (Kemp and O’Hanley, 2010; Neeson et al., 2015). With the advent of geospatial databases and associated spatial algorithms, these approaches offer salient management strategies to prioritize dam removal as it is now possible to quantify which dam, once removed, may liberate the greatest number of free-flowing river km or offer the greatest opportunity for watershed or river restoration. For example, the US Army Corps of Engineers (USACE) is proposing to investigate dam removals as part of an overall “portfolio” approach to ecosystem restoration at the watershed scale as evidenced in their recent comprehensive plans for fish passage along the multi-dammed Blackstone River (USACE, 2015).

Both the “strategic opportunism” and the “priority list” approaches, however, assume a social arena free of political confrontation, an institutional structure or arrangement that has the political and economic will and resources to make environmentally informed decisions, and/or a general agreement that dam removal is the most effective restoration strategy (Fox et al., 2016). Indeed, current research on dam removals in New England highlights the vagaries of efforts to promote watershed resilience through dam removal and outlines the numerous pathways that local political processes can derail even the most thoughtful restoration efforts (Fox et al., 2016). Our results point to perhaps, by default, a “happy medium” wherein dam removal – and its associated environmental gains – has progressed incrementally through political, economic, and

environmental expediency to achieve some of the stated management and river restoration goals. Yet, lacking any significant sustained monitoring or post-removal assessment, it is difficult to specifically determine the actual gains ecologically from removal.

Assessments are further complicated by the lack of common ecological metrics or stated management goals to evaluate the success of a given restoration strategy or outcome (Bernhardt et al., 2005; Palmer et al., 2005; Bernhardt et al., 2007), a condition common to management efforts in the Anthropocene (Seidl et al., 2013). NOAA does provide baseline metrics for assessment (Wildman, 2013), but in most instances, the benchmark may be merely the re-introduction of migratory and resident fish species to previously unattainable watershed locales (Hogg et al., 2013, 2015; Pess et al., 2014) or the dam removal may generate more re-connected coupled geomorphic and ecological attributes (Magilligan et al., 2016). The lack of a singular metric of restoration success for dam removals also manifests as dams are removed for numerous socio-economic reasons (e.g. safety, liability, aesthetics, etc.) that often lack a clearly articulated ecological goal. Even when environmental reasons are stated, dam removals rarely identify clearly stated ecological standards. In some instances, the implicit assumption by many pro-removal NGOs is that a river with a removed dam is in a more “natural” state and therefore the restoration goal is self-evident. More often, the stated primary goal, like at the recent large dam removals on the Elwha (WA) and Penobscot (ME) Rivers, is re-connecting migratory fish runs, yet the metric of success is unclear: is it fish presence, fish abundance, or long-term viability of populations? Because these demographic metrics are difficult to measure or assess scientifically, and, in the case of diadromous fish, are also determined by coastal and marine influences, NGOs (e.g. American Rivers) and federal agencies (e.g. NOAA) that fund dam removals will commonly just present the number of river kilometers opened up by the removal – again signaling that a watershed with more kilometers of a “re-connected” free-flowing access is in a more natural state. Although still limited in regional or temporal scope, recent literature in New England suggests that “if you take it down, they [fish] will come” (Hogg et al., 2013, 2015; Pess et al., 2014). Our results highlight some of these ambiguities in river restoration, but also show that measurable “gains” can result from dam removal – at least from a watershed resilience perspective based on achieved gains in accessible river habitat. This is particularly salient when considering the Anthropocene context where baseline ecological knowledge is difficult if not impossible to determine and human-altered systems are the new ecological reality.

### *A forever dam(n)ed landscape?*

From a management and restoration perspective, New England remains a dammed landscape (Figure 1A). “Hit list” or basin-oriented perspectives may initially appear attractive but the optimal coalescence of cost, ecological gain, and political/institutional arrangements may not manifest in strategic and meaningful ways. For example, the much heralded removals of two dams on the Penobscot River required sustained negotiations and political maneuvering (Day, 2006; Opperman et al., 2011), yet our GIS-based results indicate that due to the watershed structure – where few major tributaries enter the mainstem and the remaining presence of the upstream dam – very few river kms were made available by these removals. Fish passage along the mainstem may have been achieved, but it remains to be seen whether successful access to a greater extent of upstream spawning habitat can or will occur.

Management strategies are slowly becoming more coordinated in New England and there has been some movement away from the singular removal to think in a more “portfolio” approach to removals. For example, the near collapse of the ~200 year old Whittendon Dam on the Mill River near Taunton MA in 2005 generated an initial political frenzy to “save the dam”, but the response slowly shifted to a more holistic strategy to remove each of the three abandoned mill dams over a period of 3–5 years. Rather than merely removing the decaying Whittendon Dam – that would have offered minimal gains as the Hopewell Mills Dam still existed downstream – a partnership of nonprofit groups and state and federal agencies coalesced to initiate the removal of three closely spaced dams that will now liberate more than 50 km of free flowing river length. The aforementioned plan, spearheaded by the Corps of Engineers, to systematically assess the viability of multiple dam removals and other rehabilitation measures for the entire Blackstone River watershed in Massachusetts and Rhode Island is another example of the more coordinated approach. Although still politically charged and institutionally fragmented, these broad-scale prioritizations can offer greater opportunities for river restoration regionally and can help guide the removal process.

### *Toward watershed resilience in the Anthropocene*

The concept of resilience as applied within ecology and the management of complex social-ecological systems (SES) has been the subject of decades of debate and refinement (see Curtin and Parker (2014) for an overview). We understand resilience as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks” (Walker et al., 2004). While there have been some efforts to apply resilience to watershed systems (see McCluney et al., 2014; Nemec et al., 2014), these efforts have failed to clarify what watershed resilience might look like and

how it might be measured. Most research quantifies the loss of resilience due to acute and chronic human interventions (Nemec et al., 2014; Waldman et al., 2016), but less effort has addressed the gain in, or metric of, resilience following some restoration mitigation effort such as dam removal. Some metrics used in a SES approach to assess a watershed's improved resilience post-removal are difficult if not impossible to determine with certainty. Other metrics (e.g., presence of formerly absent diadromous fish species), while superficially appealing and potentially important, may not reveal much about the overall integrity of a watershed but, instead, reveal more about fish community resilience following dam removal (Waldman et al., 2016). These limitations are especially significant in regions such as New England with a relatively long history of intensive human modification. Instead, watershed resilience is perhaps best characterized by the capacity of a watershed, as a complex social-ecological system, to absorb an on-going or future stressor in a way that limits degradation of not only the habitats of aquatic organisms but also an array of biophysical functions, structures, and processes.

Our results underscore the capacity of dam removal to certainly enhance watershed resilience in the sense of river stretches opened up and greater connectivity. These are the expected benefits of ecological interventions such as dam removal. However, one of the less expected benefits of removal has been improvement to critical habitats in the upstream catchments of New England's watersheds. A brief example illustrates this point. As climate change progresses and average annual temperatures continue to climb over the coming decades, viable habitat for cold-water fish species becomes even more crucial. The removal of dams in upper catchments of New England's rivers capitalizes on decades-long improvements in forest cover (Figure 8) and water quality, implying that the resilience of these systems in the face of broader-scale and long-term anthropogenic changes may be enhanced. In a very real sense, dam removal links the scale of catchment and reach level biophysical dynamics (e.g., connectivity, fish migrations) to broader scales of environmental change (e.g., climate change). While impossible to predict the longer-term impacts of dam removal given the rapidly changing social-ecological contexts of the Anthropocene, there is some room for cautious optimism that dam removal and other interventions may actually enhance watershed resilience in important and unexpected ways.

## Conclusion

There has been considerable effort over the past several decades to re-establish longitudinal and lateral watershed connectivity and to, more broadly, "restore" rivers in the United States and globally. River restoration is a broad (and often contested) term that may take multiple forms and is often scale dependent: these strategies are often localized and occur primarily at the reach scale (Bernhardt et al., 2005, 2007). At somewhat larger scales, river restoration may refer to the re-establishment of river connectivity by environmental flow releases (Arthington et al., 2006; Hughes and Mallory, 2008; Poff and Zimmerman, 2010), but these efforts can be fraught with design, implementation, and management issues surrounding sediment flux and ascertaining the correct magnitude and timing of flow releases (Mahoney and Rood, 1998; Richter and Thomas, 2007; Schmidt et al., 2001). Moreover, environmental flow releases may serve to enhance downstream lateral connectivity, but because the dam remains, they do not un-fragment watersheds or promote longitudinal connectivity. For these reasons, perhaps a turn towards thinking about dam removals as a kind of ecological intervention designed to enhance watershed resilience offers an opportunity to more carefully situate dam removal within the broader goals and activities of ecological restoration.

Our region-wide analysis points to the greater scale of restoration associated with dam removal, and its ability to regenerate a suite of riverine processes including enhanced sediment connectivity, unfragmenting watersheds to allow fish passage, and the opening up significant river length and important habitat for resident and diadromous fish. Dam removal is progressively becoming part of the management toolkit nationally, and our results point to the greater potential for re-connectivity at the watershed scale and, perhaps more importantly, for enhanced watershed resilience. Accordingly, our results point to some unexpected biophysical benefits of undamming New England rivers. Dam removal is at best presented by restoration advocates as a means of enhancing fish passage and returning watersheds to some previous state that is virtually impossible to determine with precision. Some of these claims are accurate, but there is a value added to dam removal that is rarely voiced. This value is related to the capacity of dam removal to increase watershed resilience—as evidenced by the opening up of critical upstream habitats for certain fish species—in the context of large-scale and enduring anthropogenic changes (e.g., climate change). To be certain, additional research is necessary to specify how the multiple-scale dynamics associated with dam removal function. The results presented here represent a step in that direction, and bolster the notion that dam removal is a potentially critical tool not only for restoration activities but also for thinking about and assessing watershed resilience.

## References

- American Rivers. 2014. Mapping Dam Removal Success. <http://www.americanrivers.org/blog/mapping-dam-removal-success/>.
- Arthington AH, Bunn SE, Poff NL, Naiman RJ. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecol Appl* 16: 1311–1318.
- Bednarek AT. 2001. Undamming rivers: A review of the ecological impacts of dam removal. *Environ Manage* 27: 803–814.
- Bellmore JR, Vittum KM, Duda JJ, Greene S. 2015. USGS Dam Removal Science Database [online]. Accessed 27 May 2015. <http://dx.doi.org/10.5066/F7K935KT>.
- Bernhardt E, Palmer M, Allan J, Alexander G, Barnas K, et al. 2005. Synthesizing U. S. river restoration efforts. *Science (Washington)* 308: 636–637.
- Bernhardt ES, Sudduth EB, Palmer MA, Allan JD, Meyer JL, et al. 2007. Restoring rivers one reach at a time: Results from a survey of US river restoration practitioners. *Restor Ecol* 15: 482–493.
- Born SM, Genskow KD, Filbert TL, Hernandez-Mora N, Keefer ML, et al. 1998. Socioeconomic and institutional dimensions of dam removals: The Wisconsin experience. *Environ Manage* 22: 359–370.
- Bunt C, Castro-Santos T, Haro A. 2012. Performance of fish passage structures at upstream barriers to migration. *River Research and Applications* 28: 457–478.
- Bushaw-Newton KL, Hart DD, Pizzuto JE, Thomson JR, Egan J, et al. 2002. An integrative approach towards understanding ecological responses to dam removal: The Manatawny Creek Study. *J Am Water Resour As* 38: 1581–1599.
- Curtin CG, Parker JP. 2014. Foundations of resilience thinking. *Conserv Biol* 28: 912–923. doi: 10.1111/cobi.12321.
- Dade WB, Friend PF. 1998. Grain size, sediment transport regime, and channel slope in alluvial rivers. *J Geol* 106: 661–676. doi: 10.1086/516052.
- Day LR. 2006. Restoring native fisheries to Maine's largest watershed: The Penobscot River restoration project. *Journal of Contemporary Water Research & Education* 134: 29–33.
- Doyle MW, Harbor JM, Stanley EH. 2003. Toward policies and decision-making for dam removal. *Environ Manage* 31: 453–465. doi: 10.1007/s00267-002-2819-z.
- Doyle MW, Havlick DG. 2009. Infrastructure and the environment. *Annual Review of Environment and Resources* 34: 349–373.
- Doyle MW, Stanley EH, Havlick DG, Kaiser MJ, Steinbach G, et al. 2008. Aging infrastructure and ecosystem restoration. *Science* 319: 286–287.
- Doyle MW, Stanley EH, Orr CH, Selle AR, Sethi SA, et al. 2005. Stream ecosystem response to small dam removal: Lessons from the Heartland. *Geomorphology* 71: 227–244. doi: 10.1016/j.geomorph.2004.04.011.
- East AE, Pess GR, Bountry JA, Magirl CS, Ritchie AC, et al. 2015. Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change. *Geomorphology* 246: 687–708. doi: 10.1016/j.geomorph.2015.04.027.
- Foster D, Aber J, Cogbill C, Hart C, Colburn E, et al. 2010. Wildlands and woodlands: A vision for the New England landscape.
- Fox CA, Magilligan FJ, Sneddon CS. 2016. “You kill the dam, you are killing a part of me”: Dam removal and the environmental politics of river restoration. *Geoforum* 70: 93–104. doi: 10.1016/j.geoforum.2016.02.013.
- Gartner JD, Magilligan FJ, Renshaw CE. 2015. Predicting the type, location and magnitude of geomorphic responses to dam removal: Role of hydrologic and geomorphic constraints. *Geomorphology* 251: 20–30. doi: 10.1016/j.geomorph.2015.02.023.
- Graf WL. 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resour Res* 35: 1305–1311.
- Grant G. 2001. Dam removal: Panacea or Pandora for rivers? Invited commentary. *Hydrol Proc* 15: 1531–1532.
- Grant GE, Lewis SL. 2015. The remains of the dam: What have we learned from 15 years of US dam removals?, in: *Engineering Geology for Society and Territory – Volume 3*. Springer: pp. 31–35.
- Haro A, Castro-Santos T. 2012. Passage of American shad: Paradigms and realities. *Marine and Coastal Fisheries* 4: 252–261.
- Hart DD, Johnson TE, Bushaw-Newton KL, Horwitz RJ, Bednarek AT, et al. 2002. Dam removal: Challenges and opportunities for ecological research and river restoration. *BioScience* 52: 669–682.
- Hayhoe K, Wake CP, Huntington TG, Luo L, Schwartz MD, et al. 2007. Past and future changes in climate and hydrological indicators in the US Northeast. *Clim Dynam* 28: 381–407.
- Hobbs RJ, Hallett LM, Ehrlich PR, Mooney HA. 2011. Intervention ecology: Applying ecological science in the twenty-first century. *BioScience* 61: 442–450.
- Hobbs RJ, Higgs E, Harris JA. 2009. Novel ecosystems: Implications for conservation and restoration. *Trends Ecol Evol* 24: 599–605.
- Hodgkins GA, Dudley RW, Huntington TG. 2003. Changes in the timing of high river flows in New England over the 20th Century. *J Hydrol* 278: 244–252. doi: 10.1016/s0022-1694(03)00155-0.
- Hoenke KM, Kumar M, Batt L. 2014. A GIS based approach for prioritizing dams for potential removal. *Ecol Eng* 64: 27–36. doi: 10.1016/j.ecoleng.2013.12.009.
- Hogg R, Coghlan Jr SM, Zydlewski J. 2013. Anadromous sea lampreys recolonize a Maine coastal river tributary after dam removal. *T Am Fish Soc* 142: 1381–1394.
- Hogg RS, Coghlan Jr SM, Zydlewski J, Gardner C. 2015. Fish community response to a small stream dam removal in a Maine coastal river tributary. *T Am Fish Soc* 144: 467–479.
- Hughes DA, Mallory SJL. 2008. Including environmental flow requirements as part of real-time water resource management. *River Research and Applications* 24: 852–861. doi: 10.1002/rra.1101.
- Isaak D, Wollrab S, Horan D, Chandler G. 2012. Climate change effects on stream and river temperatures across the northwest US from 1980–2009 and implications for salmonid fishes. *Climatic Change* 113: 499–524.
- Jerneck A, Olsson L, Ness B, Anderberg S, Baier M, et al. 2011. Structuring sustainability science. *Sustainability Science* 6: 69–82.
- Jin S, Yang L, Danielson P, Homer C, Fry J, et al. 2013. A comprehensive change detection method for updating the national land cover database to circa 2011. *Remote Sens Environ* 132: 159–175.

- Kanno Y, Letcher BH, Coombs JA, Nislow KH, Whiteley AR. 2014. Linking movement and reproductive history of brook trout to assess habitat connectivity in a heterogeneous stream network. *Freshwater Biol* 59: 142–154.
- Kemp PS, O'Hanley JR. 2010. Procedures for evaluating and prioritising the removal of fish passage barriers: A synthesis. *Fisheries Manag Ecol* 17(4): 297–322. doi: 10.1111/j.1365-2400.2010.00751.x.
- Kondolf GM, Wilcock PR. 1996. The flushing flow problem: Defining and evaluating objectives. *Water Resour Res* 32: 2589–2599.
- Kornis MS, Weidel BC, Powers SM, Diebel MW, Cline TJ, et al. 2014. Fish community dynamics following dam removal in a fragmented agricultural stream. *Aquat Sci*. doi: 10.1007/s00027-014-0391-2.
- Letcher BH, Nislow KH, Coombs JA, O'Donnell MJ, Dubreuil TL. 2007. Population response to habitat fragmentation in a stream-dwelling brook trout population. *PLoS One* 2: e1139.
- Lovett RA. 2014. Dam removals: Rivers on the run. *Nature* 511: 521–523.
- Magilligan FJ, Nislow KH, Kynard BE, Hackman AM. 2016. Immediate changes in stream channel geomorphology, aquatic habitat, and fish assemblages following dam removal in a small upland catchment. *Geomorphology* 252: 158–170. doi: 10.1016/j.geomorph.2015.07.027.
- Magirl CS, Hilldale RC, Curran CA, Duda JJ, Straub TD, et al. 2015. Large-scale dam removal on the Elwha River, Washington, USA: Fluvial sediment load. *Geomorphology* 246: 669–686. doi: 10.1016/j.geomorph.2014.12.032.
- Mahoney JM, Rood SB. 1998. Streamflow requirements for cottonwood seedling recruitment – An integrative model. *Wetlands* 18: 634–645.
- McCluney KE, Poff NL, Palmer MA, Thorp JH, Poole GC, et al. 2014. Riverine macrosystems ecology: Sensitivity, resistance, and resilience of whole river basins with human alterations. *Frontiers in Ecology and the Environment* 12: 48–58. doi: 10.1890/120367.
- Mullaney J. 2004. Summary of Water Quality Trends in the Connecticut River, 1968–1998. *American Fisheries Society Monograph*: 273–286.
- Neeson TM, Ferris MC, Diebel MW, Doran PJ, O'Hanley JR, et al. 2015. Enhancing ecosystem restoration efficiency through spatial and temporal coordination. *P Natl Acad Sci* 112: 6236–6241.
- Nemec KT, Chan J, Hoffman C, Spanbauer TL, Hamm JA, et al. 2014. Assessing resilience in stressed watersheds. *Ecology and Society* 19. doi: 10.5751/ES-06156-190134.
- Nislow KH, Hudy M, Letcher BH, Smith EP. 2011. Variation in local abundance and species richness of stream fishes in relation to dispersal barriers: Implications for management and conservation. *Freshwater Biol* 56: 2135–2144.
- Nislow KH, Marks CO, Lutz KA. 2010. Aquatic conservation planning at a landscape scale, in, *Landscape-Scale Conservation Planning*. Springer: pp. 99–119.
- O'Connor JE, Duda JJ, Grant GE. 2015. 1000 dams down and counting. *Science* 348: 496–497. doi: 10.1126/science.aaa9204.
- Ogden L, Heynen N, Oslender U, West P, Kassam K-A, et al. 2013. Global assemblages, resilience, and Earth Stewardship in the Anthropocene. *Frontiers in Ecology and the Environment* 11: 341–347.
- Olsson P, Galaz V, Boonstra WJ. 2014. Sustainability transformations: A resilience perspective. *Ecology and Society* 19(4): 1.
- Opperman JJ, Royte J, Banks J, Day LR, Apse C. 2011. The Penobscot River, Maine, USA: A basin-scale approach to balancing power generation and ecosystem restoration. *Ecology and Society* 16: 7.
- Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, et al. 2005. Standards for ecologically successful river restoration: Ecological success in river restoration. *J Appl Ecol* 42: 208–217. doi: 10.1111/j.1365-2664.2005.01004.x.
- Pearson AJ, Snyder NP, Collins MJ. 2011. Rates and processes of channel response to dam removal with a sand-filled impoundment. *Water Resour Res* 47.
- Pess GR, Quinn TP, Gephard SR, 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 Fisher* 24: 881–900. doi: 10.1007/s11160-013-9339-1.
- Pizzuto J. 2002. Effects of dam removal on river form and process. *Bioscience* 52: 683–691.
- Poff NL, Zimmerman JK. 2010. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshwater Biol* 55: 194–205.
- Pohl MM. 2002. Bringing down our dams: Trends in American dam removal rationales. *J Am Water Resour As* 38: 1511–1519.
- Rainwater FH. 1962. Stream composition of the conterminous United States. *Hydrologic Investigation Atlas HA-61. U.S. Geological Survey*. Washington, D.C.
- Randle TJ, Bountry JA, Ritchie A, Wille K. 2015. Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment. *Geomorphology* 246: 709–728. doi: 10.1016/j.geomorph.2014.12.045.
- Richter BD, Thomas GA. 2007. Restoring environmental flows by modifying dam operations. *Ecol Soc* 12: 26.
- Saunders R, Hachey MA, Fay CW. 2006. Maine's diadromous fish community: Past, present, and implications for Atlantic salmon recovery. *Fisheries* 31: 537–547.
- Sawaske SR, Freyberg DL. 2012. A comparison of past small dam removals in highly sediment-impacted systems in the US. *Geomorphology* 151: 50–58.
- Schmidt JC, Parnell RA, Grams PE, Hazel JE, Kaplinski MA, et al. 2001. The 1996 controlled flood in Grand Canyon: Flow, sediment transport, and geomorphic change. *Ecol Appl* 11: 657–671.
- Seidl R, Brand FS, Stauffacher M, Krütli P, Le QB, et al. 2013. Science with society in the Anthropocene. *Ambio* 42: 5–12.
- Service RF. 2011a. Will busting dams boost salmon? *Science* 334: 888–892.
- Service RF. 2011b. Rejected salmon plan could bring changes to US dams. *Science* 333: 811–811.
- Sethi SA, Selle AR, Doyle MW, Stanley EH, Kitchel HE. 2004. Response of unionid mussels to dam removal in Koshkonong Creek, Wisconsin (USA). *Hydrobiologia* 525: 157–165.
- Sivapalan M, Konar M, Srinivasan V, Chhatre A, Wutich A, et al. 2014. Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future* 2: 225–230.
- Smith SV, Renwick WH, Bartley JD, Buddemeier RW. 2002. Distribution and significance of small, artificial water bodies across the United States landscape. *Sci Total Environ* 299: 21–36.
- Snyder NP, Nesheim AO, Wilkins BC, Edmonds DA. 2013. Predicting grain size in gravel-bedded rivers using digital elevation models: Application to three Maine watersheds. *Geol Soc Am Bull* 125: 148–163.

## River restoration by dam removal

- Stanley EH, Doyle MW. 2003. Trading off: The ecological removal effects of dam. *Frontiers in Ecology and the Environment* 1: 15–22.
- Steffen W, Persson Å, Deutsch L, Zalasiewicz J, Williams M, et al. 2011. The Anthropocene: From global change to planetary stewardship. *Ambio* 40: 739–761.
- USACE. 2015. The Blackstone (lower) River fish passage project. [WWW Document]. Accessed 7.28.15. <http://www.nae.usace.army.mil/Missions/ProjectsTopics/LowerBlackstone.aspx>.
- Van Andel J, Aronson J. 2012. *Restoration ecology: The new frontier*. John Wiley & Sons.
- Vedachalam S, Riha SJ. 2014. Small is beautiful? State of the dams and management implications for the future. *River Research and Applications* 30: 1195–1205. doi: 10.1002/rra.2698.
- Waldman J, Wilson KA, Mather M, Snyder NP. 2016. A resilience approach can improve anadromous fish restoration. *Fisheries* 41: 116–126. doi: 10.1080/03632415.2015.1134501.
- Walker B, Holling CS, Carpenter SR, Kinzig A. 2004. Resilience, adaptability, and transformability in social-ecological systems. *Ecology and Society* 9: 5.
- Walter RC, Merritts DJ. 2008. Natural streams and the legacy of water-powered mills. *Science* 319: 299–304. doi: 10.1126/science.1151716.
- Warrick JA, Bountry JA, East AE, Magirl CS, Randle TJ, et al. 2015. Large-scale dam removal on the Elwha River, Washington, USA: Source-to-sink sediment budget and synthesis. *Geomorphology* 246: 729–750. doi: 10.1016/j.geomorph.2015.01.010.
- Wilcox AC, O'Connor JE, Major JJ. 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 Surface* 119: 1376–1394.
- Wildman L. 2013. Dam removal: A history of decision points. *Rev Eng Geol* 21: 1–10.

### Contributions

- Contributed to conception and design: FJM, BEG, and KHN
- Contributed to acquisition of data: BEG, FJM, and KHN
- Contributed to analysis and interpretation of data: FJM, BEG, KHN, JWC, CSS, and CAF
- Drafted and or revised the article: FJM, KHN, CSS, CAF, JWC, and BEG
- Approved the submitted version for publication: FJM, BEG, KHN, JWC, CSS, and CAF

### Acknowledgments

Alex Jospe and Erik Martin at The Nature Conservancy (TNC) provided invaluable help with the TNC database. We thank Sam Creek from the Chewonki Foundation for the use of the photo of the lower Montsweag Brook dam in Figure 2. This paper benefited tremendously from ongoing discussions with colleagues at the USGS Powell Center in Ft. Collins, CO.

### Funding information

This research was supported in part by the National Science Foundation (BCS-1263519) and from the Rockefeller Center at Dartmouth College.

### Competing interests

The authors have no competing interests to declare.

### Data accessibility statement

The dataset on existing dams was generated from the National Inventory of Dams (NID) and from state inventories (where available). Data on dam removals for New England were compiled from the American Rivers database and from public documents searched using Google. The dam removal dataset can be made available upon request.

### Copyright

© 2016 Magilligan et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.