

Water Resources Research

COMMENTARY

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Key Points:

- Dam removal is an increasingly common approach to river restoration in the United States
- Dam-removal studies provide insights on key controls influencing the physical and ecological responses to dam removal
- Although many aspects of physical and ecological systems react quickly to dam removal, overall response trajectories depend on how and where dams are removed and overall watershed conditions

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Dam removal: Listening in

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Abstract Dam removal is widely used as an approach for river restoration in the United States. The increase in dam removals—particularly large dams—and associated dam-removal studies over the last few decades motivated a working group at the USGS John Wesley Powell Center for Analysis and Synthesis to review and synthesize available studies of dam removals and their findings. Based on dam removals thus far, some general conclusions have emerged: (1) physical responses are typically fast, with the rate of sediment erosion largely dependent on sediment characteristics and dam-removal strategy; (2) ecological responses to dam removal differ among the affected upstream, downstream, and reservoir reaches; (3) dam removal tends to quickly reestablish connectivity, restoring the movement of material and organisms between upstream and downstream river reaches; (4) geographic context, river history, and land use significantly influence river restoration trajectories and recovery potential because they control broader physical and ecological processes and conditions; and (5) quantitative modeling capability is improving, particularly for physical and broad-scale ecological effects, and gives managers information needed to understand and predict long-term effects of dam removal on riverine ecosystems. Although these studies collectively enhance our understanding of how riverine ecosystems respond to dam removal, knowledge gaps remain because most studies have been short (< 5 years) and do not adequately represent the diversity of dam types, watershed conditions, and dam-removal methods in the U.S.

1. The Evolving Landscape of Dam Removal

Humans and rivers have a complex, interdependent, and evolving relationship [Doyle, 2012]. Dam building, and more recently dam removal, exemplify this changing connection. More than 1300 dams have been removed in the U.S. (Figures 1 and 2) [O'Connor et al., 2015], and they continue to be removed at an increasing rate in the U.S. and abroad [American Rivers, 2016; World Commission on Dams, 2000]. Dams are removed for many reasons, commonly because their age and loss of function have rendered them unsafe, obsolete, or economically nonviable [Heinz Center, 2002; Pohl, 2002]. Another key motivation is to rehabilitate rivers by restoring physical and ecological attributes and functions [Pohl, 2002]. But does dam removal restore rivers? If so, how does recovery happen, and what outcomes might be expected? What might be unforeseen or go wrong?

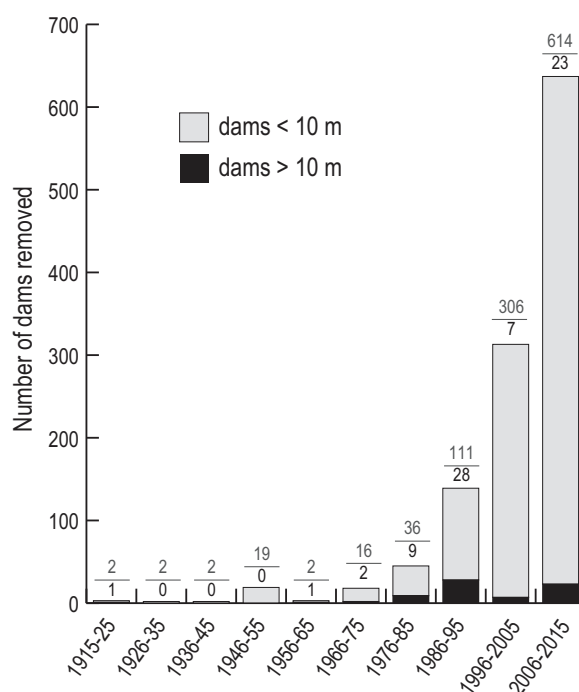


Figure 1. Dam removals by decade [American Rivers, 2016]. Of the 1300 known dam removals, removal year is reported for 1181, including 71 of the 83 removed dams known to be taller than 10 m.

As the rate of dam removals increased in the 1990s, scientists began asking these critical questions to understand the processes and rates by which dam removal may affect rivers and ecosystem connections [Grant, 2001; Grossman, 2002; Hart *et al.*, 2002; Pizzuto, 2002; Shafroth *et al.*, 2002; Stanley *et al.*, 2002; Graf, 2003]. These early studies outlined river responses to dam removal, largely based on geomorphic and ecological theory and analogs. Nearly 20 years and hundreds of dam removals later, a growing body of dam-removal literature allows us to take stock of how rivers are responding. This is especially the case for large dam removals—those taller than 10 m—that have been removed and studied with increasing frequency during the last 30 years (Figure 1). Recent studies build on early observations and hypotheses, providing wide-ranging empirical evidence of river response to dam removal and valuable perspective as the number and rate of dam removals accelerates [American Society of Civil Engineers (ASCE), 2013]. Emerging questions and lessons learned from dam removals are also

important because dam *building* is on the rise in developing nations [Zarfl *et al.*, 2015]. Knowledge of ecological and physical responses to dam removal can inform dam emplacement decisions about where and how dams are built to avoid or minimize environmental disturbance and future economic liabilities.

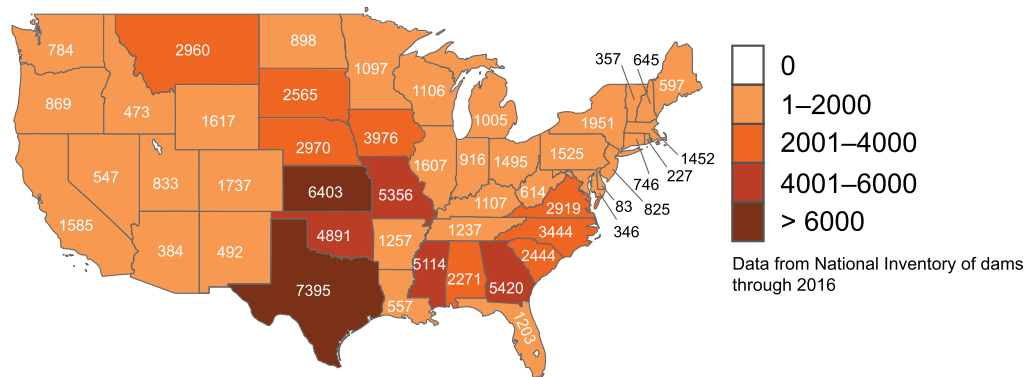
This synthesis—conducted by a working group at the USGS John Wesley Powell Center for Analysis and Synthesis—summarizes our findings from dam removal research in the U.S. It draws heavily from a new bibliographic database of 207 dam-removal studies (Figure 2) [Bellmore *et al.*, 2015, 2017b; Duda *et al.*, 2016], including peer-reviewed literature, reports, and dissertations published through 2015 (more details in Bellmore *et al.* [2017b]). Our conclusions also derive from focused analysis of the distribution and types of dam-removal studies [Bellmore *et al.*, 2017b], the physical [Major *et al.*, 2017] and ecological responses to dam removal, dam-removal management concerns [Tullos *et al.*, 2016], and the geographic context of dam removal and ecosystem response [Foley *et al.*, 2017a].

In many cases, these recent studies confirm earlier predictions about the processes and controls of river response to dam removal, particularly for physical responses. Additionally, physical responses to several large dam removals in recent years have followed predictable trajectories, suggesting consistent primary controls on river response. Although these findings could be perceived as indicating little progress since the earliest dam-removal studies, the observation-based validation of many aspects of these earlier studies is critical affirmation of dam-removal science, particularly as dams continue to come down at an accelerating rate. Moreover, recent studies reveal new information; in particular physical responses have in several instances been faster than anticipated, with rivers taking years, not decades, to stabilize after dam removal. The response of ecological communities has varied tremendously, depending on individual circumstances of the removal and the encompassing watershed. We also identify issues and questions where more research is needed.

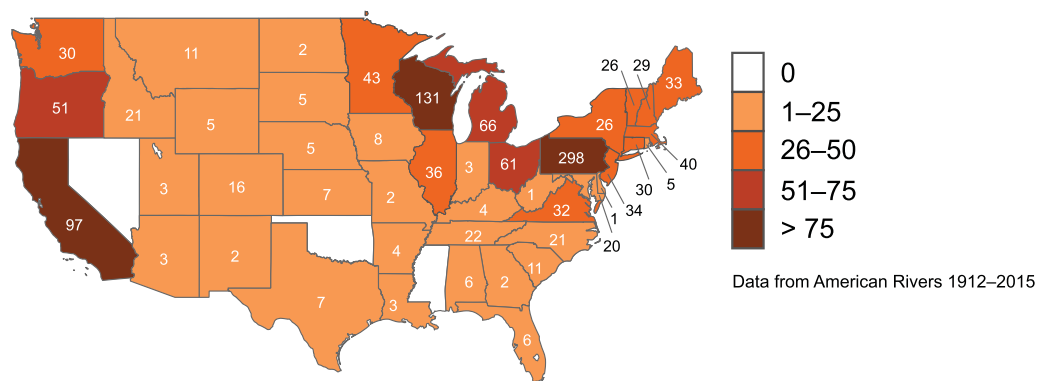
2. What Are the Rivers Saying?

Dam-removal science thus far has been relatively uncoordinated and largely opportunistic. Yet as a whole, the rivers are speaking, and scientists, river restoration practitioners, and decision makers are listening. Here

A. Number of dams



B. Dams removed



C. Dams removed with published research or monitoring

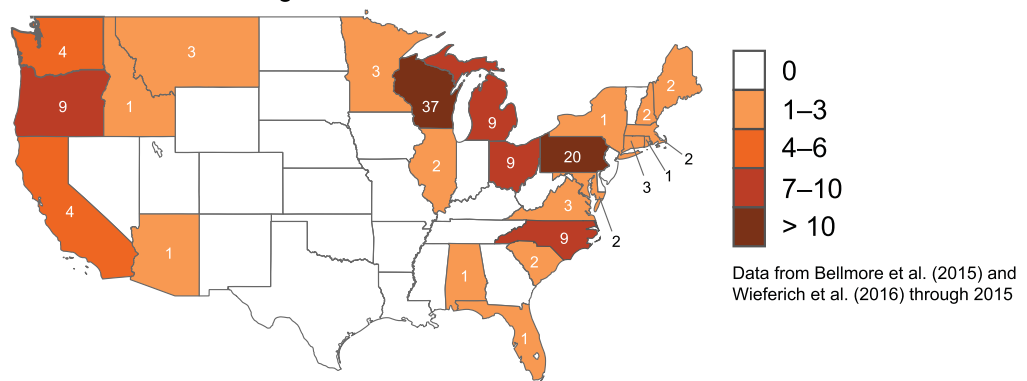


Figure 2. The number and distribution of (a) dams > 7.6 m high from the National Inventory of Dams [U.S. Army Corps of Engineers, 2013], (b) removed dams through 2015 [American Rivers, 2016], and (c) dam-removal research within the contiguous United States [Bellmore et al., 2015; Wiefelich et al., 2016]. Modified and updated from Bellmore et al. [2017b].

we summarize overall patterns of river response to dam removal, but also point to knowledge gaps, biases, and limitations in our understanding.

2.1. Sediment Can Move

Removing a dam exposes sediment accumulated over years to decades to erosion and downstream transport and exhumes formerly underwater surfaces for plants and animals to colonize. The fate of this sediment—along with contaminants, nutrients, and organic material—is commonly the chief concern and expense associated with dam removal [Wildman, 2013; Evans, 2015; Tullos et al., 2016]. Accordingly, Wildman and MacBroom's [2010] decision tree for implementing small-dam removal starts with the question "Sediment present?"

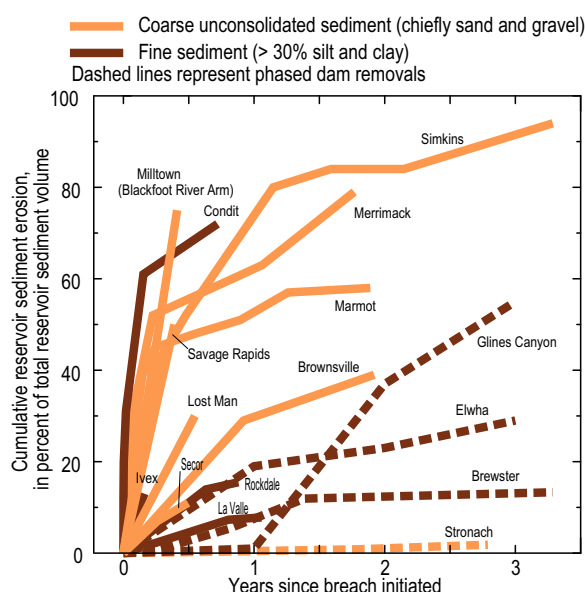


Figure 3. Percentage of reservoir sediment eroded with time after dam removal. Modified from Major et al. [2017], Sawaske and Freyberg [2012], and Grant and Lewis [2015].

The fate of the impounded sediment depends chiefly on the character of the deposits and the pace of dam removal (Figure 3) [Sawaske and Freyberg, 2012; Grant and Lewis, 2015; Major et al., 2017]. Removing a dam lowers local base level by the height of the impoundment. In removals where the base-level fall is gradual and impoundments are not full of sediment, downstream transport of sediment from the impoundment may be limited [e.g., Evans et al., 2000; Burroughs et al., 2009; Major et al., 2017]. For impoundments full of sediment, a knickpoint or knickzone—a short, steep section of channel where fluvial energy and erosion are focused—tends to form when base-level falls quickly at the dam site and migrates upstream through the impounded sediment [Doyle et al., 2005]. Incision at the knickpoint exposes the impounded sediment to further erosion by lateral channel migration and mass movements [Major et al., 2012; Wilcox et al., 2014], introducing additional sediment into the river channel. Within the

impounded reach, sediment deposition and bar formation may promote lateral channel migration and erosion in a positive feedback until the channel gradient approaches the predam slope and the bed and banks coarsen or otherwise stabilize [Major et al., 2017]. In some situations, the channel may incise upstream of former reservoirs once they attain predam grades, eroding through deposits that formed above the reservoir while the dam was in place [Evans et al., 2007].

Studies to date indicate that river discharge alone may have little effect on the ultimate volume of reservoir-sediment erosion. For many dam removals, a majority of reservoir sediment was eroded in the absence of large peak flows [Kibler et al., 2011; Pearson et al., 2011; Major et al., 2012; Bountry et al., 2013; Wilcox et al., 2014; Magirl et al., 2015; Warrick et al., 2015; Collins et al., 2017]. In the case of Marmot Dam, a 10 year flood 4 years after dam removal produced little sediment erosion from the reservoir area because earlier, smaller flows had already eroded much of the stored sediment [Major et al., 2012]. Similarly, phased removal of the 64 m-tall Glines Canyon Dam and 32 m Elwha Dam on the Elwha River, Washington, resulted in evacuation of more than 10 million tons (~35%) of the reservoir sediment over 2 years by flows substantially less than a 2 year flood [Magirl et al., 2015; Warrick et al., 2015]. For these removals, base-level fall at the former dam site drove a majority of sediment evacuation and did not require high flow events.

In some cases, high flows may be needed to erode additional sediment, especially after the channel has incised through the impounded reservoir sediment [Pearson et al., 2011; Gartner et al., 2015; Collins et al., 2017]. For example, base-level falls associated with the removal of the Merrimack Village (4 m, Souhegan River, New Hampshire) and Simpkins dams (6 m, Patapsco River, Maryland), initiated erosion of approximately 50% of impounded sediment in each case, but subsequent flows greater than a 5 year recurrence interval were needed to erode additional reservoir sediment (Figure 3) [Collins et al., 2017]. For dam removals where knickpoints do not form or where sediment entrainment thresholds are high, moderate to high flows are required to mobilize reservoir sediment, such as in the removal of 4 m-tall Homestead Dam on the Ashuelet River, New Hampshire [Gartner et al., 2015]. These studies suggest that for most dam removals, substantial reservoir-sediment erosion does not require high flow. Flow sequencing may influence the timing and trajectory of reservoir-sediment erosion but will likely have little effect on the total volume of sediment eroded.

Erosion is quickest when a dam is breached rapidly, reservoir sediment is unconsolidated, and the resulting knickpoint—if one forms—is tall relative to dam height. Under those conditions, significant fractions of the reservoir sediment—50% or more—have been eroded from former impoundments within weeks or months

of breaching (Figure 3) [Pearson *et al.*, 2011; Sawaske and Freyberg, 2012; Wilcox *et al.*, 2014; Grant and Lewis, 2015; Collins *et al.*, 2017; Major *et al.*, 2017]. Instantaneous dam removals—where the dam is removed or the reservoir emptied of water in one action—exposes impounded sediment to rapid base-level fall equal to the impoundment height. This base-level fall triggers immediate incision of reservoir sediment, regardless if the reservoir is completely or partially full of sediment. Most instantaneous removals have involved small dams, but exceptions include the 15 m-tall Marmot Dam on the Sandy River, Oregon [Major *et al.*, 2012], and the instantaneous breach and reservoir drainage during removal of the 38 m-tall Condit Dam on the White Salmon River, Washington [Wilcox *et al.*, 2014].

Phased dam removals, by contrast, incrementally lower the dam crest over multiple stages before ultimate removal. This removal strategy is usually motivated by logistical factors or to manage the timing of sediment release. For phased removals, the full thickness of the sediment in the impoundment is not subject to erosion until the final stage of dam removal. If the impoundment is full of sediment, a series of multiple, small knickpoints tend to migrate upstream and gradually release sediment from the impoundment. If the impoundment is partially filled with sediment, the greatest sediment release may be delayed until remobilized reservoir sediment reaches the dam site or the dam elevation is lowered to the top of the sediment deposit, allowing sediment to spill over the dam. Once sediment transport is established past the dam site, sediment commonly moves out of reservoirs quickly [Magirl *et al.*, 2015; Randle *et al.*, 2015]. Many small dams have been taken down in phases [Sawaske and Freyberg, 2012; Major *et al.*, 2017], but large, phased dam removals have also occurred recently. The largest to date was the removal of the Glines Canyon and Elwha dams on the Elwha River between 2011 and 2014. The removals were phased to minimize effects on increased turbidity on fish and control the rate of reservoir sediment erosion such that downstream sediment transport would keep pace with upstream supply. Similarly, Milltown Dam (12.8 m) on the Clark Fork, Montana, was breached in 2008, but the complete removal occurred over multiple years to facilitate remediation of contaminated reservoir sediments [Evans and Wilcox, 2014].

Within the reservoir reach and downstream, the grain size of the impounded sediment strongly affects physical river response. Sand and gravel erode quickly from the reservoir reach and are transported downstream [Burroughs *et al.*, 2009; Major *et al.*, 2012; Tullos *et al.*, 2014; Harris and Evans, 2014; Tullos and Wang, 2014; Major *et al.*, 2017], whereas cohesive silt and clay erode more slowly (Figure 3). For example, the removal of the 3.3 m-high Rockdale Dam on the Koshkonong River, Wisconsin, resulted in only 11% of the fine-grained reservoir sediment evacuating in the eleven months following breaching [Doyle *et al.*, 2003], compared to 17% of the coarse-grained reservoir sediment behind Marmot Dam eroding in the first 60 h (Figure 3) [Major *et al.*, 2012]. However, even cohesive fine-grained sediment can erode rapidly if major, abrupt base-level fall induces mass failures in the reservoir [Wilcox *et al.*, 2014].

Downstream of the former dam sites, river channels and floodplains adjust to increased sediment supply. Initially, most downstream sediment comes from the eroding impoundment, but eventually the supply derives from reconnected upstream sediment sources. When large quantities of sediment are released, downstream pools fill, grain size decreases, and channels commonly aggrade and widen, and become more braided with more bed relief [Harris and Evans, 2014; East *et al.*, 2015; Zunka *et al.*, 2015; Major *et al.*, 2017], as a function of initial channel conditions. These changes are similar to increased sediment transport caused by volcanism and landslides [Major *et al.*, 2000]. These initial responses may occur within hours to months (Figure 4). In the first few days following removal of Marmot Dam, for example, the downstream channel was buried by as much as 4 m of gravel in a sediment wedge extending more than 2 km downstream [Major *et al.*, 2012].

After the first pulse of reservoir-sediment erosion and downstream aggradation, rivers typically incise the freshly deposited sediment and transport it downstream, resulting in subsequent downstream channel narrowing, decreased braiding, and bed-sediment coarsening. This change from aggradation to incision can be swift, within days to months after removal [e.g., Pearson *et al.*, 2011; Wilcox *et al.*, 2014; East *et al.*, 2015], but can also take several years [Major *et al.*, 2017]. In many situations, sediment transported down a river channel during and after dam removal—particularly sand, silt, and clay—eventually enters lower-energy fluvial, lacustrine, or marine environments [Burroughs *et al.*, 2009; Kibler *et al.*, 2011; Peck and Kasper, 2013]. Such transitions commonly result in delta and beach building, as well as localized lake-bottom and seafloor sedimentation. For example, sand from the Elwha River dam removals widened local beaches along the Strait of Juan de Fuca by 100s of meters [Warrick *et al.*, 2015; Gelfenbaum *et al.*, 2015]. In contrast, eroded reservoir

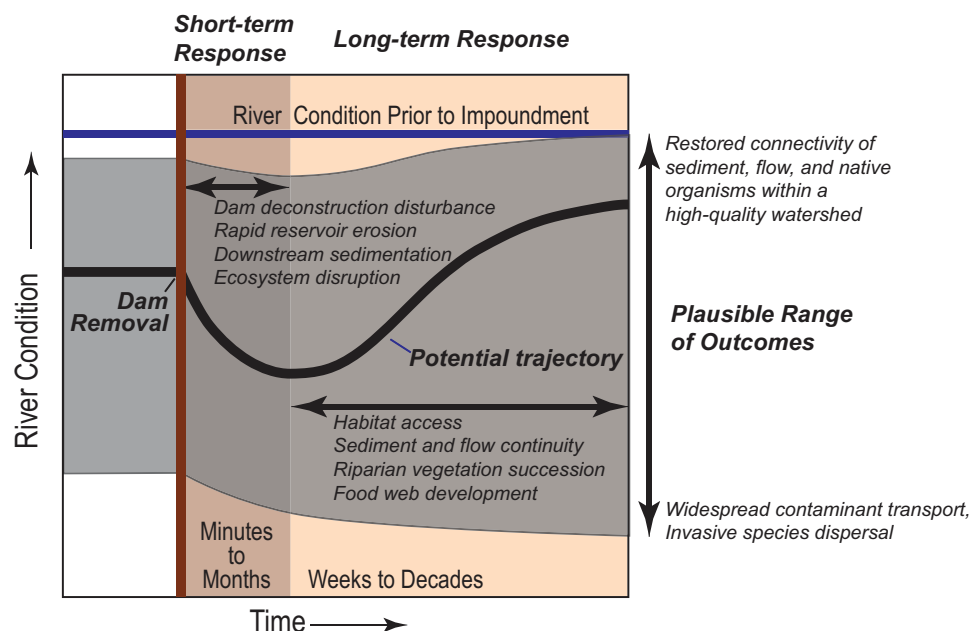


Figure 4. Conceptual river response to dam removal. Prior to dam removal, physical and ecological river condition is likely altered to some degree from preimpoundment conditions by changed flow, sediment regime and aquatic connectivity. Dam removal will typically result in short-term disturbance, but the system will approach a new steady state dictated by overall watershed conditions. The indicated potential trajectory is just one of many possible outcomes within the gray shaded area depending on the original effects of the dam and reservoirs, their sizes, removal strategy, and regional environmental conditions.

gravel is commonly deposited close to the dam site, often in wider reaches of the river, as during the Marmot Dam removal [Major et al., 2012].

For many dam removals, downstream suspended sediment loads and turbidity may not exceed the magnitude or duration measured during floods, particularly for small removals [Tullos et al., 2016]. Sediment concentrations and loads can be higher during the initial pulse following removal, particularly if sediment release occurs during a low flow period [Magirl et al., 2015]. And for dams storing large quantities of fine sediment, dam removal may cause exceptionally high sediment transport rates that are orders of magnitude greater than background rates during similar flows [e.g., Doyle et al., 2003; Major et al., 2012; Wilcox et al., 2014; Magirl et al., 2015]. Within weeks to months, however, sediment transport rates typically return to background levels.

The volume and grain size of the impounded sediment often motivate much of the planning, engineering, monitoring, and adaptive management of dam removal [Downs et al., 2009]. Managing the impounded sediment is also likely the single most important control managers can use to influence the physical and ecological response to dam removal. Management approaches can include methods that prevent or slow the downstream movement of sediment, such as incremental lowering of the dam crest, or stabilization or excavation of material. During the removal of the San Clemente Dam, Carmel River, California, reservoir sediments were stabilized in place to prevent downstream deposition that would raise the flood stage. When necessary, sediment may be directly removed from reservoirs [Claeson and Coffin, 2016], particularly if the impoundment contains contaminated sediment, as in the Milltown Dam removal [Evans and Wilcox, 2014]. Dam removal could also be paused if necessary to stop sediment release, as occurred during the Elwha dam removals where downstream sedimentation affected critical infrastructure.

2.2. Species Can Change

Although the fate of sediment may be the chief concern associated with dam removal, the recovery of species and ecosystems is often the long-term goal. Similar to sediment responses, ecological responses are highly context dependent. Environmental conditions of the watershed, as well as the spatial domain of the ecological community strongly influence ecological responses.

Dam removal typically does not directly disturb ecosystems upstream of former impoundments, but ecological response can be substantial because reestablishing connectivity and removing barriers to species movement allows mobile organisms to reestablish populations in habitats that may have been formerly inaccessible [Pess *et al.*, 2014]. Fish response to barrier removal is typically rapid [Burroughs *et al.*, 2010; Poulos *et al.*, 2014; Kornis *et al.*, 2015], and restoring upstream connectivity can increase fish species richness [Catalano *et al.*, 2007; Burroughs *et al.*, 2010; Kornis *et al.*, 2015] and life-history diversity [Hitt *et al.*, 2012; Pess *et al.*, 2014]. Additionally, recolonizing migratory fish may transport marine-derived nutrients upstream, which can increase watershed productivity [Helfield and Naiman, 2002; Walters *et al.*, 2009; Hogg *et al.*, 2013; Pess *et al.*, 2014; Tonra *et al.*, 2015].

The former impoundment is typically the reach most physically and ecologically altered by dam emplacement and removal because the hydrology, hydraulics, and substrate may rapidly evolve. If a reservoir is present, it changes from a lentic (lake) to lotic (riverine) system after dam removal, changing the type of flora and fauna in the impounded reach. Primary producers and invertebrate consumers may also shift from feeding upon pelagic—typically phytoplankton and zooplankton—to benthic communities of periphyton and associated insects [Bushaw-Newton *et al.*, 2002; Stanley *et al.*, 2002]. Conversion of reservoirs to free-flowing rivers also shifts fish-community assemblages from those that favor slow-water environments to species better adapted to free-flowing rivers [Catalano *et al.*, 2007]. Pioneer vegetation species, including nonnative species, can quickly colonize newly exposed sediment and streamside riparian areas within the former impoundment [Tullos *et al.*, 2016]. Initial colonization depends on the timing of reservoir drawdown [Johnson, 2002] and the composition of the surrounding vegetation and seed bank [Shafroth *et al.*, 2002].

Downstream of the former dam, initial ecological response is generally governed by the transport and deposition of reservoir sediments, which can increase water turbidity [Warrick *et al.*, 2012; Major *et al.*, 2012; Magirl *et al.*, 2015], and scour and bury benthic habitats [Keigley 1993; Bednarek 2001; Orr *et al.*, 2008; Chiu *et al.*, 2013]. Sediment deposition downstream of the dam during and after removal is typically the main driver of decreased macroinvertebrate species abundance and altered species assemblages [Orr *et al.*, 2008; Chiu *et al.*, 2013; Evans and Wilcox, 2014]. Additional downstream effects may result from influxes of organic material (including large woody debris), nutrients, and contaminants that are mixed with or attached to sediment particles [Stone and Droppo, 1994].

Downstream sediment deposition may create new aquatic and terrestrial habitats that can be colonized by invertebrates, fish, and vegetation [Shafroth *et al.*, 2002; Stanley *et al.*, 2002]. For example, the number of salmon redds on the Elwha River tripled between the first and third years of dam removal as spawning habitat increased [McHenry *et al.*, 2015]. Downstream vegetation colonization and community change tend to be correlated with the volume of sediment released during dam removal [Shafroth *et al.*, 2016]. Ongoing studies on the Elwha River [McHenry and Pess, 2008; Foley *et al.*, 2017b] and White Salmon River [Allen *et al.*, 2016] are evaluating how these newly formed or reworked habitats affect distributions of fishes, aquatic invertebrates, and vegetation.

Downstream colonization of new habitat is influenced by the grain size of deposited sediment. Most aquatic organisms living on the streambed require some level of sediment stability, while many river fishes require larger-sized gravels to build redds that are resistant to scouring flows [e.g., Quinn, 2011]. Changes in grain size following dam removal (generally coarsening in the reservoir and fining downstream) can also alter riparian vegetation composition [Krasny *et al.*, 1988], mainly by affecting erosion potential and moisture retention [Slawson, 2004]. As sediment regimes stabilize to watershed conditions, however, downstream species composition tends to shift to assemblages characteristic of the new sediment and flow conditions (Figure 4). Downstream benthic invertebrate abundance, for example, tends to increase and species assemblages transition to resemble sites upstream of the former dam [Bushaw-Newton *et al.*, 2002; Hansen and Hayes, 2012; Tullos *et al.*, 2014]. Changing geomorphic conditions commonly pace these shifts in benthic macroinvertebrate abundance and community composition, and species recovery may take weeks or months [Bushaw-Newton *et al.*, 2002] or even decades [Burroughs *et al.*, 2010; Hansen and Hayes, 2012]. In some cases, however, ecological recovery is faster than the geomorphic response. For example, Tullos *et al.* [2014] found that benthic invertebrate communities downstream of the Brownsville (2.5 m, Calapooia River, Oregon) and Savage Rapids (12 m, Rogue River, Oregon) dams resembled upstream control sites within a year after dam removal, whereas geomorphic changes were still occurring 2 years following dam removal.

Over decadal time scales, the common hope is that reestablishing flow patterns, temperature, and sediment regimes to conditions to which native organisms are adapted will enable sustained ecological recovery [Ward and Stanford, 1983; Poff *et al.*, 1997; Wohl *et al.*, 2015]. Documenting such recovery may also require decades in many cases. Because ecosystem recovery exceeds the duration of most dam-removal studies so far, our understanding of long-term ecological trajectories is still limited. Longer-duration monitoring of dam removals of various sizes—particularly those that release large quantities of sediment—will improve our knowledge of how ecosystems recover when environmental dynamics are reestablished.

2.3. Size Matters

Dam height, reservoir size, and volume and grain size of the impounded sediment are important controls on river response to dam removal. These factors control the amount and types of material that are available to create new, postdam-removal landscapes.

Most (94%) removed dams have been small, standing less than 10 m high (Figure 1) and impounding less than 10,000 m³ of sediment [Major *et al.*, 2017]. The overall geomorphic and ecological effects of most of these small dam removals have been minor [e.g., Skalak *et al.*, 2011; Sawaske and Freyberg, 2012; Tullos *et al.*, 2014]. The physical effects of removing large dams, however, are more substantial and less well known [Allen *et al.*, 2016; Major *et al.*, 2017]. Releasing sediment fluxes that are large in comparison to background sediment fluxes appears to affect longer reaches of downstream channels for longer periods of time [Podolak and Wilcock, 2013; East *et al.*, 2015] than small volumes [Skalak *et al.*, 2009; Csiki and Rhoads, 2010, 2014]. This conclusion is tentative, however, because no large dam removals have been monitored for more than 10 years after removal [Bellmore *et al.* 2017b].

Removals of large dams also likely have greater ecological effects than removals of small dams, particularly where small dams have little effect on environmental conditions. For example, Mbaka and Mwaniki [2015] found that benthic invertebrate assemblages were similar upstream and downstream of some smaller dams, indicating minimal ecological effect on some species. However, many small dams completely block upstream travel for aquatic species and their removal is ecologically significant, particularly for migratory fish [Hitt *et al.*, 2012; Lasne *et al.*, 2014]. The size of the former impoundment can also influence vegetation colonization and succession. Removals of small dams impounding small volumes of sediment may result in minor changes to vegetation upstream and downstream, whereas erosion and redeposition of large sediment deposits could significantly alter the composition and spatial distribution of vegetation [Shafroth *et al.*, 2016].

2.4. Location Is Important

The overarching importance of location in motivating dam removal is evident in the geographic distribution of dam removals in the U.S. (Figure 2). Although a majority of existing dams within the National Inventory of Dams database [U.S. Army Corps of Engineers, 2013] are concentrated in the Plains states and Southeast, most dam removals have been in the Northeast, upper Midwest, and western coastal states [Bellmore *et al.*, 2017b; Foley *et al.*, 2017a]. These dams tend to be old, failing after decades or centuries of inadequate maintenance, or no longer serve their initial purpose, such as powering mills [Evans *et al.*, 2000; Pohl, 2002; Stanley and Doyle, 2003; Wildman, 2013]. The concentration of dam removals in the U.S. Pacific Northwest, in part, owes to companies choosing to decommission dams rather than investing in expensive Federal Energy Regulatory Commission relicensing requirements [Bowman, 2002], particularly when the dams are not in compliance with the Endangered Species Act or Clean Water Act [Becker, 2006].

Geographic location can also influence the effects of dam removal. Removals within watersheds with few other dams can restore connectivity to a high proportion of the watershed [Magilligan *et al.*, 2016], particularly if the removed dam is low in the river network [Grill *et al.*, 2014]. In contrast, isolated dam removals may have little effect on connectivity if many dams remain in the watershed [Cooper, 2013]. Dam removal on the Elwha River restored connectivity to large areas of high-quality fish habitat upstream in Olympic National Park by removing all man-made barriers in the river network [Duda *et al.*, 2008]. The proposed synchronous removal of four hydroelectric dams on the Klamath River in Oregon and California will provide access to over 600 km of presently unavailable habitat for anadromous salmonids [Hamilton *et al.*, 2005].

The sedimentary and hydrologic responses to dam removal also depend on dam position within the stream network in relation to downstream sources of water and sediment. Release of sediment from dams

upstream of major sediment sources will likely have limited downstream sedimentary effects [Major *et al.*, 2012]. Similarly, where flow from downstream tributaries masks any flow changes imposed by dam operation, downstream channel response is less pronounced [Grant *et al.*, 2003; Schmidt and Wilcock, 2008], as would also be the case for any hydrologic change caused by dam removal. Removing dams on small tributaries is unlikely to have large geomorphic effects on downstream mainstem rivers, except in the immediate vicinity of their confluences where low gradients may promote local deposition [Wilcox *et al.*, 2014]. The strategic removal of multiple, smaller dams in the same watershed has the potential to deliver large amounts of sediment at the watershed scale [Magilligan *et al.*, 2016] with overall effects similar to those of larger dam removals.

Location is being given greater scrutiny, particularly where the desire to remove dams is greater than the funding and resources available to remove them. This is evident in the increased use of ecological modeling to prioritize dam removal for optimizing structural and functional connectivity for migratory fish [McKay *et al.*, 2016]. For example, Branco *et al.* [2014] examined a large watershed in Portugal, showing that graph theory, habitat suitability modeling, and prioritization modeling could increase habitat connectivity for native fish more than 30% compared to randomly selected dam removals. Most prioritization models seek to increase the amount of high quality habitat and reconnected river miles [Hoenke *et al.*, 2014]. Dam removal decisions are rarely based on a single criterion, and methods are developing to include social, economic, and ecological criteria [Hermoso *et al.*, 2012]. Future evaluations will likely also need to consider climate change, which affects dam-related social and ecologic factors such as water and energy use, river flow, and temperature [Null *et al.* 2014; Poff *et al.*, 2015].

The predominance of studied dam removals from narrow environmental settings with the U.S. limits current understanding of the effects of dam removal. Most dam removals in the U.S. are not in areas with the greatest concentration of dams (Figure 2). With a few prominent exceptions, most dam removals have been low-head, run-of-river dams from low-elevation watersheds [Doyle *et al.*, 2003; Tonitto and Riha, 2016; Foley *et al.*, 2017a], reflecting the sociopolitical, economic, and ecological considerations motivating most removals. Our knowledge of the breadth of biophysical responses to dam removal will improve as more studies are conducted across a diversity of landscapes and biogeographic settings.

2.5. Surprises Happen

Several dam removals have had unexpected outcomes. Although few have been calamitous, the surprises remind us that all dam removals have different starting conditions and are influenced by complex interactions among physical processes, ecological responses, and local-river and watershed history.

Reservoir erosion may be more rapid and extend farther upstream than anticipated. This was the case during the Condit Dam removal, where unexpected incision of coarse sediment at the upstream end of the reservoir eroded 24% of redds established by Chinook salmon that had been translocated upstream of the dam prior to breaching [Allen *et al.*, 2016]. The breaching of Condit Dam also resulted in unexpectedly high sediment conditions [Wilcox *et al.*, 2014]. In hindsight, the depth of the reservoir, grain size and geometry of the accumulated sediment behind Condit Dam, and the anticipated rate of reservoir drainage should have indicated that landslide and slurry generation were possible. That dam removal, however, was of a scale and type outside most previous experience.

Reservoirs may contain toxic substances, and the release of contaminants in the accumulated sediment are a major concern for local communities [Wildman and MacBroom, 2005], especially after the calamitous 1973 removal of Fort Edward Dam on the Hudson River released PCB-contaminated sediment [Shuman, 1995]. Because many reservoirs were created decades or centuries ago, neither the original topography nor the composition of accumulated materials may be well known. Evaluation of potential contaminants such as DDT, heavy metals, toxins, and radionuclides is now common, and purposeful dam removals are engineered to prevent or limit their release [e.g., Stanley and Doyle, 2003; Evans and Wilcox, 2014; Evans, 2015].

Former rapids, bedrock outcrops, older dams, and other preexisting structures may exist beneath reservoir sediment [Harris and Evans, 2014; Wilcox *et al.*, 2014; Gartner *et al.*, 2015]. Besides potentially adding to materials being transported downstream and creating hazards, such structures, if exposed, could affect upstream/downstream connectivity and modify reservoir responses to dam removal [Wildman and MacBroom, 2005; Harris and Evans, 2014; Zunka *et al.*, 2015; Magilligan *et al.*, 2016]. Specifically, knickpoints

eroding through reservoir sediment may stall on structures, resistant soil horizons, or bedrock outcrops, thereby halting upstream propagation and local channel widening [Evans *et al.*, 2013]. This may slow reservoir sediment erosion [Wilcox *et al.*, 2014; Zunka *et al.*, 2015] and inhibit fish passage and navigation. Large logs were exhumed and mobilized during the Condit, Chiloquin, Milltown, and Elwha dam removals [Warrick *et al.*, 2015], locally affecting channel dynamics.

Ecological surprises commonly result from unintended effects of restored connectivity. After the removal of the 3.4 m high Big Spring Dam on Big Spring Creek, Wisconsin, white sucker and yellow perch—lentic-adapted reservoir fish species from downstream impoundments—expanded into previously inaccessible upstream habitats [Kornis *et al.*, 2015]. These two species established significant upstream populations, doubling the total fish biomass but reducing the density and biomass of mottled sculpin, the dominant upstream species prior to removal. Several recent dam removals have mobilized unexpectedly high rates of organic materials, which can alter nutrient cycling rates and food web dynamics in aquatic and terrestrial habitats [Peterson *et al.*, 1985; Bellmore *et al.*, 2017a].

Exposure of fertile reservoir sediments may lead to the unintentional spread of nonnative plants. The proportion of nonnative species in former reservoirs tends to be similar to surrounding riparian zones [Tullos *et al.*, 2016]. However, introduced species can form a significant component of the overall plant community, in some cases suppressing the establishment of native plants. Reed canary grass, for example, is one of the most common invasive plant species colonizing former reservoirs in the U.S., often hindering native vegetation recovery [Orr and Stanley 2006; Tullos *et al.*, 2016].

2.6. Response Is Rapid, but Recovery Trajectories Vary

For most settings and removal styles, rivers respond rapidly after dam removal. Rivers generally transport sediment eroded from the reservoirs quickly, trending toward their predam slope profiles and morphology. Rapid physical response results from the strong upstream/downstream coupling intrinsic to river systems. In the case of dam removals, this is manifest by rapid downstream sediment transport and deposition. A key finding is that the physical river response is rapid in many instances, commonly stabilizing in years, not decades, and generally faster than model-generated predictions [Major *et al.*, 2012; Costigan *et al.*, 2014; Tullos *et al.*, 2014; Major *et al.*, 2017].

Aquatic organisms are also quick to take advantage of newly created or reconnected habitats after dam removal, particularly if they survive the initial sediment pulse [Sethi *et al.*, 2004; Pess *et al.*, 2014; Tullos *et al.*, 2014]. Mobile organisms, such as fish, quickly recolonize habitats upstream of former migration barriers [Burdick and Hightower, 2006; Hitt *et al.*, 2012; Pess *et al.*, 2014; Allen *et al.*, 2016]. Anadromous fishes such as salmon have passed former dam sites within days to weeks after removal, as was observed following removal of the Marmot Dam (the authors, personal observations). Downstream habitats initially disturbed by sediment deposition can be quickly colonized by the transport of algae, terrestrial plants, and aquatic invertebrates delivered from upstream [Bushaw-Newton *et al.*, 2002; Tullos *et al.*, 2014].

Although individual organisms can recolonize relatively quickly, the speed at which entire populations and communities recover varies and depends upon population growth rates, ability of individuals in those populations to move [Doyle *et al.*, 2005], and availability of high quality food and habitat [Bukaveckas and Wood, 2014]. Organisms with high rates of biological turnover, such as algae and some invertebrates can double their population size in days to weeks and quickly recover once the initial sediment pulse has passed [Stanley *et al.*, 2002; Bushaw-Newton *et al.*, 2002]. Organisms that are slow to colonize, grow, and reproduce, such as amphibians, fishes, and freshwater mussels, may take months to years to recover [Poulos *et al.*, 2014]. The reestablishment of mature riparian canopies on former reservoir surfaces can take decades or longer [Orr and Stanley, 2006].

2.7. Predammed Condition May Not be Possible

Implicit in the notion of dam removal “restoring” rivers is that once dams are removed, the river will return to a baseline condition similar to its predammed state. This may not be the case, however, because local and watershed-scale changes in land and water use, water quality, and climate can influence physical and ecological recovery trajectories and the ultimate outcomes of dam removal (Figure 4) [Palmer *et al.*, 2010; Feld *et al.*, 2011; Webb-Sullivan and Evans, 2014; Magilligan *et al.*, 2016; Warren *et al.*, 2016]. Dam removals may not achieve complete ecosystem restoration until broader landscape-scale stressors are addressed. For

example, channels trend toward their predam longitudinal profiles within months to years of dam removal [Major *et al.*, 2017], but those profiles are also strongly controlled by the watershed-imposed balance among slope, flow, channel width, channel depth, sediment supply, and grain size that results in equilibrium sediment transport down the river [Lane, 1955; Schmidt and Wilcock, 2008]. If these factors have been altered in other parts of the watershed during the lifetime of the dam, postremoval channel conditions may differ from those prior to impoundment.

Former impoundment sites may not return to predam conditions either. Some fraction of the impounded sediment may remain as elevated benches out of reach from flooding and protected from lateral erosion by underlying valley-wall outcrops. This is most likely to occur at sites where reservoirs are large and occupy the entire valley bottom and in impoundments where relatively small proportions of sediment erode [Doyle *et al.*, 2003]. These terraces or benches, long-lasting legacies of dams, can provide habitats for disturbance-adapted plants, including nonnative species.

As physical conditions trend toward a predam state, the stage is set for biological systems to follow. The trajectories and timeframes of biological response are less certain than for physical systems and recovery may not approach the same level (Figure 4), particularly for exploited species that are subject to stressors that are spatially separate from habitat recovered by dam removal. Additionally, other watershed processes and impacts, such as logging, roads, and culverts may reduce the habitat quality of upstream reaches that were formerly inaccessible. The degree to which these factors affect the long-term recovery of biota is unknown, largely because recovery time for some organisms may take decades or even centuries [Doyle, 2006], which is beyond the duration of dam-removal monitoring thus far [Bellmore *et al.* 2017b]. In many cases, native species may have to compete with nonnative species introduced while the dam was in place [Bednarek, 2001; Pejchar and Warner, 2001; Havel *et al.*, 2005; Johnson *et al.*, 2008; Rahel and Olden, 2008]. Although dam removal may reduce the prevalence of introduced species and their effects on native biota—particularly those occupying reservoirs—complete removal of unwanted species is exceedingly difficult. Species reintroductions may restore some of the former “ecological memory” of these systems, especially if reintroduced individuals have site-specific adaptations that allow them to thrive [Lake *et al.*, 2007].

2.8. Predictive Models Are Useful But Not Widely Available

The growing interest in removing dams has prompted model development to help river managers predict the effects of dam removal [e.g., Rathbun *et al.*, 2005; Downs *et al.*, 2009; Cui *et al.*, 2017]. These models have been useful for informing sediment management plans and mitigation designs, but there is room for improvement. Quantitative models have mainly focused on predicting elements of postremoval erosion, transport and deposition [Cui *et al.*, 2006a,b; Cui and Wilcox, 2008; Konrad 2009; Gartner *et al.*, 2015], including longitudinal profile evolution of reservoir reaches and overall patterns of downstream deposition [Cui *et al.*, 2014]. In some cases, models have had difficulty predicting immediate postremoval spikes in suspended-sediment concentration, details of the timing of reservoir erosion, or magnitudes of aggradation in specific downstream locations [e.g., Cui *et al.*, 2014]. Most sediment transport models assume shear-stress limited fluvial entrainment, which does not capture rapid erosion rates accompanying knickpoint retreat and related processes. They also do not yet factor in bank erosion processes, including lateral migration (but see Cantelli *et al.* [2007]) and landsliding that were important in several removals. Laboratory models of reservoir erosion have been used in a limited number of specific dam-removal scenarios [Grant *et al.*, 2008; Bromley *et al.*, 2011]. Although challenged by scaling problems, these models have provided dam managers with insights useful for engineering the removal process.

Most models developed to explore ecological responses to dam removal have been niche or “habitat suitability” models that evaluate the quantity and quality of habitat for specific species [e.g., Gillenwater *et al.* 2006; Kocovsky *et al.* 2009; Hamilton *et al.*, 2011]. These models have also been linked with hydraulic models to predict how spatial distributions of suitable habitats change through time. On the Sandusky River (Ohio, USA), for example, a habitat suitability model was linked to a two-dimensional hydraulic model to evaluate how changes in water depth and velocity modified habitat available for fish and invertebrates associated with the removal of the St. John Dam [Tomsic *et al.*, 2007]. Although the output of these models is valuable in determining the amount and potential quality of habitat made available by dam removal, they do not yet predict how species will recover. Predicting population-level recovery requires modeling approaches that account for species colonization and population growth rates, and for migratory species—such as

salmon and eels—accounting for limitations at life stages far from the dam removal site, including ocean, estuaries, and migration corridors [Peters and Marmorek, 2001; Cheng *et al.*, 2006; Battin *et al.*, 2007].

Models that predict ecosystem or food web responses are largely absent, although supporting conceptual frameworks are available. Stanley and Doyle [2002] discussed linking ecological models with geomorphic models to predict how ecosystem processes such as nutrient retention and cycling respond to dam removal. Models developed for other contexts that link food web dynamics to instream physical habitat conditions could be adapted to dam removal [Doyle, 2006; Bellmore *et al.*, 2017a]. These models may be useful for exploring how the complex linkages and feedbacks inherent within ecological systems may govern complex dam removal responses and may identify critical data gaps and uncertainties.

2.9. Keep Listening

Dam removals to date provide a strong foundation for assessing the overall magnitude, direction, and timing of geomorphic responses to dam removal across a broad range of dam sizes. Although physical responses have been faster than predicted in many cases [Major *et al.*, 2017], studies so far largely confirm earlier results and predictions of the physical effects of dam removal [Grant, 2001; Hart *et al.*, 2002; Pizzuto, 2002; Grossman, 2002; Graf, 2003]. Past and recent studies also provide a more limited but instructive basis for predicting biological responses. Nevertheless, our synthesis identifies significant gaps, including the types of dam removals that have occurred, the geographic context of removals (e.g., interior of the U.S. and international locations), and long-term studies of river responses to dam removal.

Few dams have been removed that substantially alter flow. Emplacing dams that alter flow regimes affects downstream ecosystems [Poff *et al.*, 2007; Poff and Zimmerman, 2010]; therefore, removal of such dams will likely affect ecosystems, likely by restoring a more natural flow regime and increasing floodplain connectivity [Poff *et al.*, 1997]. Most removed dams have been run-of-river dams with little effect on downstream flow; even the large dams removed in the Pacific Northwest stored little water relative to the rivers' annual flux. Thus, little information currently exists about the physical and ecological effects of dam removal where flow is altered substantially.

Studied dam removals represent only a small fraction of potential geographies and contexts where dam removal is likely to occur in the future. Most studies of dam removal have been in the northern U.S. (Figure 2), and although some have released large quantities of fine sediment, or changed the flow regime significantly, only a small number have been studied and reported. The disturbance regime of a watershed—including processes such as fire, flooding, and landslides—may affect ecological recovery following dam removal. Ecological theory suggests that watersheds with frequent disturbances, such as those on the U.S. west coast, could be more resilient to sediment disturbance, but studies so far have yet to document this phenomenon. Observations from particular biogeographic regions, such as the arid American Southwest, are scarce. Dams in this region greatly affect flow on rivers with high background sediment loads, and store large volumes of sand—which would almost certainly result in removal effects distinct from those observed so far. There are also few studies from dam removals outside the U.S., further limiting our scope of inference.

River responses to dam removals have been followed for relatively short periods of time—in most cases only a few years [Bellmore *et al.* 2017b]. These studies are likely to capture short-term effects, but longer-term physical and ecological responses are largely unknown, particularly for large dam removals. For example, would a 50–100 year flood differently affect a previously-dammed river versus a never-dammed river? Could these differences be ecologically or physically important? In cases where dam removal is unlikely to have significant effects [Tullos *et al.*, 2016], research may not provide new insights to dam removal, but it may be necessary to monitor ecosystem response to ascertain if the removal meets restoration objectives and the removal process complies with regulatory constraints. In areas where multiple small dams are being removed, studies on the cumulative effects of these removals would be valuable, particularly when multiple removals occur in a single watershed. Insights derived from long-term and integrative studies of large-dam removals as well as from small dams in unique environments will continue to broaden our understanding of dam removal across global scales and ecologically important timescales. In light of such questions, ongoing and future studies would benefit from sampling regimes that account for and capture different time scales of response within ecosystems. While many rivers recover most of their physical forms and processes

a few years following removal, it is not yet clear how the “memory” of the former dam might linger in bed-forms, deposits, and ecosystems.

To date, most published studies focus on one or two specific elements of the dam removal response, such as sediment evacuation or individual species change. Understanding how whole ecosystems respond, however, requires analyses that integrate physical responses with water quality and biological responses. Such studies, often called for but rarely realized, could provide better knowledge of mechanistic linkages among the various physical and biological responses to dam removal [Hart *et al.* 2002; Bellmore *et al.* 2017a; Foley *et al.*, 2017b]. In turn, these holistic studies could inform the development of standardized metrics to be measured at all dam removal studies, increasing our ability to analyze responses across different removal types.

Developing and using new technologies will be an important component of expanding the temporal and spatial scale of dam removal studies. Emerging techniques in genetics, such as environmental DNA [Takahara *et al.*, 2012] or landscape genomics, and stable isotope analyses [Tonra *et al.*, 2015] are likely to help assess patterns of watershed connectivity, gene flow, and energy transfer following dam removal. These types of landscape analyses can help assess the likely success rate of watershed restoration following dam removal.

Finally, continued listening requires ready access to up-to-date information. An explicit goal of our Powell Center Dam Removal Working Group has been to create databases [Bellmore *et al.*, 2015] and tools [Duda *et al.*, 2016] that report and synthesize completed studies. An example is the Dam Removal Information Portal [DRIP; <https://www.sciencebase.gov/drip/>], an online database tool for visualizing the location of dam removals in the United States and abroad, and locating relevant studies that monitor physical and ecological responses to dam removal.

3. Concluding Remarks

River scientists have been watching and listening as the number of dam removals has grown over the past 40 years. One overarching lesson is that in some ways our learning from the rivers has eclipsed our learning from each other. Developing truly coordinated studies that bridge disciplinary gaps and integrate biological and physical response is challenging [Bellmore *et al.*, 2017b] because of insufficient funding and difficulties in developing comprehensive monitoring and analysis frameworks that span and meld the relevant biophysical timescales and complexities. Dam removals represent rare opportunities of planned disturbances where we can study the response of fluvial systems. What we are learning from dam removals is applicable in other disturbance contexts as well and serves as an opportunity to better understand the distinct and sometimes linked biophysical responses to dramatic changes in sediment and water flux. However, dam removal, like other large disturbances to rivers, is inherently transdisciplinary. Our science, languages, and concepts are not.

Dam removals will continue because aging infrastructure demands it and the process has largely been successful. Most removals have benefitted ecosystems while avoiding catastrophes. However, the future is murky. As more dams with relatively straightforward removal considerations are removed from rivers (e.g., the low-hanging fruit), attention may shift to the many large and ecologically disruptive dams across the country—particularly as some decay and their reservoirs fill with sediment. Tough decisions regarding these dams—and the building of new dams—will require balancing risks, continued economic function, and the potential for ecologic restoration. Also clouding the future is climate change, likely increasing the demand for fresh-water storage, both as a low-carbon energy source (but see Deemer *et al.* [2016]) and for consumptive use, reflecting issues already fueling the global boom in dam building [Zarfl *et al.*, 2015]. Together, these issues and uncertainties will continue to apply even more pressure on river scientists to watch, listen, and evaluate this bold effort to restore riverine ecosystems.

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