Planning and implementing small dam removals: lessons learned from dam removals across the eastern United States

Christina Tonitto¹ · Susan J. Riha¹

Received: 10 November 2015 / Accepted: 31 August 2016 / Published online: 6 October 2016
© Springer International Publishing Switzerland 2016

Abstract We review and build on a growing literature assessing small dam removal outcomes to inform future dam removal planning. Small dams that have exceeded their expected duration of operation and are no longer being maintained are at risk of breach. The past two decades have seen a number of small dam removals, though many removals remain unstudied and poorly documented. We summarize socio-economic and biophysical lessons learned during the past two decades of accelerated activity regarding small dam removals throughout the United States. We present frameworks for planning and implementing removals developed by interdisciplinary engagement. Toward the goal of achieving thorough dam removal planning, we present outcomes from well-documented small dam removals covering ecological, chemical, and physical change in rivers post-dam removal, including field observation and modeling methodologies. Guiding principles of a dam removal process should include: (1) stakeholder engagement to navigate the complexity of watershed landuse, (2) an impacts assessment to inform the planning process, (3) pre- and post-dam removal observations of ecological, chemical and physical properties, (4) the expectation that there are short- and long-term ecological dynamics with population recovery depending on whether dam impacts were largely related to dispersion or to habitat destruction, (5) an expectation that changes in watershed chemistry are dependent on sediment type, sediment transport and watershed landuse, and 6) rigorous assessment of physical changes resulting from dam

removal, understanding that alteration in hydrologic flows, sediment transport, and channel evolution will shape ecological and chemical dynamics, and shape how stakeholders engage with the watershed.

Keywords Dam removal · Small dams · Run-of-river dams · Low-head dams · Impoundment · Channel evolution · River restoration

Introduction

Watershed fragmentation is a prevalent ecological problem across the globe. More than half of the Earth's large river systems (LRS) are affected by dams (Nilsson et al. 2005). Many of these basins are strongly impacted by fragmentation; Europe has the highest total basin area that is strongly impacted (74 %), but all continents have a substantial percentage of strongly impacted LRS area (Nilsson et al. 2005).

Prevalence of aging small dams

Defunct small dams are at risk of breaching due to deterioration with age, especially if significant development within watersheds has increased impervious surface area, resulting in increased surface runoff, stormwater channeling and discharge during large precipitation events. A recent review of river restoration projects by Feld et al. (2011) found that the majority of well-studied small dam removals occurred in North America, though there is increasing interest in small and large dam removal in Europe as well (e.g. Bednarek 2001; Globevnik 2007; Kristensen et al. 2012; Lejon et al. 2009). While there are no global estimates of small dam inventory, small dams

✉ Christina Tonitto
ctonitto@cornell.edu; ctonitto@gmail.com

¹ New York State Water Resources Institute, Cornell University, Ithaca, NY 14853, USA

are widely distributed across watersheds, for example 96 % of Sweden's 5300 dams are <15 m in height (Lejon et al. 2009) and 90 % of New York's 5700 dams are <8 m in height (Vedachalam and Riha 2013). In the United States, documentation of small dams is largely left to state agencies. Poff and Hart (2002) provide examples of Wisconsin having only 17 % of its 3843 dams listed in the U.S. national database, while Utah has only 6 % of its 1641 dams documented. Research toward understanding the impacts of dam removal should address minimizing the negative, short-term effects of removal, while achieving long-term benefits of dam removal with respect to freshwater biota, watershed dynamics, safety, and water supply.

Small dams that have outlived their economic benefits are a major challenge in the Great Lakes region and eastern United States. Poff and Hart (2002) reported that about half of dams in the northeastern United States were built before 1920. Doyle et al. (2003c) estimated that 85 % of dams in the United States will have exceeded their operational period by 2020. Graham (1999) reported that over 400, largely low-force dams failed in the United States from 1985 to 1994. A National Resources Conservation Service (NRCS) survey (2000) of 22 states estimated more than 2200 small flood control dams are in need of rehabilitation, with an estimated cost of \$540 million. The authors note that over 650 dams pose a particular public safety risk as they were initially designed to mitigate flooding in agricultural landscapes, but the watershed has experienced development in the floodplain since dam installation. Local decisions to permit development in aggregate have watershed-scale impacts, including direct impact on the safety of dams. Therefore, while multiple parties contributed to the altered state of dam safety, in the United States the dam owner is generally solely liable for dam safety. With a high number of aging dams, New York State is an example of the magnitude of the financial and stakeholder engagement challenge faced by regions with dams requiring either removal or maintenance. An analysis of New York State Department of Environmental Conservation (NYSDEC) dam records demonstrates that of New York State's 5700 dams, 96 % of the highest hazard dams (failure resulting in serious infrastructure damage, economic damage, environmental damage, and potential loss of life) have an Emergency Action Plan (EAP) on file with the NYSDEC, while only 45 % of intermediate hazard class dams (failure resulting in infrastructure disruption, likely personal injury, substantial economic losses or environmental damage) have an EAP on file. As a result, approximately 375 intermediate hazard dams and 15 high hazard class dams, ranging from 3 to 65 m in height, are non-compliant with safety regulations. Neighboring northeast and mid-Atlantic states are also concerned with aging dam infrastructure and

have developed literature to facilitate dam removal planning (e.g. EOEEA 2007; POWR 2009; Princeton Hydro LLC 2015). Pennsylvania has had the largest success in streamlining the removal process by consolidating permitting through one agency. Pennsylvania also leads the way in dam removals in the eastern United States, with almost 200 dam removals between 1999 and 2015 recorded in the American Rivers dam removal list (American Rivers 2015a). Throughout the eastern half of the U.S., the majority of dams are providing recreational benefits (Poff and Hart 2002), making their economic and social value ripe for discussion.

Generalizing trends across small dam structures is complicated by the use of different classification systems. ICF Consulting (2005) defined small dams as structures not exceeding 50 feet, run-of-river dams as structures where river inflow flows over the entire barrier across the entire waterway and has limited storage capacity, and defined low-head dams as structures where the hydraulic head (head water to tail water) is less than 25 feet. Csiki and Rhoads (2010) emphasized run-of-river dams have little storage capacity and result in impounded water contained within the banks of the natural bed. Tschantz and Wright (2011) described low-head dams as constructed to allow the flow to pass directly over the entire dam structure, as generally 3–5 m in height, and constructed to raise water level for industrial and municipal water supplies as well as for recreation. For many historic low-head dams constructed as mill dams throughout the eastern U.S., dam height can exceed the channel banks upstream. As a result, mill dams can disrupt flow across an entire valley bottom, leading to sediment deposition throughout the historic floodplain, and, therefore, having different sediment dynamics than run-of-river dams (Csiki and Rhoads 2010).

Data availability for planning dam removals

Graf (2006) summarized the hydrologic changes due to large dams across 36 rivers in the U.S. using paired gages upstream and downstream of these dams. Large dams have significant hydrologic impact on river systems, including: a 67 % average reduction in annual peak discharge (up to 90 % for individual rivers), a 60 % decrease in the ratio of annual maximum/mean flow, and a 64 % decrease in the range of daily discharge (Graf 2006). Petts and Gurnell (2005) outlined expected changes to channel morphology below a dam based on how a dam affects discharge and bed load. They summarized a flow chart for mapping how a change in discharge affects downstream channel formation as: (1) for systems dominated by reduced sediment load—increased channel capacity, width, depth, roughness, slope, and conveyance is expected; (2) for systems dominated by reduced sediment load, that also experience changes from

reduced discharge—reduced channel capacity, width, and conveyance, uncertain changes in depth, and increases in roughness and slope are expected; (3) for systems dominated by reduced discharge, that also experience changes from reduced sediment load—reduced channel capacity, width, and conveyance, neutral to reduced depth, and uncertain changes in roughness and slope are expected; and (4) for systems dominated by reduced discharge—reduced channel capacity, width, depth, roughness and conveyance, and an increase in slope is expected. The validity of this typology was validated by observations from 14 regulated rivers in Britain (Petts and Gurnell 2005).

American Rivers has compiled a map of United States dam removals between 1912 and 2015, with a current tally of 1300 dams removed (see map URL in reference: American Rivers 2015b). Despite a large number of dam removals, limited observations of the removal process makes general conclusions about dam removal impact difficult. Graf (2005) discusses the serious limitation of available geomorphological research for developing a robust dam removal framework. In particular, research results are difficult to draw conclusions from because: (1) they are limited to a few locations, (2) most studies are for large dams, (3) data is of short duration, though geomorphological changes are long-time-scale processes, (4) it is unknown whether dam impacts are fully reversible, and (5) little coordinated research funding exists to address the fundamentally interdisciplinary nature of dam removal. Hart et al. (2002a) summarized physical, chemical, and biological observations following dam removals across the United States. In this review, Hart et al. (2002a) emphasized that outlining general conclusions from dam removal studies is limited by (1) studies measuring only one or two systems components rather than conducting an integrated assessment of ecosystem change, (2) studies using qualitative rather than quantitative metrics, (3) studies having poor spatial and temporal replication, and (4) the challenge in attributing causality in channel response when drastic changes simultaneously result from dam removal. ICF Consulting (2005) reviewed various databases and conducted a survey of small dam removals. Most documented dam removals have occurred since 2000 and were for dams less than 20 feet in height. Hart et al. (2002a) state that

ecological impacts of removal have been documented in only 5 % of the more than 450 U.S. dams removed in the twentieth century. Doyle et al. (2003a) suggest agencies can mitigate shortcomings resulting from limited data availability by developing a framework to determine high priority dams for removal and establishing minimum analysis criteria as part of the dam removal decision-making process. As communities and agencies move toward promoting small dam removal, decision making must proceed with incomplete data. In this paper, we compile socio-economic and biophysical outcomes from small dam removals in the eastern and central U.S. to serve as a guide for planning new removals in humid regions with year-round precipitation, moderate topography, and within a sub-urban, forested or agricultural landscape context.

Informing a dam removal process: frameworks, methods, observations, and models

Factors driving dam removal decisions

Dam removal decision framework

Synthesis of dam removal research has primarily been conducted by non-profit organizations. Table 1 describes four fundamental concepts developed by the Heinz Center (2002) for determining whether a dam should be removed or maintained. This report identified reasons for maintaining dams (water supply, irrigation, flood control, hydroelectric, navigation, recreation, and waste disposal), as well as reasons to remove dams (safety, liability, recreation, restoration, ecosystem restoration, and water quality). Additionally, this report emphasized the need to promote monitoring prior and subsequent to dam removal.

Drawing on earlier reviews of dam removal, work led by American Rivers in conjunction with the NYSDEC (Graber et al. 2010) outlined a process for organizing a dam removal (Table 2). New York activities in support of dam removal parallel initiatives in neighboring states (e.g. EOEEA 2007; POWR 2009; Princeton Hydro LLC 2015) all of which compliment work by American Rivers to facilitate defunct

Table 1 Heinz Center (2002) framework for assessing dam removal or maintenance goals

Dam removal process	Key points
Establish goals	Collect information about environmental, social, economic, regulatory, policy context
Identify concerns	Dam safety, stakeholder cultural and economic interests
Assess impact	Conduct studies of ecological, economic, social, and legal outcomes of dam removal
Stakeholder engagement	Involve stakeholders in decision process through discussion of gains/losses, costs/benefits, and private/public interests in dam removal or management

Table 2 NYSDEC and American rivers process for a dam removal (adapted from Graber et al. 2010)

Goal	Key steps
Identify scope	Assess ecological and community benefits, dam and land ownership, dam uses, infrastructure, rare species, sediment quality, community concerns, and funding sources
Site visit and planning meeting	
Fundraising	
Project design	(1) Survey and base mapping (2) Sediment management plan (3) Hydrology and hydraulics assessment (4) Channel and riparian restoration plan (5) Preliminary structural removal plan (6) Pre-project monitoring (7) Site-specific issues (8) Identify permitting needs (9) Technical memoranda, conceptual drawings, cost estimate
Stakeholder meetings	
Pre-permitting meetings	
Engineering and restoration design	
Permitting	
Project implementation	

dam removal nationally (e.g. Graber et al. 2010, 2015). Recommendations for dam removal planning outlined by Bushaw-Newton et al. (2002) in their thorough assessment of dam removal on the Manatawny Creek, Pennsylvania advocated for similarly rigorous stakeholder engagement and removal impact analysis when deciding whether or not to remove a dam, when designing the dam removal, and for subsequent dam removal impact monitoring.

Reported reasons for dam removal

Reported reasons for dam removal fall into six broad categories: (1) ecological removals to restore fish and wildlife habitat, allow for fish passage, improve water quality or other environmental amelioration, (2) economic removals resulting from the high cost of dam maintenance, (3) failure of dam, (4) removals to promote recreation, (5) removals for safety, and (6) unauthorized dam removed due to lack of a permit, improper construction, or abandonment (ICF Consulting 2005; Maclin et al. 1999).

While cost is often presented as a main driver in the decision process, a review of 131 low-head dam removals by ICF Consulting (2005) found a majority of the dams were primarily removed for ecological reasons, with economic and safety concerns being the next largest categories, with an approximate distribution of 35, 26, and 17 % of studies, respectively. The remaining studies reported multiple reasons for dam removal, including recreation and dam failure. A review by Pohl (2002) identified environmental concerns as the primary reason for

dam removals in California, whereas dam removal was largely determined by economic and safety factors in Wisconsin.

Cost

Dam removal is often the most cost effective means of dealing with an out-of-compliance dam (Graber 2002). An early cost analysis of 14 dam removals in Wisconsin found dam repair averaged more than three times the cost of dam removal (Born et al. 1998). Subsequently, Sarakinos and Johnson (2002) reviewed Wisconsin dam removal projects, tallying more than 80 since 1960, with most occurring since 1990. They reported the average height of removed dams was 14 feet and these dams largely no longer served an economic function. Across Wisconsin, these small dam removal projects (largely conducted in the 1990s) averaged a removal cost of \$115,500 in contrast to a repair estimate of \$700,000. Removal decisions were often driven by cost as removal was generally 3–5 times less costly than repair estimates.

ICF Consulting (2005) estimated dam removal costs using a linear regression of dam height and removal cost. The cost estimates were based on a database of 124 documented dam removals of studies largely conducted since 1990. However, even with the omission of extreme outliers, significant scatter remained in the data set resulting in a weak relationship between dam height and cost (total cost $R^2 = 0.2642$, deconstruction cost $R^2 = 0.1989$). An ICF Consulting summary of Pansic et al. (1998) lists the

average cost breakdown of dam removal as 30 % for deconstruction, 22 % for environmental engineering, and 48 % for sediment management. The ICF Consulting (2005) review found state and federal sources to be the main source of dam removal funding in the U.S.

Whitelaw and MacMullan (2002) emphasized that dam repair or removal has distinct impacts on different stakeholders. Therefore, an economic assessment of dam removal should thoroughly consider the economic costs and economic benefits of keeping versus removing a dam, as well as the positive and negative impacts of dam repair versus removal on employment. Subsequent foci should include (1) assessment of equity, namely which stakeholders benefit in the case of dam repair versus removal, (2) potential infringement on rights of property owners or resource users, (3) uncertainty of estimates, and (4) the full suite of ecological impacts, beyond the particular impact that may motivate the dam removal discussion.

Stakeholder engagement

Stakeholder concerns

Work by the River Alliance of Wisconsin with 25 communities identified stakeholder perception of dam removal outcomes covered four main areas of concern: (1) hydrologic—reduced or halted river flows, increased flooding, belief that impoundment will become a mudflat, (2) property rights and value—potential for government seizure of land and declining property values, (3) health—potential spread of West Nile virus and blastomycosis, and (4) culture, aesthetics and recreation—loss of an historical monument, reduced fishing and recreation access (Sarakinis and Johnson 2002). In the case of Wisconsin, property values were generally stable following a removal, though there may be a decline for a short period immediately following removal. However, the authors note that ownership of newly exposed land can be contentious depending on state laws. In addition, an analysis by Provencher et al. (2008) concluded that property values in south-central Wisconsin along a small impoundment were not higher than property values along a free-flowing stream, and that non-frontage properties near a free-flowing stream were greater than those near an impoundment. An analysis of the real estate market in Augusta and Waterville, Maine, before and after the Edwards Dam was removed from the Kennebec River, revealed that dam removal made river front properties more valuable, presumably due to the ecological restoration of the river (Lewis et al. 2008). These results indicate that concern about property values should not preclude support for dam removals.

In some cases concern about dam removal is led by the dam owner. Liability issues can be a concern, as in the case

of the Secor Dam near Toledo, Ohio. In this case, there was community interest in dam removal, but the owner was concerned about liability resulting from changes to flood regime and potential sediment contamination (Roberts et al. 2007).

Stakeholder engagement methods

There are many ways in which stakeholders can be impacted by a dam and stakeholder engagement is an important aspect of dam removal planning. Stakeholder surveys were used to assess the feasibility of dam removal in Mantua Creek, New Jersey (Wyrick et al. 2009). Residents were against dam removal (91 %), due to fear of declining home values and interest in lake recreation, as well as concern about habitat loss. A review of written concerns revealed that residents did not have an understanding of what a healthy restored river would look like, with concerns including stream recovery resulting in a ‘mud flat’. The survey revealed many residents felt policy makers were not considering their opinions, but also revealed that resident concerns could be addressed with hydrologic and ecological assessment studies, which were also conducted for this site.

Interdisciplinary modeling is a dynamic approach to socio-economic assessment of dam removal that can be used to demonstrate potential impacts of decisions to stakeholders. Zheng and Hobbs (2013) and Zheng et al. (2009) develop a multi-objective portfolio analysis (MPA) framework as a tool for selecting dams for removal. For an application to the Lake Erie basin, the framework considers: (1) ecological impact of dam removal based on walleye recruitment, (2) risks based on dam age, safety inspection record, and hazard potential classification, and (3) economic costs including dam removal, lost revenue from the dam service, and need for sea lamprey mitigation following removal. These three objectives are optimized using an integer linear program (ILP). To assess dam removal outcomes in California, Null et al. (2014) apply the CALVIN model—an economic-engineering optimization model. The CALVIN model allocates surface and groundwater to agricultural, power, and urban uses, considering the effects of climate change on water volume and making predictions about fish habitat under different dam configurations. This systems modeling approach provides economic, habitat, and water availability information under different dam removal configurations, outcomes invaluable for transparent decision making. Kuby et al. (2005) likewise advocate for applying optimization models to assess the benefits of dam removal across an entire river system, allowing the identification of dam removal configurations that lead to the greatest level of increased connectivity. Hoenke et al. (2014) used GIS to apply Multi Attribute Utility Theory

(MAUT) to rank dams for removal based on criteria including: habitat quality, habitat connectivity, water quality, avoiding social conflict, improving public safety, and improved downstream flow. For watersheds with sufficient data, interdisciplinary modeling can be used to select the optimal dams for removal.

Funding models for financing dam removals have engaged stakeholders in dam removal planning. NOAA's Community-Based Restoration Program (CRP) in support of grassroots restoration efforts (Lenhart 2003) is a key example. NOAA CRP offers funds on a competitive basis to communities, government units, and nonprofits to restore marine, estuarine, and stream habitat. The program has funded fish ladder construction as well as dam removal projects. Funded projects have been developed through engagement across the affected community.

Assessment of watershed change

Generalizations of change are difficult because rivers are unique in terms of bed composition, channel geomorphology, watershed characteristic flow and sediment inputs. Kibler et al. (2011a, b) outline possible monitoring schemes used in dam removal studies: (1) two sites—impoundment and control, 1 year of monitoring (synchronous similarity analysis, useful when no pre-removal data is available), (2) one monitoring site and 1 year each pre- and post-dam monitoring (before-after, BA), (2) two monitoring sites—impoundment and control, monitored 1 year pre- and post-dam (before-after-control-impact, BACI), (3) two sites—impoundment and control, with multiple years of monitoring (before-after-control-intervention-paired sampling, BACIPS), and (4) three or more sites, at least two control sites, pre- and post-dam (multiple-before-after-control-impact, MBACI). While these monitoring designs have been applied in rigorous dam removal studies, the authors emphasize that establishing a control reach is non-trivial and dam removal may often occur before an adequate baseline can be established. Acknowledging the need to base dam removal planning on observations, while recognizing that observations have limited replication, Kibler et al. (2011a, b) discuss *ecological significance* and *practical significance* as frameworks for establishing recommendations given system uncertainty. Ecological significance can be grounded in comparing whether management brings the system state across an ecological threshold. The authors consider practical significance as relevant for systems with high natural variability and parameter uncertainty, where statistical metrics such as *p* values would not result in statistical significance. In such systems practical significance may be demonstrated if, after accounting for measurement uncertainty, management

results in changes that exceed the change in the control system.

Aerial photography and paleohydrology techniques have been applied to describe channel and vegetation changes over the decades following historic dam breaches in Montana (Schmitz et al. 2009). For geomorphologic conditions that have not been well studied following dam removal, if breached dams exist in a watershed these reconstructive techniques can be used to outline potential post-dam trajectories after dam removal. Because it may be difficult to document the discharge rate experienced during the dam breach, the observed ecosystem recovery may differ from that which occurs under a controlled dam removal, which would generally target a low-flow season in contrast to a dam breach which would occur during a peak flow event.

ICF Consulting (2005) outlined a comprehensive list of observations for evaluating the impact of dam removal (Table 3), though no studies examine all relevant attributes. Bushaw-Newton et al. (2002) summarized observed time-scales of physical, chemical, and biological impacts (days to weeks, months, or years) as a tool for deciding on what processes can be monitored given available resources. The cost of monitoring dam removal, especially given expected long-term dam removal impacts spanning decades, is a key reason that many dam removals in the United States have not been extensively monitored. Given limited monitoring resources, a monitoring protocol will depend on dam-specific features—for instance sites with the potential for contaminated sediment transport will have different monitoring priorities than sites with the potential for post-dam flooding.

A potential tool for cost-effective post-dam monitoring may be the strategic use of citizen science initiatives. Many watersheds have vibrant non-profit groups that engage citizens in water quality monitoring. By engaging with citizen science groups interested in watershed preservation, dam removal planners can involve stakeholders in understanding the removal process and coordinate monitoring so that efforts are not duplicated.

Some recent small dam removals have been rigorously observed and documented. Table 4 provides an overview of small dam removal studies discussed in detail in the subsequent sections.

Ecological response to dam removal

Hart et al. (2002b) identified key stages of dam removal. At the time scale of days-to-years the impoundment experiences the largest changes including: (1) increased sediment export, (2) a return of natural temperature and flow regimes, (3) decreased water levels, hydraulic residence times, and role of hypolimnetic processes, (4) a shift from

Table 3 Monitoring variables across physical, chemical, biological, economic, and social attributes (adapted from ICF Consulting 2005)

Attribute	Process
Physical properties	Downstream hydrology
	Sediment degradation
	Sediment aggradation
	Grain size
	Bed load
	Channel morphology (cross sectional and longitudinal)
	Floodplain morphology (e.g., connection to channel, frequency of inundation)
	Groundwater recharge
Chemical trends	Watershed fragmentation
	Water quality (dissolved oxygen, temperature, specific conductance, pH, turbidity, suspended particulate material, and nutrients C, N, P)
	Redistribution of organic contaminants
Biological changes	Redistribution of particulate organic matter
	Algal biomass and composition
	Benthic macroinvertebrate taxa
	Freshwater mussel beds and fish hosts
	Fish community assemblages
	Fish passage and distribution
	Fish parasites
	Nonindigenous and exotic species
	Riffle and deep pool habitat
	Wetland type and acreage
	Connectivity of floodplain and stream
	Riparian vegetation
Economic assessment	Waterfowl
	Cost-benefit of dam maintenance vs. removal
	Value of services lost
	Value of services gained
	Property values
	Infrastructure costs
Social changes	Local business revenue
	Public attitudes toward project
	Recreation patterns
	Property ownership near project
	Public safety perception
	Zoning and municipal planning

lentic to lotic biota, (5) increased biotic exchange, (6) plant colonization, and (7) increase or decrease in nutrient and contaminant budgets. During this initial post-dam phase, upstream of the dam experiences increased biotic exchange, while downstream of the dam experiences increased sediment flux, a return of natural temperature and flow, increased biotic exchange, plant colonization, and increased or decreased nutrient and contaminant budgets. At the scale of years-to-decades, upstream experiences increased role of migratory species in aquatic-terrestrial linkages, while the impoundment and downstream

experience a return of natural sediment regimes and channel form, plant community succession, and an increase or decrease in the organic matter budget.

Vegetation colonization greatly affects stream ecology. Work by Orr and Stanley (2006) surveyed thirteen former impoundments representing 1–30 years since dam removal. A key observation is that vegetation colonization was rapid and bare sediment was extremely rare (<1 % of sampled area). The short-lived nature of exposed sediment has implications for sediment erosion, likely leading to erosion concentrated in the channel bank, rather than the

Table 4 Intensive studies of small dam removal

State	Waterway	Dam	Year built	Mean dis-charge (m ³ /s)	Height (m)	Width (m)	Impoundment	Material
CT	Naugatuck River	Anaconda	1800s	12.6	3.35	42		Timber crib/rock fill
		Union City	1800s	12.6	2.1	58		
CT	Eightmile River	Zemko	1720s		1.5	24.5		Stone and earth fill
IL	Fox River	South Batavia		62	1.7	105		
MI	Pine River	Stonach	1912	8.1	5.5		26.7 ha	Earth, concrete corewall
OH	Cuyahoga River	Munroe Falls	1817	8.3	3.9			Concrete (replaced timber)
OH	Cuyahoga River	Kent Dam	1800s	8.3	4.5			Concrete (replaced timber)
OH	Sandusky River	St. Johns	1900s	34	2.2	46	56 ha	Concrete
PA	Conodoguinet Creek	Good Hope	1800s	17.2	1.8	67	6.4 ha m	Concrete
PA	Manatawny Creek	Manatawny Creek	1700s	3.7	2	30		Timber crib/rock fill
NJ	Mantua Creek	Wadsworth and Sterling Lake	1800s	0.33	3		2.5 ha	
RI	Pawtuxet River	Pawtuxet Falls	1638	14.4	1.5	52		Concrete (replaced timber)
VT	Upper Connecticut	Wilder	1951					Concrete
WI	Baraboo River	LaValle	1849		>2		12 ha	
WI	Boulder Creek	Lower/upper	1950s	0.05	2.5, 1			Concrete
WI	Koshkonong River	Rockdale	1848		3.5		42 ha	Concrete (replaced timber/rock)
State	Purpose	Sediment	Geomorphology	First author	Methods ^a	Physical ^b	Chemical ^c	Biological ^d
CT		Gravel	Glacial till soil; bedrock of schist and gneiss	Wildman	BA BA	C, D, S C, D, S	S S	
CT	Mill pond	Sand, gravel, cobble	Glacial till	Poulos				F
IL	Water supply, navigation, mill	Sand, gravel	Glacial till	Maloney	BACIPS	D, S		F, M
MI	Hydro-electric	Sand, small gravel	Sandy glacial outwash; recessional moraines; consolidated clay	Burroughs	BACIPS, 31 transects	C, D, S		
OH	Mill power, water supply	Sand, gravel	Glacial outwash and till	Tuckerman	BA		Q	F, M
				Rumschlag	BACI	C, D, S		
OH	Mill power, water supply	Sand, gravel	Glacial outwash and till	Tuckerman	BA		Q	F, M
OH	Power, water supply	Sand, gravel	Limestone bedrock	Cheng	BACI	C, D, S		
PA	Mill power	Silt, clay, gravel	Carbonate bedrock	Chaplin	MBACI	C, D, S	N, Q, S	F, M, P
PA		Sand, gravel	Piedmont	Bushaw-Newton	BACI	C, D, S	N, Q, S	F, M, P, V
				Ashley	BACI		S	
				Thomson	BACI	S		F, M, P

Table 4 continued

State	Purpose	Sediment	Geomorphology	First author	Methods ^a	Physical ^b	Chemical ^c	Biological ^d
NJ	Mill pond	Sand, silt, gravel		Wyrick	HEC-RAS stakeholder survey	C, D, S		V
RI		Sand, silt	Tidally influenced	Cantwell	BACI	D	Q, S	
VT	Hydro-electric			Nislow	HEC-RAS, field surveys	D		V
WI	Mill pond	Sand, silt	Unglaciaded region	Doyle	BACI	C, D, S	N, Q	F, M, V
				Greene	BACIPS	C, D, S		
WI	Hatchery	Sand, cobble	Unglaciaded region	Orr	BACI	D, S	N, Q	P, M
WI	Mill pond	Sand, silt, gravel	Glacial deposits	Doyle	BACI	C, D, S	N, Q	F, M, V

Dam attributes reported in the literature

See references for study details: Ashley et al. (2006), Burroughs et al. (2009), Bushaw-Newton et al. (2002), Cantwell et al. (2014), Chaplin et al. (2005), Cheng and Granata (2007), Doyle et al. (2002, 2003b, 2005), Greene et al. (2013), Maloney et al. (2008), Nislow et al. (2002), Orr et al. (2008), Poulos et al. (2014), Rumschlag and Peck (2007), Thomson et al. (2005), Tuckerman and Zawiski (2007), Wildman and MacBroom (2005), Wyrick et al. (2009)

^a Methods: BA (before-after), BACI (before-after-control-impact), BACIPS (before-after-control-intervention-paired sampling), MBACI (multiple-before-after-control-impact)

^b Physical measurements: C (channel formation), D (discharge), S (sediment)

^c Chemical measurements: N (nutrients), Q (water quality), S (sediment contamination)

^d Biological measurements: F (fish), M (macroinvertebrates), P (algae, periphyton), V (riparian vegetation)

floodplain, following vegetation establishment. Sites experiencing a recent dam removal were dominated by grasses and early successional forbs, while older sites had riparian trees. However, for the first 10 years following dam removal, species diversity was variable, with some sites dominated by a few aggressive species while others where more diverse.

Dams limit stream biota due to lack of migration and lack of habitat. Doyle et al. (2005) summarized small dam removals in Wisconsin, considering impact across five categories: fish, vegetation, macroinvertebrates, unionid mussels, and nutrient dynamics. In cases where a dam primarily limited fauna migration, removal of a dam can lead to rapid colonization of indigenous species. For cases where habitat is the limiting factor, species recovery may be delayed while channel evolution creates new habitat. Observations across different systems demonstrate both migration-limited and habitat-limited biotic recovery is common following dam removal. In a comparison of control, impoundment, and downstream reaches in eight rivers in Michigan and Wisconsin 1–40 years following dam removal, Hansen and Hayes (2012) found macroinvertebrate assemblage was similar within 1 year of removal, species richness was similar 7 years after removal, but differences in macroinvertebrate densities between control and impoundment or downstream reaches could remain decades following dam removal. Table 5

outlines observations from individual waterways demonstrating cases where macroinvertebrate recovery was predominantly limited by migration (Bushaw-Newton et al. 2002; Maloney et al. 2008) versus by habitat (Stanley et al. 2002; Tuckerman and Zawiski 2007) as well as cases where fish recovery was limited by migration (Bushaw-Newton et al. 2002; Maloney et al. 2008; Tuckerman and Zawiski 2007) or habitat (Kanehl et al. 1997; Maloney et al. 2008; Poulos et al. 2014).

Sediment transport significantly affects stream ecology affecting both turbidity as well as river habitat (ICF Consulting 2005; Doyle et al. 2005). Orr et al. (2008) studied response to dam removal in Boulder Creek, Wisconsin, a watershed dominated by old growth red oak and sugar maple, and with sand and coarse cobble bed substrate. Immediately following dam removal, fine sediment transport buried benthic substrate reducing chlorophyll by 60 %; macroinvertebrate densities were also reduced following removal. Algae and invertebrate populations subsequently exhibited a steady increase in the months following dam removal, but remained lower than the control reach a year following dam removal. While the reduction in N:P ratio following dam removal is consistent with P-enrichment due to sediment transport, the authors attribute the algal and invertebrate changes to the physical, rather than chemical, disruption caused by sediment transport. Thomson et al. (2005) likewise found a short-

Table 5 Biotic recovery following dam removal. Observations of migration- and habitat-controlled recovery patterns

State	Waterway	M-I	Mussels	Fish	First author	Description
CT	Eightmile River			H	Poulos	Complete shift from lentic to lotic species was not observed after 3 years of post-dam monitoring
IL	Fox River	M		M, H	Maloney	Dam breach led to a rapid change in habitat, comparable to control reach. Macroinvertebrate assemblage recovered within 2 years, fish assemblage partially recovered within 3 years
OH	Cuyahoga River	H		M	Tuckerman	Rapid recovery of fish communities, slower recovery of macroinvertebrates
PA	Manatawny Creek	M		M, H	Bushaw-Newton	Expected shift from lentic to lotic taxa. Sediment negatively impacted downstream fish
WI	Wilwaukee River			H	Kanehl	Smallmouth bass recovery required geomorphic changes in the impoundment
WI	Baraboo River	H			Stanley	Macroinvertebrates recovered to control reach assemblages after a flood transported sediment
WI	Koshkonong River		H		Sethi	Increased silt and sand substrate, and total suspended sediment likely delayed mussel recovery

See references for study details: Bushaw-Newton et al. (2002), Kanehl et al. (1997), Maloney et al. (2008), Poulos et al. (2014), Sethi et al. (2004), Stanley et al. (2002), Tuckerman and Zawiski (2007)

M-I macroinvertebrates, *H* population recovery limited by habitat, *M* population recovery limited by migration

term reduction in benthic macroinvertebrates, algal biomass, and diatom species due to sediment transport, but the authors concluded these changes were not likely to have long-term consequences.

Long-term ecological trends following dam removal are dependent on site specifics. After reviewing studies of dam removal across Wisconsin, Doyle et al. (2005) offer two conceptual models of ecosystem recovery. In one case, a river may fully recover following dam removal, with relatively rapid readjustment of nutrients, macroinvertebrates, geomorphology, fish habitat, mussels, and vegetation over years to 1–2 decades. However, a competing view of post-dam recovery is a system experiencing partial recovery. In this case, there may be improvements in nutrients, macroinvertebrates and geomorphology in the initial years following dam removal, but fish habitat, mussels, and vegetation may never fully recover and may only improve over decades.

Given the challenge of planning dam removals in the absence of a rigorous theory of dam removal impacts, Hart et al. (2002a) propose assessing potential ecological impacts of dam removal using a risk assessment framework. Hart et al. (2002a) offer a decision framework for anticipating post-dam removal trends based on ranking the impacts of current barriers (ranging from waterfalls, and debris and beaver dams, through small to large man-made dams) on river function (in particular, flow regime, temperature, sediment transport, biogeochemistry, biotic migration, and habitat), and subsequently comparing the dam in question relative to the scale of impact of well-studied barriers. Another conceptual tool for designing river remediation is using a stressor-response curve to

evaluate risk. In a watershed application, the stressor-response curve defines how ecological integrity (the response) changes as a function of watershed characteristics resulting from the dam (the stressor) (Hart et al. 2002a). When ecological integrity exhibits sigmoidal decay relative to stress resulting from a dam, alteration in dam management (such as flow regulation), or dam structure (such as building fish ladders), may provide significant benefits without implementing a dam removal. For cases where ecological integrity exhibits exponential decay as a function of the dam-induced stressor, ecological improvement may only occur following dam removal. Poff and Hart (2002) discuss the potential value of hydraulic residence time (HRT, the ratio of reservoir storage volume to flow-through rate) as an integrative metric of dam impact, as HRT influences temperature stratification, impoundment sedimentation rate, plankton assemblages, biotic transport, and biogeochemical cycling. However, they also acknowledge that HRT is not broadly documented for dams and HRT is poorly correlated with broadly available data such as dam height. Dam assessment using these conceptual frameworks can help planners map expected ecological impacts following dam removal.

Chemical changes and water quality response to dam removal

Water quality trends are difficult to generalize following dam removal; outcomes depend on sediment properties, hydrologic change, and biogeochemical process rates in the system. Dam removal brings a return to lotic conditions, decreasing hydraulic residence time (ICF Consulting

2005). The net effect of a change in hydraulic flows depends on ecosystem process rates. For example, following the removal of the Manatawny Creek Dam in Pennsylvania Velinsky et al. (2006) observed no significant difference before and after dam removal across dissolved and particulate species of C, N (except for dissolved NH_4^+), and P, as well as alkalinity, specific conductivity, and oxygen status. The lack of a significant change in water quality following dam removal was attributed to the small hydrologic impact of the dam with a short (less than 2 h) residence time of the impoundment at base flow and infrequent temperature stratification (Bushaw-Netwon et al. 2002; Velinsky et al. 2006). Additionally, there was little accumulation of fine-textured, high organic matter sediment which supports biological reactions. In contrast, in a study of the Rockdale Dam removal on Koshkonong Creek in Wisconsin, Stanley and Doyle (2002) found that the impoundment released fine-textured sediment that was high in phosphorous, which could potentially result in eutrophication. An additional nutrient study of the Koshkonong River, Wisconsin by Doyle et al. (2003b) demonstrated the retention of phosphorus (P) in the impoundment prior to removal, and modeled how changes in discharge altered P concentration, namely lower concentrations were predicted for lower discharge. In a study of Conodoguinet Creek in Pennsylvania, continuous measurements were taken of diurnal fluctuations in temperature, dissolved oxygen, pH, and specific conductance (Chaplin et al. 2005). These data demonstrated that dam removal allowed a rapid return of the diurnal pattern within the previous impoundment zone. Dam alteration and removal on the Cuyahoga River, Ohio was motivated by a need to attain Clean Water Act (CWA) Total Maximum Daily Load (TMDL) standards. The Kent Dam alteration and Munroe Falls Dam removal on the Cuyahoga River resulted in significant improvement in dissolved oxygen concentrations, and the authors concluded that dam removal is a viable approach to restoring biological and chemical properties of rivers to meet CWA standards (Tuckerman and Zawiski 2007).

Physical changes following dam removal: channel evolution, floodplain dynamics and flood risk

Channel adjustment occurs as a change in substrate-size distribution, pool filling, bed degradation or aggradation, lateral instability, a change in channel planform, or floodplain aggradation. Predicting dam removal impact on flood risk is necessary before implementing a dam removal. Low-head dams are generally not used for flood control, therefore, removal does not directly drive flooding events. However, if an impoundment has significant sediment that causes downstream channel aggradation following dam removal,

hydrologic flows can be altered and lead to flooding (ICF Consulting 2005). The potential for aggradation which influences hydrologic flows should be assessed prior to dam removal. In addition to flood risk, sediment movement and channel formation resulting from dam removal can impact bridge scour, with the potential to undermine bridge safety (e.g. Kattel and Ericson 1998). To minimize risk, potential trajectories of channel formation following dam removal are critical to assess prior to a removal.

Discharge: modeling tools and observations

Discharge is commonly estimated using the U.S. Army Corps of Engineers model HEC-RAS. The HEC-RAS model is based on Manning's equation, determining water velocity as a function of hydraulic radius, energy slope and Manning's roughness coefficient (Nislow et al. 2002). A limitation of planning based on model predictions is that the accuracy of HEC-RAS predictions depends on the accuracy of input data. For example, model discharge predictions can be inaccurate if bed aggradation or degradation occurs as a result of river management, causing initial estimates of model driving parameters to be inaccurate (Nislow et al. 2002).

Table 6 outlines HEC-RAS applications to understand the impact of dams on discharge and flood risk and demonstrates that model inputs can be derived from varied data sources and methodologies. HEC-RAS modeling identified dams which provided little flood control (Roberts et al. 2007; Wyrick et al. 2009), as well as dams whose removal incurs a flood risk (Endreny and Higgins 2008) requiring incremental dam breaching or wetland storage capacity. Dam-induced changes to discharge influence riverine ecological dynamics in addition to flood risk. HEC-RAS application by Nislow et al. (2002) found dam presence had little effect on frequent bankfull discharge events, but reduced the frequency of large flood events. They concluded that reduced floodplain inundation determined vegetation community dynamics.

Statistical tools for defining flow frequency are an alternative to complex simulation models. Khan (2009) used river flow data to establish probability density functions (PDFs) to define expected flows during the dam removal period for dam removals requiring the construction of a cofferdam. Khan emphasized that dam removal should be scheduled for the low flow season, and, therefore, flow frequency analysis should focus on a 3–4 month period with the lowest seasonal flow. This recommendation is in contrast to a sediment management discussion from an ecological perspective in Bednarek (2001) that emphasized turbidity problems can be enhanced if dam removal occurs during low flow conditions if there is insufficient force to clear sediment.

Table 6 HEC-RAS model applications to study discharge and flood risk

Site	Inputs	Results	First author	Year
Onodaga Creek, NY	USDA TR-20 for peak flow following rainfall-runoff events	Discharge predicted with TR-20 calibrated model similar to prediction using flood frequency analysis (FFA) of historic streamflow data	Endreny	2008
	NEXRAD radar for rainfall	Established flood risk is possible following dam removal Recommended incremental breaching or wetland storage capacity		
Upper Connecticut River, VT	Historic low and high discharge events used to calibrate HEC-RAS	Bankfull discharge (2-year flood) similar frequency pre-/post-dam	Nislow	2002
	Model analysis supplemented with channel cross-section observations of geomorphology and vegetation communities	5-year flood reduced to 20-year frequency, 10-year flood reduced to 100-year frequency post-dam Reduced flooding especially in high floodplain terrace; reduced flooding shifts vegetation community		
Ottawa River OH	High-resolution LIDAR to generate topography	Established Secor dam provided little flood control	Roberts	2007
	Digital ortho-photography combined with ArcGIS for stream channel and bank location	Non-cohesive sediment would not resist incision following dam removal		
Mantua Creek, NJ	HEC-RAS calibrated using channel geometry, roughness, and stage-discharge rating curves	Predict average water velocity would not be greatly altered following removal of Wadsworth or Sterling dams, because dams provide little flood control	Wyrick	2009
	Input data derived from field and aerial surveys Model calibrated by adjusting channel roughness until stage and velocity predictions matched field observations			

See references for study details: Endreny and Higgins (2008), Nislow et al. (2002), Roberts et al. (2007), Wyrick et al. (2009)

Sediment management: sediment load, transport, and contamination

Sediment trapping efficiency has been empirically calculated to represent sediment retention as a percentage of sediment inflow. Sediment trapping is controlled by how a dam affects river hydraulics. When a dam's storage capacity represents a measureable proportion of annual flow, we can expect sediment trapping to occur. Based on reservoir volume at capacity and mean inflow, Brune (1953) estimated sediment trapping to be 75–100 % for storage capacity >10 % of annual flow, while sediment trapped is estimated to be 30–55 % when a reservoir stores 1 % of average annual flow. However, Csiki and Rhoads (2010) note that little is known about sediment trapping in run-of-river dams. Because run-of-river dams generally have low hydraulic residence times, they do not necessarily trap significant sediment. During low-flow periods run-of-river dams may result in impoundments. The extent to which high flow periods can re-suspend and transport sediment past the dam will depend on the system hydraulics and sediment characteristics. Observations of run-of-river dams in various geomorphologies have found varied sediment trapping patterns including: minimal sediment

accumulation upstream of the dam (Bushaw-Newton et al. 2002; Csiki and Rhoads 2014; Lindloff 2003; Roberts et al. 2007), as well as sediment accumulation in the impoundment (Wildman and MacBroom 2005; Orr and Koenig 2006) or sediment accumulation further upstream (Cheng and Granata 2007).

Sawaske and Freyberg (2012) compared sediment dynamics among 12 small dam removals from highly sediment-impacted systems across the northern U.S. They found low sediment erosion (as percent volume) for cohesive sediment and fine-textured sediment. Additionally, they characterize sites by erosional efficiency (volume sediment per volume streamflow), finding that cohesive and layered sediments erode more efficiently, proceeding with stepped knickpoints (with potential energy concentrated over a short channel length), while non-cohesive, nonlayered sediments more often had nonstepped knickpoints (with potential energy dissipated over a longer reach stretch). No trends were established between erosion volume and sediment height or discharge rate.

To mitigate sedimentation hazards, Wohl and Rathburn (2003) advised data collection to: (1) map grain-size distribution, (2) map shear stress and sediment transport capacity, (3) map potential deposition zones and assess

‘acceptable’ aquatic habitat losses, (4) design discharge and sediment release regimes, and (5) develop plans to remove, treat, contain, and track contaminants. Estimation of sediment load and transport following small dam removal requires site-specific assessment during the planning phase. Typical dam removal planning includes estimation of impoundment sediment volume using bathymetric surveys and sediment cores to determine depth as well as chemical toxicity. Isotope methods using ^{137}Cs analysis of sediment cores to date sediment accumulation is a potential method of estimating sediment load (Csiki and Rhoads 2014). Tools for sediment transport modeling such as the Dam Removal Express Assessment Models (DREAMs; Cui et al. 2006), includes the ability to simulate silt/sand sediment transport as well as gravel deposits.

Sediment contamination should be monitored to test whether sediment must be ameliorated prior to dam removal. Smith et al. (1996) developed threshold methods to assess sediment contamination. Under this method, sediment cores were tested for exceedance of the threshold effect level (TEL—the concentration below which harmful effects are rare) and the probable effect level (PEL—contaminant concentration above which harmful effects are frequent). In a study of the Ottawa River, Roberts et al. (2007) found the TEL was commonly exceeded for As and Cd, but the PEL was exceeded in only 7 % of samples. Roberts et al. (2007) also found polychlorinated biphenyls (PCBs) at higher concentrations in some sediment cores from the Ottawa River, OH, but analysis suggested little contamination risk from sediment transport. Applying the TEL/PEL classification system, Ashley et al. (2006) likewise found removal of the Manatawny Creek Dam did not significantly redistribute sediment contaminated with polycyclic aromatic hydrocarbons (PAHs), PCBs, and heavy metals. In contrast, sediment analysis of the Nausaugatuck River revealed contamination with polycyclic aromatic hydrocarbon compounds (PAHs); the sediment was removed to a landfill prior to the Union City Dam removal (Wildman and MacBroom 2005). Cantwell et al. (2014) demonstrated that passive samplers are effective for measuring dissolved organic contaminants, which was established in comparison to observations from sediment traps. The authors found that removal of a low-head dam on the Pawtuxet River, Rhode Island did not significantly alter dissolved or particulate PCBs or PAHs over the year following dam removal relative to pre-dam removal measurements.

Channel formation

Pizzuto (2002) emphasized that post-dam geomorphology is significantly impacted by how a removal is implemented. Designing dam removals requires decisions about

stabilizing or removing sediment in the impoundment, as well as decisions about the timing and rate of removing the dam structure (and subsequent rate of hydrologic and sediment equilibrium). Sediment transport following removal is conceptualized as following: (1) a dispersion process in which a pulse of sediment decays in place with the decayed sediment redistributed downstream in a pattern representing a classic diffusion process, (2) a translation process in which a sediment wave travels downstream without a decrease in amplitude, or (3) a combination of dispersion and translation (Pizzuto 2002).

The channel evolution framework described by Simon (1989) facilitates comparison of post-dam dynamics across studies. Doyle et al. (2002) and Pizzuto (2002) outline post-dam geomorphological changes consistent with the channel evolution framework, including: (1) lowered water level, (2) degradation, (3) degradation and widening, (4) aggradation and widening, and ultimately (5) quasi-equilibrium.

Observations of channel formation following dam removal Observations of channel evolution show convergence in post-dam stages, as well as differences in post-dam dynamics especially with respect to sediment transport. Table 7 describes observed patterns of post-dam channel formation including work conducted using a channel evolution framework, as well as work based on changes in key geomorphological traits (stream width, bank slope, stream velocity, sediment particle size and spatial distribution). Observations demonstrated that sediment composition determined channel dynamics with lower sediment transport observed in systems dominated by coarse (Burroughs et al. 2009; Cheng and Granata 2007) or non-erodible (Chaplin et al. 2005) bed material, and, therefore, suggesting that headcut migration does not occur in all systems. As expected, discharge impacts sediment transport, with low-flow periods corresponding to low transport observations (Chaplin et al. 2005) and high-flow periods concurrent with high transport observations (Bushaw-Newton et al. 2002). In a study of the IVEX Dam failure on the Chagrin River, Ohio, Evans (2007) found the system followed the predictions of the channel evolution framework, with the exception of the aggradation and widening phase. Instead, following the degradation and widening period, the system was characterized by lateral channel migration including both incision and aggradation. The formation of lateral terraces was, therefore, formed by incision and lateral accretion, rather than by vertical accretion.

River response to dam removal is also influenced by undocumented non-dam infrastructure. Following the Union City Dam removal, a headcut rapidly developed upstream creating an incised channel which widened more than expected. An abandoned sewer pipe with

Table 7 Similarity and dissimilarity in observed patterns of channel formation following dam removal

Process	Observations following dam removal	Site	First author	Year
Channel evolution framework				
Lower water level	Dam breaching returns river to natural water level	Baraboo River, WI	Doyle	2005
		Koshkonog River, WI		
		Naugatuck River, CT	Wildman	2005
		Cuyahoga River, OH	Rumschlag	2007
Anabranching channel formation	Mixed sediment load causes differential transportation and deposition of bed material. Often results in mid-impoundment island or bar formation	Naugatuck River, CT	Wildman	2005
Degradation and widening	Channel bed incises, flow becomes concentrated in narrow, deep channel with high flow velocity. Head-cut migration causes fine sediment migration downstream, ultimately followed by coarser sediment	Baraboo River, WI	Doyle	2005
		Koshkonog River, WI		
		Naugatuck River, CT	Wildman	2005
		Cuyahoga River, OH	Rumschlag	2007
Aggradation and widening	If channel depth exceeds critical bank height, widening of channel occurs as sediment is deposited starting with coarsest material	Baraboo River, WI	Doyle	2005
		Koshkonog River, WI		
		Naugatuck River, CT	Wildman	2005
		Cuyahoga River, OH	Rumschlag	2007
Quasi-equilibrium	Channel aggradation reduces bank height, vegetation establishes, and reduced groundwater elevation result in reduced bank erosion	Baraboo River, WI	Doyle	2005
		Koshkonog River, WI		
		Naugatuck River, CT	Wildman	2005
		Cuyahoga River, OH	Rumschlag	2007
Geomorphological trait				
Stream width	Upstream reference width stable, impoundment width decreased as erosion progressed	Pine River, MI	Burroughs	2009
Bank slope	Following dam removal: (1) impoundment bankslope gradually increased, (2) upstream banks exhibited stable, increased, or decreased slope consistent with geomorphology, and (3) downstream banks were stable	Pine River, MI	Burroughs	2009
	Little change in channel banks attributed to low-flow conditions and erosion-resistant bedrock upstream and downstream of dam	Conodoguinet Creek, PA	Chaplin	2005
Stream velocity	Increased stream velocity in lower impoundment and downstream	Pine River, MI	Burroughs	2009
Sediment distribution	Slight change in sediment distribution. Bed composition with dam: coarse upstream, fine (sand and gravel) in impoundment, and sand downstream. Post-dam upstream had reduced sediment size, while impoundment and downstream had slight increase in median size	Pine River, MI	Burroughs	2009
	Major change in channel form from sediment transport. Sand, pebbles, and granules transported from the impoundment during high flows leaving a coarser bed and forming mid-channel bars. Expect stable riffle/pool structure to result and bar stabilization with vegetation colonization	Manatawny Creek, PA	Bushaw-Newton	2002
	Low sediment transport. Attributed to low-flow conditions and erosion-resistant bedrock upstream and downstream of dam	Conodoguinet Creek, PA	Chaplin	2005
	Low sediment transport. Impoundment bed gravel and sandy pebbly sediment, estimated transport <1 %	Sandusky River, OH	Cheng	2007

See references for study details: Burroughs et al. (2009), Bushaw-Newton et al. (2002), Chaplin et al. (2005), Cheng and Granata (2007), Doyle et al. (2005), Rumschlag and Peck (2007), Wildman and MacBroom (2005)

armoring across the river prevented upstream migration of the headcut and acted like a weir. A mid-channel bar formed redirecting flow against the outer banks; it took 5 years for the mid-channel bar to begin breaking up,

allowing headcut migration. Undocumented infrastructure is likely to cause unexpected sediment erosion and transport dynamics when historic small dams breach or are removed.

Tools for predicting channel evolution Predicting channel evolution is a critical step in understanding the risk from dam removal. Estimating sediment volume movement is important for understanding how post-dam hydrology will influence sediment transport potential, which determines contamination potential, changes to stream habitat, and sediment buildup near stream infrastructure such as water intakes. Comparison of post-dam channel formation to classic Channel Evolution Models (CEMs) demonstrated that sites diverge from expectations based on river geomorphology, hydrology, and dam duration and management history. In a comparison of observations to the classic CEM developed by Simon and Hupp (1986), Doyle et al. (2002) found both agreement and divergence from expectations. In the Koshkonong River, Wisconsin dam removal caused expected changes including an upstream channel incision in the sediment of the lower reservoir, a headcut that migrated upstream, and a narrow and deeply incised channel downstream of the headcut. However, observations not anticipated from CEM theory included limited downstream deposition and reaches upstream that maintained water levels similar to those when the dam was present, suggesting that the temporal trajectory of channel formation depends on the frequency of peak hydrologic events. In the Baraboo River, Wisconsin, Doyle et al. (2005) found that frequent dewatering had caused channelization of reservoir sediment prior to dam breaching. These Wisconsin system outcomes demonstrated that dam management history influences the time scale of channel evolution. Regularly dewatered reservoirs had little consolidated or coarse sediment and rapidly eroded following dam removal, while contrasting sites with consolidated fine sediment exhibited limited headcut migration and, therefore, slower channel evolution. Hydraulic and geomorphologic modeling by Greene et al. (2013) demonstrated that post-dam-removal management greatly influences channel dynamics. Their modeling work predicts that bank stabilization that created a riffle structure following the La Valle Dam removal on the Baraboo River, Wisconsin has long-term implications for sediment transport. The riffle structure facilitates sediment mobilization from the former impoundment during extreme flood events, leading to potential long-term sediment impacts on ecological recovery of the system.

Work by Cannatelli and Curran (2012) highlighted the importance of local hydrology and vegetative growth in developing predictive CEMs. By including an analysis of slope, fluvial regime, vegetation, and sediment on channel evolution following dam removal in the Atlantic coastal plain they demonstrated that channel formation was dominated by the post-dam hydrologic regime, but vegetation

establishment was also important in channel formation and stabilization. The authors also noted that multiple studies support the view that quasi-equilibrium is only attained after sufficient low-flow periods allow for vegetation establishment and, therefore, buffering from erosion during high-flow periods. Since channel aggradation and vegetation stabilization were observed during the low-flow season, Cannatelli and Curran (2012) suggested that planning dam removal when a watershed is transitioning from a high- to low-flow season will minimize the lateral migration and sediment yield during channel evolution and allow vegetation to establish, a recommendation in agreement with the statistical modeling outcomes reported by Khan (2009).

In their study of Naugatuck River, Connecticut Wildman and MacBroom (2005) found that classic CEMs do not accurately model sediment transport in a system with steep gravel beds. In contrast to expectations based on Simon (1989), Wildman and MacBroom (2005) observed that bank failure occurred for a lower critical height and with less sediment mass due to beds with coarse-grain sediment. Additionally, channel transport exceeded sediment supply and all but the coarsest material was moved resulting in little or no bed aggradation.

Skalak et al. (2009) studied the impact of intact, small dams on streams with planar, cobble, or boulder beds in Maryland and Pennsylvania as a tool for assessing the potential impact of dam removal. Using a reach upstream of the dam for comparison, they found that downstream reach geomorphology was not significantly impacted by small dams, with downstream effects mostly resulting in decreased fine sediment accumulation. They conclude that dam removal in these systems should have limited long-term effects on geomorphology following a transient phase of fine sediment redistribution, attributing the limited impact to channels characterized by inerodible bedrock, low-mobility boulders, and well-vegetated and cohesive banks.

Predicting potential geomorphic response to dam removal is challenging, as systems demonstrate varied response time-scales. Channel evolution models generally depict a river channel system as being in a state of dynamic, or “quasi”, equilibrium (ICF Consulting, 2005). In practice, observations demonstrate long-term change post dam removal, with geomorphic changes occurring over years to decades. Pizzuto (2002) outlined how commonly applied 1-D numerical models of channel evolution have inadequate representation of key processes for sediment transport, such as knickpoint and headcut formation, change in channel width or depth from erosion and deposition, floodplain processes, overbank flows, and the impact of vegetation. As a result, predicting channel evolution following dam removal remains difficult, especially transient width and depth during the equilibration process (Pizzuto 2002). Pizzuto (2002) argues for coordinated,

multidisciplinary observation of dam removals to improve understanding of post-removal dynamics across a range of dam width and heights, impoundment sizes, impoundment sediment types, and channel hydrology. Because of the high cost in thoroughly studying dam removals, coordinated research could facilitate improving model capacity by ensuring observations cover a range of system characteristics.

Informing a small dam removal process using available observations

Though there are a limited number of well-studied small dam removals, available analyses provide guidance for structuring future removals. This review of dam removal planning frameworks and dam removal implementation observations demonstrates that general principles have emerged to facilitate the removal planning and implementation process of aging, small dams.

- Stakeholders: Dams exist in a complex landuse landscape. Stakeholder engagement is necessary to inform watershed residents of economic, ecological, and safety aspects of dam maintenance or removal, allowing for informed watershed planning.
- Planning: Given the complexity of planning needs, standardizing steps in a dam removal process could reduce costs. State-specific guidelines for establishing funding resources, successful structural removal options, pre-project monitoring methods, permitting, format of technical documentation, and facilitation of stakeholder engagement would assist communities in undertaking the stages of dam removal outlined in Table 2. Establishing a permitting process specific to dam removal will greatly simplify the process, especially with regard to sediment transport following removal of a multi-decadal impoundment.
- Methods to improve our understanding of dam removals:
 - Monitoring ideally includes observations of pre- and post-dam removal for a control and impoundment reach.
 - Pre-removal analysis should include simulation of physical processes to estimate patterns of hydrologic flows, sediment transport and channel formation. Pre-removal analysis should also include sediment sampling when the presence of contamination is an issue.
 - Pre- and post-dam removal observations should concurrently measure physical, chemical, and biological changes to be most informative toward developing a decision tree of potential dam removal outcomes.
- Ecological expectations:
 - Short- and long-term dynamics.
 - Population recovery depends on whether the dam primarily limited migration or habitat. In cases where physical and chemical habitat changes are necessary, recovery from dam removal may take years to decades, and may never fully occur. For cases where the dam was mainly a barrier to biota, improved populations could be seen with-in the first year of dam removal.
 - Vegetation colonization of a dewatered impoundment is rapid, though the species composition will be highly variable. Anticipate the need for vegetation management where invasive species are present or when a particular riparian community is desired.
- Chemical expectations are variable:
 - In small dam systems with a short water residence time, dam removal may lead to little chemical change.
 - For systems with significant sediment storage, the sediment may cause chemical changes due to industrial contamination or nutrient enrichment.
- Physical expectations:
 - Prioritize hydrologic flow forecasting, commonly accomplished using the HEC-RAS model.
 - All scenarios of sediment accumulation can be observed—including impoundments with minimal accumulations, sedimentation limited to the impoundment, and sediment accumulation observed upstream of the impoundment.
 - Anticipate watersheds may have fine sediment accumulation from erosion due to agricultural or forest land management. Sediment influences channel formation as well as habitat recovery and water chemistry.
 - Consistent channel evolution patterns emerge, though bed composition leads to different trajectories across systems. Channel formation followed the channel evolution framework, including stages of lowered water level, degradation, channel widening, aggradation, and ultimately quasi-equilibrium.
 - Anticipate that channel evolution may be altered by undocumented infrastructure (e.g. abandoned sewer pipes).

Acknowledgments This work was supported by the Hudson River Estuary Program of the NY State Department of Environmental Conservation. The authors thank Dr. Geoff Petts and anonymous

reviewers for their thoughtful comments on an earlier version of this manuscript.

References

- American Rivers (2015) Dam removal data set 1999–2015. http://www.americanrivers.org/wp-content/uploads/2012/09/DamsRemoved_1999-2015.pdf?c38e77. Accessed 20 March 2016
- American Rivers (2015) Dam removal map 1912–2015. <http://www.americanrivers.org/initiatives/dams/dam-removals-map/>. Accessed 20 March 2016
- Ashley JRF, Bushaw-Newton KL, Wilhelm M et al (2006) The effects of small dam removal on the distribution of sedimentary contaminants. *Environ Monit Assess* 114:287–312. doi:10.1007/s10661-006-4781-3
- Bednarek AT (2001) Undamming rivers: a review of the ecological impacts of dam removal. *Environ Manag* 27:803–814. doi:10.1007/s002670010189
- Born SM, Genskow KD, Keefer ML, White KA (1998) Socioeconomic and institutional dimensions of dam removals: the Wisconsin experience 22:359–370
- Brune G (1953) Trap efficiency of reservoirs. *Trans Am Geophys Union* 34:407–418
- Burroughs BA, Hayes DB, Klomp KD et al (2009) Effects of Stronach Dam removal on fluvial geomorphology in the Pine River, Michigan, United States. *Geomorphology* 110:96–107. doi:10.1016/j.geomorph.2009.03.019
- Bushaw-Newton K, Hart DD, Pizzuto JE et al (2002) An integrative approach towards understanding ecological responses to dam removal: the Manatawny Creek study. *JAWRA J Am Water Resour Assoc* 38:1581–1599. doi:10.1111/j.1752-1688.2002.tb04366.x
- Cannatelli KM, Curran JC (2012) Importance of hydrology on channel evolution following dam removal: case study and conceptual model. *J Hydraul Eng* 138:377–390. doi:10.1061/(ASCE)HY.1943-7900.0000526
- Cantwell MG, Perron MM, Sullivan JC et al (2014) Assessing organic contaminant fluxes from contaminated sediments following dam removal in an urbanized river. *Environ Monit Assess* 186:4841–4855. doi:10.1007/s10661-014-3742-5
- Chaplin JJ, Brighthill RA, Bilger MD (2005) Effects of removing Good Hope Mill Dam on selected physical, chemical, and biological characteristics of Conodoguinet Creek, Cumberland County, Pennsylvania. *US Geol Surv Sci Investig Rep* 5226:45
- Cheng F, Granata T (2007) Sediment transport and channel adjustments associated with dam removal: field observations. *Water Resour Res* 43:1–14. doi:10.1029/2005WR004271
- ICF Consulting (2005) A summary of existing research on low-head dam removal projects
- Csiki S, Rhoads BL (2010) Hydraulic and geomorphological effects of run-of-river dams. *Prog Phys Geogr* 34:755–780. doi:10.1177/0309133310369435
- Csiki SJC, Rhoads BL (2014) Influence of four run-of-river dams on channel morphology and sediment characteristics in Illinois, USA. *Geomorphology* 206:215–229. doi:10.1016/j.geomorph.2013.10.009
- Cui Y, Braudrick C, Dietrich WE et al (2006) Dam removal express assessment models (DREAM). *J Hydraul Res* 44:308–323. doi:10.1080/00221686.2006.9521684
- Doyle MW, Stanley EH, Harbor JM (2002) Geomorphic analogies for assessing probable channel response to dam removal. *J Am Water Resour Assoc* 38:1567–1579. doi:10.1111/j.1752-1688.2002.tb04365.x
- Doyle MW, Harbor JM, Stanley EH (2003a) Toward policies and decision-making for dam removal. *Environ Manag* 31:453–465. doi:10.1007/s00267-002-2819-z
- Doyle MW, Stanley EH, Harbor JM (2003b) Hydrogeomorphic controls on phosphorus retention in streams. *Water Resour Res* 39:1–17. doi:10.1029/2003WR002038
- Doyle MW, Stanley EH, Harbor JM, Grant GS (2003c) Dam removal in the United States: emerging needs for science and policy. *EOS Trans AGU* 84(4):29–36. doi:10.1029/2003EO040001
- Doyle MW, Stanley EH, Orr CH 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
- Endreny T, Higgins M (2008) Adding radar rainfall and calibration to the TR-20 watershed model to improve dam removal flood analysis. *J Water Resour Plan Manag* 134:314–317. doi:10.1061/(ASCE)0733-9496(2008)134:3(314)
- EOEEA (Executive Office of Energy and Environmental Affairs) (2007) Dam removal in Massachusetts: a basic guide for project proponents. <http://www.mass.gov/eea/docs/eea/water/dam-removal-guidance.pdf>. Accessed 5 October 2015
- Evans JE (2007) Sediment impacts of the 1994 failure of IVEX Dam (Chagrin River, NE Ohio): a test of channel evolution models. *J Great Lakes Res* 33:90–102. doi:10.3394/0380-1330(2007)33[90:SIOTFO]2.0.CO;2
- Feld CK, Birk S, Bradley DC et al (2011) From natural to degraded rivers and back again. A test of restoration ecology theory and practice. *Adv Ecol Res* 44:119–209. doi:10.1016/B978-0-12-374794-5.00003-1
- Globevnik L (2007) Briefing small water bodies
- Graber B (2002) Potential economic benefit of small dam removal. In: Graf WL (ed) *Dam removal research: status and prospects*, chap 4. Proceedings of The Heinz Center's dam removal research workshop. The H. John Heinz III Center for Science, Economics and the Environment. http://www.penobscotriver.org/assets/Dam_Research_FullReport.pdf
- Graber B, Lindloff S, Cuppett S et al (2010) Removing small dams in New York
- Graber B, Singler A, McClain S, Thomas-Blate J (2015) Removing small dams: A basic guide for project managers. American rivers. http://www.americanrivers.org/wp-content/uploads/2015/06/NatlDamProjectManagerGuide_06112015.pdf?1ef746. Accessed 5 October 2015
- Graf WL (2005) Geomorphology and American dams: the scientific, social, and economic context. *Geomorphology* 71:3–26. doi:10.1016/j.geomorph.2004.05.005
- Graf WL (2006) Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology* 79:336–360. doi:10.1016/j.geomorph.2006.06.022
- Graham WJ (1999) A procedure for estimating loss of life caused by dam failure. In: Report DSO-99-06, U.S. Department of the Interior, Bureau of Reclamation, Denver
- Greene SL, Krause AJ, Knox JC (2013) A decade of geomorphic and hydraulic response to the La Valle Dam Project, Baraboo River, Wisconsin. *J Am Water Resour Assoc* 49:1473–1484. doi:10.1111/jawr.12100
- Hansen JF, Hayes DB (2012) Long-term implications of dam removal for macroinvertebrate communities in Michigan and Wisconsin Rivers, United States. *River* 28:1540–1550. doi:10.1002/rra
- Hart DD, Johnson TE, Bushaw-Newton KL et al (2002a) Dam removal: challenges and opportunities for ecological research and river restoration. *Bioscience* 52:669–681. doi:10.1641/0006-3568(2002)052[0669:DRCAOF]2.0.CO;2
- Hart DD, Johnson TE, Bushaw-Newton KL et al (2002b) Ecological effects of dam removal: an integrative case study and risk assessment framework for prediction. In: Graf W (ed) *Dam removal research: status and prospects*. H. John Heinz III Center

- for Science, Economics and the Environment, Washington, D.C., pp 67–80
- 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](https://doi.org/10.1016/j.ecoleng.2013.12.009)
- Kanehl PD, Lyons J, Nelson JE (1997) Changes in the habitat and fish community of the Milwaukee River, Wisconsin, following removal of the Woolen Mills dam. *N Am J Fish Manag* 17:387–400. doi:[10.1577/1548-8675\(1997\)017](https://doi.org/10.1577/1548-8675(1997)017)
- Kattell J, Eriksson M (1998) Bridge scour evaluation: screening, analysis, and countermeasures. USDA Forest Service, United States Department of Agriculture, Washington
- Khan LA (2009) Selecting flow frequency distributions for designing a small low-head dam removal cofferdam. *J Hydrol Eng* 14:935–943. doi:[10.1061/\(ASCE\)HE.1943-5584.0000073](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000073)
- Kibler K, Tullos D, Kondolf M (2011a) Evolving expectations of dam removal outcomes: downstream geomorphic effects following removal of a small, gravel-filled dam. *J Am Water Resour Assoc* 47:408–423. doi:[10.1111/j.1752-1688.2011.00523.x](https://doi.org/10.1111/j.1752-1688.2011.00523.x)
- Kibler KM, Tullos DD, Kondolf GM (2011b) Learning from dam removal monitoring: challenges to selecting experimental design and establishing significance of outcomes. *River Res Appl* 27:967–975. doi:[10.1002/rra](https://doi.org/10.1002/rra)
- Kristensen EA, Baattrup-Pedersen A, Jensen PN et al (2012) Selection, implementation and cost of restorations in lowland streams: a basis for identifying restoration priorities. *Environ Sci Policy* 23:1–11. doi:[10.1016/j.envsci.2012.06.013](https://doi.org/10.1016/j.envsci.2012.06.013)
- Kuby MJ, Fagan WF, ReVelle CS, Graf WL (2005) A multiobjective optimization model for dam removal: an example of trading off salmon passage with hydropower and water storage in the Willamette Basin. *Adv Water Res* 28(8):845–855
- Lejon AGC, Renöfalt BM, Nilsson C (2009) Conflicts associated with dam removal in Sweden. *Ecol Soc*
- Lenhart CF (2003) A preliminary review of NOAA's community-based dam removal and fish passage projects. *Coast Manag* 31:79–98
- Lewis LY, Bohlen C, Wilson S (2008) Dams, dam removal, and river restoration: a hedonic property value analysis. *Contemp Econ Policy* 26:175–186. doi:[10.1111/j.1465-7287.2008.00100.x](https://doi.org/10.1111/j.1465-7287.2008.00100.x)
- Lindloff SD (2003) Institutionalizing the option of dam removal: the New Hampshire initiative. *Water Sci Technol* 48:9–16
- Maclin E, Sicchio M, Blackwelder B et al (1999) Dam removal success stories
- Maloney KO, Dodd HR, Butler SE, Wahl DH (2008) Changes in macroinvertebrate and fish assemblages in a medium-sized river following a breach of a low-head dam. *Freshw Biol* 53:1055–1068. doi:[10.1111/j.1365-2427.2008.01956.x](https://doi.org/10.1111/j.1365-2427.2008.01956.x)
- Nilsson C, Reidy CA, Dynesius M, Revenga C (2005) Fragmentation and flow regulation of the world's large river systems. *Science* (80) 308:405–408
- Nislow KH, Magilligan FJ, Fassnacht H et al (2002) Effects of dam impoundment on the flood regime of natural floodplain communities in the Upper Connecticut River. *J Am Water Resour Assoc* 38:1533–1548. doi:[10.1111/j.1752-1688.2002.tb04363.x](https://doi.org/10.1111/j.1752-1688.2002.tb04363.x)
- NRCS (2000) A report to congress on aging an analysis and strategy for addressing the Nation's Aging Flood Control Dams
- Null SE, Medellín-Azuara J, Escrivá-Bou A et al (2014) Optimizing the dammed: water supply losses and fish habitat gains from dam removal in California. *J Environ Manag* 136:121–131. doi:[10.1016/j.jenvman.2014.01.024](https://doi.org/10.1016/j.jenvman.2014.01.024)
- Orr CH, Koenig S (2006) Planting and vegetation recovery on exposed mud flats following two dam removals in Wisconsin. *Ecol Restor* 24:79–86. doi:[10.3368/er.24.2.79](https://doi.org/10.3368/er.24.2.79)
- Orr CH, Stanley EH (2006) Vegetation development and restoration potential of drained reservoirs following dam removal in Wisconsin. *River Res Appl* 22:281–295. doi:[10.1002/rra.891](https://doi.org/10.1002/rra.891)
- Orr CH, Kroiss SJ, Rogers KL, Stanley EH (2008) Downstream benthic responses to small dam removal in a coldwater stream. *River Res Appl* 24:804–822. doi:[10.1002/rra](https://doi.org/10.1002/rra)
- Pansic N, Austin RJ, Finis M (1998) Sediment management for dam decommissioning. In: 15th annual USCOLD lecture series
- Petts GE, Gurnell AM (2005) Dams and geomorphology: research progress and future directions. *Geomorphology* 71:27–47. doi:[10.1016/j.geomorph.2004.02.015](https://doi.org/10.1016/j.geomorph.2004.02.015)
- Pizzuto J (2002) Effects of dam removal on river form and process. *Bioscience* 2002 52(8):683–691
- Poff NL, Hart DD (2002) How dams vary and why it matters for the emerging science of dam removal. *Bioscience* 52(8):659–668
- Pohl MM (2002) Bringing down our dams: trends in American dam removal rationales. *J Am Water Resour Assoc* 38:1511–1519. doi:[10.1111/j.1752-1688.2002.tb04361.x](https://doi.org/10.1111/j.1752-1688.2002.tb04361.x)
- Poulos HM, Miller KE, Krackowski ML et al (2014) Fish assemblage response to a small dam removal in the Eightmile River System, Connecticut, USA. *Environ Manag* 54:1090–1101. doi:[10.1007/s00267-014-0314-y](https://doi.org/10.1007/s00267-014-0314-y)
- POWR (Pennsylvania Organization for Watersheds and Rivers) (2015) Small dam removal in Pennsylvania: Free-flowing watershed restoration. <http://pawatersheds.org/wp-content/uploads/2009/04/damremoval.pdf>. Accessed 5 October 2015
- Princeton Hydro, LLC (2015) Review of New Jersey regulations pertaining to dam removal & stream restoration. <http://www.americanrivers.org/assets/pdfs/dam-removal-docs/review-of-new-jersey-dam-removal-regulations.pdf?1ef746>. Accessed 5 October 2015
- Provencher B, Sarakinos H, Meyer T (2008) Does small dam removal affect local property values? An empirical analysis. *Contemp Econ Policy* 26:187–197. doi:[10.1111/j.1465-7287.2008.00107.x](https://doi.org/10.1111/j.1465-7287.2008.00107.x)
- Roberts SJ, Gottgens JF, Sponberg AL et al (2007) Assessing potential removal of low-head dams in urban settings: an example from the Ottawa River, NW Ohio. *Environ Manag* 39:113–124. doi:[10.1007/s00267-005-0091-8](https://doi.org/10.1007/s00267-005-0091-8)
- Rumschlag JH, Peck JA (2007) Short-term sediment and morphologic response of the Middle Cuyahoga River to the removal of the Munroe Falls Dam, Summit County, Ohio. *J Great Lakes Res* 33:142–153. doi:[10.3394/0380-1330\(2007\)33\[142:SSAMRO\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2007)33[142:SSAMRO]2.0.CO;2)
- Sarakinos H, Johnson SE (2002) Social perspectives on dam removal. In: Graf W (ed) *Dam removal research: status and prospects*. H. John Heinz III Center for Science, Economics and the Environment, Washington, D.C., pp 40–55
- Sawaske SR, Freyberg DL (2012) A comparison of past small dam removals in highly sediment-impacted systems in the U.S. *Geomorphology* 151–152:50–58. doi:[10.1016/j.geomorph.2012.01.013](https://doi.org/10.1016/j.geomorph.2012.01.013)
- Schmitz D, Blank M, Ammond S, Patten DT (2009) Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals. *J Environ Manag* 90:S237–S248. doi:[10.1016/j.jenvman.2008.07.028](https://doi.org/10.1016/j.jenvman.2008.07.028)
- Sethi SA, Selle AR, Doyle MW et al (2004) Response of unionid mussels to dam removal in Koshkonong Creek, Wisconsin (USA). *Hydrobiologia* 525:157–165. doi:[10.1023/B:HYDR.0000038862.63229.56](https://doi.org/10.1023/B:HYDR.0000038862.63229.56)
- Simon A (1989) A model of channel response in disturbed alluvial channels. *Earth Surf Process Landforms* 14:11–26. doi:[10.1002/esp.3290140103](https://doi.org/10.1002/esp.3290140103)
- Simon A, Hupp CR (1986) Channel evolution in modified Tennessee channels. Proceedings of fourth federal interagency sedimentation conference, Las Vegas
- Skalak K, Pizzuto J, Hart DD (2009) Influence of small dams on downstream channel characteristics in Pennsylvania and

- Maryland: implications for the long-term geomorphic effects of dam removal. *J Am Water Resour Assoc* 45:97–109
- Smith SL, MacDonald DD, Keenleyside KA et al (1996) A preliminary evaluation of sediment quality assessment values for freshwater ecosystems. *J Great Lakes Res* 22:624–638. doi:[10.1016/S0380-1330\(96\)70985-1](https://doi.org/10.1016/S0380-1330(96)70985-1)
- Stanley EH, Doyle MW (2002) A geomorphic perspective on nutrient retention following dam removal. *Bioscience* 52:693–701. doi:[10.1641/0006-3568\(2002\)052\[0693:AGPONR\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2002)052[0693:AGPONR]2.0.CO;2)
- Stanley E, Luebke M, Doyle MW, Marshall DW (2002) Short-term changes in channel form and macroinvertebrate communities following low-head dam removal. *J N Am Benthol Soc* 21:172–187. doi:[10.2307/1468307](https://doi.org/10.2307/1468307)
- Thomson JR, Hart DD, Charles DF et al (2005) Effects of removal of a small dam on downstream macroinvertebrate and algal assemblages in a Pennsylvania stream effects of removal of a small dam on downstream macroinvertebrate and algal assemblages in a Pennsylvania stream. *J N Am Benthol Soc* 24:192–207
- Tschantz BA, Wright KR (2011) Hidden dangers and public safety at low-head dams. *J Dam Saf* 9:8–17
- Tuckerman S, Zawiski B (2007) Case studies of dam removal and TMDLs: process and results. *J Great Lakes Res* 33:103–116. doi:[10.3394/0380-1330\(2007\)33\[103:CSODRA\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2007)33[103:CSODRA]2.0.CO;2)
- Vedachalam S, Riha SJ (2013) Small is beautiful? State of the dams and management implications for the future. *River Res Appl* 30:1195–1205. doi:[10.1002/rra](https://doi.org/10.1002/rra)
- Velinsky DJ, Bushaw-Newton KL, Kreeger DA, Johnson TE (2006) Effects of small dam removal on stream chemistry in southeastern Pennsylvania. *J N Am Benthol Soc* 25:569–582
- Whitelaw E, MacMullan E (2002) A framework for estimating the costs and benefits of dam removal. *Bioscience* 52:724–730
- Wildman LAS, MacBroom JG (2005) The evolution of gravel bed channels after dam removal: case study of the Anaconda and Union City Dam removals. *Geomorphology* 71:245–262. doi:[10.1016/j.geomorph.2004.08.018](https://doi.org/10.1016/j.geomorph.2004.08.018)
- Wohl E, Rathburn S (2003) Mitigation of sedimentation hazards downstream from reservoirs. *Int J Sediment Res* 18:97–106
- Wyrick JR, Rischman BA, Burke CA et al (2009) Using hydraulic modeling to address social impacts of small dam removals in southern New Jersey. *J Environ Manag* 90:S270–S278. doi:[10.1016/j.jenvman.2008.07.027](https://doi.org/10.1016/j.jenvman.2008.07.027)
- Zheng P, Hobbs B (2013) Multiobjective portfolio analysis of dam removals addressing dam safety, fish populations, and cost. *J Water Resour Plan Manag* 139:65–75. doi:[10.1061/\(ASCE\)WR.1943-5452.0000209](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000209)
- Zheng PQ, Hobbs BF, Koonce JF (2009) Optimizing multiple dam removals under multiple objectives: linking tributary habitat and the Lake Erie ecosystem. *Water Resour Res* 45:1–14. doi:[10.1029/2008WR007589](https://doi.org/10.1029/2008WR007589)