Dam Removal: Challenges and Opportunities for Ecological Research and River Restoration

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We develop a risk assessment framework for understanding how potential responses to dam removal vary with dam and watershed characteristics, which can lead to more effective use of this restoration method

Water flow is a "master variable" (sensu Power et al. 1995) that governs the fundamental nature of streams and rivers (Poff et al. 1997, Hart and Finelli 1999), so it should come as no surprise that the modification of flow caused by dams alters the structure and function of river ecosystems. Much has been learned during the last several decades about the adverse effects of dams on the physical, chemical, and biological characteristics of rivers (Ward and Stanford 1979, Petts 1984, Poff et al. 1997, Poff and Hart 2002). Increasing concerns about these impacts, together with related social and economic forces, have led to a growing call for the restoration of rivers by removing dams (AR/FE/TU 1999, Pejchar and Warner 2001). For the purposes of this paper, we define restoration broadly as an effort to compensate for the negative effects of human activities on ecological systems by facilitating the establishment of natural components and regenerative processes, although we acknowledge that these efforts rarely eliminate all human impacts (see Williams et al. 1997 for alternative definitions).

Interest in dam removal as a means of river restoration has focused attention on important new challenges for watershed management and simultaneously created opportunities for advancing the science of ecology. One challenge lies in determining the magnitude, timing, and range of physical, chemical, and biological responses that can be expected following dam removal. This information is needed to decide whether and how dam removals should be performed to achieve specific restoration objectives (Babbitt 2002). Opportunities for advancing ecological research also exist because dam removal represents a major, but partially controllable, perturbation that can help scientists test and refine models of complex ecosystems. In contrast to the small-scale experiments that traditionally have been employed in stream and river ecology, the unusually large magnitude and spatial extent of dam removal "experiments" creates the potential for examining river responses by means of both mechanistic and whole-system approaches.

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The overall objectives of this article are to assess the current understanding of ecological responses to dam removal and to develop a new approach for predicting dam removal outcomes based on stressor–response relationships. We begin by explaining how a simplified spatial and temporal context can be helpful for examining dam removal responses. Three alternative approaches for predicting ecological responses to dam removal are then evaluated: (1) predictions based on studies of actual dam removals; (2) predictions based on studies of existing dams; and (3) predictions based on mechanistic and empirical models (e.g., sediment transport models).

A preliminary conclusion of this evaluation is that useful generalizations about dam impacts and ecological responses to dam removal cannot be made without considering the nature of stress imposed by dams of different size and operational type across a variety of watershed settings. Furthermore, expected responses to removal are often based on knowledge about large (e.g., > 15 meters [m] height) flood control or hydropower dams that can dramatically alter water quality and flow regimes (Petts 1984), whereas most of the dams being removed are relatively small structures (≤ 5 m height) that may have less marked effects on river ecosystems. There is relatively little information on the ecological impacts of these smaller dams, however, and the limited studies of small dam removals have yielded variable results. To address this knowledge gap, we develop a risk assessment framework for evaluating relationships between dam impacts and dam characteristics across a broad range of dam sizes, with the ultimate goal of predicting restoration outcomes for different types of dams and rivers.

Finally, we briefly explore two additional issues associated with the use of dam removal in watershed management. First, although the long-term ecological benefits of dam removal are potentially quite large, the removal process can also have some adverse effects on river ecosystems. Thus, there is a need to develop methods for anticipating and mitigating these impacts. Second, dam removal is but one of many potential tools and practices for restoring and protecting rivers, so comprehensive approaches are required to determine the best combination of methods for achieving watershed management goals.

A spatial and temporal context for examining ecological responses to dam removal

Efforts to understand dam removal responses must first consider how these responses are likely to vary in space and time (figure 1). Responses to dam removal include those that result from the removal process itself, as well as changes that occur when various impacts caused by the dam's presence are eliminated. The rate, magnitude, duration, and spatial extent of these changes will depend on various characteristics of the dam, river, and watershed (Poff and Hart 2002), as well as the method of dam removal.

Spatially, it is useful to distinguish among responses to dam removal that occur downstream from the dam, within impounded areas, and in the free-flowing areas farther upstream. For example, when the impoundment becomes free-flowing following dam removal, changes can occur in a variety of important hydraulic parameters (e.g., slope, velocity field) and geomorphic processes (e.g., channel incision, bank failure) that influence habitat conditions. In areas downstream from the dam, the erosion and downstream transport of accumulated sediment from the former impoundment can lead to deposition and other channel changes. Changes in flow regime (including the size, timing, and duration of maximum and minimum flows) in this downstream area can range from minor, in the case of a 2-m-high mill dam, to major, in the case of a 50-m-high peaking hydropower dam or other highly regulated dam. The principal effects of dam removal upstream of the impoundment are likely to be mediated through biotic responses to the restoration of connectivity, including upstream colonization by migratory fauna and associated nutrient transport and genetic changes.

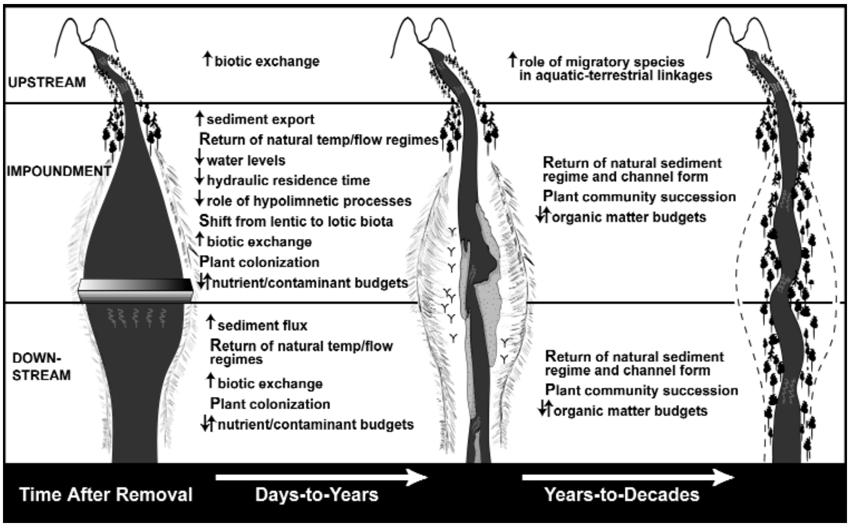

Figure 1. A simple spatial and temporal context for examining potential ecological responses to dam removal. Prior to removal, upstream and downstream free-flowing areas are separated by an impoundment. Dam removal initiates a series of abiotic and biotic changes that vary among areas and occur at different rates. For example, the rate of sediment transport and channel adjustment is a function of the distribution of sediment particle sizes and flow magnitudes, and the response rate of aquatic and riparian biota to these changes depends on their dispersal and growth rates. Key changes occurring within each spatial and temporal area have been highlighted. For some processes, arrows indicate net change as either increases (↑) or decreases (↓), though in other cases the change may be in either direction (↑↓).

There may also be reductions in fauna that formerly dispersed upstream from the impoundment.

Ecological responses to dam removal can also occur over a broad range of time scales. For example, short-term changes associated with the downstream transport of fine sediment from the former impoundment begin as soon as the dam is breached, and fish whose upstream movements were formerly obstructed by the dam may begin to move into the former impoundment within days after removal. Over longer periods, changes in channel morphology generally propagate upstream from the dam site by headward erosion. Establishment of an equilibrium channel morphology, new floodplains, and native riparian vegetation in the former impoundment area may take much longer, on the order of years to decades. Similarly, some faunal changes may occur rapidly (within days), but other long-term changes occur as species adjust to changes in channel form.

Alternative approaches for predicting ecological responses to dam removal

Observed ecological responses to dam removal. One approach for developing predictive models is by means of the analysis and synthesis of results from a large set of dam removal studies. This approach, however, is currently limited by the scarcity of scientific studies of actual dam removals (Bednarek 2001). Although more than 450 dams have been removed in the United States during the last century (AR/FE/TU 1999), less than 5% (approximately 20) of these removals were accompanied by published ecological studies. We are also aware of about 10 ongoing studies (as of December 2001) that will contribute further to our understanding of ecological responses to dam removal. The knowledge gained from these newer studies, however, is restricted to an understanding of relatively short-term changes. In contrast, recovery of certain ecological attributes may take years to decades. Nonetheless, we can begin to summarize some of the physical, chemical, and biological responses to removal that have been documented to date (table 1).

Shifts in patterns of sediment movement have been one of the most prominent and significant ecological responses to dam removal. Changes in sediment transport control the process of channel evolution (e.g., the rate of headward erosion in the former impoundment, the aggradation of downstream reaches, channel narrowing, creation of new floodplains), which also has important consequences for biogeochemical cycling and habitat availability. Although dam removal allows sediment stored in the impoundment to be transported downstream, observed rates and patterns of sediment transport can be quite variable, depending on the amount and type of sediment, channel slope, and flow magnitude. Many studies refer to increased sediment flux following dam removal (e.g., Clearwater River dams, Shopiere Dam, Woolen Mills Dam; table 1), but few have attempted to quantify sediment transport rates. In the first 9 years after the removal of the Newaygo Dam on the Muskegon River (MI), Simons and Simons (1991) estimated that the downstream rate of sediment movement averaged nearly 2 km per year (median grain size = 0.25 mm). They estimated that complete flushing of the system could take an additional 50 to 80 years (Simons and Simons 1991). Mobilization of fine-grained sediment was also reported immediately following the removals of dams on several other rivers (e.g., the Clearwater, Baraboo, AuSable, Mad, and Milwaukee Rivers; table 1). Accumulated sediment may be coarse grained, however, and not easily mobilized. For example, Johnson and colleagues (2001) observed little increase in suspended or bedload transport during the breaching of the Manatawny Creek Dam (table 1). Rather, most of the sediment (median grain size = 45 mm) did not move downstream until several months later when discharge increased from less than 3 $m^3 \cdot sec^{-1}$ to nearly 100 $m^3 \cdot sec^{-1}$. No quantitative geomorphic study has continued long enough to document the establishment of an equilibrium channel morphology following dam removal, although the time frame could range from years to decades or more (Pizzuto 2002).

Dam removal can affect water quality through the downstream transport of sediment-bound contaminants (e.g., organic substances and heavy metals) and the alteration of biogeochemical cycles. For example, a large volume of fine sediment contaminated with polychlorinated biphenyls (PCBs) was present in the impoundment upstream of Ft. Edward Dam on the Hudson River, and these contaminants were transported downstream when the dam was breached (Shuman 1995). Unfortunately, the dam owner did not perform an adequate preremoval assessment of potential sediment contamination, despite knowledge that PCBs were produced in an upstream industrial facility (Shuman 1995). The impoundment created by a small mill dam on the Manatawny Creek in southeastern Pennsylvania also contained some contaminants within the sediments (e.g., heavy metals, PCBs, and polycyclic aromatic hydrocarbons, or PAHs), but this situation was very different from that in the Hudson River (Bushaw-Newton et al. 2001). Specifically, the fine sediments to which these contaminants preferentially sorb were very uncommon in the impoundment, so the total volume of contaminated sediment was minimal. Moreover, concentrations of these contaminants per unit of fine sediment were generally low, and similar concentrations were observed in fine sediment samples collected from free-flowing reaches located upstream and downstream of the dam. One exception to this pattern occurred for PAHs, which exhibited elevated concentrations at a few locations within the impoundment, presumably because of the dam's urban setting. Sediment contamination has not been a major issue for many other dam removals, however. For example, preremoval studies of Salling Dam on the AuSable River in Michigan indicated that the sediment primarily comprised flocculated organics, and no contaminants were present (Pawloski and Cook 1993). Future efforts to assess the risks associated with potential sediment contamination should focus particular attention on current and former human activities within the watershed, as well as

Table 1. Observed effects of dam removal on the physical, chemical, and biological components of a river ecosystem.

Dam river system (dam life span[a])	Estimated Size[b] Height by Length (meters) Impoundment (hectares)	Physical[c]	Chemical	Biological	Reference
Dead Lake Dam Chipola River, FL (1960–1987)	5 x 240 2700	Alteration of flow regime	Improvement in overall water quality	Restoration of fish passage; increase in fish diversity	Estes et al. 1993, Hill et al. 1994
Edwards Dam Kennebec River, ME (1837–1999)	7 x 280 462	Erosion at dam site; bank slumping at deepest section of former impoundment		Shift from pelagic to benthic algae in former impoundment; restoration of fish passage (striped bass and sturgeon); plant colonization	Casper et al. 2001, O'Donnell et al. 2001
Ft. Edward Dam Hudson River, N.Y. (1898–1973)	9 x 179 79	Increased sediment transport	Mobilization of organic contaminants		Shuman 1995
Fulton Dam Yahara River, WI (1849–1993)	3 x n.d. 20			Change in community composition; loss of reservoir species	ASCE 1997, Born et al. 1998
Grangeville Dam Clearwater River, ID (1903–1963)	17 x 134 n.d.	Increased sediment transport			Winter 1990
Jackson Street Dam[d] Bear Creek, OR (1960–1998)	3 x 37 1			Restoration of fish passage (salmon)	Smith et al. 2000
Kettle River Dam Kettle River, MN (1915–1995)	6 x 46 n.d.	Increased sediment transport		Decrease in mussel abundance downstream due to sedimentation	Johnson 2001
Lewiston Dam Clearwater River, ID (1927–1973)	14 x 323 n.d.	Increased sediment transport		Restoration of fish passage (salmon); improvement of fish habitat	Williams 1977, Winter 1990, Shuman 1995
Manatawny Creek Dam Manatawny Creek PA (late 1700s–2000)	2 x 30 1.5	Increased sediment; transport; downstream channel aggradation; channel formation; and channel substrate coarsening in former impoundment	Minimal contaminant storage; no change in most forms of nitrogen and phosphorous between upstream and and downstream	Shift in macroinvertebrate and fish species composition from lentic to lotic in former impoundment; decrease in fish parasites in former impoundment; stranding of organisms due to drawdown; plant colonization	Bushaw-Newton et al. 2001, Hart et al. 2001, Horwitz et al. 2001, Johnson et al. 2001
Nelsonville Dam Tomorrow River, WI (1860–1988)	2 x n.d. 9	Decreased water temperatures		Spawning of trout; reclassified as a class 1 trout fishery	Born et al. 1998
Newaygo Dam Muskegon River, MI (1853–1968)	n.d. n.d.	Increased sediment transport			Simons and Simons 1991
Oak Street Dam Baraboo River, WI (1860–2000)	4 x 63 6–15	Increased sediment transport; channel formation		Shift in benthic macroinvertebrate species composition from lentic to lotic informer impoundment; increase in fish community quality in former impoundment; decrease in fish community quality downstream	Catalano et al. 2001, Stanley et al. 2002

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Dam river system (dam life span[a])	Estimated size[b] Height by Length (meters) Impoundment (hectares)	Physical[c]	Chemical	Biological	Reference
Quaker Neck Dam Neuse River, N.C. (1952–1998)	2 x 79 n.d.			Restoration of fish passage (American shad and striped bass)	Bowman 2001
Rockdale Dam Koshkonong Cr, WI (1848–2000)	2 x 23 42	Increased sediment transport	Mobilization of phosphorus; predicted loss of nitrogen retention		Stanley and Doyle 2001, 2002
Salling Dam AuSable River, MI (1914–1991)	5 x 76 22	Increased sediment transport; decreased water temperature in former impoundment and downstream	No contaminated sediment	Plant colonization	Pawloski and Cook 1993
Shopiere Dam Turtle Cr, WI (1848–1999)	4 x n.d. 6	Increased sediment transport		Change in benthic macroinvertebrate species composition at former damsite	Pollard and Reed-Anderson 2001
Stronach Dam[e] Pine River, MI (1912–1996 ongoing)	4 x 23 12	Progressive downcutting and transport of sediment; Increased water velocity in former impoundment; downstream channel aggradation		Increase in lotic fish species in former impoundment (brown and rainbow trout)	Burroughs et al. 2001
Sweasey Dam Mad River, CA (1938–1969)	17 x n.d. n.d.	Increased sediment transport		Improved fish passage	Winter 1990
Waterworks Dam Baraboo River, WI (1858–1997)	4 x n.d. 19	Increased sediment transport; channel formation		Shift in macroinvertebrate species composition from lentic to lotic in former impoundment; increase in quality of fish community in former impoundments; decrease in quality of fish community downstream	Catalano et al. 2001, Stanley et al. 2002
Woolen Mills Dam Milwaukee River, WI (1870–1988)	6 x n.d. 27	Increased sediment transport		Increase in quality of fish habitat; decrease in carp and increase in smallmouth bass abundance in former impoundment	Nelson and Pajak 1990, Kanehl et al. 1997

Note: n.d., not defined.

a. The life span of the dam reflects the total time a dam has been present.

b. Dam sizes are estimates because many studies did not explicitly state whether height reflected either hydraulic or structural measurements. Impoundment size is based on surface area. Length and impoundment size were not defined in many studies.

c. For most studies the physical changes are descriptive rather than quantitative.

d. Partial removal.

e. Staged removal to be completed in 2003.

on the total volume and particle size distribution of sediment within the impoundment.

The effects of dam removal on biogeochemical processes have varied among studies, probably because of variations in key physical characteristics of different systems. For instance, Stanley and Doyle (2002) studied the impoundment upstream from Rockdale Dam on Koshkonong Creek (WI), which was dominated by fine sediment. Prior to removal, the impoundment retained some forms of phosphorus (P) and was a sink for nitrate; after removal, there was a net export of P-rich sediments to downstream reaches (Stanley and Doyle 2001). Stanley and Doyle (2002) predict that nitrate concentrations will decrease in the former impoundment because of greater sediment–water contact resulting from channel widening, but many months could elapse before measurable declines are evident. In contrast, Bushaw-Newton et al. (2001) studied a small impoundment with little fine-sediment accumulation and a very short hydraulic residence time (approximately 2 hours; calculated as impoundment volume/discharge) on the Manatawny Creek. They observed no significant upstream–downstream differences in dissolved oxygen, temperature, or most forms of nitrogen (N) and P, either before or after dam removal. They proposed that the likelihood of observing impoundment-mediated transformations of these N and P cycles was ultimately related to the depth and hydraulic residence time of the impoundment, which influence not only the magnitude of fine-sediment accumulation but also the potential for thermal stratification and the development of an anoxic hypolimnion.

Biotic responses to dam removal have often been large and rapid. Some of the most dramatic changes stem from the removal of the dam as an obstruction to upstream movement by migratory fish. Within a year after the removal of Edwards Dam on the Kennebec River, large numbers of American eel (*Anguilla rostrata),* alewife *(Alosa pseudoharengus),* Atlantic and shortnose sturgeon *(Acipenser oxyrhynchus* and *A. brevirostrum),* and striped bass *(Morone saxatilis)* were observed in upstream habitats that had been inaccessible to these species for more than 150 years (O'Donnell et al. 2001). Two years after removal, more than 1000 larval and juvenile American shad *(Alosa sapidissima)* were collected in the newly accessible reach, and many of these appear to be derived from wild stocks that have migrated upstream (M. O'Donnell, Maine Department of Marine Resources, Augusta, ME, personal communication, 2001). Similar responses by migratory species have been observed following the removal of dams on Bear Creek, Oregon (Smith et al. 2000); Mad River, California (Winter 1990), Neuse River, North Carolina (Bowman 2001); and Clearwater River, Idaho (Shuman 1995). Of course, migratory species are not always present downstream from a dam that is being removed, especially when dams located farther downstream obstruct their upstream movements (see, e.g., Horwitz et al. 2001).

Even in the absence of migratory fish, dam removal permits resident fish species to extend their movements throughout the system. This pattern was observed in the Chipola River, Florida (Estes et al. 1993, Hill et al. 1994); Pine River system, Michigan (Burroughs et al. 2001); Milwaukee River, Wisconsin (Nelson and Pajak 1990, Kanehl et al. 1997); and the Baraboo River system, Wisconsin (Catalano et al. 2001) (table 1). For example, within days or weeks after breaching of the Manatawny Creek Dam, fish that had been tagged downstream from the dam prior to removal were collected in the former impoundment and subsequently observed 1 km upstream (Horwitz et al. 2001). Many studies have also described a general shift from lentic (still water) to lotic (flowing water) species in the former impoundment, such as from carp (*Cyprinus carpio*) to smallmouth bass (*Micropterus dolomieu*) in the Milwaukee River (Nelson and Pajak 1990, Kanehl et al. 1997). Other potential responses to the reversal of dam impacts, including changes in predation on downstream migrants (Zimmerman and Ward 1999) and changes in genetic and population structure (Jager et al. 2001, Neraas and Spruell 2001), have not yet been observed in actual dam removal studies.

Other organisms whose movements are less likely to be hindered by dams can also show dramatic responses to dam removal. For instance, species of benthic algae and macroinvertebrates that were rare or absent within the impoundment in Manatawny Creek increased in abundance within months after dam removal, transforming this zone from a lentic to lotic environment (Hart et al. 2001). Similar results for algae have been observed in Kennebec River, Maine (Casper et al. 2001), and for macroinvertebrates in Baraboo River, Wisconsin (Stanley et al. 2002), and in Turtle Creek, Wisconsin (Pollard and Reed-Anderson 2001).

Given the small number of dam removal studies, as well as the wide range of observed outcomes, we cannot yet draw general conclusions about the range, magnitude, and trajectory of expected ecological responses. Several other factors limit our ability to draw more robust conclusions:

- Most studies are of only a few components of the system (e.g., fish or sediment), rather than an integrated assessment of ecological responses.
- Some studies have relied on qualitative observations rather than quantitative measurements of responses.
- The sampling designs used to make inferences about dam removal effects are often limited by inadequate spatial and temporal replication.
- Dam removal usually causes many abiotic factors to change simultaneously (e.g., flow, sediment transport, water temperature), thereby hampering the identification of causal pathways that govern observed responses.

Improved understanding will require not only that these limitations be overcome but also that a greater focus be placed on how responses to removal vary with dam type, river characteristics, and watershed setting.

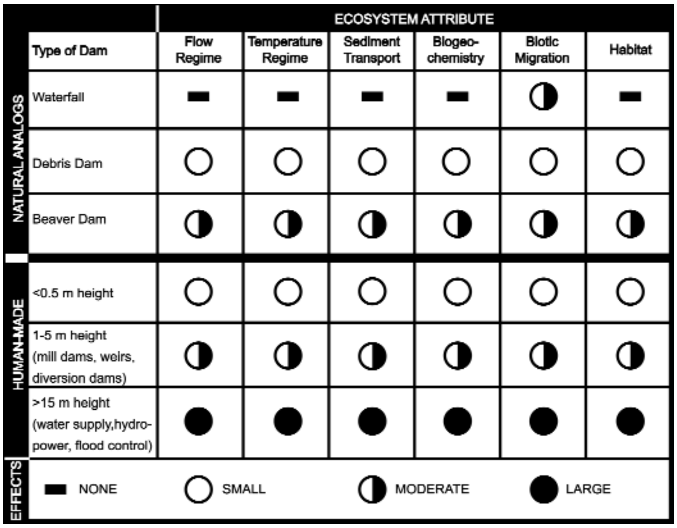
Predictions based on ecological effects of existing dams. A simpler, alternative procedure for predicting dam removal responses is to assume that the ecological impacts of an existing dam can be reversed once the dam is removed; we examine the validity of this assumption below. This method seeks to identify the expected ecological conditions, or restoration endpoints, that would exist after a sufficient time period has elapsed following dam removal to permit complete recovery. The approach is more limited than analyses of actual dam removals, however, because it cannot predict the time course of ecological responses. Some useful insights regarding the sequence and rate of these responses can potentially be gained from Petts (1984), who examined various time scales at which different physical, chemical, and biological characteristics responded to the construction of dams.

A central challenge in applying this approach is to determine the type and magnitude of impacts caused by an existing dam. For example, dams vary greatly in size, operation, and watershed setting, and this potentially creates large differences in their ecological impacts (Poff and Hart 2002). Unfortunately, ecologists have not yet studied a wide enough range of dam types to make accurate predictions about the effects of such variation on the structure and function of river ecosystems. Most studies have focused on the ecological effects of large storage dams, which clearly have major impacts on rivers (Ward and Stanford 1979, Petts 1984, Collier et al. 1996). Yet most dams being removed are small, and the effects of small dams may be quite different from those of large dams (Benstead et al. 1999, Poff and Hart 2002). Despite the fact that small, human-made dams have received little study, some insights about their ecological effects can be gained from research on natural analogs of small dams (box 1). For example, beaver (*Castor canadensis*) dams often cause large changes in aquatic habitat types and biogeochemical cycles as well as moderate changes in sediment transport, but they usually have smaller effects on downstream flow regimes. In contrast, waterfalls probably have negligible effects on most ecosystem characteristics, but they can be potent barriers to the upstream movements of fish.

The ecological effects of small human-made dams are likely to be intermediate between the effects of various small natural dams and those of large human-made dams. Figure 2 explores how various ecosystem attributes (e.g., flow regime, sediment transport, biotic migration) may be affected by different types of human-made dams and natural analogs of small dams. For example, beaver dams and small mill dams probably have qualitatively similar effects on nutrient cycling, habitat, and biotic migration, but the range and magnitude of beaver dam effects are presumably reduced because of their porosity and intermittent breakage. Similarly, both small mill dams and large flood control dams can potentially affect flow and temperature regimes, but the impact of the latter structures generally is magnified because of their greater storage capacity, hydraulic residence time, and tendency to stratify thermally. Indeed, recent studies support the idea that small, human-made dams have reduced effects on thermal regimes (Newcomb 1998, Lessard 2000) and flow regimes (Magilligan and Nislow 2001), compared with large storage dams.

Ultimately, the ability to predict ecological responses to dam removal from a knowledge of existing dam effects could be greatly improved by studying a broader range of dam sizes and types, especially smaller dams. For example, simple scaling considerations may facilitate the prediction of dam effects on some ecosystem attributes as a function of dam and river characteristics, such as the effect of dam height on fish blockage. For this approach to yield useful predictions, however, we need to determine whether the ecological effects of existing dams are actually reversible.

Are the impacts of dams reversible? Given a sufficient amount of time, many of the ecological impacts that dams have on rivers are likely to be largely reversed following dam removal. To date, however, no studies of dam removal have continued long enough to determine the response rates of all ecosystem components. The time course and sequence of recovery will also differ among rivers, dam types, and climatic settings, which must be accounted for to develop realistic expectations about restoration outcomes. Moreover, future



		ECOSYSTEM ATTRIBUTE					
	Type of Dam	Flow Regime	Temperature Regime	Sediment Transport	Biogeo-chemistry	Biotic Migration	Habitat
NATURAL ANALOGS	Waterfall	▬	▬	▬	▬	◑	▬
	Debris Dam	○	○	○	○	○	○
	Beaver Dam	◑	◑	◑	◑	◑	◑
HUMAN-MADE	<0.5 m height	○	○	○	○	○	○
	1-5 m height (mill dams, weirs, diversion dams)	◑	◑	◑	◑	◑	◑
	>15 m height (water supply, hydro-power, flood control)	●	●	●	●	●	●

EFFECTS: ▬ NONE ○ SMALL ◑ MODERATE ● LARGE

Figure 2. Hypothetical relationship between dam type and various ecosystem attributes. Dam types include both natural dams (generally small) and human-made dams of varying heights and operations. The effects level can be defined in terms of the magnitude of change (e.g., the difference between the maximum annual downstream temperature in the presence vs. absence of the dam), the spatial extent of change (e.g., the length of the downstream zone in which temperatures are altered), and the temporal duration of change (e.g., the time interval between beaver dam failures during which biotic migration is obstructed). Thus, the effect of a 1 m mill dam on downstream temperatures is reduced compared with a 50 m flood control dam with a hypolimnetic release, in terms of both the absolute temperature change and the downstream distance at which such changes are manifested.

Box 1. Natural analogs to small dams: Similarities and differences

Natural analog	Small dam comparison
Debris dams	Debris dams alter stream flow, habitat structure, and particulate transport (Bilby and Likens 1980, Wallace and Benke 1984). Debris dams are typically small (< 1 m), porous, and relatively ephemeral.
Beaver dams	Beaver dams have the potential to alter the hydrology, channel geomorphology, biogeochemistry, and productivity of a stream ecosystem (Naiman et al. 1988). Beaver dams may be short-lived, but some dams may exist for decades, and beaver populations may maintain dams at various sites within a watershed over long periods. There is a general shift in the biota of these impoundments from lotic to lentic (Naiman et al. 1988, Snodgrass and Meffe 1998), and fish passage may be blocked (Avery 1992). Beavers alter the riparian areas by cutting mature trees for both dam building and food, which, in turn, opens the surrounding canopy, alters the litter input to the stream, and in many cases causes a shift in vegetation from tree to shrub (Naiman et al. 1988). Most beaver dams are small (< 2 m), semiporous, and subject to intermittent periods of flow between partial breaks and repair.
Landslides	Although there has been increasing attention to landslides as geomorphic agents (Naiman et al. 2000), there has been less attention to impoundment and downstream effects.
Waterfalls	Waterfalls can block fish passage, in some cases providing upstream refuges from introduced species. Impoundment and downstream effects depend on the precise geological conditions of the falls.
Lake outlets	Reservoirs create many of the major impacts on downstream reaches. Lake outlets provide a natural analog to many of these effects, without effects of blockage. Sedimentation, reduced downstream transport of coarse sediments, increased residence time (and consequent geochemical effects), increased primary production and downstream export of plankton, stratification, and support of lentic species occur in both lakes and reservoirs. Increased abundance of filter-feeding macroinvertebrates (e.g., hydropsychid caddis flies, black fly larvae) has been demonstrated in both lake outlet and tailwater locations (Richardson and Mackay 1991). Reservoirs are often very different from natural lakes (due to hypolimnetic releases, significant flow regulation and manipulation of reservoir levels, dendritic topography, etc.), but outlets may provide analogs for smaller, run-of-river dams. More information is needed, however, on the ecological, geochemical, and geomorphic effects of lakes on outlet streams.

research may identify management practices (e.g., timing of dam breaching, sediment management, control of exotic species, riparian planting, improving in-stream habitat, or reintroducing desirable organisms) that can increase recovery rates in some circumstances.

Our previous discussion of observed responses to dam removal has direct relevance to the question of ecological reversibility, and it is useful to review some of the major factors likely to influence the recovery process and the potential for reversibility. For example, soon after dam removal, many features of the river's flow regime may be restored. The effects of a dam on water quality and thermal regime often are rapidly reversed because of decreased hydraulic residence time and stratification, which in turn affect sedimentation and nutrient cycling. The time course of geomorphic adjustments to dam removal varies with the sediment types within the former impoundment and the ability of the river to transport that sediment (Pizzuto 2002, Stanley and Doyle 2002). Several years to more than a decade may be needed to reestablish an equilibrium channel. The slower time scale of geomorphic change may also control the rate of change in other ecosystem attributes. For instance, sediment-bound nutrients in the former impoundment may continue to affect water quality. Several important ecosystem features (e.g., pattern of floodplain inundation and habitat characteristics) are strongly affected by hydrology, which in turn depends on channel morphology, so the restoration of these ecological attributes follows the time scale of channel changes.

Biota respond to the physical removal of the barrier, as well as to changes in water chemistry, habitat, and flow regime. The potential for recovery of various taxa following dam removal varies markedly, depending in part on their ability to colonize and thrive in new habitats. For instance, algae, some higher plants, and many invertebrates may quickly colonize the former impoundment and downstream reaches by means of downstream transport. Plant seeds may also be present in impoundment sediments (Shafroth et al. 2002). Although initial colonization may be rapid, population recovery in the former impoundment and downstream reaches ultimately depends on restoration of habitat conditions (e.g., temperature, substrate, topography, large woody debris) that are strongly influenced by channel morphology, flow regimes, and riparian vegetation. The time course of recovery is influenced by individual and population growth rates (e.g., benthic algae recover more quickly than riparian trees). Similarly, unionid mussels may colonize slowly because of their relatively slow growth rates and specific habitat requirements, as well as their dependence on fish for dispersal (Watters 1996).

Studies of biotic recovery have focused particular attention on the elimination of blockage to anadromous fish migrations. These species are quite mobile and can move many miles upstream from the dam site within weeks to months following removal. Recolonization of migratory species may occur slowly or not at all without active introduction programs, however, if migration depends on the existence of stocks that have imprinted on natal streams or that require cues based on conspecific pheromones (Vrieze and Sorensen 2001).

Determining whether dam impacts are reversible not only requires a focus on the processes that contribute to ecological recovery following dam removal, it also depends on how the concept of reversibility is defined. To some, reversal may denote the attainment of ecological conditions that existed before the dam was constructed or that are present in regional reference sites (NRC 1992). Given the widespread occurrence of beaver dams in North America prior to European settlement (Naiman et al. 1988), however, some qualitative effects of dams undoubtedly existed long before humans constructed dams (see box 1 and figure 2). More important, dams are usually not the only factor impairing river ecosystems, which can lead to unrealistic expectations about recovery following dam removal. Many dams are located in watersheds that are stressed by other forms of habitat alteration (e.g., channelization, loss of riparian vegetation) as well as a diverse array of point source and non–point source pollutants.

Mechanistic and empirical models for predicting responses to dam removal. Given the wide range of possible impacts of dams and dam removal, and the complex ways these impacts depend on dam, river, and watershed characteristics, models can potentially serve as an important predictive tool. For example, conceptual models of sediment transport provide a valuable framework for understanding changes in channel form following dam removal, although precise quantitative models do not yet exist (Pizzuto 2002). Similarly, population fragmentation models used to predict dam impacts on migratory and resident fishes (Jager et al. 2001) may help in evaluating population consequences of dam removal.

Simple models are needed that can predict the occurrence and magnitude of important impoundment processes (e.g., sedimentation, stratification, and nutrient transformations) on the basis of characteristics such as dam and reservoir dimensions or hydraulic residence time (volume/discharge). For example, various formulations of lake nutrient models relate concentrations to geometric and hydraulic parameters such as the surface overflow rate, calculated as either discharge/surface area or depth/hydraulic residence time (Chapra and Reckhow 1983, Reckhow and Chapra 1983). The occurrence of thermal stratification is related to depth, wind speed, water velocity, and heat flux (Condie and Webster 2001). For instance, surface area/depth has been used as a simple predictor of susceptibility to stratification in lakes (Stefan et al. 1996). Although these indices may correctly rank some relative effects of large and small dams, no single parameter of dam size can properly scale all dam effects. For example, models designed to incorporate the effects of river inflows and outflows and the complex topography of impoundments usually require more complex terms for advection (e.g., river-run models; Chapra and Reckhow 1983) and spatial subdivision (Schnoor 1996).

Dam removal and river restoration

Risk assessment framework for evaluating the potential effects of dam removal. If dam removal is to become an effective method of river restoration, we must be able to predict the potential benefits of any proposed removal. As discussed above, prior dam removal studies, as well as assessments of existing dam impacts, indicate that the ecological effects of dam removal are likely to vary from project to project because of differences in dam, river, and watershed characteristics. How can we improve the scientific basis for dam removal decisions if ecological responses to removal are so variable?

We propose an ecological risk assessment framework that can be used to account for many of the factors that influence variation in potential responses to dam removal, thereby enhancing our ability to predict those responses. In ecological risk assessment, ecological effects are characterized by determining the potential effects imposed by a stressor, linking these effects to assessment endpoints, and evaluating how effects change with different stressor levels (USEPA 1998). As used above, "effects" are the observed changes in various ecological attributes, and "endpoints" are the broader environmental values or management goals that give context and meaning to the observed effects. This basic framework can be used to evaluate the effects of dam removal by considering dams as stressors and dam size (or another measure that accounts for dam, river, and watershed characteristics) as a measure of stressor level. The ecological effects of dam removal can then be determined as a function of variation in dam and watershed characteristics. Application of this framework allows an assessment of the potential benefits of dam removal across a range of dam and river or watershed conditions in the context of specific watershed management goals (e.g., fisheries production, water quality enhancement, habitat improvement). In turn, this information can be used to help select and prioritize dam removal projects, thereby maximizing the effectiveness of dam removal in river restoration.

Central to this approach is the determination of how the ecological effects of dam removal vary across a range of dam and watershed characteristics. In the language of ecological risk assessment, the relationship between a river's ecological integrity (response) and a particular dam or watershed characteristic (stressor) such as dam size is called a stressor–response relationship (figure 3). When a reference condition is considered together with a stressor–response relationship, the maximum "potential" benefit of a particular dam removal can be determined. For example, the maximum potential benefit for curve 2 at a dam stressor level of *x* is shown by the arrow (figure 3). Given the shape of the stressor–response relationship and the magnitude of the stressor, a maximum potential benefit can thus be estimated for any ecological attribute resulting from the removal of a dam. Achieving the maximum potential benefit assumes complete recovery of the system to predam conditions, which may not always be possible. As in all restoration, selection of reference conditions is extremely important, and the methods used to determine reference conditions are likely to differ among ecological attributes. For example, potential reference conditions could be based on upstream conditions, historical conditions prior to dam construction, or conditions at regional reference sites.

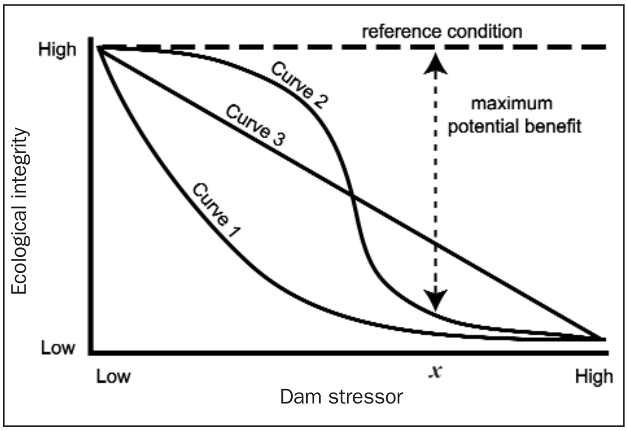


Figure 3. Generalized linear and nonlinear relationships between dam stress (stressor) and ecological integrity (response). Dam stress may be characterized as crest height or dam width, or it may be scaled according to various river and watershed characteristics. Ecological integrity can refer to any physical, chemical, or biological attribute of the river system. Many nonlinear forms of this relationship are possible. For a given stressor level, the maximum potential benefit of dam removal is shown as the difference between the stressor–response curve and a reference condition.

To apply this risk assessment framework, it is important to understand how the effects of dam removal differ across a range of dam and watershed characteristics, and to recognize that the shape of the stressor–response relationship varies with different ecological effects and endpoints. For example, three potential relationships are shown in figure 3, although many more are possible. Curve 1 depicts a nonlinear relationship where the reduction in ecological integrity with a unit increase in dam stress is greatest at low dam stress levels. This could potentially describe the effect of dam height on the upstream migration of river herring, whose passage is obstructed by even the smallest of dams and culverts. Curve 2 also shows a nonlinear relationship, but in this case there are two thresholds rather than one. This may be representative of changes in temperature or various biogeochemical processes affected by thermal stratification. For instance, a lower threshold in depth or hydraulic residence time has to be exceeded before stratification begins, and once the upper threshold for this relationship is exceeded, no further changes in stratification occur. Lastly, curve 3 shows a simple linear relationship where the ecosystem response is directly proportional to the dam stress. It is not yet clear what components of ecological integrity might be linearly related to particular dam stressors. Note that if the stressor–response relationship is nonlinear, then the potential benefits of dam removal vary in a complex way depending on dam and watershed characteristics. For example, if the stressor–response relationship is similar to curve 2, then the removal of dams with stressor levels below the lower threshold may yield relatively small ecological benefits.

Currently, the shape of these stressor–response relationships is not well known, but relationships can be developed using any of the three approaches for predicting ecological responses to dam removal discussed previously. Establishing relationships based on observation of completed dam removal projects, however, would require comprehensive studies lasting many years at numerous sites across a gradient of dam, river, and watershed characteristics. This may not be possible for a number of years, because so few studies of dam removal have been completed. Likewise, the development of mechanistic models describing ecosystem structure and function has not yet advanced to the stage where they can be readily used to predict stressor–response relationships. Thus, we suggest that the best opportunity at the present time for developing stressor–response relationships and predicting restoration outcomes is to examine the effects of existing dams. We are currently quantifying these relationships across a range of dam and river types in the Mid-Atlantic region, with the ultimate goal of using this approach to prioritize dam removals so that restoration benefits are maximized. We also strongly encourage studies of actual dam removals and the development of better mechanistic models to help define stressor–response relationships.

The successful application of this risk assessment approach depends on the ability to extrapolate from the known ecological effects of a sample of dams to predict the effects of other dams being considered for removal. This requires that ecological responses to the removal of a particular dam are similar to the responses that would occur for other dams of similar size, operational type, hydraulic residence time, drainage area, and so on. Given the potential for marked geographic variation in dam impacts and river responses, this requirement is more likely to be met in a restricted physiographic region. We also need to identify appropriate measures or scaling factors that can quantify the relative stress imposed by a given dam on a particular river. Although dam height is clearly important, the impact of a dam on a river is also likely to vary depending on river characteristics such as flow regime, channel form, sediment transport, and nutrient status. A number of different measures may also prove useful in predicting dam impacts, including the impoundment's hydraulic residence time, ratio of dam height to a reference channel width, degree of flow modification, and frequency of thermal stratification within impoundments.

Potential adverse effects of dam removal. The risk assessment framework can help guide dam removal decisions based on expected restoration outcomes, but we must also be mindful that dam removal can have negative effects. For example, ecological impacts sometimes result from large movements of sediment (especially when contaminants are present). An ongoing dam removal study on Kettle River, Minnesota, revealed declines in downstream mussel populations following a dam removal; the declines were attributed to the export of coarse sediment from the former impoundment. The extent to which these effects were offset by restored fish host access to upstream areas is unclear (L. Aadlund, Minnesota Department of Natural Resources, Fergus Falls, MN, personal communication, 2001) (table 1). In the Baraboo River system (WI), the removal of several dams improved fish habitat quality within the former impoundments but decreased fish habitat downstream (Catalano et al. 2001). Substantial reductions in the abundance of several nonmigratory fish species were observed immediately downstream from the former dam following several major sediment transport events that occurred after the removal of Manatawny Creek Dam (Horwitz et al. 2001). These negative effects were probably due to habitat modification (e.g., sediment accumulation in pools and parts of riffles, and sediment scouring in other parts of riffles) that caused fish to move to other areas. Partial recovery of fish assemblages in these riffles was observed a year after removal, and full recovery is likely once sediment from the former impoundment has moved downstream.

Other adverse effects may include reductions in wetland habitat or groundwater recharge, as well as shifts in species abundance and distribution. For example, declines in recreationally important biota have been observed for several removals. In addition, despite the recommended usage of dam removal to eliminate barriers to fish movement, there are some situations where removal could potentially increase the chances that exotic species presently blocked by dams could invade upstream habitats. For instance, dam removal could permit sea lamprey (*Petromyzon marinus*) to invade various rivers that drain into the Great Lakes (Dodd 1999), or flathead catfish (*Pylodictis olivaris*) could move upstream in various rivers of the Atlantic coastal plain (T. Kwak, North Carolina State University, Raleigh, NC, personal communication, 2001).

Some of these adverse responses to dam removal are probably transient, however, and might be considered analogous to the short-term impairment of human performance that often occurs during the recuperative period following surgery. Other impacts (e.g., those due to sediment transport) are perhaps best evaluated in the context of natural disturbance regimes. For example, the magnitude, timing, and duration of sediment effects associated with dam removal may be no different from those caused by natural variations in sediment transport. Alternatively, suspended and bedload transport following dam removal may greatly exceed natural levels, thus producing ecological changes far beyond those caused by natural disturbance. Some undesirable effects of dam removal can potentially be reduced by developing improved restoration practices, particularly with respect to sediment management (ASCE 1997). For instance, inexpensive but effective methods are needed to assess and mitigate contaminant risks. These assessments should include a review of the historical usage of the watershed, as well as an analysis of the type and grain size of sediments in the impoundment (Bushaw-Newton et al. 2001). Even when contaminants are absent, we need to know how much sediment can safely be released, and during what seasons, to minimize downstream impacts. Such information could guide efforts to control sediment releases by removing dams incrementally (ASCE 1997), or by planting riparian vegetation to stabilize sediments (e.g., Shafroth et al. 2002). In some cases, species of special concern may be particularly vulnerable during dam removal. For example, some species of fish or mussels may be stranded as the impoundment is drawn down, which may create a need for inexpensive methods of collecting and relocating these species.

Comprehensive watershed management and dam removal. Dam removal may be the most direct and effective method for eliminating the negative effects of dams on the structure and function of river ecosystems, but it is only one of several dam management alternatives. Depending on the particular dam, these options may include no action, structural repair, dam removal, or changes to dam operations (ASCE 1997). The last option potentially involves a variety of actions, such as the installation or improvement of devices to allow fish passage, modification of water release practices to create more natural flow and sediment transport regimes (Webb et al. 1999), or the enhancement of downstream water quality by aeration and temperature modification (Higgins and Brock 1999). Wherever possible, objective criteria and formal models should be used to evaluate the costs and benefits of these dam management alternatives (Whitelaw and MacMullan 2002). In cases in which dam removal is not considered a viable option (e.g., for economic or political reasons), various reoperation strategies have the potential to reduce some (but not all) of the negative effects that dams can have on ecological integrity.

In most watersheds, however, successful river restoration will require a focus on more than just the problems created by dams. Effective watershed management depends on an integrative approach that identifies the full range and types of stressors impairing the ecosystem and implements controls and practices to reduce these impacts. Because many streams and rivers are impaired by more than one kind of stressor, a coordinated effort is clearly needed. For example, a particular river system may potentially be impaired by acid mine drainage or sediment from logging operations in its headwaters, by hydropower dams and nutrient-enriched runoff from agricultural fields in its middle reaches, and by high contaminant levels emanating from urban sources (e.g., wastewater effluent as well as stormwater runoff) near its mouth. Dam removal may prove to be a particularly useful method for reducing some forms of ecosystem impairment, but it needs to be considered as part of a broad, watershed-scale management plan (Stanford et al. 1996). To accomplish effective river restoration, dam removal will likely need to be coupled with other protection and restoration practices.

Conclusion

Over the last few years, there has been an increasing focus on the potential value of dam removal in river restoration by ecological researchers, watershed managers, and policymakers. The growing number of scientific studies provides an important opportunity to learn how better to manage watersheds and improve our understanding of the science of river restoration. Increases in the number of completed and prospective dam removals also create a significant challenge, however. Without an integrated scientific framework within which to predict and examine potential ecological responses, there is the danger that these projects will proceed without sufficient learning to improve the effectiveness of future removals. By placing some of our current knowledge in a risk assessment framework, scientists, managers, and other stakeholders can begin to understand and predict how dam removal can be used most effectively to achieve watershed restoration goals.

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