# How Dams Vary and Why It Matters for the Emerging Science of Dam Removal

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Dams are structures designed by humans to capture water and modify the magnitude and timing of its movement downstream. The damming of streams and rivers has been integral to human population growth and technological innovation. Among other things, dams have reduced flood hazard and allowed humans to settle and farm productive alluvial soils on river floodplains; they have harnessed the power of moving water for commerce and industry; and they have created reservoirs to augment the supply of water during periods of drought. In the 5000 or so years that humans have been building dams, millions have been constructed globally, especially in the last 100 years (Smith 1971, WCD 2000).

If dams have successfully met so many human needs, why is there a growing call for their removal? The answers to this question require an appreciation of society's changing needs for, and concerns about, dams, including the emerging recognition that dams can impair river ecosystems (Babbit 2002). But decisions about dam removal are complex, in no small part because great scientific uncertainty exists over the potential environmental benefits of dam removal. Certainly, the scarcity of empirical knowledge on environmental responses to dam removal contributes to this uncertainty (Hart et al. 2002). More fundamentally, however, a scientific framework is lacking for considering how the tremendous variation in dam and river attributes determines the ecological impacts of dams and the restoration potential following removal. Such an ecological classification of dams is ultimately needed to support the emerging science of dam removal.

In this article, we develop a conceptual foundation for the emerging science of dam removal by (a) reviewing the ways that dams impair river ecosystems, (b) examining criteria used to classify dams and describing how these criteria are of limited value in evaluating the environmental effects of dams, (c) quantifying patterns of variation in some environmentally relevant dam characteristics using governmental databases, (d) specifying a framework that can guide the development of an ecological classification of dams, and (e) evaluating the ways that dam characteristics affect removal decisions and the future of dam removals. We restrict our analysis to the United States, where dam removals are currently hotly debated; however, the ecological framework we advocate could also be generalized to other parts of the world.

AN ECOLOGICAL CLASSIFICATION OF DAMS IS NEEDED TO CHARACTERIZE HOW THE TREMENDOUS VARIATION IN THE SIZE, OPERATIONAL MODE, AGE, AND NUMBER OF DAMS IN A RIVER BASIN INFLUENCES THE POTENTIAL FOR RESTORING REGULATED RIVERS VIA DAM REMOVAL

## How dams impair river ecosystems

Although the rationale for dam removal often includes a range of social and economic concerns (RAW/TU 2000), the central justification for removing dams from an environmental perspective is that they adversely impact the structure and function of river ecosystems. Both individually and cumulatively, dams fundamentally transform river ecosystems

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in several ways: (a) They alter the downstream flux of water and sediment, which modifies biogeochemical cycles as well as the structure and dynamics of aquatic and riparian habitats. (b) They change water temperatures, which influences organismal bioenergetics and vital rates. (c) And they create barriers to upstream–downstream movement of organisms and nutrients, which hinders biotic exchange. These fundamental alterations have significant ecological ramifications at a range of spatial and temporal scales.

***Local effects.*** The local, or site-specific, alterations caused by dams, especially very large dams, have been studied extensively over the last few decades (Ward and Stanford 1979, Petts 1984, Ligon et al. 1995, Collier et al. 1996, Pringle et al. 2000). Storage of water and capture of sediment by dams cause profound downstream changes in the natural patterns of hydrologic variation and sediment transport. Numerous ecological adjustments follow. For example, reduction in the magnitude of downstream peak flows typically isolates the main channel from the floodplain, resulting in reduced recruitment of riparian species (Scott et al. 1996) and reduced access to floodplain habitats for fishes (Bayley 1995). Long-term storage and nonseasonal release of floodwaters can severely alter downstream food webs and aquatic productivity (Wootton et al. 1996). Many hydropower dams operate to produce dramatic daily flow variation that effectively reduces downstream habitat and aquatic productivity (see Poff et al. 1997 for examples). Water released from the reservoir may carve into the downstream river channel as it reestablishes its transport capacity, causing channel incision and isolating it from adjacent floodplains or tributary outlets (Petts 1984, Collier et al. 1996). Fine sediments are preferentially transported, often resulting in an excessive coarsening and armoring of the riverbed and a reduction in habitat quality for bottom-dwelling organisms.

If reservoirs exceed a certain depth and flows are slow enough, thermal stratification can occur. Deep waters can have very different temperatures than those on the surface, often maintaining temperatures near 4°C. Thus, downstream from reservoirs that release this deep water, the thermal regime is characteristically "summer cool, winter warm." Because temperature directly affects the growth and developmental rates of aquatic organisms, such altered thermal regimes greatly modify the densities and kinds of species present. This new downstream regime is favorable for cold-adapted species like trout, and warm-adapted species often diminish in abundance or are lost (Ward and Stanford 1979). Thermal alteration and biological disruption can persist for tens of kilometers (km) downstream, depending on downstream tributary inflows (Muth et al. 2000).

***Landscape effects.*** Dams occur so frequently in many watersheds that their cumulative ecological effects are likely to be profound, although this idea has received less attention than studies of individual dams. For example, Benke (1990) reported that there are only 42 high-quality, undammed rivers longer than 200 km remaining in the continental United States, and Wisconsin has an average of one dam for every 14 km of river (WDNR 1995). The extensive fragmentation of free-flowing rivers promotes ecosystem isolation. The imperiled status of many salmon stocks in the Pacific Northwest is in part attributable to the gauntlet of dams these fish encounter in their migrations to and from the ocean (NRC 1996). Fragmentation also prevents the dispersal and persistence of inland species. For example, the diversity of European riparian communities is probably reduced because of the interruption by multiple dams of the downstream transport of water-dispersed seeds (Nilsson and Berggren 2000). Prevention of exchange among isolated populations may also imperil inland fish populations and other species such as mussels (Pringle et al. 2000, Fausch et al. 2002).

Water storage and sediment capture by thousands of dams has also measurably altered earth surface processes at regional and global scales (Graf 1999, Rosenberg et al. 2000). For example, the suspended-sediment loads carried by the Mississippi River to the Gulf of Mexico have decreased by one-half since the Mississippi Valley was first settled by European colonists, mostly from the construction since 1950 of large reservoirs on the sediment-laden Missouri and Arkansas rivers (Meade 1995). Other associated cumulative effects of dams that have either been demonstrated or postulated include alteration of sea level (Chao 1991), generation of greenhouse gases (St. Louis et al. 2000), and disruption of the hydrologic flux to the oceans (Sahagian 2000).

## Criteria used to describe dams and their scientific limitations

Several criteria are used to characterize dams from an engineering perspective. Some of these criteria bear more strongly on the issue of dam removal and river restoration than others. Chief among these are the size of a dam, its operational purpose, and its age. Dam size not only influences such engineering considerations as construction and repair costs, it also affects the potential range and magnitude of ecological disturbances to the aquatic ecosystem (ASCE 1997). A dam's operational plan influences the type, magnitude, frequency, and timing of environmental impacts on the riverine ecosystem. The age of a dam can affect structural repair costs, as well as the cumulative magnitude of downstream channel alteration because of sediment accumulation within the impoundment. Traditionally, dam size and operational type have been discussed among engineers in simple categorical terms, such as small versus large dams, or storage versus run-of-river dams. In reality, these characteristics are more continuous and multidimensional, and it will be important to analyze and synthesize this complexity in developing an ecological classification to support the emerging science of dam removal.

***Dam size.*** Structures have generally been small for most of the history of dam building, reflecting preindustrial technical skills and agrarian social needs. During the 19th and 20th centuries, however, new technologies allowed the construction of much larger and more complicated structures to generate hydroelectricity, control floods, provide drinking water, support large-scale irrigation, and improve navigation (Smith 1971, Schnitter 1994). In the United States, the pace of dam building accelerated dramatically after World War II, though relatively few dams have been constructed in the last 10 to 20 years (Graf 1999). It is during this period of building large dams that the burgeoning scientific understanding of the environmental impacts of river regulation has developed, with its focus on the large structures that dramatically alter riverine ecosystems. Yet most of the dams on the planet are relatively small structures, and evaluation of their environmental impacts is critical to the issue of dam removal.

Dams vary tremendously in size (height and width) and hence in their reservoir storage volume, factors that have very important direct and indirect environmental impacts (see below). Thus it is very tempting to use size as a primary descriptor of a dam's potential ecological impact. Unfortunately, the criteria used by governmental agencies and organizations to classify dam size do not adequately reflect this variation, and these criteria are not always used in a consistent manner. For example, the US Army Corps of Engineers' National Inventory of Dams (USACE 2000) emphasizes dam safety and defines dams as large if they meet one of three criteria: (1) a high hazard potential (i.e., likely loss of human life if the dam fails), regardless of the dam's absolute size; (2) a low hazard potential but height exceeding 7.6 meters (m) and storage capacity greater than 18,500 cubic meters ($m^3$); or (3) a low hazard potential but height exceeding about 1.8 m and storage exceeding 61,700 $m^3$. Other organizations have adopted quite different criteria for defining dam size. For example, the International Commission on Large Dams classifies dams as large if either their height exceeds 15 m or their height is between 5 and 15 m and a reservoir greater than $3 \times 10^6$ $m^3$ is impounded (WCD 2000). Yet another classification defines hydropower dams as either low-head or high-head, depending on whether their height is less than 30 m or greater than 30 m, respectively (EnergyIdeas 2001). The criteria for classifying dams even differ among states.

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There are at least two reasons why these criteria are problematic for defining dam characteristics from the perspective of environmental effects. First, as illustrated above, the same dam can be classified as large according to one definition and small according to another. Second, even if only one definition is adopted, dams that are grouped together can vary tremendously in size. For example, the USACE (2000) database of large dams includes structures with heights ranging from less than 2 m to more than 200 m, and storage volumes from less than 100 $m^3$ to $3.7 \times 10^{10}$ $m^3$. Such marked differences in dam size will necessarily translate into very different uses and environmental effects.

***Dam operations.*** Although designed to meet many different human needs, the two basic functions of dams are to store water and raise water levels (McCully 1996). The storage ability of dams allows runoff to be retained for subsequent controlled release, whereas the ability to raise upstream water levels permits water diversion, increases hydraulic head for hydropower generation, creates impoundments for recreation, and so on. The most common classification of operational characteristics divides dams into two groups, storage and run-of-river, based in large part on these functional differences (USBR 2001). For example, a storage dam typically has a large hydraulic head and storage volume, long hydraulic residence time, and control over the rate at which water is released from the impoundment. By contrast, a run-of-river dam usually has a small hydraulic head and storage volume, short residence time, and little or no control over the water-release rate (EPA 2001).

As with dam size, however, this dichotomous classification has several limitations. First, different criteria are sometimes used to place dams in an operational class. For instance, the state of Pennsylvania defines run-of-river dams as relatively small structures whose impoundments are confined completely within the banks at normal flow levels (Pennsylvania Fish and Boat Commission 2001), a much more restricted definition than that used by most federal agencies. Second, membership in a single class can conceal large and important variation. For instance, storage dams can include flood-control dams that dramatically alter seasonal flow patterns, as well as hydropower dams that impact flow regimes primarily on a time scale of hours to days, in response to fluctuating electrical demand. Likewise, run-of-river dams can have whole-reservoir turnover times ranging from a few hours to many weeks, and impoundment depths ranging from 1 m to more than 30 m. Finally, many "multipurpose dams" are used for flood control, irrigation, navigation, power generation, and recreation and do not fit neatly in either operational class.

Despite the challenges involved in creating a simple classification system that effectively describes variation in the size and operational characteristics of dams, such variation can have markedly different ecological effects (Hart et al. 2002). For example, the flow regime below a flood-control dam 50 m high will be moderated to reduce peak flows, increase base flows, and alter natural seasonal timing of flow variations (Petts 1984). By contrast, a run-of-river hydropower dam that is 10 m high may only occasionally modify peak flows and is unlikely to substantially alter thermal regimes downstream;

however, it will capture the coarser fraction of transported sediment. Very small dams, such as a 2-m-high diversion dam and run-of-river mill dam, are likely to have relatively limited effects on peak flows or downstream sediment regime by virtue of their small storage volume, although they may still reduce low flows downstream and prevent upstream movement of small fishes. Thus the development of a more complete understanding of dam effects, as well as responses to dam removal, will require improvements in our ability to characterize variation in ecologically important dam characteristics such as size and operational mode.

***Damage.*** Dams have a finite life span, so dam age can be an important factor affecting removal decisions. Two of the major factors influencing the aging process are the deterioration of construction materials and the accumulation of sediment within the dam's impoundment.

**Infrastructure safety and repair.** As dams age, they become more prone to failure. For example, the failure of three dams during the 1970s (Buffalo Creek, Teton, and Toccoa Creek) resulted in 175 fatalities and more than $1 billion in losses (ASCE 2001a). More recently, heavy rains from a single tropical storm in 1994 caused more than 230 dams to fail in Georgia (FEMA 2001). Because of the boom in US dam construction that occurred from 1950 to 1980, we now face problems stemming from aging dams. This challenge is exacerbated by the fact that one-third of high-hazard dams have not even undergone safety inspections in the last 8 years (ASCE 2001b). Although the failure of a small dam may threaten fewer lives and cause less property damage than a large dam, many small dams are much older and in poorer condition than large dams. Of course, the life span of some dams can be substantially increased by continuous maintenance, but the associated costs can be high. For example, the cost of repairing a small dam can be as much as three times greater than the cost of removing it (Born et al. 1998). We emphasize, however, that the relative costs of repair and removal are likely to vary markedly, depending on the regulatory policies of different states, especially as they address potential concerns about the quantity and quality of accumulated sediments. Nevertheless, these safety and repair issues underscore the challenges of maintaining an aging dam infrastructure.

**Sedimentation.** Sediment capture by dams reduces reservoir storage capacity and impairs dam functionality. For modern dams, this process generally happens at a much faster rate than the loss of structural integrity of construction materials. Thus sedimentation is often a factor limiting a dam's useful life (Morris and Fan 1998). For example, high sedimentation rates have reduced the storage capacity of Matilija Dam in southern California by about 50% since it was built in 1948 (Matilija Coalition 2000). By contrast, some dams with low sedimentation rates have remained functional for extremely long periods, in some cases up to many hundreds of years (Schnitter 1994).

The importance of sedimentation is now widely recognized, but sedimentation rates were not consistently factored into dam design criteria until the 1960s (Morris and Fan 1998), and many dams are expected to fill in with sediment at rates exceeding design expectations (Dendy 1968). Sedimentation rates vary greatly from watershed to watershed, however, because of spatial variation in sediment supply and delivery that is controlled by basin geology, slope, drainage density, and land use or cover. Erosion occurs largely in response to large precipitation events, so climate is also an important controlling factor in dam aging. Engineers now typically design reservoirs to incorporate a 100-year sediment storage pool, but human disturbance of land surfaces can greatly increase sediment yield and thus reduce a reservoir's effective life span. For example, sediment yield can increase by two orders of magnitude in regions with extensive road construction (Morris and Fan 1998).

## Patterns of variation in dam characteristics

Various agencies and organizations are responsible for maintaining inventories of dams and their characteristics, particularly for purposes such as dam safety and water supply. For example, the International Commission on Large Dams has a global inventory of about 45,000 large dams (WCD 2000). In the United States, the Army Corps of Engineers maintains the National Inventory of Dams (USACE 2000), which includes more than 76,500 "large" structures. In addition to these structures are an estimated 2,000,000 or more "small" dams in the United States that are not included in this national database (Graf 1993). Information for these smaller structures is compiled and maintained largely by state regulatory agencies and is therefore much more dispersed and uneven in geographic coverage. Indeed, only a few states have compiled comprehensive state-wide electronic databases for these smaller structures.

We examined variations in characteristics of dams in the federal database and then compared them with dam characteristics for two states, Wisconsin and Utah. The size (height) distribution of federally cataloged dams is illustrated in figure 1. Almost half the dams in the federal database are in the 4 to 16 m height range. The smallest dams (< 2 m) are relatively rare in the federal database, especially when compared with their estimated abundance on the landscape (Graf 1993). Dams in different parts of the United States are often operated in a different fashion because of regional variation in climate and economic activity. Such operational differences are clearly seen by dividing the United States into eight geographic regions that reflect broad differences in physical setting (climate, topography) and settlement history (figure 2).

The picture of operational purposes of dams shown in figure 2 is unlikely to represent operations for the 2,000,000 or so smaller dams that are not in a national database. In an effort to evaluate this expectation, we analyzed data for Wisconsin and Utah, two states that have relatively complete inventories and that differ markedly in climate and topography. These two states might offer some measure of the range of variation in operational purposes of small dams (although we

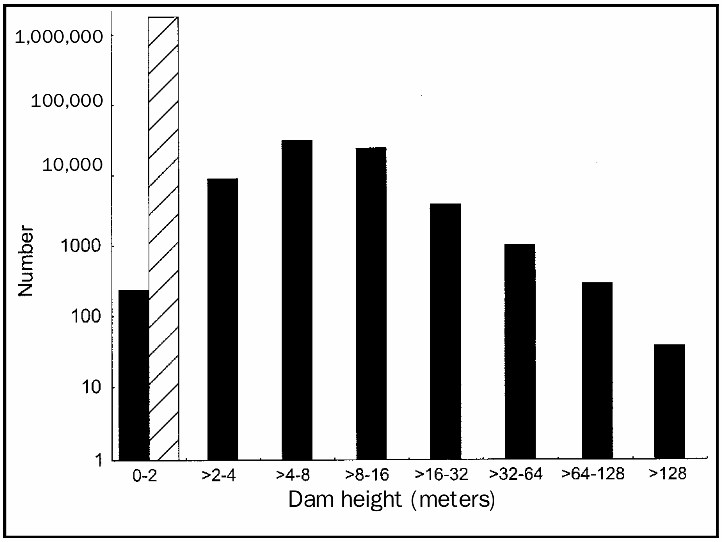


*Figure 1. Distribution of US dams by structure height. Data are from the National Inventory of Dams (solid bars; USACE 2000) and estimated by USACE for dams less than 2 meters in height (diagonally hatched bar; Graf 1993).*

do not argue they are statistically representative of the United States as a whole). By comparing the overlap of dams in these statewide databases with the more comprehensive national database, one can get a sense of the adequacy of using the national database to evaluate the distribution and function of the much more numerous small dams, which are more likely to be prime candidates for removal in the future.

Figure 3a compares the size distribution of the 3843 Wisconsin dams for which height is recorded in the state database with the 655 Wisconsin dams listed in the national database (USACE 2000). As expected, the national database under-represents the proportion of smaller structures (< 2 m) and overrepresents the proportion of larger structures (> 8 m). Moreover, the correspondence between the state and national databases in terms of operational purpose is poor. Most (39.4%) dams are classified by the state as "protection, stock or small farm pond," a use category represented by only 2% in the national database. By contrast, the national inventory overestimates recreation, fish and wildlife ponds, flood control, and hydropower categories, but is reasonably representative for dams classified as irrigation, which is not a major use in Wisconsin (data not shown).

In the Utah database, 1641 dams are listed, of which only 104 are included in the national inventory. As shown in figure 3b, the size distribution of dams in the state database is very poorly represented by the national database, with the proportion of dams less than 4 m in height being under-represented and dams greater than 8 m in height being over-represented in the national database. In both the state and national databases, dams designated as primarily irrigation are the most prevalent use category (data not shown), although the national database overestimates their proportional representation by a factor of two relative to the state database. Stock ponds constitute 22% of state-identified dams, but are completely absent from the national inventory. Similarly, the national database underestimates the occurrence of flood control structures in Utah by a factor of six relative to the state database.

Thus, in summary, the national database for large dams does a relatively poor job of characterizing small dams in terms of size distribution and operational purpose for both Utah and Wisconsin.

## *The need for an ecological classification of dams*

A formal characterization of how dams modify river ecosystems represents a major scientific challenge, especially because the type and magnitude of environmental alteration stems from interactions among natural processes, dam characteristics, and management practices. At present, little empirical data are available to allow meaningful generalization. This reflects, in part, the fact that readily available, simple descriptors for dams (e.g.,

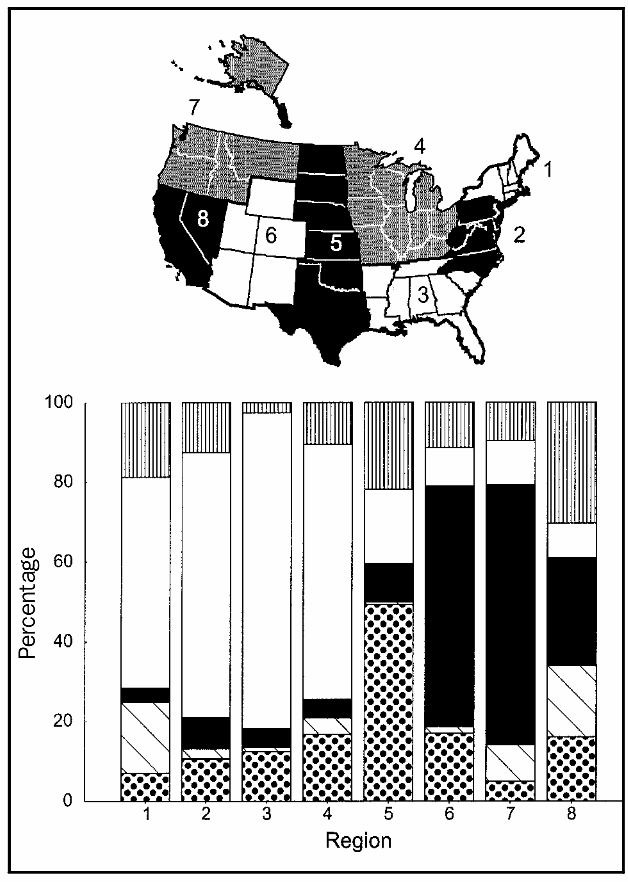


*Figure 2. Percentage distribution by geographic region of dams falling into five categories of primary operational purpose, as defined in the national inventory of dams (USACE 2000). Dam uses are defined as flood control (stippled), hydropower (diagonally hatched), irrigation (solid black), recreation (solid white), and public supply (vertically hatched). These five uses represent 71% of the dams (54,903 dams).*

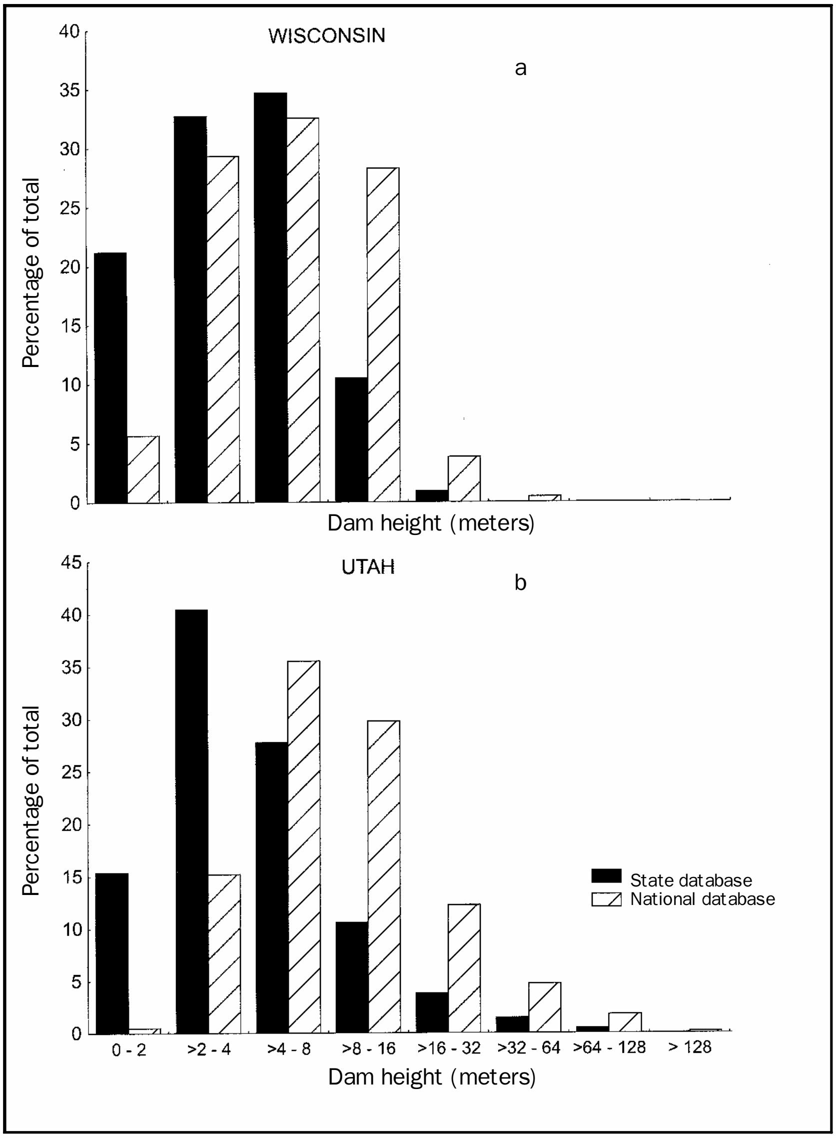


***Figure 3. Percentage distribution by dam height for dams in state databases (solid black) and the National Inventory of Dams (diagonally hatched; USACE 2000) for (a) Wisconsin and (b) Utah.***

size) are not adequate for building a robust classification. More fundamentally, the framework for identifying the critical variables needed to form a classification does not exist; therefore, meaningful classification variables have not been systematically identified and collected.

Figure 4 provides a conceptual framework for how critical biophysical processes are modified by dams and reservoirs. The natural river system can be considered as a set of baseline conditions, characterized by temporal patterns of water flow, sediment (and organic matter) transport, temperature conditions, biogeochemical cycling, and biotic movements. These conditions are functions of climate, geology, land cover/use, and biogeography, and they show substantial geographic variation (see Poff 1996 for an example of flow regimes). In theory, the effect of a particular dam could be defined by the ways it modifies these natural regimes. In many instances, however, the prevailing biophysical regime already reflects the impact of upstream dams, which greatly complicates the task of characterizing how a particular downstream dam is modifying the natural river ecosystem (figure 4). Although not shown, downstream dams can also modify a given dam's impacts because of their effects on the upstream movements of river biota (Pringle et al. 2000). A further consideration in assessing a dam's effect on baseline conditions is the position of a reservoir in the drainage basin. For example, the degree of thermal deviation from natural conditions below a deep release reservoir is much greater in warmer, downstream reaches of a river than in cooler headwaters (Ward and Stanford 1983). Thus river size can be an important consideration in classifying the effects of dams on riverine ecosystems.

Many of the effects that dams have on the biophysical regime are related to the dam's size and operational mode. Dam size (height, width) strongly influences many environmental effects, such as the likelihood of temperature stratification and thermal regime modification, the dam's effectiveness as a barrier to biotic migration and sediment transport, and its ability to store peak flows. Dam size also interacts with dam operations to influence a key variable, the hydraulic residence time (HRT), which in turn affects many different facets of the biophysical regime. The HRT is defined as the ratio of the storage volume ($m^3$) of the reservoir to its flow-through rate ($m^3$ per year), the latter being a function of natural inflow to, and human controlled outflow from, the reservoir. The HRT can potentially influence the settlement of sediment within the reservoir, the development of planktonic assemblages and processes, the transport of biota through the reservoir to downstream reaches, the type and rate of biogeochemical cycling, and the occurrence of thermal stratification (Morris and Fan 1998, Kalff 2002). Thus dams of similar sizes can potentially have different ecological effects because of differences in their HRTs. Further, seasonal variation in reservoir operations can result in HRT being seasonally variable (e.g., if a reservoir is drawn down before annual spring flooding).

Although information on HRT is critical to the development of ecological classification of dams, HRT data are not directly available for most impoundments. The situation arises in part because information on seasonal inflows into the reservoir or operational rules for reservoir discharge are often not reported, especially for smaller dams. Moreover, only about one-third of the dams in the national database (USACE

2000) have reliable reported values for reservoir storage volume.

Indirect measures of HRT might provide an avenue for dam characterization; however, such measures are themselves limited. For example, in natural lakes, about 33% of the variation in HRT is statistically explained by variation in lake volume (Kalff 2002), so an indirect measure of reservoir volume might provide a rough estimate of HRT. Unfortunately, the most reasonable predictor variable, dam height, is only weakly correlated ($r^2 = 0.21$ for log–log data) for that portion of the national database containing values for both variables. Thus HRT is unlikely to be predicted meaningfully from dam height. In natural lakes, the unexplained 67% of the variation between HRT and lake volume probably reflects differences in regional runoff patterns and in lake morphometry (surface area to volume ratio) (Kalff 2002). Similarly, with reservoirs, regional differences in inflows will affect HRT. For example, Graf (1999) estimated maximum reservoir capacity ($m^3$) to store mean annual runoff ($m^3$ per year) to range from 0.25 to 0.37 years of storage in the upper Midwest and Northeast to 3.8 years in the arid Southwest. These values provide a sense of how HRT is regionally variable; however, predicting HRT for individual reservoirs will require that operational mode also be taken into account, since human control over dam outflows are a determinant of active reservoir storage and HRT.

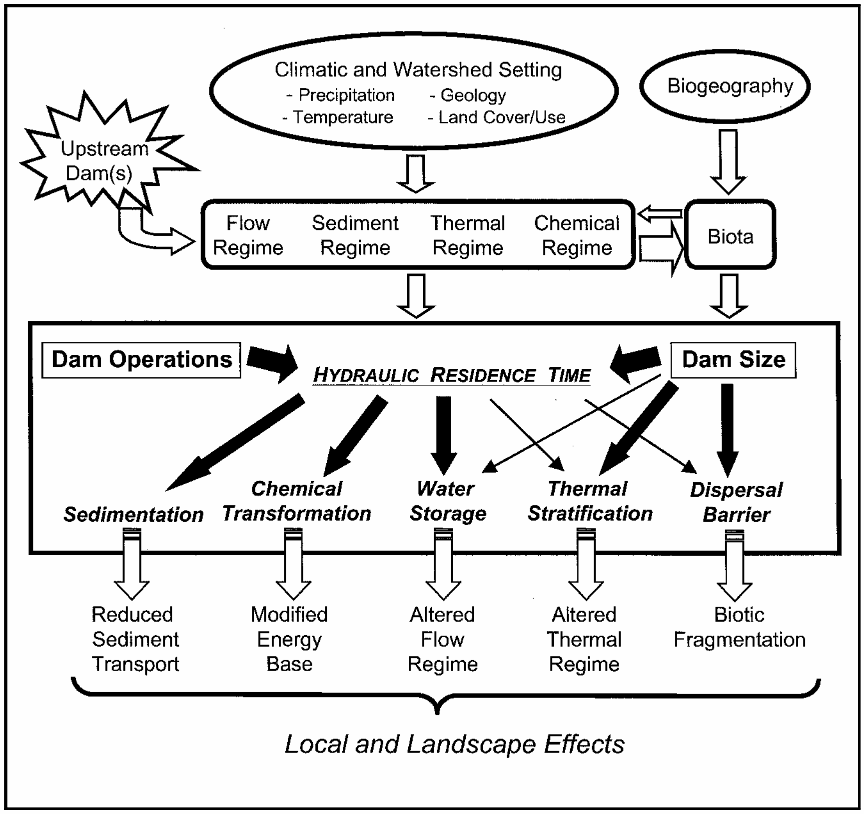


*Figure 4. Flow chart illustrating how attributes of dam–reservoir systems, especially dam size and operations, modify fundamental riverine biophysical processes to cause alterations with local and landscape environmental effects.*

Ultimately, efforts to categorize dam operations (and thus key variables like HRT) from a scientific perspective must account for differences in management practices that reflect variable social settings, economic conditions, and human preferences. Beyond the regional differences in climate and runoff, individual reservoirs are often managed for multiple purposes that can vary over time. Clearly, different types of operations can have very different environmental effects. For example, flood storage dams are often drawn down before a predictable flooding season and they are thus able to store peak flows, thereby modifying downstream flow and sediment regimes. Run-of-river dams of similar size, by contrast, tend to pass peak flows and are therefore less likely to detain fine sediment or modify downstream high flows. Alternatively, dams of very different sizes can have similar downstream hydrologic effects depending on how they store and release water over time. However, characterizing dam operations in a meaningful way may be easier for smaller structures (e.g., many of those not included in the national database), because of their smaller storage capacity and limited range of management options.

## The influence of dam characteristics on removal decisions

According to a recent compilation, 467 dams have been completely or partially removed in the United States in the 20th century (AR/FE/TU 1999). At least another 30 dams have been completely removed through 2001 (Molly Pohl, Department of Geography, San Diego State University, personal communication, 5 March 2002). What kinds of dams are being removed, and how might future dam-removal decisions be related to variation in dam characteristics?

There are two striking dam-removal patterns: Dams are being removed at an accelerating rate (figure 5a), and the majority of dams being removed are less than 5 m in height (figure 5b). Several factors suggest that small dams will continue to be removed more often than large dams: As indicated by the Wisconsin and Utah databases, dams less than 5 m in height are far more numerous than large dams. Most of these small dams do not generate hydroelectricity or control floods, so the economic benefits of maintaining them are not as great when compared with large dams. Small dams are often older than large dams, which makes it more likely that they will be in poor condition. In fact, concerns about public safety, as well as high repair costs, were major factors affecting decisions to remove a number of old dams (average age > 100 years) in Wisconsin (Born et al. 1998). Small dams are more likely to be abandoned, so that financial burdens associated with their safety, repair, and maintenance often fall to local governments and, ultimately, to taxpayers. Indeed, many dams that have been removed were previously abandoned (Shuman 1995). These patterns clearly demonstrate that the current focus on small dam removal is influenced by social and economic factors, as well as by concerns about the environmental effects of small dams (AR/FE/TU 1999, Doyle et al. 2000).

Sediment accumulation in reservoirs is another factor that can influence many dam-removal decisions. This issue can be complicated, depending on the quality and quantity of accumulated sediments, as well as on public and agency attitudes about potential downstream effects of sediment. For example, if toxic contaminants are present in the sediment, there are certain to be concerns about the risks associated with the downstream release of sediments following dam removal, and the potential effects of these sediments on human and ecosystem health (Shuman 1995).

Even when contaminants are absent, accumulated sediment can still influence the likelihood of dam removal. For example, as reservoirs fill with sediment, they often become less effective in controlling floods, storing water, and generating hydropower, which could accelerate calls for dam removal. A useful index of the operational problems caused by accumulated sediments is the time it takes for 50% of the storage capacity of the reservoir to be lost to sediment deposition (Morris and Fan 1998). The proportional rate at which a reservoir's storage volume fills with sediment depends on basinwide erosion rates (which vary regionally), but also exhibits an inverse relationship to dam size. Empirical data collected for reservoirs across the country by Dendy and colleagues (1973) showed that those having a storage capacity between $1.2 \times 10^6$ and $12 \times 10^6$ $m^3$ had a median time to half-filling of 91 years (based on data reported in Morris and Fan 1998). Taking the median value of this size range, 92% of the approximately 76,500 dams in the national database are expected to become half-filled with sediment in an average of 91 years. The regional distribution of these short-lived dams varies somewhat (figure 6), with between 74% (California, Nevada) and 94% (Southeast) of dams falling into this category. The age of existing dams also shows regional variation, with as many as 50% of dams having construction dates before 1920 in the Northeast, and as few as 5% in the Plains states.

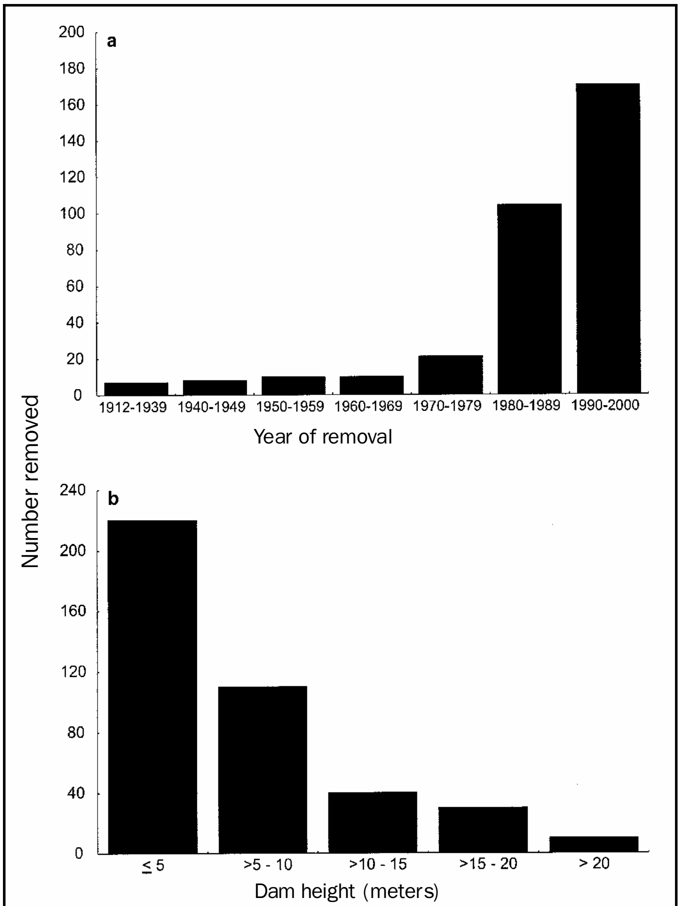


***Figure 5. Dam removal in the United States by (a) decade and (b) structure height. (Data taken from AR/FE/TU 1999 and Doyle et al. 2000.)***

The extent of this sediment problem is even greater if we consider the estimated 2,000,000 small dams not in the national inventory. These structures are defined as having less than $6.2 \times 10^4$ $m^3$ of storage (Graf 1993) and thus would be expected to become half full of sediment within roughly 25 to 40 years. Dendy (1968) estimated that "if present siltation rates continue, about 20% of the Nation's small reservoirs will be half filled with sediment...in about 30 years." The lack of a national database for these structures precludes an estimation of their retirement times. Many in the Northeast are already full of sediment, however (Laura Wildman, American Rivers, Northeast Field Office, personal communication, 22 May 2002), and literally thousands more nationwide will fill in the coming decades. For example, in Wisconsin alone, over 800 dams are less than 2 m high, and about one-third of these were built before 1960. On the basis of the previous estimates, these dams should already have lost more than 50% of their storage capacities.

Sediment accumulation can be a factor that either increases or decreases the likelihood of dam removal, depending in part on local circumstances. For example, in situations where sediment accumulation has reduced the functional ability of dams (e.g., for flood control) and disrupted downstream geomorphic processes, there have been increased calls for dam removal (Matilija Coalition 2000). By contrast, concerns have sometimes been raised about the possibility that downstream habitats, species, and ecosystem processes could be adversely affected (at least in the short term) by the release of large volumes of sediment during dam removal. Mechanized removal before dam breaching is one alternative to sediment release (ASCE 1997), although this can be very expensive. For many of the smaller dams currently being removed, however, the volume of accumulated sediment may be similar to the average annual sediment flux. In these situations, no special management practices are employed, and

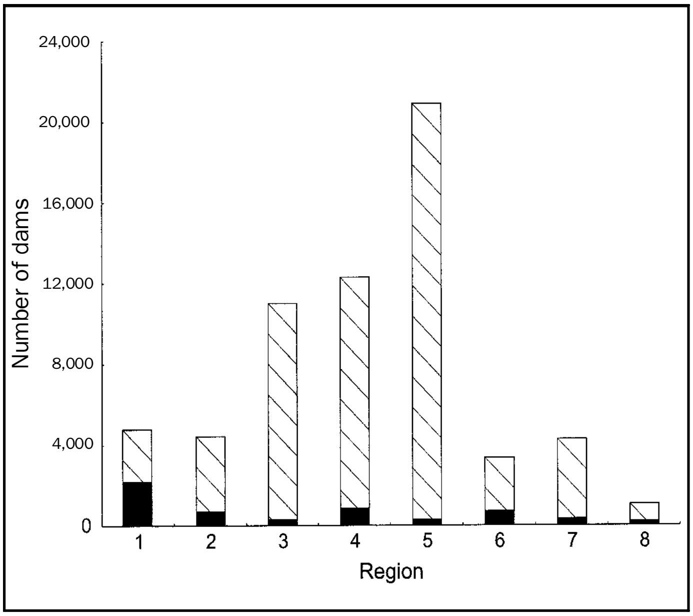


***Figure 6. Number of dams by geographic region in the National Inventory of Dams database (USACE 2000) with estimated average time to half-filling with sediment being 91 years or less, on the basis of reservoir storage volumes. Dams are divided into those constructed before (solid black) and after (diagonally hatched) 1920. Refer to figure 2 for regional key.***

sediments are allowed to move downstream following dam removal.

## The future of dam removals

The rapid aging of dams (especially small ones) and the costs of maintaining old dams practically ensures that dam removal will continue at a brisk pace for the foreseeable future. An open question is whether these removals will be guided by scientific principles aimed at river restoration and conservation or whether they will simply follow utilitarian economic principles (Pejchar and Warner 2001).

In the last decade, an understanding about how dams severely impair free-flowing rivers has become firmly established both in the United States and abroad (Ligon et al. 1995, Collier et al. 1996, NRC 1996, Pringle et al. 2000, WCD 2000). This knowledge has entered into the public debate on river conservation, both in terms of greater willingness of reservoir managers to minimize downstream ecological effects (Muth et al. 2000) and of increased calls for outright dam removal (Pyle 1995, Joseph 1998, AR/FE/TU 1999). These scientific and social currents have led some to call for a new "water ethic" of increasing water-use efficiency through nonstructural means (Gleick 1998, Postel 2000). Such an ethic is needed if human demands for freshwater continue to grow in the coming decades (Postel 2000) and if society wishes to maintain the long-term sustainability of river ecosystems (Naiman and Turner 2000, Baron et al. 2002).The growing pressure for dam removal represents a real opportunity for scientists. Certainly, dam removals provide excellent opportunities for scientists to perform large-scale experiments in river restoration (Grant 2001, Hart et al. 2002) and thus expand our empirical knowledge base. Moreover, scientists are increasingly likely to be asked to predict the success of dam removal in specific situations where controversy exists over potential benefits and costs. Because dam removal can sometimes be expensive and its ecological effects hard to predict, scientists need to develop a better framework for characterizing dams according to their current environmental effects, as well as to the potential environmental benefits that could accrue following removal. For example, Hart and colleagues (2002) present a graphical model for examining how potential responses to dam removal vary with dam and watershed characteristics. This scientific challenge is made more difficult because the effects of dams result both from their alteration of natural biophysical processes and from human management practices. In this article, we have attempted to highlight some of the more salient attributes of this complex, multidimensional challenge. Developing a more predictive environmental science of dam removal is needed to help society decide where to spend limited resources to maximize restoration potential for impaired river systems in the United States and elsewhere.

## Acknowledgments

We thank Dave Pepin for assistance with database analysis and graphics and Chester Watson for providing literature on dam aging. The ideas in this article have benefited greatly from discussions with many colleagues in the Patrick Center's Institute for River Restoration. We thank Matt Greenstone, Laura Wildman, Emily Stanley, and two anonymous reviewers for providing valuable comments on an earlier draft of this manuscript. N. L. P.'s contribution to this project was supported, in part, by grants from the National Science Foundation (# DEB-0075352) and the US Environmental Protection Agency (SPO # BS0056363). D. D. H.'s work was partially supported by the Patrick Center Endowment Fund. Completion of our manuscript was also facilitated by support from The Pew Charitable Trusts.

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# A Framework for Estimating the Costs and Benefits of Dam Removal

ED WHITELAW AND ED MACMULLAN

**Although dams provide a variety of economic goods** and services, including electric power, flood control, water supply, reservoir recreation, and navigational services, they also have detrimental effects on riverine ecosystems (Petts 1984). As a result, many people want to know the socioeconomic and ecological benefits and costs of rehabilitating or restoring rivers through dam modification or removal (AR/FE/TU 1999).

Cost–benefit analysis is one economic tool that helps decisionmakers choose among policy alternatives (Boardman et al. 1996). Ideally, cost–benefit analysis includes all of the costs and benefits associated with each policy alternative. In fact, however, costs and benefits can be difficult to measure—estimating the value of an endangered species, for example—or may not be fully recognized at the time a study is conducted. Thus using cost–benefit analysis in evaluating the removal of a dam can challenge even seasoned analysts.

In spite of these limitations, decisionmakers and stakeholders frequently rely on cost–benefit analysis for insights into the potential consequences of modifying or removing dams. The Edwards Dam on the Kennebec River in Maine, removed in 1999, illustrates the point. A cost–benefit study concluded that necessary structural repairs would have cost 1.7 times the cost of removing the dam and restoring anadromous fish passages (AR/FE/TU 1999).

Edwards Dam is small compared with other dams recently under consideration for removal. The US Army Corps of Engineers completed a draft cost–benefit analysis of a proposal to remove a series of four large dams on the lower Snake River in the Pacific Northwest. Wild salmon stocks have dipped perilously low on the river, and many people believe the costs of keeping the dams outweigh the benefits.

In this article, we describe principles we believe are effective in assessing the economic consequences of environmental management decisions. We then describe how those principles might be used for a cost–benefit analysis regarding dam removal using the dams on the lower Snake River as a case study. We examine parts of the US Army Corps of Engineers' draft cost–benefit analysis for these dams and suggest modifications to the Corps' analysis that would more fully account for relevant costs and benefits.

SOUND COST–BENEFIT ANALYSES OF REMOVING DAMS ACCOUNT FOR SUBSIDIES AND EXTERNALITIES, FOR BOTH THE SHORT AND LONG RUN, AND PLACE THE ESTIMATED COSTS AND BENEFITS IN THE APPROPRIATE ECONOMIC CONTEXT

## *Analytical principles*

On 9 September 1998, 78 economists sent a letter to the governors of the four Pacific states and the premier of British Columbia, urging them "to consider the full range of economic consequences" when they and members of their administrations make salmon-management decisions (Whitelaw et al. 1998). Box 1 presents the six principles that the economists emphasized should guide an assessment or cost–benefit analysis of the economic consequences of practically any environmental management decision, including whether to keep or remove a dam.

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**Box 1. Six principles that should guide the analysis of the economic consequences of removing or keeping a dam. From a 1998 letter by concerned economists (Whitelaw et al.) to Governors Kitzhaber, Knowles, Locke, and Wilson and Premier Clarke regarding the economic issues of salmon recovery.**

*Primary analytical principles*

1. **Benefits as well as costs**
Removing or keeping a dam would generate economic benefits as well as economic costs. Consider them both to understand the full effect on the value of the goods and services derived from streams, forests, and other resources.
2. **Positive as well as negative impacts on jobs**
Dealing with a dam would have both positive and negative effects on job opportunities. Consider them both to understand the full effect on workers, their families, and their communities.

*Secondary analytical principles*

3. **Distribution of consequences and fairness**
Those who enjoy the benefits or jobs of a decision on a dam would not necessarily be the same as those who would bear the costs or job losses. Consider the full distribution of economic consequences to understand who wins, who loses, and the fairness of the distribution.
4. **Rights and responsibilities**
With any decision on a dam, property owners and resource users behave differently than they otherwise would. Consider whether these changes represent infringement of their rights or enforcement of their responsibilities.
5. **Uncertainty and sustainability**
Any decision on a dam would rely unavoidably on information insufficient to guarantee the outcome. Consider fully the potentially high costs from decisions yielding undesirable outcomes that are irreversible or extremely difficult to reverse.
6. **More than just salmon conservation**
Removing or keeping a dam would have a variety of ecological and economic effects, such as changes in the quality of stream water used for other purposes, that may seem peripheral. But consider all the effects.

Two of the six principles play primary roles by addressing the two key effects of a decision on a dam: (1) the effect of the decision on the value of the goods and services derived from the environmental resources; and (2) the effect on jobs and associated variables, such as incomes and the well-being of communities. The other four play secondary roles, offering guidance on the issues that should be addressed when applying the first two principles. The four secondary principles are just as important as the primary ones, but they play a different role, defining the range of issues that should be taken into account as one looks at the benefits, costs, and effects on jobs.

The first principle—first in order and first in priority—admonishes decisionmakers to consider both the benefits and the costs. Though this may seem eminently reasonable, the economists observed that many economic studies of environmental management decisions predominantly emphasize the costs (Whitelaw et al. 1998). Doing so reduces the perceived economic importance of the environmental resources. When weighing the benefits and costs, decisionmakers should take into account how their decision would affect all goods and services with economic value, not just those traded in markets with monetary prices. In addition, a full accounting must be provided of the true value of each affected good or service, taking into account the market price, as well as all factors, such as subsidies, taxes, and environmental externalities, that distort the level of supply or demand. (Environmental externalities occur, for example, when those who generate pollution benefit financially while others downstream or downwind pay the costs of the pollution.) Finally, the estimates of economic impacts—costs, benefits, employment consequences, and so on—should be placed in the context of the size and makeup of local and regional economies. Considering impacts without the proper context limits the usefulness of information to decisionmakers or stakeholders.

A decision to remove a dam also would have both positive and negative effects on jobs and incomes. When examining these effects, decisionmakers should take into account the economy's ability to adjust over time to exploit the positive and attenuate the negative. The decision to remove a dam may expand or contract the demand for labor and, hence, increase or decrease job opportunities. The actions taken may affect the quality of life in a local area or region and, hence, influence where people prefer to live, work, play, and shop. Analysis of the employment effects associated with a management decision on a dam must also separate these consequences from the employment consequences associated with larger economic forces and trends *unrelated* to decisions on the dam, but which may affect local and regional economies in proximity to the dam.

Because the decision on a dam generates both benefits and costs, and produces both positive and negative effects on jobs and incomes, it creates both winners and losers. The economists recommended that such distributional effects not be overlooked. They also emphasized the importance of having a clear understanding of how the decision affects the rights and responsibilities of landowners and resource users. The value society places on the decision that restricts property owners' rights can differ markedly from the value of otherwise comparable measures that induce the property owners to comply with their responsibilities. In addition, the economists observed that, given the uncertainty regarding a decision to remove a dam, there always is the possibility it would yield undesired outcomes, and care should be taken to avoid outcomes that are costly—or even impossible—to reverse. Finally, the economists stressed that although the primary economic consequences of an environmental management decision have to do with the specific environmental resource itself, others do not. A full analysis should include the costs, benefits, and effects peripheral to the specific resource at issue.

The six principles identified in the economists' letter provide an analytical foundation for assessing the costs and benefits of removing a dam. The analytical approach outlined in this section describes the economic implications of removing a dam, from large dams that facilitate barge traffic to small dams such as those that provided water to long-abandoned mills. Removing larger dams is likely to generate more significant impacts than removing smaller dams; therefore, depending on the specifics of the dam, a full-blown economic analysis may not be appropriate. (See Trout Unlimited 2001 for information on the economic benefits of removing small dams.) However, a cost–benefit analysis of removing a dam using the principles described in box 1 ensures that the analysis captures the full range of economic consequences.

## Application to dams on the lower Snake River

In this section we describe the application of the analytical approach described above to the question of removing the four dams on the lower Snake River in Washington.

***Background regarding the impacts of dams on endangered salmon.*** Four dams are situated in the lower Snake River, between the Snake's confluence with the Columbia River at Pasco, Washington, and Lewiston, Idaho. The US Army Corps of Engineers (USACE) constructed the dams between 1962 and 1975, primarily to create a series of ponds so barges could reach Lewiston, and secondarily to provide easy access to water for irrigation and to generate hydroelectricity.

Wild salmon stocks returning to the Snake River have plummeted since the dams' construction, and a chorus of fisheries biologists and others has called for breaching or bypassing the dams, that is, removing the earthen mounds adjacent to the concrete portions of the dams and letting the rivers run free. Proponents argue that breaching the dams would, among other things, restore endangered wild salmon, return traditional sites and fisheries to Indian tribes, improve water quality, reduce taxpayer subsidies to corporate irrigators and barging companies, and comply with numerous laws and treaties. Opponents claim such actions would prove prohibitively costly, even wreck the Northwest's economy.

In December 1999, the US Army Corps of Engineers released a draft Feasibility Report/Environmental Impact Statement (FR/EIS), which, among other things, provides an estimate of the economic effects of breaching the four dams on the lower Snake River (USACE 1999a). The FR/EIS describes, to varying degrees, the costs and benefits of dam removal on different sectors of the regional and national economies, including tribal interests; recreational use; anadromous fisheries; irrigated agriculture; transportation; electrical utilities; and municipal, industrial, and private water use.

In the remainder of this article, we evaluate the Corps' analysis of the economic effects of breaching the dams in light of the analytical principles described in box 1. We have limited our critique of the Corps' analysis to the primary analytical principles of the overall costs and benefits of removing the dams and the associated impacts on jobs. Readers interested in a more in-depth discussion of the primary analytical principles and the related secondary principles as they apply to the Corps' cost–benefit analysis should consult ECONorthwest (1999, 2000).

***Evaluating the Corps' analysis of economic effects.*** First we describe the overall structure of the Corps' cost–benefit analysis, and then we review the Corps' analysis of costs and benefits. This section concludes with our critique of the Corps' analysis of the employment impacts of removing the dams.

**The Corps' overall analytical approach.** When federal agencies such as the Corps conduct cost–benefit analyses of proposed water projects, they typically follow the Principles and Guidelines developed by the US Water Resources Council (USWRC) in the early 1970s to provide guidance on decisionmaking and analytical procedures as they apply to water resources. The Principles and Guidelines, which replaced the Principles and Standards, were last updated in 1983 (USWRC 1983). Other federal agencies that use the Principles and Guidelines are the Bureau of Reclamation, the Natural Resources Conservation Service, and the Tennessee Valley Authority (NRC 1999). According to the Corps (USACE 1999b), the Principles and Guidelines recommend that a cost–benefit analysis include the following socioeconomic factors:

- National economic development (NED) effects, which describe the changes in the economic value of the national output of goods and services
- Environmental quality effects, which describe nonmonetary consequences for significant natural and cultural resources
- Regional economic development (RED) effects, which address changes in the distribution of regional economic activity such as jobs and income
- Other social effects, which describe potential effects from relevant perspectives that are not reflected in the other three types of effects

In spite of the comprehensive approach outlined in the Principles and Guidelines, the Corps considered only a portion of this information in its decisionmaking process for the dams on the lower Snake. The Corps' FR/EIS states, "The NED account is the only account required under the WRC [Water Resources Council] guidelines" (appendix I, pp. I1-1–I1-2). As calculated by the Corps, the impact of dam removal on the value of the nation's goods and services apparently determined the outcome of its cost–benefit analysis.

The National Research Council (NRC) reviewed the Corps' use of the Principles and Guidelines in a number of applications and concluded that the Corps' approach ignores important impacts, is out-of-date, and does not reflect current thinking on the role that water resources play in local, regional, or national economies (NRC 1999). The NRC concluded (pp. 4–5):

> While they were in effect, the P&S [Principles and Standards] were consistently reviewed and updated by federal and other water planning specialists. By contrast, the P&G [Principles and Guidelines] have not received the same degree of attention and, as a result, do not adequately reflect contemporary water resource planning principles and practices.... Movement away from consideration of the National Economic Development (NED) account [is] the most important concern. Today, ecological and social considerations are often of great importance in project planning and should not necessarily be considered secondary to the maximization of economic benefits. Strict adherence to the NED account may discourage consideration of innovative and nonstructural approaches to water resources planning.... In summary, the committee recommends that the federal Principles and Guidelines be thoroughly reviewed and modified to incorporate contemporary analytical techniques and changes in public values and federal agency programs.

Applying the NRC's criticisms of the Corps' overall analytical approach to the analysis of impacts of removing the Snake River dams, we see that the Corps' analysis provides limited useful information and misleading results. For example, as we describe below, the Corps' NED analysis is incomplete because, among other deficiencies, it excludes the impact of subsidies. Thus the Corps violated the first principle in box 1 of considering the full range of economic benefits and costs. Even though the Corps estimated RED impacts, they ignored these impacts during the decisionmaking process and focused exclusively on the NED impacts. By excluding RED impacts from the decisionmaking process, they violated the second principle of considering the full range of employment impacts. Likewise, the Corps excluded the range of secondary analytical principles in box 1 from its analysis.

**Changes in benefits and costs.** The Corps' analysis of costs and benefits—the NED effects described in the Principles and Guidelines, and the effects that drove the Corps' decisionmaking process—has significant deficiencies. We first discuss two of the major drawbacks of the Corps' analysis: excluding subsidies from the cost–benefit analysis and ignoring benefits associated with tribal circumstances and nonmarket values. The former overestimates the cost of taking out the dams. The latter underestimates the benefits of taking out the dams. We then discuss the Corps' results and place these results in the context of the regional economy of Washington, Oregon, and Idaho.

Certain sectors of the region's economy that rely on the dams benefit from subsidies provided by the federal government. In effect, taxpayers throughout the United States subsidize the economic activities and profits of these businesses. Taking out the dams would generate negative economic consequences for these businesses, but there are positive economic consequences for US taxpayers because they would no longer pay subsidies to these businesses.

Transportation is one example. Snake River waterway users pay a fuel tax that generates a few hundred thousand dollars annually, which covers but a small portion of the actual costs of using the waterways. Federal taxpayers make up the difference, contributing $10 million annually to subsidize transportation's share of operations and maintenance costs for the Snake River dams (Dickey 1999). The Corps did not include this and other subsidies in their analysis. For example, describing the analysis of transportation impacts, the FR/EIS states, "The analysis does not take into consideration the effects of taxes or subsidies, which represent transfer payments within the national economy" (USACE 1999b, p. I3-62). Furthermore, subsidies are more wide-reaching than simply transferring wealth from one group to another. When a service, such as transportation along the Snake River, is subsidized, so that users do not face a price reflecting the full production cost, they have an economic incentive to consume more of the service than they would otherwise. The Corps' cost–benefit analysis failed to account for this overconsumption, which biases the analysis in favor of those sectors of the economy that receive subsidies.

In estimating the benefits from breaching the dams, the Corps excluded a number of relevant values, including tribe-related benefits and the benefits that all of us gain from the existence of both the increased salmon runs and a free-flowing lower Snake River. First, the Corps' estimate of tribe-related benefits included the number of acres of sacred and traditional sites that the tribes would regain access to, as well as the number of pounds of fish from treaty-protected subsistence and ceremonial fisheries, but it did not include the economic benefits that tribal members and other Northwesterners and Americans would gain from these changes (USACE 1999b). In not doing so, it overlooked economic benefits to tribal members that constitute real increases in the value of national goods and services. As a result, the Corps underestimated how breaching the dams would benefit the tribes, and how that, in turn, would benefit all of us.

Second, the Corps excluded from its cost–benefit tally what it calls passive-use benefits that Northwesterners and other Americans would enjoy from both the increased salmon runs and from converting the lower Snake to 140 miles of free-flowing river. These values come not from using the resources—the salmon or the river—but from knowing the salmon and the free-flowing river exist and that future generations would get to enjoy them. These values aren't trivial. Economists working for the Corps estimated that the passive-use values of these two resources range from $486 million to nearly $1.3 billion (USACE 1999b). The Corps' estimates of the overall costs and benefits of taking out the dams ranged from a net cost of $300 million to a net benefit of $1.3 billion, in 1998 dollars (Whitelaw 2000). If passive-use values were incorporated into the Corps' overall estimate of net costs and benefits, the range would change to a low of $186 million net benefits and a high of $2.6 billion net benefits. This huge range stems largely from the wide range in the estimates of the benefits from river recreation that would result from breaching the dams, a range of $11 million to $1.5 billion (USACE 1999b).

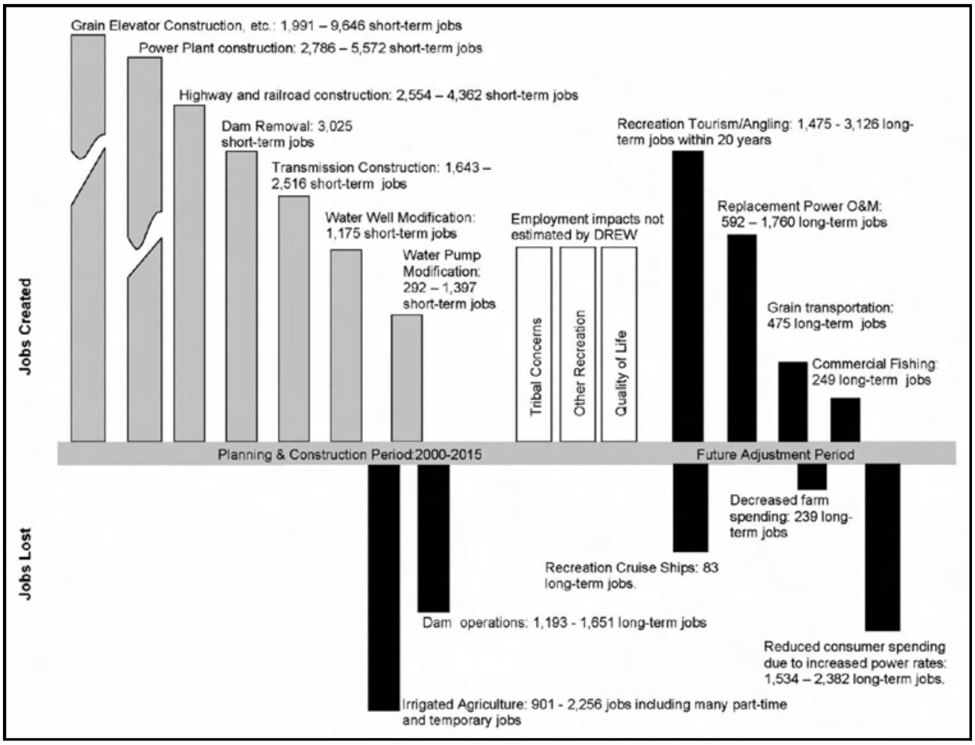


*Figure 1. Employment impacts of the bypass. Adapted by ECONorthwest with data from USACE (1999b).*

Personal income provides one measure of the ability of a region to pay for some good, service, or action. In this case it serves as a context for the Corps' cost–benefit results. Comparing the region's personal income with the net costs or benefits of taking out the dams provides insights into the relative expense or benefit of the action. Personal income in Oregon, Washington, and Idaho in 2000 exceeded $310 billion (USDC 2001). The Corps' worst-case estimate of net costs of $300 million represents 0.1% of the region's personal income. The actual impacts would be even smaller because, as we described above, the Corps overestimated the costs and underestimated the benefits of taking out the dams.

**Employment impacts.** In spite of the Corps' emphasis on changes in costs and benefits at the national level, the impacts on jobs, especially jobs in the local and regional economy, are what concern many people. We discuss how the Corps' analysis overstates the employment impacts and then place the Corps' analytical results in the proper context, in this case, the local and regional economies that would be affected by the decision. We also illustrate the importance of considering relevant economic forces and trends in an analysis of employment impacts.

Figure 1 summarizes the Corps' estimates of the effects that breaching the dams would have on jobs, that is, the regional economic development effects. (See ECONorthwest 1999 and Whitelaw 2000 for a detailed discussion of the employment impacts of bypassing the dams.) According to the Corps, breaching the dams would create 13,400 to 27,700 short-term jobs during the decade of deconstruction and construction (USACE 1999b).

In the long term, there would be job losses and gains. The biggest gains, between 1475 and 3126 jobs, would result from improved recreational tourism and angling opportunities. The largest losses of long-term jobs would occur in irrigated agriculture (between 901 and 2256 jobs), the operations of the existing dams and locks (between 1193 and 1651), and reduced spending caused by increased electricity rates (between 1534 and 2382). Taking the midpoints of the ranges shown in figure 1, breaching the dams would cause a net loss of 1081 long-term jobs in the Pacific Northwest (4200 jobs gained, 5281 jobs lost). The Corps generated ranges of employment impacts by using low, medium, and high scenarios for various data and assumptions.

The Corps overestimated the negative employment consequences of bypassing the dams because it failed to account for the economic forces and trends acting on the relevant economies. The tool the Corps employed to estimate the impact of breaching on jobs and incomes "presents a picture of the economy at a single point in time," the Corps states, and that point is 1995 (USACE 1999b, p. I6-5). Furthermore, the Corps assumes "the long-run effects are permanent and continue for the 100-year period analyzed in this study" (USACE 1999b, p. I6-3). In other words, the Corps assumed that the basic structure of the economy would remain fixed in its 1995 form, unchanged for the next 100 years. For example, the Corps estimated a maximum of 2256 jobs would be lost in irrigated agriculture (figure 1). To arrive at 2256, the Corps assumed that, when breaching the dams eliminates reservoir water for irrigation, the affected 13 corporate farms would take out of production all 37,000 acres of their farmland. This assumption ignores other possible outcomes, including switching to groundwater, adopting different irrigation practices, and altering crops. In effect, the Corps assumed that the owners of these corporate assets would quit and the assets would remain idle for 100 years. Furthermore, the Corps assumed, in effect, that for the next century, those who lost their jobs as a result would never work again; local and regional firms that otherwise would have sold goods and services to those who lost their jobs instead would lose those sales and wouldn't find replacement sales; owners of the farming enterprises wouldn't switch to any other economic activities; and those throughout the chain who lost their jobs would act exactly the same way as the original job losers in that they would never work again.

The Corps' rigid analytical structure produces an extreme worst-case scenario, unsupported by economic theory or by the historical performance of the local and regional economies. The Corps' analysis freezes all economic interactions in 1995. Such a constraint ignores the dynamic adjustments that economies—employees and employers, buyers and sellers, savers and investors, and all other economic decisionmakers—undertake all the time. For example, since the four dams began service, the agricultural sector experienced four major contractions, each of which affected more than 2256 workers, the maximum that breaching the dams would affect, the Corps predicts. And yet the local and regional economies have expanded steadily during this period (USDC 1998, ECONorthwest 1999).

These data and economic trends indicate that a snapshot of lost jobs at a point in time tells very little about how a real economy reacts to the breaching of four dams or any other changes. Such rigid and unrealistic assumptions cannot produce a credible forecast of economic consequences under the breaching scenario. University of Montana economist Tom Power equates such an analytical approach to driving by looking in the rearview mirror (Power 1996).

A comprehensive assessment of likely employment consequences of bypassing dams would include these elements:

- Feasible alternatives to permanently idling assets that are negatively affected by the bypass
- Information on the average periods of unemployment in the local and regional economies
- Likely mitigation options that would reduce negative employment consequences
- Projected employment demand in economic sectors unaffected by the bypass

It is instructive to put these estimates in perspective. By the end of 2000, Washington, Oregon, and Idaho had approximately 6.2 million workers (USDC 2001). For the three states, the net loss of 1081 jobs would amount to less than 0.02% of all jobs. For the counties in southeastern Washington, northeastern Oregon, and central Idaho near the lower Snake River—the counties the Corps treated as the relevant local economy—the Corps estimated a net loss of 711 long-term jobs, less than 0.3% of the employment in these 15 counties. (In 1996, the local economy of the 15 counties that border the lower Snake River employed approximately 266,000 workers.) For another perspective, compare the total number of jobs the Corps predicted would be lost—5281 gross, not net—with the 25,000 jobs lost in Oregon and Washington's timber industry during the past decade (USDC 2000).

Placing the Corps' results regarding employment impacts in the context of the size of the local and regional economies (and ignoring the issues raised by the NRC) indicates that bypassing the dams would generate minimal negative employment consequences relative to the size of the local and regional economies. Even though the negative employment impacts would be minimal overall, they represent hardships for the affected workers and their families. The limited nature of the negative impacts, however, means that mitigating the negative employment consequences would be manageable. (For more information on mitigation options, see ECONorthwest 1999.)

## *Discussion and conclusions*

In a 27 July 1999 speech, Senator Slade Gorton (R–WA) claimed that removing the four Snake River dams would be an "unmitigated disaster and an economic nightmare" (Hughes 1999). In February 2000, George W. Bush said, "Breaching the [Snake River] dams would be a big mistake....The economy and jobs of much of the Northwest depend on the dams" (*Seattle Times,* 26 February 2000, p. A1). In its 1 May 2000 editorial, the *Oregonian* likened breaching the dams to "taking a sledgehammer to the Northwest economy." The Clinton administration, perhaps sensitive to these claims, decided to leave the dams in place while other salmon-recovery methods were attempted.

Just 10 years ago, many politicians offered similar predictions on the disastrous effects of protecting the northern spotted owl. Representative Bob Smith (R–OR) predicted the owl listing would "wreak havoc on the people and economy of the Pacific Northwest" (Ulrich and Ota 1990). During a campaign swing through the Pacific Northwest in 1992, President George Bush warned, "It is time we worried not only about endangered species, but endangered jobs" (Hong and Yang 1992). President Bush and many of the other politicians in those years—Senators Mark Hatfield and Bob Packwood and Representative Bob Smith—embraced the simplistic logic of owls versus jobs, just as some today frame the dam-breaching debate as salmon versus jobs: We can protect endangered jobs, or we can protect endangered species, but not both.

In fact, the Pacific Northwest economy has boomed, consistently outperforming the national economy, whether measured by jobs, income, or sheer exuberance, throughout the 1990s. Between 1988 and 1998, logging in Oregon and Washington fell 91% on federal lands and 52% overall, and timber-industry employment dropped 20%. But new jobs in other sectors offset these losses. Total employment actually increased 31%, while inflation-adjusted per capita income grew 26% (USDC 2000, Warren 1990–2000). Ten years ago this region had never experienced widespread economic changes to protect a species. The current deliberations on the fate of the Snake River dams would benefit from a consideration of these experiences and the implications for developing and conducting cost–benefit analyses. Ignoring the constraints inherent in the Corps' analysis and the resulting biases that overestimate costs and underestimate benefits, the jobs losses predicted by the Corps do not describe a "disaster," "nightmare," or "sledgehammer" for either the local or the regional economy.

An incomplete or otherwise flawed analysis lends itself to such misrepresentation. It also fails to characterize accurately the range of potential economic consequences. By applying the analytical principles in box 1, however, cost–benefit analysts would meet the relevant professional standards and, not incidentally, provide more useful information to decisionmakers. For emphasis and clarification, we describe below the important components of the two primary analytical principles.

**Measure all relevant costs, benefits, and employment gains and losses.** A policy decision will rarely, if ever, generate only costs or only benefits. The impacts of removing dams, for example, extend far beyond dams, fish, and farmers, just as the Pacific Northwest found that the impacts of restricting logging extended far beyond owls and timber workers. In some cases a policy decision may generate costs or benefits some distance away from the area directly affected by the decision. For example, removing a dam may influence populations of anadromous fish, which in turn influences incomes and employment far downstream in coastal communities engaged in commercial fishing.

**Account for all costs and benefits including subsidies and externalities.** Ignoring the subsidies to the transportation sector overestimates the true costs of the bypass. To the extent that the existence and operation of a dam generates negative externalities, such as raising the temperature of the water, removing a dam yields benefits.

**Place the estimated costs and benefits in the appropriate context.** In this case, the context for an analysis of removing the dams is the same as it was for protecting the spotted owl: the local and regional economies affected by the decision.

The goal of cost–benefit analyses is providing decisionmakers and others with useful information on the range of likely economic consequences of policy decisions. As with other analytical efforts, the overall structure of the analysis influences the extent to which this goal is achieved. We believe that the set of principles outlined in this article provide a sound framework for estimating the costs and benefits of removing dams.

## Acknowledgments

We thank Angela Bednarek for her valuable comments on an earlier draft of the manuscript, and The Pew Charitable Trusts for providing support that helped us complete this article.

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# The Conceptual Basis for Ecological Responses to Dam Removal

STAN GREGORY, HIRAM LI, AND JUDY LI

**Scientists and resource managers have proposed** the removal of nonfunctioning dams or dams that cause environmental harm or present unsafe conditions (Poff et al. 1997, Hart and Poff 2002). The basis for assessment of the ecological responses to dam removal and for the design of ecologically effective removal practices is largely conceptual. Particularly in the Pacific Northwest, the adverse effects that large dams have on endangered anadromous salmon require extensive mitigation measures, such as transporting salmon around dams by barge (figure 1), and are a major factor driving dam removal proposals. The introductory article in this series by Hart and Poff (2002) identifies some of the general effects of dams and the responses to dam removal. This article will extend those issues and illustrate the challenges faced in western North America in the removal of high dams, such as the dams on the Elwha and Snake Rivers.

Although more than 75,000 dams have been built in the United States (Shuman 1995), fewer than 500 have been removed. Most dams that have been removed are less than 10 meters (m) high, and no dams higher than 30 m have been removed. Now, however, at least seven high dams in the Pacific Northwest are being reviewed for possible removal (table 1). Citizens and resource managers face a critical question: How much do we know about likely ecological responses to the removal of dams? Stanley and Doyle (2002) have described empirical studies of the ecological responses that follow removal of small dams, and Smith and colleagues (2000) reported on a regional study of those responses in the Pacific Northwest, but no empirical studies of the effects of removing high dams have been conducted.

This article provides a conceptual perspective of the ecological responses to large dam removal, based on our understanding of the structure and function of river ecosystems and on insights gained from small dam removals, where appropriate. We discuss geomorphic responses, hydrologic effects, and several major biological interactions that are affected by dams or their removal. These issues are illustrated in the scientific deliberations concerning removal of high dams in two river basins in the Pacific Northwest—the Elwha River and the Lower Snake River.

> RESOURCE MANAGERS FACE ENORMOUS CHALLENGES IN ASSESSING THE CONSEQUENCES OF REMOVING LARGE DAMS FROM RIVERS AND EVALUATING MANAGEMENT OPTIONS

## *Geomorphic structure*

The fundamental geomorphic change associated with a dam's presence on or removal from a river is the alteration of the longitudinal profile of the river. Dams create a long, flat water surface marked by an abrupt drop in elevation at the dam. After a dam is removed, water levels and channel positions more closely resemble the original morphology of the river, and the sediments that had been stored behind the dam are sculpted by the subsequent river flow. This adjustment to a new longitudinal profile can cause major changes in the distributions of aquatic organisms.

One of the major environmental challenges of removing high dams is the height of sediments behind the reservoir. This

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*Figure 1. Barge transporting salmon around dams on the Columbia River (photograph from the US Army Corps of Engineers).*

is less of a concern with low-head dams or dams in wide valleys, because the vertical relief of the low sediment deposits does not create as much potential for abrupt vertical erosion. The elevation of natural floodplains in most rivers is a small fraction (e.g., less than 1% to 10%) of the width of the bankfull river channel ("bankfull" is a hydrological measure that generally indicates the height or stage of water that just fills the channel). After high dams have been constructed, deposits of sediment upstream of the dam may exceed the relative dimensions of floodplain and bankfull channels found in natural river networks. The removal of a dam with deep sediment deposits may create high, unstable terraces that are accessible to flood waters at the upstream end of the reservoir that existed before the dam's removal but perched far above the channel at the downstream end. The potential for episodic flood erosion of these high terraces and incision of lateral channels into the terraces complicates the restoration of the river and its floodplain after dam removal.

The volume of sediments associated with dams—even low-head dams, in some cases—can have major geomorphic and biological consequences for downstream reaches. Removing a dam can release large volumes of sediment to downstream reaches over short periods of time and creates easily eroded floodplains. The timing of sediment release and the downstream extent of sediment deposition are difficult to predict, thus leading to a high degree of uncertainty about ecological effects. In addition, subsequent erosion of sediment deposits behind the dam results in frequent and complex channel change within the reach upstream of the dam.

## Hydrologic regimes

Dams—particularly hydroelectric and flood-control dams—almost always alter daily, weekly, monthly, and seasonal hydrologic regimes (Poff et al. 1997). Most dams dampen high flows, thereby reducing the beneficial effects of flooding (Junk et al. 1989), such as transporting food into streams from the terrestrial ecosystem, providing floodplain areas for feeding during floods, scouring pools and creating riffles, cleaning silt and fine sediments from gravels, creating deposits of gravel for spawning, and creating complex wood accumulations. In many cases, low flows are augmented to provide water during dry periods and reduce water quality problems caused by point source and non–point source pollutants. As a result, extreme flows, both low and high, are abbreviated, and their influence in shaping the composition of aquatic communities and ecological processes is greatly reduced. For example, 11 flood control reservoirs were constructed in the Willamette River basin in Oregon from 1948 to 1964. Discharge records from the gaging station at Albany for the period 1893–1997 reveal that low flows (i.e., the daily flow that is exceeded

***Table 1. High-head dams in the Pacific Northwest that federal agencies have considered for removal.***

| Dam | Location | River | Height (meters) | Constructed |
|---|---|---|---|---|
| Elwha Dam | Washington | Elwha River | 32 | 1914 |
| Glines Dam | Washington | Elwha River | 64 | 1927 |
| Condit Dam | Washington | White Salmon River | 36 | 1913 |
| Ice Harbor Dam | Idaho | Snake River | 31 | 1961 |
| Lower Monumental Dam | Idaho | Snake River | 31 | 1969 |
| Little Goose Dam | Idaho | Snake River | 30 | 1970 |
| Lower Granite Dam | Idaho | Snake River | 31 | 1975 |

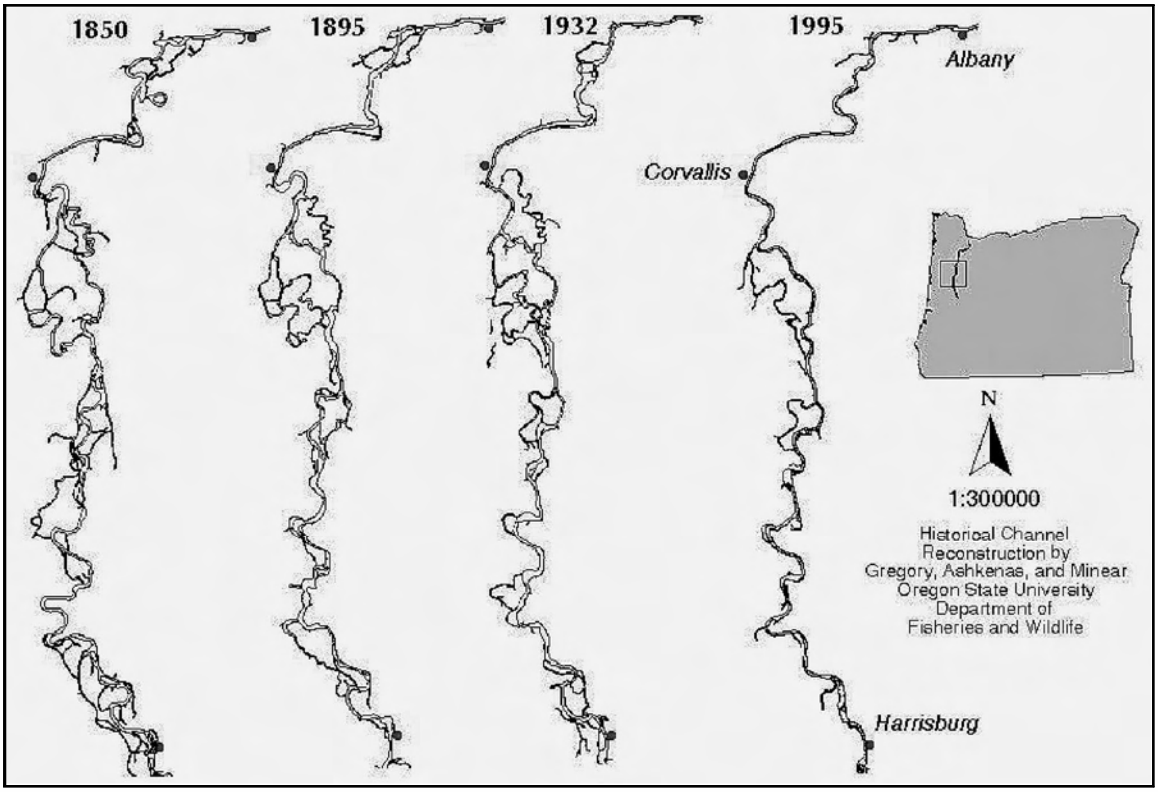


*Figure 2. Channels of the Willamette River in 1850, 1895, 1932, and 1995 (from Gregory et al. 2002).*

100% of the time) are more than 13 cubic meters per second ($m^3/s$) greater, and peak flows (i.e., the daily flows that are exceeded less than 0.01% of the time) are almost 2000 $m^3/s$ lower, after dam implementation (table 2).

One of the major ecological benefits of dam removal is the restoration of hydrologic regimes, particularly in the local reach and immediately downstream. Such hydrologic changes are possible through modification of the dam's operation (without its removal), but the benefits to connectivity and geomorphic complexity afforded by removal would not be realized. It is possible to operate a dam to provide low flows and high flows that are similar in magnitude and timing to natural flows, but some modification of flow is inevitable for dams erected to store and release water to create peaking flow for powering turbines, to dampen flood flows, or to augment low flows. Even if natural flows are closely simulated in dam operation, the geomorphic effects of trapping sediment behind the dam and loss of connectivity for migrating organisms persist.

*Table 2. Discharge (cubic meters per second) required to meet different exceedence levels in the Willamette River at Albany, Oregon, during two time periods: 1893–1976 and 1969–1997 (data from US Geological Survey flow records).*

| Percentage exceeded | Flow 1893–1976 | Flow 1969–1997 |
|---|---|---|
| 100 | 60 | 73 |
| 50 | 273 | 267 |
| 10 | 957 | 933 |
| 1 | 2010 | 1799 |
| 0.1 | 3398 | 2533 |
| 0.01 | 5239 | 3257 |

Interactions of geomorphic and hydrologic processes shape river channels through both erosional and depositional processes that occur during floods that fill the active channel and extend across river floodplains. If large floods are eliminated by dams, channels can incise and impede interaction with their floodplains. In the Willamette River in Oregon, more than 50% of the channel complexity has been reduced through active channel alteration, bank hardening, and hydrologic alteration through flood control (figure 2; Gregory et al. 2002). Though only 26% of the length of riverbanks in the Willamette has been armored by riprap (continuous cover of large boulders) on one or both banks, two-thirds of the meanders in the river are hardened and anchored by riprap and channel dynamics are severely dampened. In general, the more dynamic reaches of river are straightened and altered, and these changes are augmented by lowered peak flows through dam operations. Dam removal potentially restores hydrologic conditions and permits more dynamic channels.

However, a possible unintended consequence is that society may attempt to attain its goals (e.g., flood control, water supply, and commerce) through different means, thereby nullifying gains provided by the new hydrologic and geomorphic conditions created by removal of dams. For example, concerns about uncontrolled flooding after removal of a dam may cause landowners and agencies to attempt to reduce bank erosion through riprap, levees, and other forms of channel hardening. Efforts to "discipline" channels may diminish some of the environmental benefits of dam removal. Similarly, local needs for electrical power may cause communities to turn to other methods of power generation that have other effects on the environment, such as air quality. Dams constructed to provide water supplies may be replaced with water withdrawals from groundwater. Though these alternative actions would not entirely negate the potential benefits of dam removal, decisionmakers are rarely faced with the task of simply removing a dam; the factors that led to its construction continue to influence community actions.

## Biological responses

Dams in northwestern rivers influence salmonids and other species by eliminating spawning and rearing habitats in the area covered by reservoirs, changing water velocities that influence migration rates, altering currents that are attractants for migrating fish, forcing some fish through turbines where they experience extreme pressures, increasing river temperatures as the sun warms the slower waters of the reservoir, exposing migrating juvenile fishes to fish and avian predators, and modifying flood patterns that shape river habitats and maintain spawning gravels. Removal of dams potentially restores river temperature patterns, flow patterns for migrating fish, and flood dynamics. The potential negative impacts of dam removal on salmonids are associated primarily with the instabilities of sediments and terraces stored behind the dam. In the case of the Elwha River, planners hope to minimize these effects through temporal phasing of dam removal. In the case of the Snake River dams, federal agencies have examined options that would remove only the earthen portions of the dams and retain the concrete section to stabilize the upstream sediment deposits.

Installation of dams has caused the decline of indigenous aquatic fauna and changes to riparian vegetation worldwide (Li et al. 1987, Pfleiger and Grace 1987, Friedman and Auble 1999, Hughes and Parmalee 1999, Aparecio et al. 2000, Jansson et al. 2000, Penczak and Kruk 2000, Sharma 2001). Dams influence changes in species diversity in several ways. The stream and riparian habitats are changed by inundation, flow alterations, and influences on groundwater and the water table (Friedman and Auble 1999, Shafroth 1999, Rood and Mahoney 2000). Because dams are barriers that limit the dispersal of organisms and propagules, migration patterns are interrupted, breaking key links in the life history of riverine and aquatic organisms (Andersson et al. 2000, Jansson et al. 2000, Morita et al. 2000).

***Direct impacts on survival.*** In several ways, dams have become killing fields for native aquatic species. Each dam can be thought of as a density-independent source of mortality, a type of predator that kills through the shear forces caused by the cavitation of turbine electrical generators (Coutant and Whitney 2000). In the Columbia basin, each dam is estimated to kill 5% to 20% of all the juvenile salmonids migrating downstream (Raymond 1979, Skalski 1998). What is not known are the extended effects on survival of salmonids that pass through a number of dams through different migration paths from their natal streams to the ocean, a journey that requires weeks to months for most species of anadromous salmon. Moreover, negotiating each dam causes elevated levels of serum cortisol as a result of stress. This suppresses the immune system and exposes fish to higher risks of disease (Maule et al. 1988). Dams create conditions that cause fishes to die from gas supersaturation, a condition similar to the bends (decompression sickness) in humans (Bouck 1980, Crunkilton and Czarnezki 1980, Penney 1987). When water spills over dams into deep water, atmospheric gases are dissolved in water under high pressure. This can lead to supersaturation of nitrogen at 110%–120% levels (Montgomery and Becker 1980, Ryan et al. 2000). Unless there are shallow areas, such as riffles, where gas levels can equilibrate at the air–water interface, supersaturated conditions can extend for several kilometers. For aquatic organisms that move from deep water up to shallow depths, these conditions can lead to gas bubble disease, in which the supersaturated gases come out of solution in the organisms' body fluids and cause embolisms. Just as the bends can be fatal to scuba divers who surface too quickly, these gas bubbles can lead to dramatic kills of aquatic organisms.

***Indirect effects on nutrients and water quality.*** Dams are sediment traps that can keep nutrients such as silica sequestered behind dams, thereby changing community composition of phytoplankton downstream, as witnessed in the Black and Baltic Seas (Humborg et al. 2000). Retention of nutrients behind dams due to the reduced velocity and longer residence time of water in the reach changes the availability of nutrients and composition of plant and microbial communities. Sediment trapping by dams will accumulate and store toxic materials that are adsorbed physically on sediment particles or absorbed actively by the biota attached to the sediments (Dauta et al. 1999). Gravels and cobbles are sequestered behind dams, which limits their recruitment downstream and leads to habitat changes in streams and estuaries (Gosselink et al. 1974, Kondolf 1997).

Dams can change the natural variation of stream temperatures, depending upon the dam's size and mode of operation. Releases of hypolimnetic water (the colder, most dense layer of water in a reservoir that is thermally stratified) from high dams can lower stream temperatures, thereby limiting the reproduction of warmwater fishes and shifting downstream communities to coldwater organisms (Clarkson and Childs 2000). Conversely, low-head dams can act as heat traps and shift community composition in the opposite direction (Walks et al. 2000).

***Indirect effects on species interactions.*** Distributions and abundance of native species can be altered around or within reservoirs by interactions with either nonnative species or other native species. Dams can create novel habitats, habitats of marginal value to native species, or intensified interactions among species.

**Predators.** Sediment trapping has clarified normally turbid streams in the Colorado and Missouri basins. One result has been that native fishes are now exposed to greater predation by piscivores (Pfleiger and Grace 1987, Johnson and Hines 1999, Petersen and Ward 1999). Dams in streams of the Columbia basin created migration bottlenecks for migrating salmonids, exposing them to greater contact time with native predators such as northern pikeminnow *(Ptychocheilus oregonensis)* and avian predators (Buchanan et al. 1981). In the American West, native fishes tend to be more adapted to lotic conditions because of the relative scarcity of interconnected streams and lakes. Therefore, lentic fishes or fishes that have evolved in drainages interdispersed with lentic systems, for example, the Upper Mississippi, were introduced (Moyle et al. 1986, Li and Moyle 1999). Gamefishes are almost always carnivorous, and their introduction often foreshadowed a whole suite of novel interactions with the fauna that had not been exposed to their unique traits (Wydowski and Bennett 1981, Li and Moyle 1999). In the Columbia River, the food web has been greatly altered, and the effect of introduced piscivores appears to have increased mortality in an additive fashion (Li et al. 1987, Knutsen and Ward 1999, Ward and Zimmerman 1999). Compensation for this mortality in other stages of the organism's life has not been detected.

The distribution of piscivory varies in different reaches of the Columbia River basin. Predation by introduced sunfish and catfish is higher in the Snake River system, and predation by northern pikeminnow is greater than that by alien piscivores in the lower Columbia River (Zimmerman 1999). In part, this reflects the patchy distribution of habitats and species in the system. In the Columbia River, most of the exotic fishes are located in backwaters and reaches with lentic characteristics, and native fishes are most common in the free-flowing mainstem (Hjort et al. 1981). It also reflects the susceptibility of native fishes to alien predators. As an example, juveniles of fall run chinook salmon *(Oncorhynchus tshawytscha)* are smaller than spring–summer run chinook juveniles, and preference by alien smallmouth bass *(Micropterus dolomieui)* for them may reflect size-selective preferences (Tabor et al. 1993, Zimmerman 1999). As predicted by Li and colleagues (1987), the nocturnal northern sandroller *(Percopsis transmontana)* appears to be more vulnerable to exotic piscivores, because their size and behavior make them vulnerable to smallmouth bass and the nocturnal walleye *(Stizostedion vitreum).*

In the Colorado River, the combination of the change in seasonal patterns of river discharge, water clarity, temperature, and the introduction of exotic species—all products of regulating the river—complicates recovery of the indigenous minnows and suckers. Radiotracking studies indicate that suitable habitats for native species still exist, but dispersal becomes problematic (Irving and Modde 2000). Although cold water released from Glen Canyon Dam restricts native fishes in the Little Colorado River from dispersing to downstream reaches, such barriers offer protection from invasive species. The cold water prevents alien warmwater predators (striped bass *[Morone saxatilis]* and largemouth bass *[Micropterus salmoides])* from dispersing into upstream reaches and invading one of the last strongholds for native fishes in the Colorado River system.

**American shad.** The American shad *(Alosa sapidissima)* illustrates a paradox that occurs when a species is more abundant in a new area to which it was introduced than in its native range. American shad is a highly prized, native anadromous fish along the Atlantic seaboard of North America. Dams are a primary cause of its severe decline. Many of these dams did not provide fish ladders, thus blocking passage to spawning areas upstream, and altered habitat conditions for pelagic eggs and shad larvae (figure 3a) (Walburg and Nichols 1967). Ironically, this same fish is commonly found spawning in streams along the Pacific Coast, where it is an alien species (Lampman 1946). Introduced to the Sacramento River in 1871, it expanded its range rapidly, and by the 1890s it had reached southeastern Alaska (Welander 1940). To compound the irony, shad population growth exploded exponentially in the Columbia River following the installation of the Dalles Dam in 1960, which inundated Celilo Falls, thereby removing a barrier to upstream movement (figure 3b). Interestingly, this phase coincided with the steep decline of Pacific salmonids and the construction of several high dams.

The paradox can be explained by the fact that the dams, especially in Maine, were barriers, whereas, at least in one instance, the Dalles Dam gave shad access to spawning areas in the upper Columbia River. Further improvements to fish passage facilities may have facilitated expansion of the shad's range to Priest Rapids Dam in the upper mainstem Columbia River and to Lower Granite Dam in the Snake River drainage (Monk et al. 1989). Celilo Falls was not an impediment for Pacific salmonids migrating up the Columbia River; but the mainstem dams reduced salmon migration and also eliminated spawning habitat of fall run chinook salmon, which spawn only in higher-order streams.

A second factor is the effects of commercial harvest on shad populations—at its peak, approximately 50 million pounds were caught off the Atlantic Coast, a figure that is 13 million pounds greater than the highest shad run ever recorded for the Columbia River (from Boschung et al. 1983). Commercial harvest of shad in the Columbia River is small, approximately 740,000 pounds. Populations of shad may continue to expand in the Columbia River, but numbers are still only a fraction of what they must have been historically for shad on the Atlantic Coast. Columbia River fisheries managers, who have noticed the correlation between shad increase and salmon decline, are concerned about the potential for competition for food between shad and salmonids. The alternative explanation for the increase of shad in the Columbia River while Pacific salmon are declining is that the high dams of the Columbia River have opposite effects on shad and salmon.

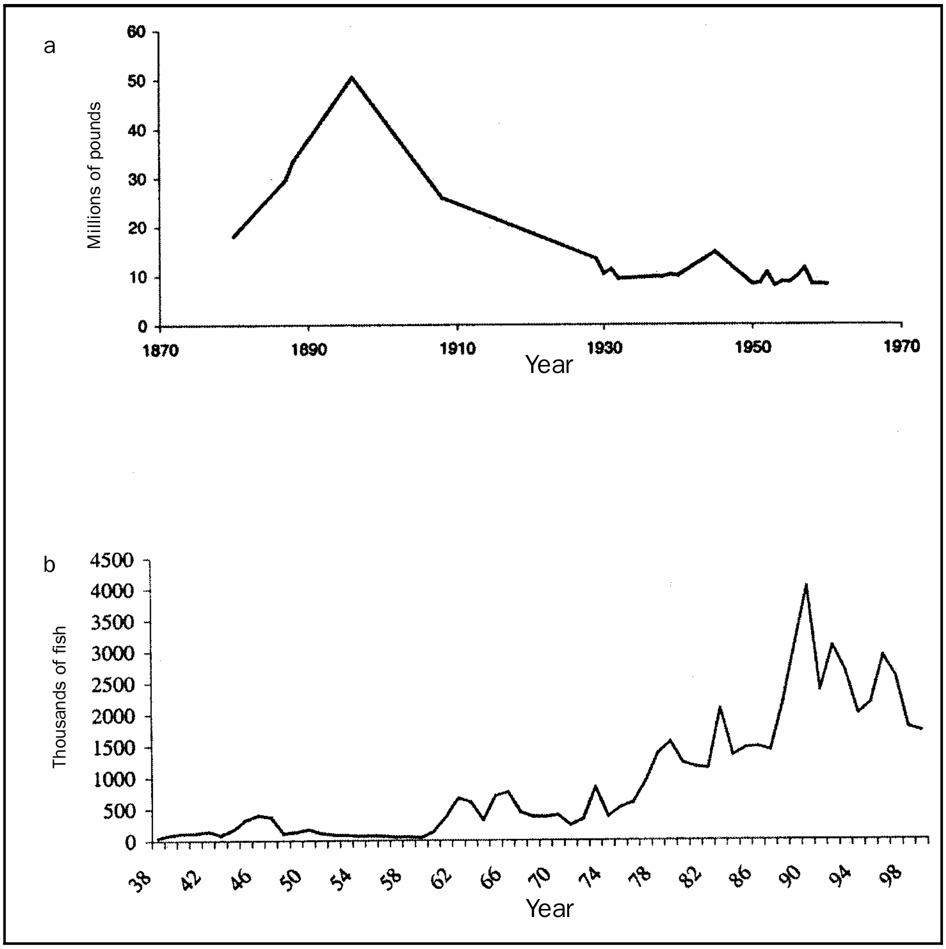


***Figure 3. Trends in shad abundances over time. (a) Atlantic Coast shad harvest 1880–1960. (b) Columbia River shad run minimum estimates from 1938–1999.***

Until we learn more about shad ecology in the Columbia River and conduct informative experiments and monitoring programs, the factors responsible for declines of shad on the Atlantic Coast and increases in shad on the Pacific Coast, including the influence of dams in the population trends, will remain controversial.

**Freshwater mussels.** Changes in flow, sediments, and temperatures when dams are removed may have noticeable effects on beds of freshwater bivalves. The hypolimnetic waters that are released by dams prevent gametogenesis and spawning of warmwater mussels (Neves 1999). Fish species upon which mussel species depend during the glochidia stages (when the young mussel larvae are parasitic on fish) may also be affected by alteration of flow and temperatures downstream of dams; loss of host organisms creates an indirect negative effect on mussel colonization and survival. Within a few years of reservoir inundation, water depths and changes in sedimentation eliminate upstream bivalve beds. Because mussels and other bivalves depend on flowing water and unimpeded movements of host fish, dam removal may allow reconnection of populations of bivalves fragmented by lentic waters behind dams.

## *Case studies*

In the Pacific Northwest, dams on the Columbia River system have eliminated access of anadromous salmonids to an estimated 55% of the total area and 33% of the total stream miles (Lichatowich 1999). The National Research Council report on salmon concluded that "as many as 90% of young salmon might survive passage over, around, and through any individual hydropower project on the Columbia–Snake river mainstream" (NRC 1996). For example, fish that must pass through a sequence of five dams with 90% success of passage through each dam would experience a loss of 41% of the original number that attempted to migrate downstream. Such cumulative effects of multiple dams on mainstem rivers are widely accepted as a major influence on the decline of anadromous salmon in the western United States.

The concepts and challenges described above can be illustrated through case studies of specific dams of the Pacific Northwest. The Elwha River dams, which may be the first high-head dams to be removed in the United States, illustrate the possible approaches for dealing with the challenges created by removing dams that have developed deep sediment deposits upstream (Stoker and Harbor 1991). The Snake River dams provide examples of the complex decisions concerning endangered species and resource uses that removal of major dams entails. Collectively, these case studies point to some of the intricate issues facing decisionmakers in the consideration of the removal of large dams.

***Dams of the Elwha River.*** The Elwha River flows for 72 km north out of the Olympic Mountains to the Straits of Juan de Fuca in northwestern Washington state. It drains more than 161 km of tributary streams and falls 1372 m in elevation, with an average annual instantaneous flow of approximately 43 $m^3/s$ (Bureau of Reclamation 1996). More than 80% of the Elwha River basin is located in the Olympic National Park. Elwha Dam was built between 1910 and 1912, 7.9 km upstream of the confluence with the Straits of Juan de Fuca (figure 4). Behind this concrete and earth-fill dam, Lake Aldwell can store 10 million $m^3$ with a surface area of 108 hectares (ha). Upriver 13.7 km, the larger Glines Canyon dam is a tall, 64-m-high, single-arch concrete dam; it holds Lake Mills, which can

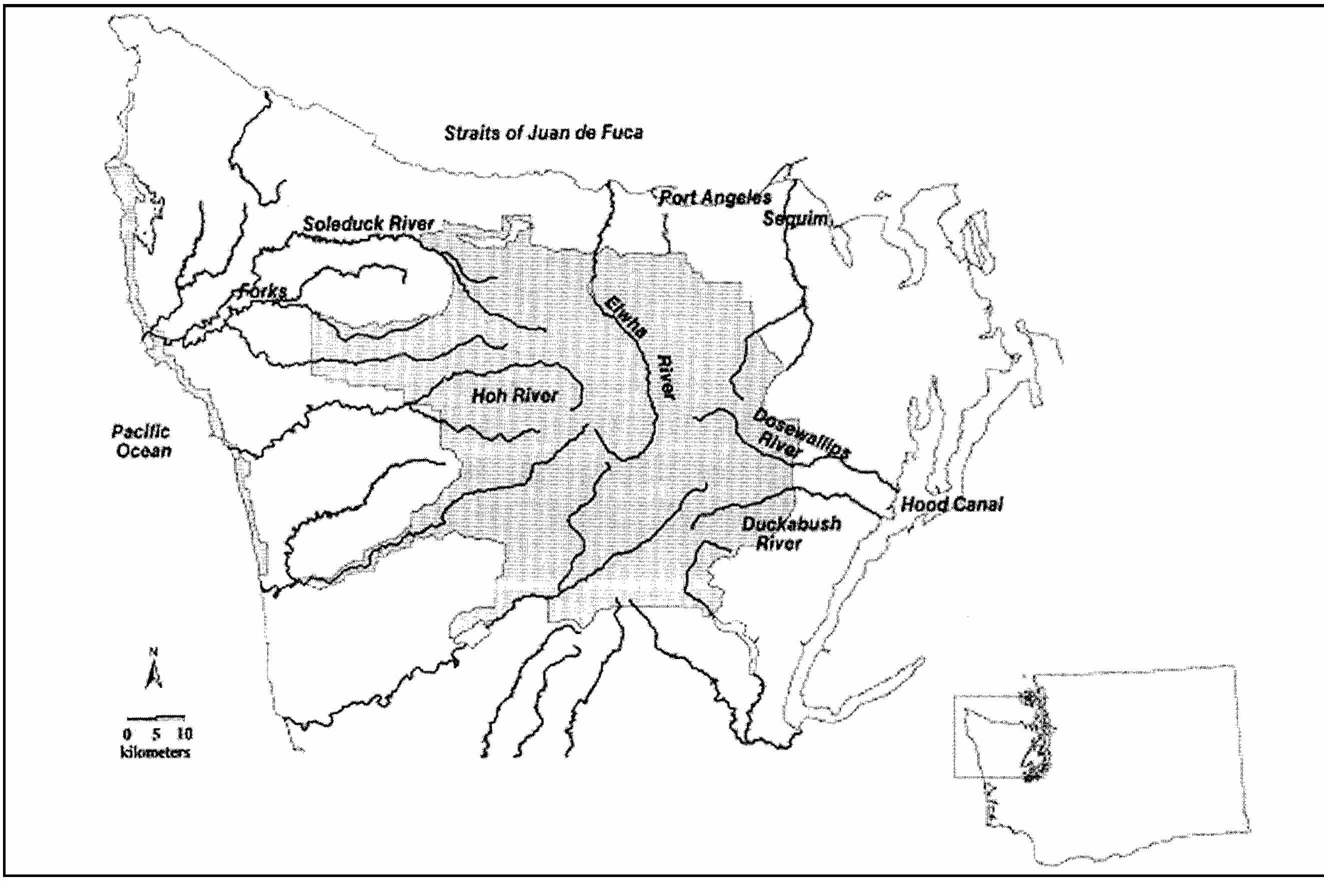


***Figure 4. Elwha River on the Olympic Peninsula in Washington (diagram from National Park Service).***

contain 50 million $m^3$, with a surface area of 168 ha. Both dams are operated as run-of-river dams (i.e., daily flows are not altered by the dams), but daily hydrological regimes are modified by the dams. But these dams block fish passage and trap more than 13 million $m^3$ of sediment, mostly behind Glines Canyon Dam. Plans to remove these dams to restore this ecosystem, particularly its salmonid runs, received federal approval with the Elwha River Ecosystem and Fisheries Restoration Act (PL 102-495), signed by President Bush in 1992, which authorizes the secretary of the interior to acquire the dams and remove them if their removal is necessary to achieve "the full restoration of the Elwha River ecosystem and native anadromous fisheries." The Department of the Interior purchased the dams in 2000, and they are scheduled to be removed in 2003 if additional funding can be obtained. The size of these dams, the magnitude of river discharge, and volume of sediments behind the dams make the prospective dam removal a much larger undertaking than other projects to date.

The precarious status of salmonids in the Pacific Northwest and the potential gain for spawning habitat of the Elwha's anadromous salmonid stocks provided the impetus for this ambitious project (Wunderlich et al. 1994). There are no precise estimates for historical production in this river, but according to 1987 estimates by the Joint Fish and Wildlife Agencies, there were potentially high numbers of pink *(O. gorbuscha)* and chum salmon *(O. keta),* and relatively high numbers of chinook and steelhead *(O. mykiss)*, compared with other streams in the region. The river was renowned for the size of its fish, especially the chinook, which reportedly weighed more than 100 pounds apiece in the 1930s (FERC 1991). Other salmonids present in the Elwha are anadromous coho *(O. kisutch),* resident and anadromous Dolly Varden *(Salvelinus malma),* and sea-run cutthroat *(O. clarki).* Hatchery coho, steelhead, and chinook are important competitors in the lower reaches. Pink salmon runs have declined rapidly since 1979, plummeting from runs of about 40,000 in 1959 to mere hundreds in recent years. Reduction of pink and chum salmon was related to predation by hatchery fish in other systems (Johnson 1973, Cardwell and Fresh 1979), and predation may be an important factor in the lower Elwha as well.

The uppermost river reach is very steep, and most of the main river to Lake Mills meanders through alluvial deposits, sometimes flowing through steep canyons. A major waterfall at 55 km upstream from the mouth would limit some species from using much of the upper river reach. At present the middle reach is highly armored and dominated by cobble and large boulders. The short-term effects of dam removal will include the redistribution of large volumes of silt downstream (Stoker and Harbor 1991), but eventually additions of gravels will open up extensive reaches of usable spawning habitat in the middle reach. These changes would likely affect species that occupy the lower reaches of the river the most (e.g., chinook, pink, and chum salmon).

Return of anadromy could also affect food webs upstream. For example, resident steelhead and Dolly Varden would lose some spawning habitats associated with reservoirs and also be subject to greater competition and predation by juveniles of other salmonid species. Increased fish densities will benefit piscivorous predators such as common mergansers, great blue heron, and belted kingfishers. Presently, bald eagles, whose numbers are highly correlated to chum escapement in other Olympic watersheds, are uncommon (only six observations in winter 1990). Their scarcity is likely due to lack of prey. Based on estimates from the nearby Skagit River where bald eagles are numerous, 18,000 chum would attract about 140 bald eagles to the drainage (DellaSala et al. 1990). Availability of anadromous salmonids as prey for bald eagles will depend on coincidence of fish migrations and eagle arrivals. Salmon with migratory patterns less synchronized than chum with eagle movements, particularly pinks and chinook, could provide food only for eagles arriving in early winter.

The lake-like conditions of the reservoir reaches have created favorable conditions for almost a century for some plants and animals that will be adversely affected by dam removals. Shoreline cover along Lake Aldwell will greatly diminish and thus significant habitat for lacustrine mink will be removed (FERC 1991). Surprisingly, beaver are likely to increase with recolonization of hardwoods along riverine terraces. Wetland biomes that have developed along lake edges will disappear with their associated plants, one of them a bicolored linanthus unique to the Elwha valley (FERC 1991). Eventually other wetlands are expected to develop along stabilized backwater and meanders of the reestablished floodplains.

Overall, removing the dams will greatly enhance anadromous fish runs and, consequently, food chains. Dramatic increases in salmon carcasses are expected to provide nutrients and food resources to juvenile fishes and other aquatic predators. Changes in hydrology and return to natural flow patterns will influence downstream temperatures and instream dynamics. Average temperatures in the middle and lower river reaches will be lower than at present. Maximum daily water temperatures are 15°C–20°C in low water years (Washington Department of Fisheries, Elwha hatchery records); these levels are most likely harmful to fish eggs. These elevated water temperatures may increase the infection rate of *Dermocystidium* bacteria, which attack salmonids as they come from marine systems into fresh water (FERC 1991). Lowered water temperatures after dam removal would decrease the incidence of the disease and thus potentially increase salmonid survival.

In 1990, invertebrates that were collected downstream of Glines Canyon Dam were significantly less diverse than in upstream reaches; they were characterized by early-colonizing species and abundant filter-feeding caddis flies. Dominance of baetid mayflies and chironomid midges reflected the almost daily fluctuating flows as dam releases pulsed through the system. Though the dams were managed as run-of-the-river flows, daily fluctuations were not conducive for stable invertebrate populations, especially organisms in habitats associated with the river margin, with potentially similar effects on young fish. More naturally predictable flows will contribute to increases in productivity at all levels.

Where the Elwha River flows into the Straits of Juan de Fuca, its estuary supports clam beds. When the Elwha and Glines Canyon dams are removed, an estimated increase of 160,000 $m^3$ in sediments will be supplied at the mouth of the river (FERC 1991). It is possible that these sediments will have short-term impacts on downstream communities and nearshore marine benthic communities and shellfish at the mouth of the Elwha River. During the years of the dams' operation, there has been a dramatic reduction of sediments (from approximately 115,000 to only 1835 $m^3$ per year). Coastal sediments have been reduced by 36%. The sand, gravel, and cobbles that would be reintroduced into the coastal zone may provide sufficient sediments to support a small increase in shellfish.

***Dams of the Snake River.*** The Snake River, which once produced 45% of all chinook salmon found in the Columbia River basin (Hassemer et al. 1997), has four dams—Ice Harbor, Lower Monumental, Little Goose, and Lower Granite Dams—that affect species of anadromous salmon listed as endangered under the Endangered Species Act (figure 5). A study of historical patterns of survival of different stocks of chinook salmon in the Columbia River basin concluded that survival dropped sharply in reaches affected by dams soon after construction, but survival did not change abruptly in reaches not influenced by dam construction (Schaller et al. 1999). Removal of these dams might decrease the risk of extinction for these species. Coho salmon are now extinct in the Snake River. Sockeye were listed as endangered in 1992, and spring chinook, summer chinook, fall chinook, and steelhead were listed as threatened from 1993 to 1998. In February 2001, federal courts ruled that the US Army Corps of Engineers was required to comply with the Clean Water Act in its management of dams. The courts determined that the dams caused temperature increases and gas supersaturation that exceeded limits under the Clean Water Act. Future dam management operations must address the water quality goals and policies of the state and federal governments. Most management actions have focused on reducing effects of the dam by retrofitting dams with better passage facilities, trucking and barging the fish around the dams, or increasing the spill of water over the dams so that fewer fish went through the turbines. But all of these actions essentially coexist with the existing dams. The economic impacts have been hotly debated (see Whitelaw and MacMullan 2002), but the consequences of dam removal on the risk of extinction of salmonids also has been controversial. More than 200 scientists signed a letter to President Clinton calling for removal of the four Snake River dams.

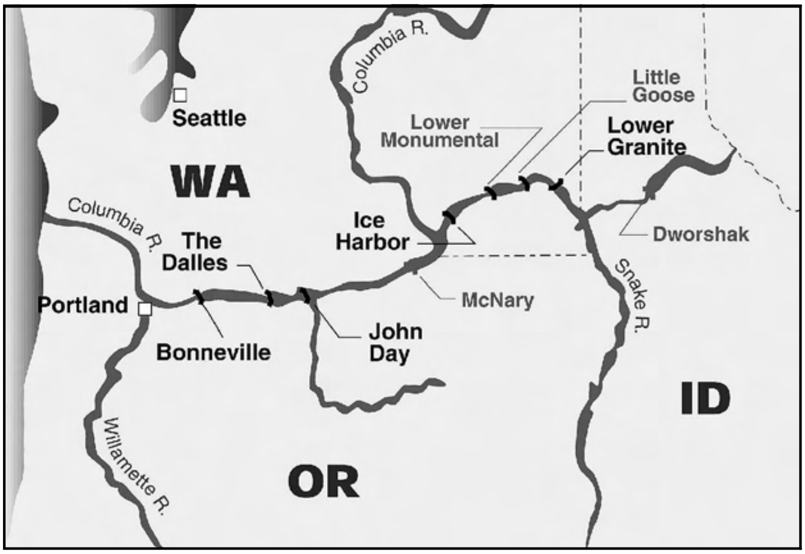


*Figure 5. Dams on the Columbia River. The four Snake River dams considered for removal are on the Snake River immediately upstream of the confluence with Columbia River (diagram from US Army Corps of Engineers).*

Recently, the US National Marine Fisheries Service estimated that anadromous salmon stocks have a 55%–100% probability of extinction over the next 100 years (NMFS 2000). Despite dam passage improvements that have dramatically mitigated direct mortality associated with dams, the NMFS concluded that the removal of the dams would not reduce the risk of extinction under current conditions. They found that Snake River spring–summer chinook salmon would probably continue to decline toward extinction, and therefore NMFS recommended "modest reductions in first-year mortality or estuarine mortality [to] reverse current population declines" (Kareiva et al. 2000). Other scientists modeled these populations incorporating delayed first-year mortality. They considered the possibility that juvenile fish migrating downstream to the ocean might experience delayed mortality. If fish die later because of stress or injury, simple estimates of fish mortality as they pass directly through the immediate vicinity of a dam may be substantially lower than actual mortality. Modeling runs that incorporate higher delayed mortality rates indicated that removal of the Snake River dams could potentially reverse declines in Snake River chinook salmon (Dambacher et al. 2001). Recent analysis of several data sources and modeling concluded that salmon smolts migrating through the dams experience delayed mortality (Budy et al. 2002). All studies (Marmorek and Peters 1998, NMFS 2000, Budy 2001) reviewed by these authors concluded that fish that migrated through the hydrosystems in the river had survival rates that were approximately 25% to 50% lower than those for fish that were transported around the entire hydrosystem.

Studies suggest that upriver salmon will not benefit from the breaching of the Snake River dams (Kareiva et al. 2000, Zabel and Williams 2000), but other interpretations of the data differ if delayed mortality is considered (Marmorek and Peters 1998, Nemeth and Keifer 1999, Schaller et al. 1999, 2000, Dambacher et al. 2001, Petrosky et al. 2001). Questions about mortality rates of different life history stages of anadromous salmon point to the need for better information about the impacts of human actions on salmonid populations and life history stages.

## Connecting science and policy

Ecological responses to dam removal cannot be predicted with a high degree of certainty in complex river ecosystems. Public values and social actions also have large effects on ecosystems and the nature of resource decisions. Most people are reluctant to deconstruct anything they built and financed, even if they later realize that the decision may have been flawed. Resource managers must make critical decisions in the face of uncertainty and complicated social values. In such cases, one approach is the application of a precautionary philosophy in conjunction with the concepts of adaptive management. The precautionary principle generally suggests that, in the face of uncertainty, efforts to reduce impacts are prudent and reversible choices should be favored over irreversible choices (Ludwig et al. 1993 ). But this too may be inadequate unless we integrate the larger cultural backdrop (social, economic, political, and legal aspects) concerning decisionmaking. Blumm and colleagues (1998) suggest that they have made this complete analysis for the Snake River dams. In their judgment, breaching these is the most logical step. Additional analysis will improve the basis for this decision, but the technical data will always be limited and decisionmakers will be forced to consider the weight of evidence and will have to make very difficult social and environmental decisions.

Dam removal or the breaching of dams will be controversial in many cases because of the many vested social and political interests. The role of science in forming policy is rapidly changing, and public confusion over the positions of dueling scientists is not uncommon. The current debate surrounding the Snake River dams and the dams of the Elwha River in Washington illustrates the high degree of uncertainty inherent in projecting ecological responses to dam removal. The first challenge is the complexity of physical responses in the naturally variable environments of river systems. Projections of geomorphic and hydrologic changes are not simple and will vary greatly based on local landscapes and climate. Ecological interactions are complex because of the interactions between adjacent terrestrial and aquatic ecosystems, predator–prey interactions, competition, succession, and dispersal of aquatic and terrestrial organisms. Even more complex is the array of social actions in river systems that dictate ecological responses, such as hydrologic alteration, water diversion, bank hardening, land use conversion, exotic species introductions, and water quality impairment. Resource managers and the public must recognize that precise predictions of ecological change after dam removal are not possible. Nevertheless, the conceptual framework provided by our knowledge of stream ecosystems and their interactions within the landscape provide a basis for prudent choices and adaptive management to local responses to dam removal.

## Acknowledgments

Publication of this paper was supported, in part, by the Thomas G. Scott Publication Fund, Oregon State University. Figure 3 was prepared by Peter Barber, Josh Hanson, and Steve Starcevich.

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# What Goes Up, May Come Down

BRUCE BABBITT

**Once upon a time (not long ago, during the early** years of my tenure at the US Department of the Interior), vigilant watershed-based communities could often be seen gathered on the banks of their streams, waving homemade signs, heckling politicians, and vowing to lie down in front of government bulldozers, united by their singular passion to Stop Dams! Save Our River!

No longer.

Rapid developments in the last few years have given rise to a new protest movement. This one, also grassroots, musters its forces, raises funds, organizes committees, shouts down federal officials, lobbies legislators, waves placards for the press, and promises civil disobedience if the government proceeds with its engineering plans. Only this time, the words painted on their banners read "Stop Rivers! Save Our Dam!"

Yet this is only the most visible level of irony. Peel away simple media images and a second level emerges: Ideological opposites on dams are now reversing roles, exchanging hats, and switching arguments with each other.

Consider: Dam opponents once were the true fiscal conservatives. They urged caution, pointing out that dams typically cost taxpayers more than estimated in early projections, and that alternatives to dams exist. They favored the status quo, noting that there was too much uncertainty to allow concrete pouring without more and more laborious environmental and social impact studies. They championed the rights of human lives and livelihoods for Native American tribes who earned their food and made their homes on the banks of rivers but who were still displaced involuntarily and without meaningful compensation.

Back then, it was the dam builders who were pressing for rapid change. They said, "Trust us"—with all the benefits their dam would surely provide, all other concerns would be sorted out...once the dam was under way. They just instinctively *felt* that construction was the right way. Dams were the panacea for floods or fire, irrigation or navigation, voltage or storage. Dams, we were confidently assured, were the answer.

And so they seemed, at the time, to many.

> LEARNING FROM OUR EXPERIENCES WITH DAM CONSTRUCTION IN THE PAST CAN GUIDE AND IMPROVE DAM REMOVAL IN THE FUTURE

But gradually, over the years, water evaporated from reservoir surfaces or got choked by algal blooms; concrete crumbled under pressure and time; structures severed salmon migration, collected silt, and cost millions to repair or replace. Scientific studies of unforeseen negative impacts mounted. Slowly, then quickly, dam removal became an answer as well. It became a means for restoring ecologically degraded rivers.

Now, the pro-dam lobby is the one making the conservative case for fiscal austerity, blasting some removals as too expensive, arguing that local owners, ratepayers, and taxpayers (who benefited from a dam) should not have to finance the dam's deconstruction (even though in many cases dam removal is the least expensive option in dam decisions). They demand economic compensation for any displaced downstream irrigators, sawmill operators, energy consumers, or marina owners (who in turn once displaced the tribal fishermen). They agitate over the social rights of landowners around the reservoir, who moved in thinking the dam would stand safely forever, cost free. Surely, they say, other options must be pursued. Most ironic, it is the pro-dam lobby that presses for extensive, time-consuming environmental studies about potential impacts of removal in the face of uncertainty.

It would seem easy to brush off such concerns as hypocritical, given the dam proponents' earlier blasé expediency or their rush to press new dams elsewhere. With dams on the

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defensive, it is tempting to say, "Trust us—removal is the answer." For quite often, removal does make the most ecological *and* economic sense.

And lest there be any misunderstanding, my own stand on consensus-based dam removal is on the record. It became increasingly pronounced over the past half-decade as I graduated from one level to the next, embracing sledgehammer, jackhammer, wrecking ball, sky crane, and even C-4 plastic explosives to help dismantle dozens of obsolete structures, structures that had either outlived their function or outweighed their benefits with costs that society was no longer willing to pay.

The change has come. The heyday of dams has come and gone. From my perspective, there is no turning back.

Yet some questions over dam removal linger and should not be too quickly or easily dismissed. They deserve thoughtful answers and, more important, scientific follow-up documentation to back those answers up. The impacts of dam *de*-construction should be carefully estimated before removal and objectively evaluated afterward, even if—especially if—both predam and postdam examinations were never conducted when the dam was built. And dam proponents should be recognized even by—especially by—those same dam opponents who were excluded from past decisions to build.

Why? Why hold dam removal to a higher standard than construction ever faced? Because if such concerns go unanswered, the future of dam removal may eventually erode to become as vulnerable, unstable, and obsolete as some of the dams it will erase.

In one respect, the dam removal juggernaut is proceeding on solid ground. As shown in this issue of *BioScience,* many leaders at the local and national levels follow the precautionary principle, asking the right questions and raising issues in advance. Moreover, in-depth explorations that address broad stakeholder interests are being conducted by the Heinz Center and Aspen Institute, among others. Some dams are better candidates for removal than others, such as those where the benefits of removal outweigh the uses and benefits of the dam. And scientific study can help to identify the best candidates.

Rather than simply exchange the old simple approach to dams (build now, ask questions later) with a new, equally simple plan (remove now, analyze outcomes later), these initiatives have begun to recognize the socioeconomic and ecological complexity of what we are doing, and they affirm our obligation to the past, to each other, and to our surroundings. In carrying out our obligation, we can use what we have learned from the impacts of dams to help model, predict, and monitor the impacts of their absence.

Science has made it increasingly and painfully clear that a single dam can produce impacts that extend the entire length of a river and beyond, damaging nearby estuaries, beaches, and ocean and adversely affecting biodiversity on a regional scale. Likewise, we must continue to use science to inform and explain the costs and benefits of removal throughout the watershed.

*Through documentation and analyses of case studies, we can be guided by the light of science rather than curse the darkness in which we must make projections.*

This can take time. Edwards Dam on the Kennebec River in Maine underwent years of study before its removal. At Savage Rapids Dam, another prime removal candidate on the Rogue River watershed, environmental and economic impact studies go back more than a decade.

It can also involve watershed economies. Before undertaking removal of Glines Canyon and Elwha Dams on the Olympic Peninsula of Washington, the Department of the Interior compiled a history of impacts on fisheries in the watershed and began modeling the expected impacts of silt changes in the river and at the mouth of the stream to ensure that the final decision incorporated shellfish harvests at the delta as much as angling revenues in the headwaters.

In addition, estimating impacts in advance can save time and money. The Bureau of Reclamation has begun taking coring samples of the sediment clogged behind the 190-foot-high Matilija Dam in Southern California. By doing so, they can begin to develop and test models as to possible movement, quality, impacts, and aquatic health once the dam comes down. It helps point the way toward the safest, most cost-effective way of getting all that sand from the shallow reservoir back down to the beaches, which have been without it for the past four decades. One emerging possibility is to do this gradually, stage by stage, layer by layer, to minimize impacts to endangered steelhead while opening up their spawning habitat.

This last example, considered the largest dam removal project under way in the world right now, raises a common-sense point that should be made nonetheless: Size matters. The larger the dam, the more extensive the impacts, and thus the more thorough and extensive the scope of preremoval analysis should be. Conversely, there is less reason to do a 5-year environmental impact analysis for removal of a 6-foot-high abandoned dam.

Each example teaches us more about the potential, the possibilities, and, well, the limits of our understanding about dams and dam removal. What works or fails in one place may not apply on another river. By exposing the gaps, we can fill them. By recognizing where there is a need for caution, we can proceed with more confidence. Through documentation and analyses of case studies, we can be guided by the light of science rather than curse the darkness in which we must make projections.

Most recent complex dam removals have proceeded after analysis of potential impacts and consideration of dam proponents' concerns. For the most part, the pressing issues have been raised in advance, and the right questions have been asked. But have they been well answered? Not as completely or thoroughly as they could be, which highlights why and where we can demand more scientific information. Not just to project impacts and outcomes in advance, for this is being done, but also to confirm that predicted benefits were in fact met and that no negative impacts occurred.

It has been disturbing, looking back, to realize that despite the scale and cost and hype over the past century, almost no postproject scientific analysis was ever done on dam construction. We cannot let that shortcoming extend to dam *removal,* despite several obstacles.

One obstacle is sheer velocity. What once appeared impossible suddenly seems inevitable. Five years ago, people asked of dam removal, Why? or whether. Society now asks: Which ones, when, and how? Each year that I was with the interior department, I was so busy rushing to champion dam removal events—in Oregon, Washington, Wisconsin, Maine, North Carolina, Pennsylvania, and California—that it was hard to distill the patterns and to follow up to ensure expectations were met. But moving from one project to the next does not mean we cannot revisit those removals to assess and determine whether expectations were met.

Another obstacle is overcoming our instincts. Removal feels so right and makes so much sense to so many: Surely, consensus-based dam removal would heal the hidden wounds that dams inflicted, restore river functions, bring back the anadromous fisheries from coast to coast. There are signs and suggestions that it is doing just that. It is gratifying to learn that, for the first time in many decades, thousands of Chinook swam up Butte Creek past the site of the former McPherrin Dam, Atlantic salmon and striped bass migrated up the Kennebec past the old site of Edwards Dam, vast schools of shad spawned (and were caught by fishermen) up the Neuse River on the outskirts of Raleigh. But even though we have anecdotal evidence of improvements, there is little hard evidence to confirm it. The lack of studies cries out for new research and peer-reviewed papers by experts in social, economic, and ecological fields.

A third obstacle is economic limits—that is, cost. Not one removal I took part in came top-down from Washington, DC. Each opportunity was driven upward, by local necessity—safety, cost, health, imminent extinction, budgets, and litigation. Local forces were the mothers of invention; we adapted our approach, funding, constituency, answers, funding, tools, and management to the unique needs of the watershed in which the dam belonged. That is politically sound but economically difficult. It often proved hard enough to scrape together funds to ensure safe, low-impact removal, let alone to set aside money for postremoval studies.

These obstacles explain our current situation but do not explain it away. However powerful, no force is an adequate, long-term substitute for clear, science-driven, consensus-based, and transparent written and accountable policy. Decades ago, dams were built to meet certain laudable goals, goals few can object to even in hindsight. But goals are not enough, unless they are met and, more important, shown to have been met. Dam removal, with equally laudable goals and carried out carefully with the best of intentions, cannot neglect the process of collecting and evaluating the evidence to determine whether the goals were met. This process of evaluation is the cornerstone of adaptive ecosystem management.

*The lack of studies cries out for new research and peer-reviewed papers by experts in social, economic, and ecological fields.*

The proper role of science is to light candles in dark corners. It should reveal paths that can guide and improve decisions by society. This is the case in conservation issues like endangered species, forestry, fire, wetlands, and air and water regulations. Yet when it comes to dams, and now to dam removal, all too often, rather than illuminate and lead policy well ahead of us, the academic field follows from behind.

But in issues like the one in your hands, we show that we are learning lessons from our history. Specifically, we are learning from our legal, societal, ecological, hydrological, economical, biological, and conceptual history of both dams and dam removal.

On that note, let us tip our hats here to those groups and foundations and scientists and land managers who not only herald the healing success stories involved with dam removal that we are proud of, but who are also brave enough to highlight the disappointing outcomes that we learn from.

For wherever we act, there is the potential for wounds to be inflicted and mistakes to be made—mistakes of planning, of expectations, of understanding, and of execution. Though its impacts appear far more beneficial than costly, let us still be humble. Dam removal, like dam construction, is not an end unto itself, only a means to an end. It is a means by which humans can live more responsible lives in harmony with creation, a means that requires the illumination of science, ensuring that we look clearly back, and down, before we can truly move forward on solid ground together.

# Legal Perspectives on Dam Removal

MARGARET B. BOWMAN

**For more than 100 years, America has led the world** in dam building—blocking and harnessing rivers for hydropower, irrigation, flood control, water storage, and other purposes. Now, some 75,000 large dams span our nation's waterways and thousands of smaller dams plug our rivers and streams (NRC 1992, AR/FE/TU 1999, USACE 2001a). Although many dams provide important benefits, some no longer serve any significant purpose, or they have negative impacts that are greater than their benefits. In these cases, dam removal is becoming an increasingly attractive option for achieving conservation goals such as river and fisheries restoration, public safety goals such as elimination of unsafe dams, and other community-revitalization goals through increased recreation and green space.

In the past few decades, the United States has also been a world leader in protecting rivers and wildlife from threats such as point source pollution and unsound riverside development. To accomplish this, the United States has developed a series of laws—the Clean Water Act (CWA) and the Endangered Species Act (ESA), for example—designed to stop further damage to our rivers and to the fish and wildlife that depend on them. Today, our increasing interest in dam removal and our strong environmental protection laws are increasingly interacting, with some unexpected results.

Many legal issues are associated with removal of a dam. Decisions about whether or not to remove a dam are often made in the context of regulatory proceedings. In addition, once a decision has been made to remove a dam, federal, state, and local permits are required for the physical removal of the dam from the river. But because many of the laws that are triggered by a dam removal decision focus on environmental *protection,* they are not easily adapted to the environmental *restoration* activities associated with dam removal, and some laws actually discourage environmental restoration efforts.

This article outlines the legal issues associated with both decisions about whether or not to remove a dam and decisions about how to remove a dam. It then examines how implementation of environmental restoration activities such as dam removal fits into our existing legal system and how environmental laws may need to evolve to address the increasing interest in environmental restoration.

THIS ARTICLE OUTLINES THE LEGAL ISSUES ASSOCIATED WITH DAM REMOVAL AND EXAMINES HOW ENVIRONMENTAL RESTORATION ACTIVITIES SUCH AS DAM REMOVAL FIT INTO THE EXISTING US LEGAL SYSTEM

## *Legal issues associated with deciding whether to remove a dam*

The decision of whether or not to remove a dam is not a centralized decision that is made by one entity. Depending on who owns the dam, what services the dam provides, and the type and significance of the dam's negative impacts, a decision on dam removal can be made by a federal agency, a state agency, or a private dam owner. Although sometimes dam removal is a voluntary undertaking, many dam removal decisions are the result of legal proceedings—either as a formal outcome of the proceedings or through a negotiated settlement associated with the proceedings.

***Dam safety proceedings.*** The most common legal proceedings resulting in dam removal are safety-related inspections of dams at the state level. Most states have dam safety

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laws that require periodic state inspections of every dam over a certain size. For example, New Hampshire has jurisdiction over any structure that is more than 1.2 meters (m) tall or has a storage capacity of 2467 $m^3$ or more (NHDES 2001). If a dam has safety problems, the state official usually can issue a notice to the dam owner requiring the owner to address those problems (e.g., State of Massachusetts 2002). Usually the state cannot order the dam to be removed, but it can instead order that the safety problem be eliminated. This provides the dam owner with a choice of either repairing the dam or removing it. Removal of smaller dams often costs less than repairs. In Wisconsin, for example, an examination of small dam removals showed that removal typically costs three to five times less than estimated safety repair costs (Born et al. 1998).

***Hydropower dam regulation.*** Another regulatory arena that has resulted in dam removals is the regulation of hydropower dams by the Federal Energy Regulatory Commission (FERC) pursuant to the Federal Power Act (US Code, title 16, sec. 791 et seq.) (all US Code citations are available online at *http://uscode.house.gov).* Eleven FERC-regulated dams have been removed since 1963 (Emery 2001), with more than 25 currently under consideration.

There are three regulatory avenues for FERC involvement in a dam removal: (1) dam relicensing, (2) dam safety inspections, and (3) the surrender of a dam's operating license.

**Hydropower dam relicensing.** The first regulatory avenue is through hydropower dam relicensing. All hydropower dams not owned by the federal government must obtain an operating license from FERC, unless the dam has been issued an exemption or is on a nonnavigable river (US Code, title 16, sec. 797[e]). When these 30- to 50-year licenses expire, the dam owner must reapply to FERC to obtain a new license (US Code, title 16, sec. 808). As part of this licensing process, FERC must determine whether issuing a new license is in the public interest, providing equal consideration to power development and nonpower uses of the river (e.g., fish and wildlife habitat, recreation, aesthetics) (US Code, title 16, sec. 797[e]). In 1994, FERC issued a policy statement concluding that it had the authority as part of a relicensing proceeding to deny a relicense application and to order a dam to be removed if it determines such an action is in the public interest (Project Decommissioning at Relicensing: Policy Statement, 60 Federal Register 339, Code of Federal Regulations [CFR], title 18, sec. 2.24; all CFR citations are available online at *www.access.gpo. gov/nara).* FERC expressly exercised this dam removal authority once, in their 1997 order requiring removal of the Edwards Dam on the Kennebec River in Maine (Edwards Mfg. Co., 81 FERC 61,225 [1997]). In addition, FERC has used this authority to study the option of dam removal in several cases, such as on the Clyde River in Vermont, where FERC recommended in a 1996 final environmental impact statement that a breached dam be removed as part of a five-dam relicensing (FERC 1996a)(the dam was subsequently removed pursuant to a settlement agreement), and on the Presumpscot River in Maine, where FERC is currently considering the option of removing three dams as part of a five-dam relicensing (FERC 2001).

FERC relicensing proceedings have also led to dam removal through settlement agreements. Two dams have been removed through relicensing agreements (Emery 2001), with several additional settlements involving dam removal currently undergoing review at FERC. Some of these settlements have included removal of the dam that was the focus of the relicensing. For example, on the White Salmon River in Washington, FERC considered the alternative of removing the Condit Dam and instead ordered installation of fish passage devices (FERC 1996b). However, the dam owner determined that fish passage devices would be more expensive than dam removal, and thus entered into a settlement with intervening parties to remove the dam (PacifiCorp 1999). In addition, several relicensing settlements have included removal of smaller dams in a multidam hydroelectric project or nonhydro dams on tributary streams as mitigation for the ongoing operations of the primary hydropower dams. For example, on the Menominee River in Wisconsin, Wisconsin Electric entered into a comprehensive settlement for the relicensing of eight projects on the Menominee, Michigamme, and Paint Rivers. The parties agreed to support the relicensing (with certain operating conditions) in exchange for Wisconsin Electric removing three tributary dams (Order Issuing Non-Power License to Wisconsin Electric and Approving Decommissioning Plan, 96 FERC 61,009 [2001]).

**FERC dam safety authority.** The second regulatory avenue for FERC involvement in a dam removal is through dam safety inspections. FERC has the authority to inspect and ensure maintenance of dam safety at all dams under their jurisdiction (CFR, title 18, part 12). These inspections generally occur every 5 years (CFR, title 18, sec. 12.38). As in state dam safety situations, if FERC identifies safety problems at a dam, it will order the dam owner to alleviate the problem. The dam owner may choose to remove the dam rather than make repairs. For example, a FERC safety inspection of Mussers Dam on Middle Creek in Pennsylvania identified significant safety problems, and the dam owner decided it was cheaper to remove the dam than repair it (Order Accepting Surrender of License, Mussers Dam, 64 FERC 62,097 [1993]). At least four FERC-regulated dams have been removed where the cost of safety repairs was a factor in the removal decision (Emery 2001).

**Issuance of license surrender order or nonpower license.** The third regulatory avenue for FERC involvement in a dam removal is through the surrender of a dam's operating license. Whenever a FERC-licensed dam is slated for removal, FERC must approve the removal through a license surrender order or the issuance of a nonpower license (US Code, title 16, secs. 799, 808[f]). The question of when it is appropriate to use the license surrender versus the nonpower license approach is still evolving at FERC (e.g, APS 2001, PacifiCorp 2001, FERC 2002).

As part of issuing a license surrender or nonpower license, FERC can impose conditions on how the dam is removed. The requirement to obtain a FERC surrender order or nonpower license applies to removals related to dam relicensing and dam safety, as well as to voluntary removals unrelated to safety or relicensing. For example, the licensee of the Grist Mill Dam on the Souadabscook River in Maine received approval from FERC to surrender its license and complete a voluntary dam removal to restore habitat for migratory fish (Order on Surrender of Exemption, Grist Mill Dam. 84 FERC 61,196 [1998]). And FERC issued a nonpower license to Wisconsin Electric for the removal of the Sturgeon Dam in the Upper Menominee River Basin (Order Issuing Non-Power License to Wisconsin Electric and Approving Decommissioning Plan, 96 FERC 61,009 [2001]).

In addition, whenever a dam owner plans to cease generation of hydropower, the owner must obtain a license surrender or nonpower license from FERC. As part of this proceeding, FERC has the authority to order that the dam be removed, even if this is not the intention of the dam owner. In practice, however, when the dam owner does not wish to remove the dam, FERC has to date issued the license surrender or nonpower license without any associated obligation to remove the structure or demonstrate a plan for periodic dam safety maintenance (e.g., Order Accepting Surrender of Exemption, Walker Mill Hydroelectric Project, 91 FERC 62,208 [2000]).

***The Endangered Species Act.*** The third main legal mandate that has resulted in dam removals is the Endangered Species Act (US Code, title 16, secs. 1531–1543). The ESA has never been used to compel dam removal, although it has been used to consider dam removal in a few cases and has in many cases been the impetus for voluntary removals.

Three sections of the ESA have bearing on dam removal decisions: (1) the prevention of jeopardy provisions in section 7, (2) the prohibition of taking a listed species in section 9, and (3) the recovery planning and implementation provisions in section 4(f).

**Section 7 jeopardy consultations.** Section 7 prohibits federal actions that jeopardize the continued existence of listed species or that destroy or adversely modify critical habitat (US Code, title 16, sec. 1536[a][2]). Critical habitat can include not only habitat currently occupied by the species but also habitat not currently occupied but "essential for the conservation of the species" (US Code, title 16, sec. 1532[5][A][ii]).

If an activity might result in jeopardy, the federal actor must consult with the US Fish and Wildlife Service (USFWS) or the National Marine Fisheries Service (NMFS). *Jeopardy* means threatening either survival or recovery of the species (see *Sierra Club v. Fish and Wildlife Service,* 245 F.3d 434 [5th Cir. 2001]). As a result of the consultation, NMFS or USFWS will issue a biological opinion determining whether jeopardy will result from the proposed action and recommending "reasonable and prudent alternatives" that can be taken to avoid jeopardy (US Code, title 16, sec. 1536[b][3]). ESA regulations mandate that reasonable and prudent alternatives be implementable in a manner consistent with the original project purposes and be within the legal authority of the federal actor (CFR, title 50, sec. 402.02). If no reasonable and prudent alternative exists, NMFS or USFWS must issue a jeopardy opinion with no reasonable and prudent alternative. At this point, an application for exemption from the provisions of the ESA could be made to the Endangered Species Committee (or "God Squad") (US Code, title 16, sec. 1536[g]). In determining whether exemption is warranted, the God Squad may consider "alternative courses of action" that are not limited to original project purposes (US Code, title 16, secs. 1532[1], 1536[h]). The God Squad provision has been treated as a legal and political last resort, being used in only a very small number of cases (Weston 1993).

If a dam is threatening the continued survival or recovery of a species, and if the dam is not central to the purpose of the project and removal is within the authority of the federal actor, the ESA may authorize USFWS or NMFS to issue a jeopardy opinion that recommends removal of the dam. NMFS has recommended in a section 7 biological opinion the notching of a half-constructed dam (the Elk Creek Dam in Oregon) as the only alternative that would avoid jeopardy (NMFS 2001) and has in at least one other biological opinion (regarding the Eel River's Potter Valley Project in California) recommended studying dam removal for salmon protection (NMFS 2000a). However, the Eel River dam removal study recommendation was not made as part of the biological opinion's reasonable and prudent alternatives, but instead as part of the less enforceable recommended conservation measures. In addition, NMFS has considered—and temporarily rejected—dam breaching as an option for salmon protection and restoration in its 2000 biological opinion regarding four federal dams on the Lower Snake River in Washington (NMFS 2000b).

The use of section 7 to mandate removal has been problematic in several ways, however:

- First, section 7 applies only to actions taken (or licensed) by the federal government. Thus if there is no federal actor, this section will not apply.
- Second, section 7 is triggered only by a proposed action, and it can be a challenge to characterize the continued existence of a dam as a proposed action. In the case of the Snake River dams, the federal government's annual operating plan for the dams has been sufficient to trigger section 7 consultation (e.g., *Idaho Department of Fish and Game, et al. v. National Marine Fisheries Service,* 56 F.3d 1071 [9th Cir. 1995]). However, in other situations, it is not settled whether section 7 consultation must be initiated for ongoing federal activities. For example, FERC has ruled that section 7 consultation obligations are not triggered by provisions in FERC licenses that allow FERC to reopen the license if necessary to protect fish and wildlife (Order Dismissing Conservation Groups' Request for Rehearing re Puget Sound Energy, Inc., under P-2150. 95 FERC 61,319

[2001]), but this conclusion is currently on appeal in federal court *(Washington Trout, Washington Environmental Council and American Rivers v. Federal Energy Regulatory Commission,* case no. 01-71307 [US Court of Appeals, 9th Cir., filed 30 July 2001]).

- Third, another obstacle became apparent with the 2000 biological opinion for the Snake River dams: It can be hard to demonstrate not only that a dam jeopardizes the continued existence of an entire species, but also that dam removal is necessary to avoid jeopardy.
- Fourth, reasonable and prudent alternatives must be consistent with the original project purposes. Because dam removal usually eliminates the uses of the dam, it may be difficult for NMFS or USFWS to recommend dam removal unless the dam is not central to the project's purposes.
- Fifth, although the ESA enables designation of critical habitat that is currently unoccupied (such as fish habitat above a dam where the dam has no fish passage), section 7 may only prevent destruction or adverse modification of the habitat; it is currently unsettled whether it could also require or promote restoration of critical habitat. Thus where important spawning or rearing habitat for a listed species is flooded by a dam's reservoir, it is unclear whether section 7 could be used to mandate dam removal to restore that habitat.

**Section 9's prohibition on taking listed species.** Section 9 of the ESA forbids all persons from taking a listed species (US Code, title 16, sec. 1538). The act defines *take* as "to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct" (US Code, title 16, sec. 1532[19]). Harm to the listed species' habitat may also constitute a take *(Babbitt v. Sweet Home Chapter of Communities for a Great Oregon,* 515 US 687 [1995]). To clarify the differences between section 9 and section 7 obligations, section 9 was designed to prevent an individual from fishing for and killing an endangered fish, though it also can apply to broader situations, such as the killing of fish in a dam's turbines. In contrast, section 7 was designed to address threats to the whole species, such as eliminating all fish passage on a river through construction of a dam.

As an exception to the section 9 prohibition on taking a species, the ESA allows USFWS or NMFS to permit "incidental" take when the proposed activity is not likely to jeopardize continued existence of the species and when the taking of species is not the purpose of the action. These incidental take permits may be issued only for federal actors in conjunction with a biological opinion issued pursuant to section 7 (called "incidental take statements") and for nonfederal actors in conjunction with a habitat conservation plan developed pursuant to section 10(a) (US Code, title 16, secs. 1536[b][4], 1536[o][2], 1539[a][2][A]).

Section 9 applies to all actors, and it applies when (for example) only one fish is affected, not just (as with section 7) when the action might jeopardize the existence of the whole species. Section 9 could authorize USFWS or NMFS to declare continued operations of a dam an impermissible taking where the dam's operations injure or kill listed fish. To enforce this finding, USFWS and NMFS could only issue fines, but a citizen suit to enforce a takings finding could result in an injunction (US Code, title 16, sec. 1540; *Marbled Murrelet et al. v. Pacific Lumber Co.,* 83 F.3d 1060 [9th Cir. 1996]). Where listed fish are currently using fish passage devices at a dam with a resulting mortality rate, the case that the dam is causing a take is relatively straightfo rward. However, if a dam is currently a complete block to fish passage (with no fish kills below the dam), making a case that the dam causes a take may be more challenging. NMFS has initiated take proceedings seeking dam removal only once—at the Savage Rapids Dam on Oregon's Rogue River, where ineffective fish passage is harming threatened coho salmon *(National Marine Fisheries Service v. Grants Pass Irrigation District,* no. 98-3034-HO [D.Or. filed 22 April 1998]). As part of a comprehensive settlement of both the Savage Rapids take proceedings and an associated state court water rights adjudication, NMFS issued a 1-year incidental take permit justified by the planned removal of the dam (NOAA 2001).

**ESA's recovery planning and implementation obligations.** The ESA also requires USFWS and NMFS to develop and implement recovery plans for "the conservation and survival" of threatened and endangered species unless the agency finds that "such a plan will not promote the conservation of the species" (US Code, title 16, sec. 1533[f]). It also requires all federal agencies to carry out programs aimed at recovery and requires USFWS and NMFS to use all programs they administer to further conserve the species (US Code, title 16, sec. 1536[a][1]). These provisions can be interpreted to provide authority to NMFS and USFWS to develop and implement species recovery plans that include dam removal and to require other agencies to follow those plans. However, this has not happened to date. In practice, the recovery planning and program administration obligations in the act have generally not been enforceable (Cheever 1996), and because of funding and political constraints, recovery plans are not always developed. (Of the 1244 listed species in the United States as of 31 July 2001, recovery plans have been developed for only 975 species [USFWS 2001]).

**ESA as a factor in other dam removal decisions.** Despite the fact that no dams have been ordered to be removed under ESA authority, the presence of listed species at a dam (particularly fish) has been a significant factor in many decisions to remove dams. This includes voluntary dam removals, such as on Clear Creek in California, where the Saeltzer Dam was removed in 2000 to restore habitat for threatened and endangered salmon and trout species (Hepler 2001), as well as formal proceedings to determine whether a dam should be removed, such as the CalFed Bay–Delta Program's consideration of removing Englebright Dam on the Yuba River in California to restore chinook salmon and steelhead (FOTR 1999). In fact, all seven dam removals in the Pacific Northwest and

California in 1999, 2000, and 2001 were conducted to restore endangered fishes (American Rivers 2002).

## Obtaining permits to remove a dam

Removing a dam from a river requires permits from state, federal, and local authorities. These permits are generally required to ensure that the removal is done safely and minimizes short- and long-term impacts to the river and riparian area. Although most states have the same basic categories of permits required for a dam removal, there is substantial variation from state to state in the level of review required and the standards that must be met to permit a dam removal. In some states, dam removal permitting is relatively easy, and in other states, it is difficult. Below is a summary of the types of federal, state, and local permits that may be required for removal.

### Federal permits or requirements.

**Clean Water Act section 404 permit.** Most dam removals require a CWA section 404 permit, issued by the US Army Corps of Engineers (Corps) for dredging of a navigable waterway (US Code, title 33, sec. 1344). A guideline pursuant to this statutory requirement establishes a policy of no net loss to wetlands (EPA and Department of the Army 1990). To obtain Corps approval, the project (a) should not cause or contribute to significant degradation of the waters or result in a net loss of wetlands, (b) should be designed to have minimal adverse impact, (c) should not have any practicable alternatives, and (d) should be in the public interest. In some cases, dam removal will result in a net loss of wetlands. To obtain a permit in these situations, the Corps will have to find that the benefits of dam removal outweigh the loss of wetlands, or that the loss of wetlands are mitigated by creation of wetlands elsewhere. In October 2001, the Corps issued a regulatory guidance letter that permits mitigation of wetlands impacts with nonwetland habitats (USACE 2001b). Other federal agencies are currently commenting on this letter, and it remains to be seen whether the letter effectively abandons the policy of no net loss of wetlands.

**Rivers and Harbors Act permit.** In conjunction with a CWA section 404 permit, the Corps will issue a Rivers and Harbors Act section 10 permit (US Code, title 33, sec. 403). The Rivers and Harbors Act is administered by the Corps for federal activities affecting a navigable waterway. The Corps will issue the permit if there is no adverse impact on interstate navigation.

**FERC license surrender or nonpower license approval.** If the dam to be removed is a FERC-regulated hydropower dam, the dam owner will have to apply for surrender of the FERC license or issuance of a nonpower license, as discussed in the section "Hydropower dam regulation," above.

**National Environmental Policy Act (NEPA) review.** A permitting or licensing action by the Corps or FERC may require the preparation of an environmental impact statement or environmental assessment pursuant to NEPA (US Code, title 42, sec. 4321 et seq.). A NEPA environmental document may already have been prepared as part of the process of deciding whether to remove the dam. If this is the case, it may not be necessary to prepare a new NEPA document, or only a supplemental document may be required.

**Federal consultations.** As part of issuing their permits, the Corps or FERC may need to conduct the following consultations:

- ESA section 7 consultation. If threatened or endangered species are present at or near the dam, the Corps or FERC may need to consult with USFWS or NMFS regarding the impact of the removal on these species, as discussed above in the section "The Endangered Species Act."

- Magnuson-Stevens Act consultation. The Corps and FERC may also need to consult with NMFS pursuant to the Magnuson-Stevens Act regarding the impact of the removal on any fishery management plan developed by a regional fishery management counsel (US Code, title 16, sec. 1855[b][2]). This consultation is done to ensure that the removal will not adversely affect any essential fish habitat established in the fishery management plan.

- National Historic Preservation Act consultation. Corps or FERC activities may also trigger an obligation to assess the impact of the proposed action on historic properties pursuant to section 106 of the National Historic Preservation Act (US Code, title 16, sec. 470[f]). In assessing this impact, FERC or the Corps must consult with the state historic preservation officer. Affected historic properties may range from newly exposed archaeological sites to the dam itself. The presence of a dam on the National Register of Historic Places (or eligibility for listing on the register) does not automatically preclude removal. In many situations, proper documentation of the dam before removal may be sufficient to preserve the historic values of the dam (CFR, title 36, sec. 800.1 et seq.).

**State certifications.** The Corps and FERC decisions also trigger several federal statutes that require the state to issue a certification that the actions are consistent with the state's implementation of federal law.

- Water-quality certification. For the Corps to issue a CWA section 404 permit or for FERC to issue a license surrender order or nonpower license, the state must issue a water-quality certification pursuant to CWA section 401 (US Code, title 33, sec. 1341). This certification states that the proposed activity will not result in the violation of state water-quality standards. The state may issue conditions for how the dam should be removed as part of its certification.

- Coastal Zone Management Act certification. If the dam is located in a coastal zone, in order for the Corps or FERC to permit the dam removal, the state must issue a certification pursuant to the Coastal Zone Management Act (US Code, title 16, sec. 1451 et seq.). This certification states that the proposed activity is consistent with the state's approved coastal zone management program.

Again, the state may issue conditions for how the dam should be removed as part of its certification.

### *State permits.*

**Waterways development permits.** Some states have laws that regulate the development of their waterways for hydropower, navigation, and other purposes. These laws are generally adopted to address construction of a new dam or alteration of an existing dam but may also apply to dam removal.

**Dam safety permits.** Most states have regulations that require a permit for any activity that will affect the safety of a dam. Removal of a dam may require such a permit.

**State environmental policy act review.** Many states have an environmental impact review statute similar to the federal NEPA statute. The removal of a dam may trigger the state requirement to prepare an environmental impact document. Usually the federal and state requirements can be met by preparing the same environmental impact document.

**Historic preservation review.** Most states require that before any state permit is issued, historic and archaeological issues must be investigated and approved by the state historic preservation officer. This review can usually be done in conjunction with the federal historic preservation review, described earlier.

**Resetting the floodplain.** Most states will require a review of any activity that might change the 100-year floodplain. The applicant may be required to determine the new elevation for the 100-year floodplain once the dam is gone. The Federal Emergency Management Agency would then use the analysis to create new maps.

**State certifications.** State certification requirements pursuant to federal laws are discussed above, under "Federal permits or requirements."

***Municipal permits.*** The act of demolishing the structure of the dam may require a demolition permit from the local municipality, and the construction of a temporary cofferdam or the restoration of the riverbank may require a building permit from the local municipality.

## Legal impediments to ecological restoration

***Environmental laws protect against deviations from the status quo.*** Environmental laws in the United States focus primarily on environmental protection. Recently, however, there has been an evolution of interest in environmental science and activism from protection to restoration. In many areas, the legal system has not kept up with this evolution. Many environmental laws have protection and restoration goals. For example, the stated goal of the Clean Water Act is to "restore and maintain the chemical, physical and biological integrity of the Nation's waters" (US Code, title 33, sec. 1251), and the goal of the ESA also focuses on recovery of listed species (US Code, title 16, secs. 1531[b], 1532[3]). But environmental laws effective at environmental protection (such as the CWA and ESA) are essentially effective only at maintaining the status quo. For example, the Clean Water Act's most effective provisions are focused on preventing pollution from entering rivers and other waterways, and implementation of the Endangered Species Act is focused primarily on preventing further degradation of an endangered species (Cheever 1996 discusses how ESA implementation focuses on the act's prohibitions and not on its purpose). Unlike environmental protection efforts, environmental restoration projects such as dam removal result in a deviation from the status quo (albeit positive). As a result, where laws focus on preventing deviations from the status quo to meet their protection goals, they can actually discourage restoration activities.

Dam removal is a good example of this problem. Although dams are being removed to accomplish ecological restoration goals, these removals are often being accomplished in spite of environmental laws designed to protect those resources. Instead, the decision to remove a dam may be accomplished through laws designed to allow a balancing of interests and negative deviations from the status quo, such as hydropower dam relicensing pursuant to the Federal Power Act and state dam safety laws.

Dam removal is not the only situation where this dichotomy exists. For example, the effort to reoperate the Glen Canyon Dam on the Colorado River to restore the health of the river through the Grand Canyon has met several regulatory obstacles designed to stop environmental degradation (Schmidt et al. 1998, Miller 2000). The everglades restoration effort has also encountered challenges from environmental protection laws (Rizzardi 2000).

***Example: The Edwards Dam on the Kennebec River.*** The removal of the Edwards Dam on the Kennebec River in Maine provides a good example of this dichotomy. Built in 1837, Edwards Dam blocked the migration route for seven target species of anadromous fish—Atlantic salmon *(Salmo salar),* striped bass *(Morone saxatilis),* American shad *(Alosa sapidissima),* alewife *(Alosa pseudoharengus),* rainbow smelt *(Osmerus mordax mordax),* Atlantic sturgeon *(Acipenser oxyrhynchus),* and endangered shortnose sturgeon *(Acipenser brevirostrum).* The dam also flooded unique head-of-tide habitat important for the life cycles of many of the migratory fish. The dam's license to generate power expired in 1993, and the dam owners sought a new 30-year license from FERC. In response, four environmental groups and state and federal resource agencies intervened in the licensing to seek dam removal.

After a long regulatory battle, in 1997 FERC denied the dam owner's application for license renewal and, for the first time ever, ordered the dam to be removed against the wishes of its owner (Edwards Mfg. Co., 81 FERC 61,225 [1997]). Pursuant to a subsequent settlement agreement, the dam was removed in 1999. Today, the former impoundment has been restored to a healthy river ecosystem that supports a diverse array of fish and wildlife, including the seven target anadromous fish species (NRCM 2001).

Although there were compelling environmental reasons to remove Edwards Dam, environmental laws provided little if any leverage to remove the dam—they actually created some challenges for designing and permitting the removal. The Edwards removal involved two decision points where environmental laws came into play: the decision whether to order dam removal and the permitting of the removal itself.

**The dam removal decision.** The most significant environmental law involved in the dam removal decision was the Endangered Species Act. The shortnose sturgeon—a federally listed endangered species—was present below the dam and historically migrated upstream above Edwards to spawn in the impoundment area. The relicensing proceeding required FERC to consult with USFWS and NMFS pursuant to ESA section 7. But the ESA provided no legal tools to promote dam removal. No critical habitat had been designated for the sturgeon, and no recovery plan had ever been developed. The Edwards Dam itself did not jeopardize continued existence of the shortnose sturgeon; it was simply inhibiting the species' recovery. However, section 7 simply creates an obligation not to destroy existing habitat. It has not been used to require restoration of historic habitat. In addition, even if USFWS and NMFS had developed a recovery plan under section 4(f) that called for removal of Edwards Dam to restore historic habitat, it still would have been difficult to mandate removal pursuant to the plan. FERC was the decisionmaker in the Edwards case, and FERC has no recovery obligation under section 4(f) of the ESA. Instead, an argument would have to be mounted that FERC's ESA section 7(a)(1) obligation to carry out programs aimed at recovery mandates that FERC follow the USFWS and NMFS recovery plan and order dam removal. Whether section 7(a)(1) is enforceable in this manner is unsettled, though a majority of courts have rejected these claims (Cheever 1996).

In addition, pursuant to CWA section 401, the state of Maine was charged with certifying whether the licensing would violate state water-quality standards. Removal of the dam would probably improve water quality, and the state's denial of certification would have prevented FERC from issuing a new license. Section 401 certification conditions regarding dam relicensings traditionally require actions that prevent further degradation of numeric water-quality standards (such as increased downstream flows to prevent dissolved oxygen violations), though states have increasingly been imposing non–status quo actions, such as building fishways to meet descriptive water-quality standards or designated uses (such as restoring native fish populations to river stretches designated as habitat for native fish). Although the state supported removal of the dam, it felt that it had no avenue through its Clean Water Act authority to mandate removal to improve numeric water-quality conditions above the dam, though it did recommend fish passage to ensure native fish access to historic spawning grounds (State of Maine 1996). In the end, the Edwards Dam removal resulted in significant improvement to the Kennebec's water quality—the former impoundment area changed from failing to meet Maine's minimum water-quality standard before dam removal to attainment of Class B standards within 2 months after removal (NRCM 2001).

Finally, as part of the FERC relicensing process, the USFWS and NMFS have authority to recommend conditions on a proposed license pursuant to the Federal Power Act and the Fish and Wildlife Coordination Act (US Code, title 16, sec. 661 et seq.). Although NMFS and USFWS may submit any recommended license conditions for FERC's consideration, the two agencies are granted authority to impose mandatory conditions for construction of fishways—FERC must include the USFWS and NMFS conditions in the license (US Code, title 16, sec. 811). Although the purpose of NMFS's and USFWS's involvement in FERC relicensings includes "wildlife conservation and rehabilitation" (US Code, title 16, sec. 661), they are limited to mandating fishways to enable passage at the dam—they cannot mandate dam removal even if that is the only way to achieve fish passage. In the Edwards Dam case, USFWS and NMFS had concluded that fishways would not be effective at passing the target fish species, and that dam removal was the only way the target fish species could be restored. Nevertheless, the only action they could mandate to provide fish passage at the dam was construction of fishways. Thus the agencies *recommended* dam removal, but *ordered* construction of fishways (e.g., NMFS 1996).

In the end, no environmental law provided sufficient authority to remove Edwards Dam. Instead, a nonenvironmental law—the Federal Power Act—was used to obtain an order to remove the dam. FERC's relicensing decision pursuant to the Federal Power Act was based on the economic conclusion that construction of fish passage devices would cost 1.7 times more than dam removal and on the biological conclusion that even if a fish passage device were constructed, it could be used by only three of the seven target fish species (Edwards Mfg. Co., 81 FERC 61,225 [1997]). (American Rivers [2001] provides further information about the FERC relicensing process that led to dam removal.)

**Obtaining permits for removal.** In addition to obtaining an order from FERC to remove Edwards Dam, project proponents also were required to obtain permits to carry out the removal, as described in the section "Obtaining permits to remove a dam," above.

Obtaining a CWA section 404 permit for the removal triggered a second obligation pursuant to ESA section 7 to consult with NMFS and USFWS about impacts to the shortnose sturgeon. Immediately below the dam was a large scour hole created by water flowing over the dam. The sturgeon used this hole for spawning because they were no longer able to move upstream to their historic spawning holes above the dam. Upon removal of the dam, it was expected (and it came to pass) that this hole would be filled in by debris and coarse sediments transported downstream. Although this spawning hole would be lost, access to the sturgeon's historic spawning areas would be reopened through dam removal. If the spawning hole below the dam had been formally designated as critical habitat for the shortnose sturgeon, dam removal may have been hard to accomplish because of the complete destruction of this critical habitat. However, critical habitat had never been designated for the shortnose sturgeon on the Kennebec. Thus although there was concern about the loss of the spawning hole, a formal conflict with ESA on this issue did not exist.

ESA section 9 also created challenges for the Edwards Dam removal. If removal of Edwards Dam harmed or killed any of the shortnose sturgeon residing in the river, it would have been in violation of section 9's prohibition against taking of an endangered species. The timing and method of the removal was substantially changed to avoid violation of this provision.

## Conclusions

As the Edwards Dam removal illustrates, existing laws that are effective at ensuring environmental protection will probably not be effective at promoting environmental restoration activities such as dam removal. The resulting question is how to allow positive deviations from the environmental status quo while not weakening laws and creating loopholes that will allow more negative deviations from the status quo. Basic exemption from environmental protection laws for restoration projects is not advisable, because environmental restoration projects do have impacts that need to be reviewed and minimized.

A better approach may be to provide regulatory direction or guidance that allows a decisionmaker to provide some accommodation for projects with restoration as their primary purpose. For example, a state or federal agency could establish a policy that enables flexibility in the interpretation of permitting requirements when a proposed project's primary purpose is environmental restoration. An agency could also direct permitting officials to consider the long-term benefits of a restoration project as mitigating factors in determining whether the short-term impacts of the project are acceptable. The challenge is to develop this in a fashion that avoids the appearance (or reality) of unfair treatment or relies so heavily on professional judgment that it renders the regulations unpredictable or unenforceable. And if restoration activities are given special accommodation, it will be especially important that the project proponents demonstrate that the restoration goals were actually met.

In addition to enabling existing laws to accommodate restoration in a more effective manner, these laws should be able to meet their goals of actively promoting environmental restoration. The experience to date indicates that this has been either legally or politically difficult. It remains to be seen whether the increasing attention to restoration in the scientific and activist communities will help move implementation of environmental laws toward their restoration goals or instead demonstrate the need for new legislation dedicated to environmental restoration.

## Acknowledgments

More than a dozen colleagues reviewed drafts and otherwise assisted with this article. Although they are too numerous to mention by name, they have my sincere appreciation. I am particularly grateful to Ron Kreisman, Steve Brooke, Peter Kirsch, and Dan Squire, who for years explored the legal complexities of dam removal with me on the Edwards Dam relicensing. Finally, my thanks to The Pew Charitable Trusts for their support for the development of this article.

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# A Geomorphic Perspective on Nutrient Retention Following Dam Removal

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**Streams and rivers of Wisconsin reflect the influence** of more than 100 years of human activity. These systems have been subjected to upland and channel alterations that include deforestation, wetland drainage, soil inputs from poor farming practices, dam construction, and nutrient enrichment from point and nonpoint sources. Agricultural activities in particular have influenced water quality through modifications such as fertilizer application, increased upland erosion, ditching and tile draining to move water off the land, and straightening of channel ways. The combined effect of nutrient loading and simplification of the physical structure of agricultural streams is to diminish the ability of these systems to retain nutrients (Royer et al. 2001). Because the availability of nitrogen (N) or phosphorus (P) (or both) often limits rates of biological processes in aquatic systems, recent increases in delivery of N and P to lakes, streams, and rivers have acted to fertilize not only the receiving freshwater ecosystem but also coastal areas, resulting in undesirable increases in productivity in both freshwater and marine systems (Carpenter et al. 1998, NRC 2000).

The second conspicuous human influence on streams and rivers of the state is the widespread presence of dams. There are approximately 3700 dams, or 1 dam every 14 kilometers of river in Wisconsin (WDNR 1995). Although there is a healthy representation of large dams (structures > 2 meters [m] that impound ≥ 62,000 $m^3$, or structures > 7.6 m that impound 18,500 $m^3$; USACE 1998), state waterways are more commonly populated by high densities of small, run-of-river structures, many of which are well over 80 years old. (Run-of-river structures are dams that create reservoirs with small storage capacity and do not alter the river's flow regime.) The abundance of dams can be traced back to the Milldam Act of 1840, which encouraged the use of hydropower to fuel the state's burgeoning economy (Martini 1998). Unfortunately, many of these structures are no longer economically viable, represent a safety risk, and compromise the quality of the aquatic resource (Born et al. 1998). Under these circumstances, dam removal is a logical management option, and more than 50 dams have been removed under the supervision of the Wisconsin Department of Natural Resources over the past three decades. To date, and reflective of the national trend (Doyle et al. 2000), most dams that have been removed within the state were relatively small structures.

GEOMORPHIC MODELS PROVIDE A MEANS OF PREDICTING ECOSYSTEM RESPONSES TO DAM REMOVAL

The growing interest and occurrence of dam removal underscores the inextricable link between agriculture and river modification in the Midwest. Dams were often built for milling of agricultural products, and the sediment-trapping ability of reservoirs means that topsoil and nutrients lost from farm fields are now stored behind dams. Given the growing concerns about nutrient enrichment and the potential for dam removal to affect nutrient dynamics, understanding the effects of dam removal on nutrient processes should be a research and management priority. In this article, we draw from the context of agriculturally dominated watersheds in Wisconsin to explore how dam removal may influence the movement of N and P in rivers. We approach this issue first by briefly considering nutrient transport in rivers and how reservoirs can affect nutrient processes. We then consider

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changes in nutrient dynamics following dam removal with respect to geomorphic adjustments caused by the removal. Although the specific geomorphic changes that can occur following dam removal will vary among stream types (Pizzuto 2002), the example presented herein emphasizes the link between geomorphic adjustments and ecosystem responses following dam removal.

## Nutrient retention in streams and rivers

The increase in nutrient concentrations in many aquatic systems over the past several decades is now well established (Carpenter et al. 1998, NRC 2000). Typically, N and P inputs to aquatic ecosystems are dominated by diffuse nonpoint sources from the surrounding landscape, often in association with agricultural and urban land uses. In many areas, including Wisconsin, fertilizer and manure application on farm fields represents a major input of both N and P to lakes and streams. But the paths that these two nutrients take from terrestrial to aquatic environments are distinct. In enriched systems, nitrate ($NO_3^-$) represents the dominant form of N, often accounting for more than 50% of the total N budget (Hedin et al. 1995, Goolsby et al. 1999). This form of N is highly soluble and thus travels easily in water from soil to groundwater and into surface water systems. It is also readily taken up by algae and bacteria, which can lead to excess growth of these microorganisms in aquatic systems. Fortuitously, $NO_3^-$ can be removed from water and returned to the atmosphere via the process of denitrification—that is, the conversion of $NO_3^-$ to a gaseous and relatively inert form of N ($N_2$) by bacteria. This transformation occurs under conditions in which the oxygen ($O_2$) is absent or its concentration is reduced, such as when $NO_3^-$-rich groundwater travels through wetland soils or streambed sediments. For streambeds, sediment composition plays a key role in determining whether or not denitrification can occur; streambeds with a coarse gravel substrate have a lower potential for denitrification than those with finer sediments, because oxygen concentrations generally remain high in porous sediments (Garcia-Ruiz et al. 1998). Thus an important aspect of $NO_3^-$ (and thus total N) retention in streams and rivers is the degree to which $NO_3^-$-rich water encounters areas in which $O_2$ is depleted (NRC 1992).

In contrast to the high mobility of $NO_3^-$, P movement through ecosystems is relatively slow and is dependent on erosion and sediment transport. The inorganic form of P (phosphate, $PO_4^{3-}$) has a high affinity for mineral surfaces and therefore easily attaches to sediment and soil particles. Phosphorus fertilizer applied to farm fields typically stays in place and slowly builds up over time; its transfer to the aquatic environment requires mobilization and transport of soil particles. The combination of farming and urban development has fostered both a widespread buildup of P in soils and the transport of these soils to aquatic systems (Bennett et al. 2001). Reservoirs and lakes then trap particles and store this legacy of fertilization and land use for years. Thus while movement of N is strongly influenced by the extent of interactions between $NO_3^-$-rich water and $O_2$-poor sediments (or sediment–water contact), P transport is often driven by the movement of particles in streams and rivers, particularly in sediment-rich systems characteristic of basins with substantial agricultural land use (Ng et al. 1993).

It has long been assumed that once N and P enter a stream, fluvial systems do little more than transport the nutrients to downstream environments. While the idea of streams as transporters is still pervasive, the nutrient spiraling concept (Webster and Patten 1979, Newbold et al. 1981) has emphasized the role of streams as transformers as well as transporters of elements such as N and P. With the awareness that streams and rivers can remove and transform nutrients and materials as well as transport them, questions now being explored by ecologists and hydrologists focus on understanding factors that control rates or distances of nutrient uptake within and among different systems (Fisher et al. 1998). The net effects of transport and transformation can be expressed in terms of retention: the difference in total inputs to and outputs from an aquatic ecosystem, such as a reservoir or a specified length of a river. Because retention integrates physical, chemical, and biological processes occurring throughout an area of interest, and because managers and researchers are trying to determine how to enhance the retentive abilities of streams and rivers (NRC 2000, Mitsch et al. 2001), we will focus on nutrient retention for our consideration of the effects of dam removal on ecosystem dynamics.

Intensive studies of the biogeochemistry of streams and rivers over the past decade have emphasized the importance of transient storage zones for retention of dissolved nutrients—that is, those places in the channel where the flow of water is slowed, allowing sufficient time or circumstances for nutrient processing. Streambeds formed in extensive alluvial deposits or channels with abundant pools and backwaters typically have large amounts of transient storage, and thus have great potential for nutrient retention. Similarly, the size of a channel has an important influence on N processing in streams and rivers; larger channels appear to have an extremely limited ability to influence nutrient loads because of the restricted extent of sediment–water contact relative to the large volumes of water being conveyed (Alexander et al. 2000). In short, the physical structure of the channel can exert an important control on the amount and form of nutrients exported by the stream (D'Angelo et al. 1993, Valett et al. 1996).

## Effects of reservoirs on riverine nutrient dynamics

Retention by large reservoir systems can substantially reduce regional nutrient export by rivers (Caraco and Cole 1999), such that the structure and function of receiving coastal systems are fundamentally altered following dam closure (Humborg et al. 1997). Dominant mechanisms of retention are denitrification for N (Jossette et al. 1999) and particle settling for P (Kennedy and Walker 1990). However, it is not clear how these trends of nutrient retention for large reservoirs translate to the smaller impoundments that represent the vast majority of recent removals in the United States. Ecological research on smaller reservoir systems has tended to focus on the role of these structures as barriers to migratory taxa or in creating lentic habitat for other aquatic species (Watters 1996, Benstead et al. 1999), and information regarding their influence on nutrient dynamics is scarce. Even basic questions such as "How many small dams are there?" are unanswered (Poff and Hart 2002). Often, small dams and their impoundments are not included in watershed studies, or it is assumed that these structures have negligible or limited local effects (Graf 1999). Unfortunately, this assumption is largely untested in the context of processes such as primary productivity or nutrient retention. Our limited knowledge of the starting point for subsequent changes represents a distinct challenge for studying the effects of dam removal. Perhaps one of the benefits of the current interest in dam removal will be to enhance our understanding of both the local and cumulative impacts of small impoundments on the dynamics of lotic ecosystems.

Dams do not have to create large impoundments with prolonged hydrologic residence times to foster nutrient retention. Although water may pass through small impoundments quickly relative to large reservoirs, hydrologic residence time is prolonged relative to an unimpounded channel because streamflow has the opportunity to spread out across a wide area. In older impoundments, a long history of sediment trapping means that many of these systems are now quite shallow and may have wetland-like habitats in the upper ends of the reservoir because of bedload deposition and delta formation (figure 1). These broad, shallow channels with reduced water velocities foster sediment deposition, promote P retention, and create greater sediment–water contact needed for denitrification (Kelly et al. 1987, Jansson et al. 1994). In essence, small impoundments represent unusually large transient storage zones in rivers, and the combination of sediment deposition and the creation of wetland or sandbar habitats should promote both P and N retention. Therefore, it is not surprising that we have found that nutrient concentrations immediately below even relatively small impoundments (those with dam heights < 4.5 m) are often less than concentrations upstream of the impoundment (figure 2). The percent reduction between upstream and downstream concentrations that can be achieved by passage through a small reservoir is highly variable. For relatively nutrient-poor systems, this reduction may exceed 70%; for some nutrient-replete systems, the reduction may be as small as 2%.

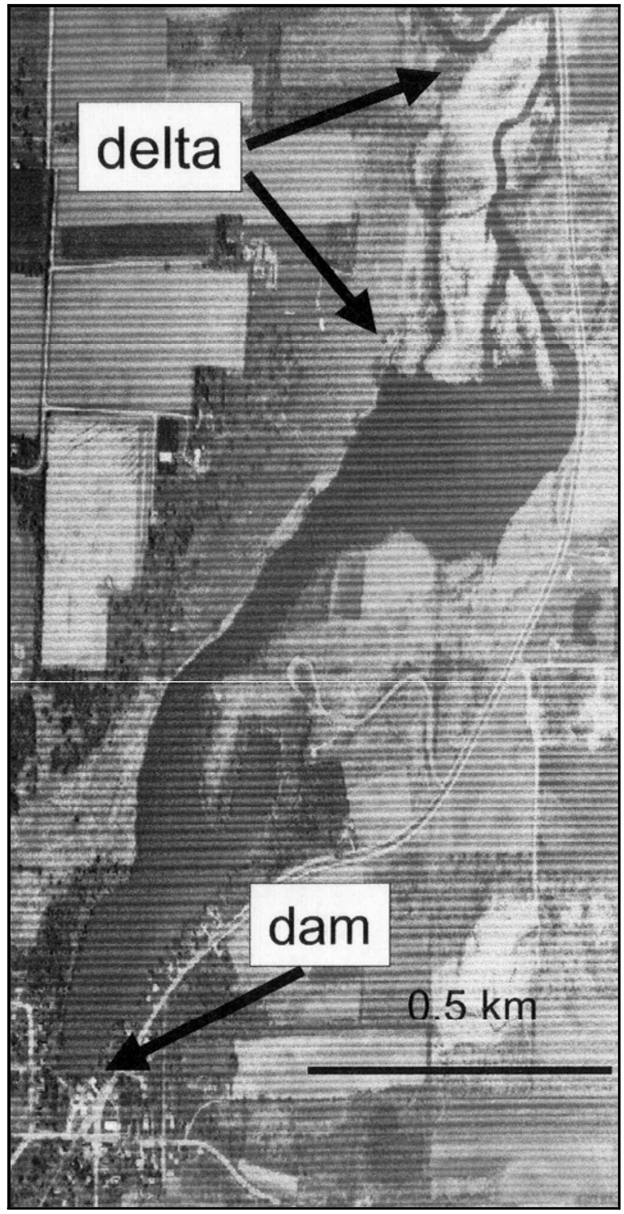



***Figure 1. Aerial photo of Rockdale Millpond on Koshkonong Creek, Wisconsin, in 1990. Deposition of sediment at the upstream end of the reservoir has resulted in the formation of an extensive wetland-like delta area. Photograph: US Department of Agriculture, Soil Conservation Society. The photograph is part of the University of Wisconsin's Arthur H. Robinson Map Library collection.***

## *Channel form and dam removal*

If P dynamics are governed by sediment storage and movement, and N retention is determined by the extent of sediment–water interactions, then it may be possible to make general predictions regarding these two critical nutrients from an understanding of changes in channel form and sediment transport triggered by the removal of a dam. Although models of geomorphic changes caused explicitly by dam removal have yet to be developed, there is a wealth of information on how channel form responds to a sudden increase in the slope of the channel, conditions that are frequently created by dam removal in relatively old reservoirs receiving inputs of fine-grained sediment, which are common throughout the midwestern United States.

If the slope of a river channel suddenly increases, for example, by channelization or closure of a meander cutoff, natural processes will act to reestablish equilibrium conditions. Channel adjustment includes a suite of alterations in the

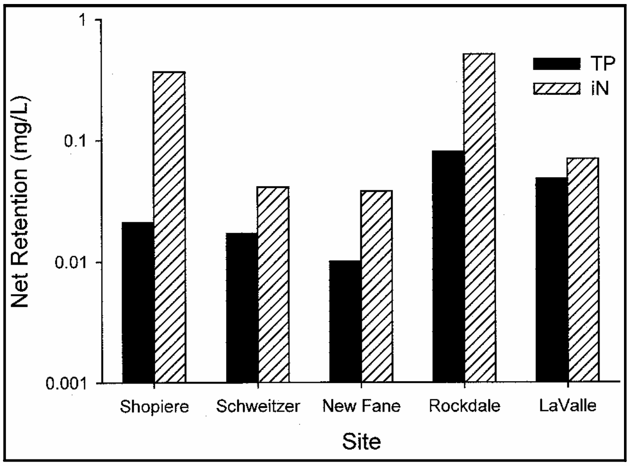



*Figure 2. Net retention of total phosphorus (TP) and inorganic nitrogen (iN), determined as the difference in the concentration of water entering versus leaving an impoundment created by low-head, run-of-river dams in southern Wisconsin. Inorganic N = ammonium ($NH_4$–N) + nitrate ($NO_3$–N) concentration. Values are based on single-day determinations of concentrations above and below impoundments.*

width, depth, and alignment of the channel as the system moves back toward equilibrium. These changes have been well documented and synthesized in the form of channel evolution models (Schumm et al. 1984, Simon and Hupp 1986). When dam removal causes an instantaneous increase in slope, these channel evolution models can be used to predict the geomorphic changes in channel form caused by dam removal (Doyle et al. 2002, Pizzuto 2002). It should be emphasized, however, that the specific changes caused by dam removal will vary among different fluvial systems and may include changes other than, or in addition to, an increase in the channel slope, and geomorphic models appropriate to studying dam removal will vary accordingly.

Drawing from the channel evolution model proposed by Simon and Hupp (1986) and from observations from several small dam removals in southern Wisconsin, Doyle and colleagues (2002) suggest that six geomorphic stages of channel development can be recognized within the impounded river reach following the removal of a dam (summarized in figure 3). Herein, we limit the scope of consideration to geomorphic changes within the former impoundment and to the channel only (i.e., we do not consider floodplain development). Stage A represents the preremoval, backwatered reservoir condition, which, as described above, often has a broad and relatively shallow form because of sediment trapping within the reservoir. The original channel is often filled completely by sedimentation, leaving little trace of the channel alignment before impoundment. Sediment trapping also means that sediment deposits are often extensive, in some cases filling the entire reservoir (Palmieri et al. 2001).

The most immediate and conspicuous change following breaching of a dam is the rapid decline in the water surface elevation (stage B). The decrease in water depth effectively increases the amount of sediment–water contact before any physical changes to the channel have occurred. The change in the slope of the water surface alone can cause an increase in water velocity, but only in the immediate vicinity upstream of the dam site. In the case of sediment-filled reservoirs, breaching also can cause a rapid increase in the channel slope, which, along with greater water-flow velocity upstream of the dam, initiates the first stage of adjustment to the channel itself (stage C). As the water surface is dropped, the channel degrades vertically into the sediments at the downstream terminus of the former reservoir to create an incised channel, and in the process, large amounts of sediment are transported downstream. Incision appears to begin immediately

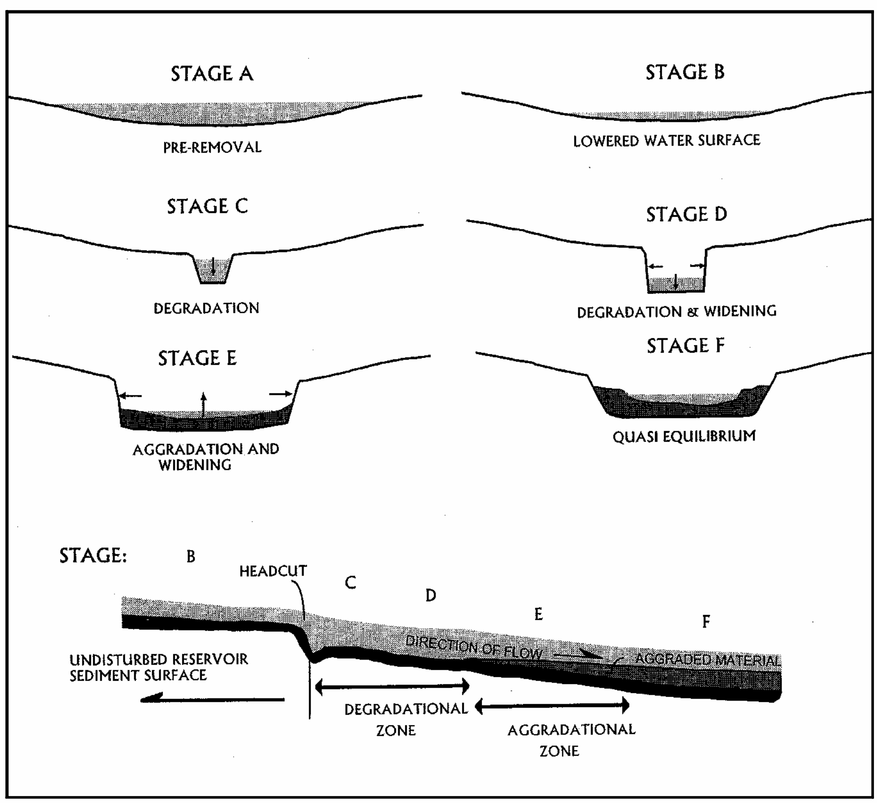



*Figure 3. Channel evolution model of geomorphic adjustments following removal of a low-head dam (from Doyle et al. 2002). The upper portion of the figure illustrates changes in the channel cross section that occur at a given place in the channel through time. The lower portion of the figure describes the longitudinal channel profile at a fixed point in time. Figure courtesy of the American Water Resources Association.*

following breaching, so we expect that some length of stage C channel will be present along with stage B as soon as the dam is removed.

In rivers dominated by fine-grained sediments, incision creates banks that are often over-steepened, making the deep, narrow channel unstable and prone to slumping. Stage D is characterized by widening of the channel via mass wasting (slumping) of the banks. Reaches undergoing widening often experience substantial sediment losses; in fact, the amount of material lost because of widening can greatly exceed the volume removed by incision during stage C (Grissinger and Murphey 1986). As degradation and widening progress, the sediment derived from upstream erosion is transported to downstream reaches within the former reservoir (and to reaches below the reservoir), where it begins to deposit. The transition between degradation and aggradation within the channel marks the start of stage E. Floodplains begin to form during this stage through overbank deposition as well (Pizzuto 2002). Finally, channel form adjustments come to an apparent steady state in stage F with establishment of woody riparian vegetation, thereby stabilizing the channel form.

Following dam removal, the entire reservoir reach does not adjust to the slope change in a uniform fashion, either spatially or temporally. In systems with fine cohesive sediment, channel evolution often begins with the formation of an abrupt vertical drop in the channel slope, known as a headcut or knickpoint (figure 3, longitudinal profile), which subsequently migrates upstream (Schumm et al. 1984). The rate of headcut migration often controls the rate of overall channel adjustment (Ritter et al. 1999). The channel immediately upstream from the headcut experiences little or no alteration other than dewatering (stage B), whereas the downstream reach is fundamentally altered by bed and bank adjustments (stages C and D). The transition between these two stages may be dramatic. For example, following the removal of the Rockdale Dam from Koshkonong Creek, Wisconsin, the river above the headcut was broad and shallow, and no physical changes in the channel had occurred, but below the headcut, water moved rapidly through a narrow, steepened channel (figure 4). Thus following dam removal, the reservoir reach becomes a shifting mosaic of channel forms. With increasing time since removal, the headcut moves farther upstream; more evolutionary stages are likely to be present and more of the entire reservoir will experience some adjustment (figure 5). The rate and extent of adjustment are influenced by site-specific conditions such as the composition of bed and bank material, the cohesion and consolidation of reservoir sediment, or the establishment of vegetation (Thorne 1989, Simon and Rinaldi 2000). However, despite variation in the rate of channel evolution from one dam removal site to another, we expect that the sequence of adjustment is common in many Midwestern rivers similar to Koshkonong Creek. Thus the channel evolution approach provides a valuable framework for understanding physical and, as we outline below, chemical changes following the removal of a dam.

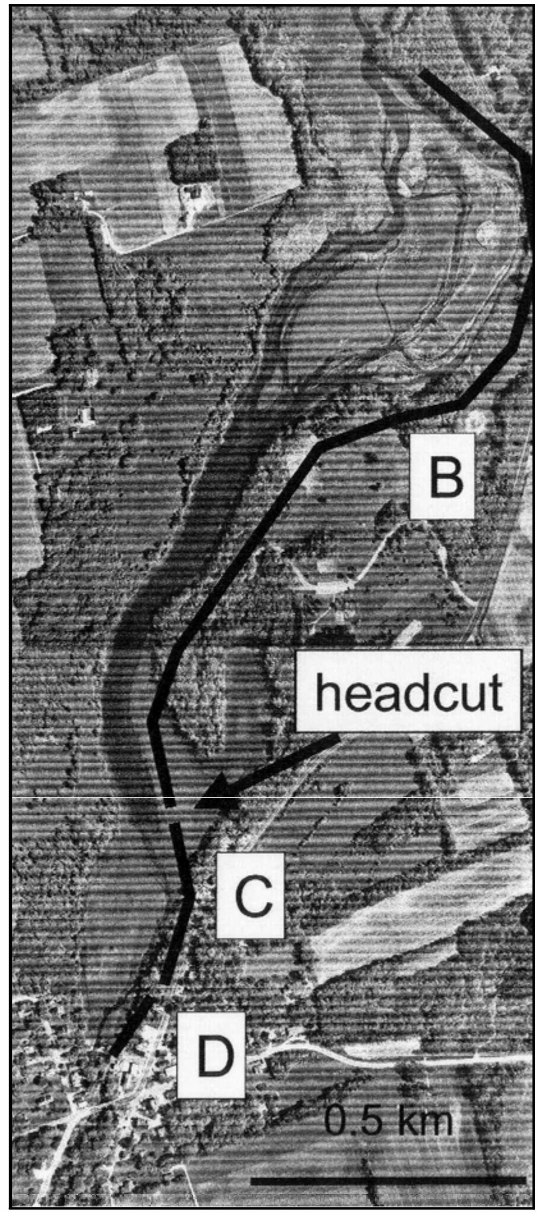



***Figure 4. The Rockdale Millpond in May 2001, 7 months after the removal of the dam. Location of the headcut marks the transition between the unadjusted channel (stage B) and reaches experiencing channel evolution. Approximate extents of different channel evolution stages depicted in figure 3 are indicated on the right. Photograph: Wisconsin Department of Transportation.***

## *Nutrient dynamics and channel evolution*

Patterns of geomorphic adjustments described above can be summarized in terms of the changes relevant to N and P retention. For N, channel form should be viewed in terms that reflect potential alterations in the degree of sediment–water contact. These changes are, at least in part, captured by measures of the wetted perimeter of the channel over time. For P, the appropriate physical variable is sediment transport.

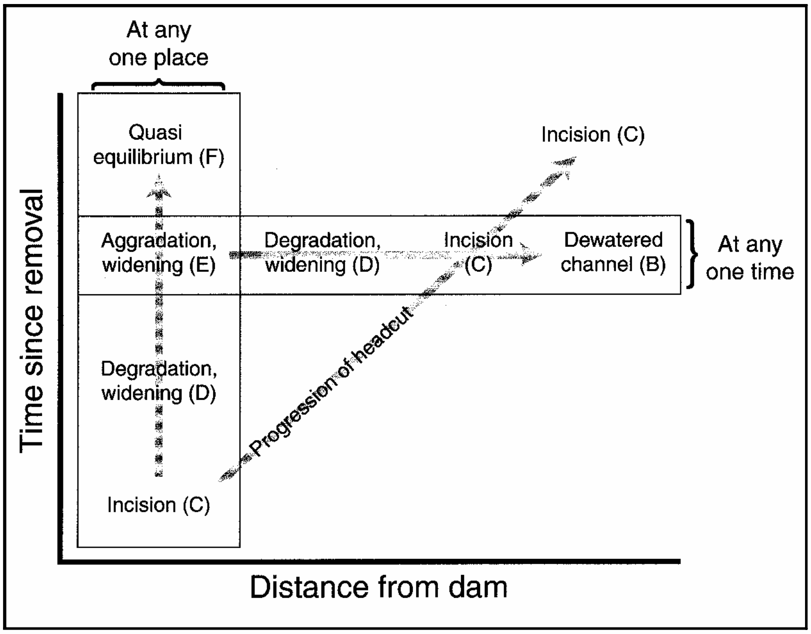


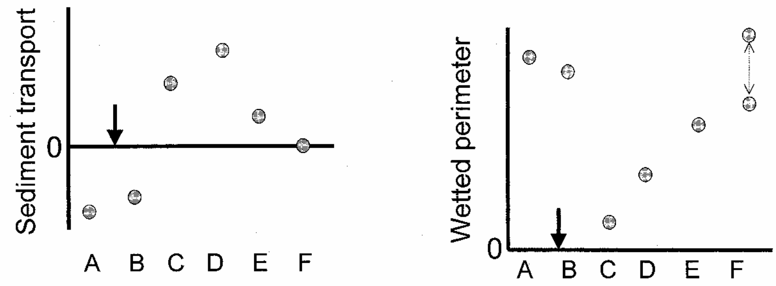

***Figure 5. Spatial and temporal distribution of channel evolutionary stages following dam removal. The upstream progression of the headcut marks the transition between the reservoir channel (stage B) and channels undergoing active geomorphic adjustment. As time since removal increases, any one place in the reservoir will progress through the different stages of adjustment; and at any one time, multiple channel stages will be present, with the most rapid progression toward the equilibrium channel occurring in reaches closest to the former dam site. Multiple channel evolution stages present at any one time can be seen in figure 4, in which stages B, C, and D were present 7 months after dam removal.***

Before removal (stage A), the wide reservoir area and modest depth characteristic of many small impoundments mean that the wetted perimeter can be an order of magnitude (or more) greater than that of the upstream or downstream channel. Further, many of these sites still retain sediment (i.e., net sediment transport is negative) before removal (figure 6). During stage B, the decline in the water elevation and subsequent dewatering cause only a minor decrease in the wetted perimeter, although the extent of change will depend on the morphometry of the specific reservoir. But as the wetted perimeter decreases, a greater proportion of the water is in contact with the sediment because of the overall reduction in water volume. Because the channel slope has not been altered, slow water velocity persists in the stage B reach, allowing continued sedimentation. Incision during stage C and widening in stage D result in large amounts of sediment transport. The wetted perimeter of the narrow, deep stage C channel is extremely small, but widening in stages D and E steadily increases the wetted perimeter. Aggradation during stage E signals a decrease in sediment transport, although the balance between retention and export of sediment will depend on relative quantities of bank erosion versus bed aggradation. As the channel moves toward a steady-state condition (reduced sediment transport and inputs generally equaling outputs), sediment retention approaches zero while the wetted perimeter gradually increases (figure 6). The extent of the wetted perimeter during stage F could eventually exceed that of the preremoval channel (stage A) if complex channel forms that include features such as backwater areas and side channels are allowed to develop.

Using the logic that P dynamics are driven by sediment transport and N by the extent of sediment–water contact, predictions about these nutrients can be generated from geomorphic trends described by the channel evolution model (figures 3, 6). Greatest P loss should occur from stage C and D channels because sediment transport is maximized, whereas stage E channels should begin to retain P because of aggradation. Similarly, extensive contact between water and sediment enhances N retention during stages A and B, but the reduced contact because of a smaller wetted perimeter, and also to greater water velocities, between nitrate-rich water and the channel in stage C suggests that N retention will be minimal. As the channel widens, sediment–water contact, and thus N retention, are expected to increase progressively in stage D, E, and F channels (figure 6).

Although the generation of predictions regarding transport or retention of different channel stages appears to be relatively straightforward thus far, these stage-based scenarios alone do not resolve the ecosystem-level effects of dam removal on nutrient retention. The amount of N or P retention occurring at any one time following dam removal will be the product of the types of channel stages present, the spatial extent of each of these stages, and the magnitude of influence of each stage on N and P dynamics. This balancing act can be illustrated by considering geomorphic adjustments observed at Koshkonong Creek following dam removal. Seven months after breaching of the dam, channel stages B, C, and D were recognizable in the former impoundment (figure 4). On the basis of our predictions above, we expect that the extensive area above the headcut in stage B should retain N, whereas little or only modest N retention would occur downstream in reaches that are undergoing active channel evolution (stage C and D channel areas). Cumulatively, this suggests that at this time, the entire reach is likely to be retaining N because of the enhanced retention and large spatial extent of the stage B channel. In contrast, modest sediment and P retention of the stage B channel is likely to be overwhelmed by losses associated with incision and widening below the knickpoint, resulting in a net loss of P from the former reservoir.

We can expand the temporally limited analysis above to suggest some general trajectories for N and P retention following dam removal for the Koshkonong Creek example. Over time, the progression of the headcut and subsequent mass wasting causes increasing export of P because of the mobilization of sediment, as well as the reduction in the extent of the channel area capable of retaining the P entering the system from upstream. Thus P losses from reservoirs may persist and even intensify over time until substantial channel lengths begin to enter into the aggradation stage (stage E). However, N dynamics over the course of dam removal are expected to be distinct from P dynamics. The upstream migration of the headcut marks the transition between two channel stages, one of which should retain N (stage B), perhaps even more strongly than the preremoval channel, and the other of which is likely to do little more than transport N downstream (stage C). Thus, on the basis of our observations of channel adjustment, it may be several months before measurable declines in N retention associated with shrinkage of the B channel are detectable at this site.




| Stage | Process | Channel form |
|---|---|---|
| B | dewatering | reservoir |
| C | incision | narrow, deep |
| D | degradation, mass wasting | wider, shallower |
| E | aggradation, widening | wide, shallow |
| F | quasi-equilibrium | complex, vegetated |

***Figure 6. Summary of the relative amounts of sediment export and wetted perimeter, and the characteristic processes and channel forms for the geomorphic stages of channel evolution following dam removal. Positive values for sediment transport indicate a net loss of sediment from the reservoir reach; negative values denote retention of sediments within the reservoir reach. Arrows indicate timing of dam removal.***

## *Assumptions and implications of linking geomorphic and ecological models*

In considering this geomorphic framework for understanding changing nutrient retention following dam removal, we have made some assumptions and simplifications that need to be addressed. The most important assumption is that $NO_3^-$ and particulate P dominate the total N and P budgets, respectively. The assumption of $NO_3^-$ and particulate P dominance led us to a second assumption, that N retention is most strongly influenced by denitrification and P retention is driven by either the settling or transport of sediments. For N, the assumptions that $NO_3^-$ represents the majority of N in transport and, more important, that denitrification is the dominant mechanism of retention, appear to be reasonable for even slightly enriched systems (Hedin et al. 1995, Saunders and Kalff 2001). However, we have not considered a potentially important pool of N in the form of particulate N, which includes both organic particles and ammonium ($NH_4^+$) sorbed to sediments. While sedimentation of particulate N does not make a large contribution to N retention in lakes and wetlands (Saunders and Kalff 2001), $NH_4^+$ concentrations in reservoir sediments can be extremely high. It is reasonable to assume that mobilization of sediments associated with incision and widening will promote N export from the reservoir in a fashion similar to P (Perrin et al. 2000). For P, water-soluble forms of this nutrient often represent a substantial fraction of total P load. Nonetheless, mobilization and transport of sediment is still likely to exert an important influence on P retention following dam removal because dissolved P (notably, phospate) will sorb to sediment particles that become entrained in the water column during channel adjustment.

An obvious simplification in this analysis has been to restrict our consideration of nutrient dynamics only to the section of river affected by impoundment. However, the effects of dams and dam removal are best understood in the larger context of the watershed. Although changes within the impounded reach are rapid and dramatic following dam removal, effects of removal may be measurable for several kilometers downstream. Depending on particle size, downstream deposition of reservoir sediments might either increase or decrease transient storage and, therefore, nutrient uptake below the dam site. Fine-particle deposition can potentially clog interstitial spaces and reduce the movement of water into and out of the streambed, or alternatively, deposition of coarse particles can lead to the formation or enhancement of bars or other bedform features, increasing sediment–water contact (Stanley et al. 2002). The balance between within-reservoir versus downstream effects of dam removal remains an important area of investigation.

A further simplification of our conceptual framework is the use of a single geomorphic parameter for assessing N dynamics, although other aspects of channel morphology and hydraulics undoubtedly play important roles. For simplicity and clarity, we have used only channel wetted perimeter, although a measure of the proportion of flow in contact with the bed would be more desirable. Also, transitions between different channel stages will affect water velocity through the channel, which in turn plays an important role in determining nutrient uptake rates (Wolheim et al. 2001). By using a single parameter to characterize the physical changes occurring within the river, we have not distinguished between the interrelated effects of changing water velocity and channel form. We expect that changes in velocity caused by altered channel form should intensify predicted nutrient responses. For example, the large amount of sediment–water contact predicted from the extensive wetted perimeter of the stage B channel will be enhanced by the slow flow rate of water over this large area. In contrast, the small wetted perimeter or extent of sediment–water contact in stage C is further reduced by high water velocity.

Despite these caveats, several points regarding the effects of dam removal emerge from this analysis. The major theme emphasized here is that changes in nutrient retention caused by dam removal are expected to be shaped by geomorphic channel adjustments. Although the specific way in which channels adjust to dam removal will vary from region to region, the change in the physical template will strongly influence the ecological responses to dam removal. Changes in nutrient retention following dam removal should be complex, reflecting a balance between the dynamics of channel adjustment and the relative influence of different channel stages on N and P processing. Following dam removal, affected sections of a river may consist of a series of reaches that have distinct and potentially contrasting influences on the form and amount of nutrients being transported downstream.

Dam removal represents an extreme example of the influence of channel morphology on nutrient dynamics in streams and rivers. While it is impossible to ignore the dramatic and relatively rapid geomorphic changes when studying dam removal, streams and rivers are dynamic physical systems subject to short- and long-term changes in channel form. Yet channel geomorphology is usually treated as a fixed or constant attribute in ecological studies. As channels change over time or from site to site in a stream, the extent of sediment–water contact or the rate of sediment transport will also vary. For example, the transition from a narrow and deep incised channel to a broader, shallow channel under conditions of constant discharge will be accompanied by a decline in water velocity, an increase in wetted perimeter, and probably an increase in the amount of interstitial flow. Because geomorphic adjustments can alter sediment transport and the extent of sediment–water contact, changing channel form alone has the potential to affect uptake lengths and rates of biologically important elements such as N and P. Although the general importance of channel form on a range of ecosystem processes, including nutrient cycling, is well established (Brussock et al. 1985, Frissell et al. 1986, D'Angelo et al. 1997), we are only beginning to understand how specific geomorphic attributes constrain nutrient dynamics in lotic systems. Dam removal can be used as an experiment for testing predictions or quantifying relationships between the dynamics of channel form and nutrient retention and thus represents a rare opportunity to gain valuable insights into the transport and transformation of nutrients as they move through watersheds.

## Acknowledgments

We are grateful to David Hart and LeRoy Poff for organizing this special issue on dam removal, and for providing us with valuable suggestions for this article. Karen Bushaw-Newton, Jim Pizzuto, and an anonymous reviewer also provided many thoughtful comments that greatly improved this article. Michael Barry assisted with graphics. This research was supported by the Purdue University Showalter Fund, the Bradley Fund for the Environment, a Horton Grant to M. W. D. from the American Geophysical Union, and NSF grant DEB-0108619 to E. H. S. We are grateful for the support The Pew Charitable Trusts provided, which allowed us to complete this article.

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

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**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.

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

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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.

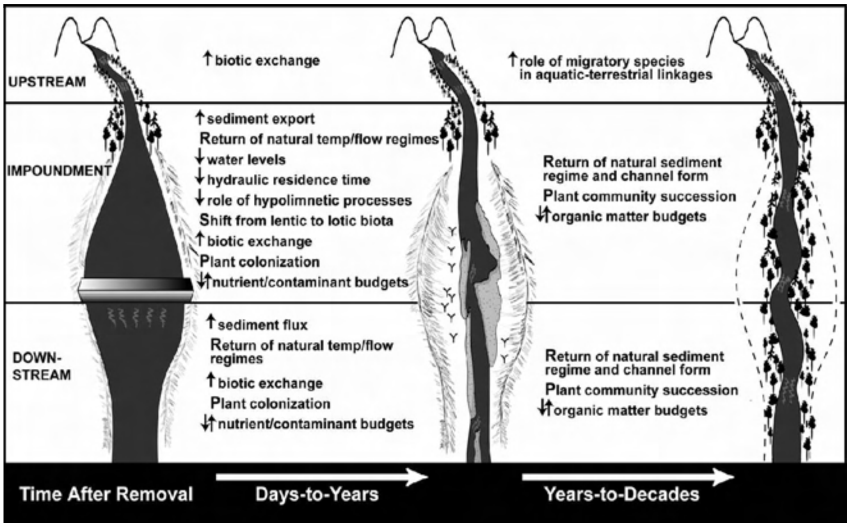


*Figure 1. A simple spatial and temporal context for examining potential ecological responses to dam removal. Prior to removal, upstream and downstream free-flowing areas are separated by an impoundment. Dam removal initiates a series of abiotic and biotic changes that vary among areas and occur at different 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<br>river system<br>(dam life span[a]) | Estimated Size[b]<br>Height by Length (meters)<br>Impoundment (hectares) | Physical[c] | Chemical | Biological | Reference |
|---|---|---|---|---|---|
| **Dead Lake Dam**<br>Chipola River, FL<br>(1960–1987) | 5 x 240<br>2700 | Alteration of flow regime | Improvement in overall water quality | Restoration of fish passage; increase in fish diversity | Estes et al. 1993,<br>Hill et al. 1994 |
| **Edwards Dam**<br>Kennebec River, ME<br>(1837–1999) | 7 x 280<br>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,<br>O'Donnell et al. 2001 |
| **Ft. Edward Dam**<br>Hudson River, N.Y.<br>(1898–1973) | 9 x 179<br>79 | Increased sediment transport | Mobilization of organic contaminants | | Shuman 1995 |
| **Fulton Dam**<br>Yahara River, WI<br>(1849–1993) | 3 x n.d.<br>20 | | | Change in community composition; loss of reservoir species | ASCE 1997,<br>Born et al. 1998 |
| **Grangeville Dam**<br>Clearwater River, ID<br>(1903–1963) | 17 x 134<br>n.d. | Increased sediment transport | | | Winter 1990 |
| **Jackson Street Dam**[d]<br>Bear Creek, OR<br>(1960–1998) | 3 x 37<br>1 | | | Restoration of fish passage (salmon) | Smith et al. 2000 |
| **Kettle River Dam**<br>Kettle River, MN<br>(1915–1995) | 6 x 46<br>n.d. | Increased sediment transport | | Decrease in mussel abundance downstream due to sedimentation | Johnson 2001 |
| **Lewiston Dam**<br>Clearwater River, ID<br>(1927–1973) | 14 x 323<br>n.d. | Increased sediment transport | | Restoration of fish passage (salmon); improvement of fish habitat | Williams 1977, Winter 1990, Shuman 1995 |
| **Manatawny Creek Dam**<br>Manatawny Creek PA<br>(late 1700s–2000) | 2 x 30<br>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,<br>Hart et al. 2001,<br>Horwitz et al. 2001,<br>Johnson et al. 2001 |
| **Nelsonville Dam**<br>Tomorrow River, WI<br>(1860–1988) | 2 x n.d.<br>9 | Decreased water temperatures | | Spawning of trout; reclassified as a class 1 trout fishery | Born et al. 1998 |
| **Newaygo Dam**<br>Muskegon River, MI<br>(1853–1968) | n.d.<br>n.d. | Increased sediment transport | | | Simons and Simons 1991 |
| **Oak Street Dam**<br>Baraboo River, WI<br>(1860–2000) | 4 x 63<br>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,<br>Stanley et al. 2002 |

*Continued from previous page*

| 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

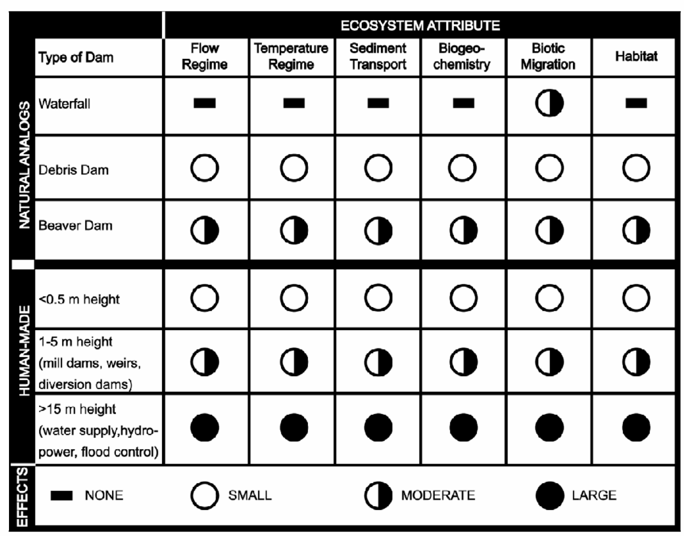


***Figure 2. Hypothetical relationship between dam type and various ecosystem attributes. Dam types include both natural dams (generally small) and human-made dams of varying heights and operations. The effects level can be defined in terms of the magnitude of change (e.g., the difference between the 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.

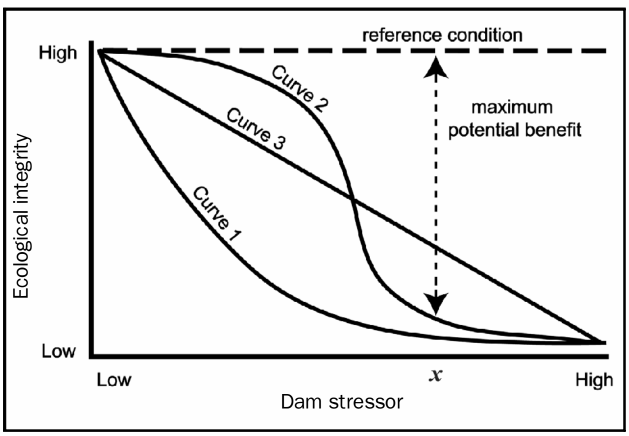


***Figure 3. Generalized linear and nonlinear relationships between dam stress (stressor) and ecological integrity (response). Dam stress may be characterized as crest height or dam width, or it may be scaled according to various river and watershed characteristics. Ecological integrity can refer to 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.

## Acknowledgments

We thank Scott Carney and Andrew Newton as well as many of our Patrick Center colleagues for useful discussions about these issues. Financial support from a Pennsylvania Department of Environmental Protection Growing Greener Grant, a private foundation, and the Patrick Center's Research Endowment Fund allowed us to examine ecosystem responses to the removal of the Manatawny Creek Dam and to develop many of the ideas in this article. The views expressed herein are those of the authors and do not necessarily reflect the views of the Pennsylvania Department of Environmental Protection.

Becky Brown, Tom Coon, Matt Greenstone, and LeRoy Poff offered valuable feedback on earlier drafts of this manuscript. Robin Davis offered outstanding editorial assistance. The Pew Charitable Trusts provided support that facilitated the completion of this paper.

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## *Roles for scientists in community-based ecological restoration*

You may not have noticed yet, but a community group near you is probably involved in the ecological restoration of a local watershed. Whether their objective is to help remove an abandoned dam, plant streamside vegetation, fence livestock out of streams, or reduce the spread of invasive species, these groups are working hard to improve environmental quality and build a brighter future for their communities. Because many of these restoration projects are initiated by grassroots and volunteer organizations rather than by large government agencies, the participants may not be familiar with the broad range of scientific and technical issues surrounding the nascent field of ecological restoration. Nor are they likely to have major funding to support research. Nonetheless, the thousands of local projects initiated around the country every year offer great opportunities for scientific participation.

Scientists can aid, and potentially benefit from, such community-based restoration in several ways. First, at its core, successful restoration is critically dependent on scientific understanding. Specifically, ecological restoration programs seek to reduce the negative effects of human activities on ecosystems, while enhancing various physical, chemical, and biological processes by which these systems recover from disturbance. Thus, biologists and other scientists can use their knowledge of "how nature works" to help identify the threats to ecological integrity and develop methods for facilitating the recovery of these complex systems.

Scientists can also help ensure that future restoration efforts produce important new understanding of ecological systems. To date, outcomes of many local restoration projects have not even been quantified. To improve this situation, scientists can develop testable hypotheses about the causes of an ecosystem's impairment, as well as the ways in which ecological recovery can be enhanced. Similarly, scientists should look for opportunities to use restoration projects as true experiments and encourage the acquisition of data to determine how ecological systems respond to the restoration "treatment." As more of these objective assessments of restoration outcomes are made, researchers will not only gain new scientific insights but also help determine which restoration practices work best, thereby contributing to more effective ecological restoration.

Scientists who participate in local restoration projects will necessarily communicate with nonscientists about the scientific enterprise and the ways it can be used both to create new knowledge and to help solve real-world problems. The more effectively we can translate the sometimes arcane world of science and explain its relevance to issues of local concern, the more likely that society will value science as a cornerstone of understanding and problem solving. Whether directly or indirectly, such dialogue can also lead to greater public support for scientific research.

Perhaps the best reason for participating in a local restoration project is the personal satisfaction it can offer. Community-based restoration is an inherently optimistic and constructive endeavor, in which citizens are working in their own backyards to help sustain the planet's life support systems. What could be more satisfying than the knowledge that you are adding value to such efforts?

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# Effects of Dam Removal on River Form and Process

JIM PIZZUTO

**Dams have a profound influence on fluvial processes** and morphology. Reservoirs formed by dams drown river channels and trap sediment. Downstream reaches respond to altered flow regimes and reduced sediment supply in varied ways (Williams and Wolman 1984, Collier et al. 1997) that are difficult to predict, although common responses include erosion and lowering of the channel bed (incision) and development of a coarse-grained surface layer (armor) in the riverbed downstream of a dam.

As dam removal continues to gain momentum as a restoration strategy, understanding how a river changes when a dam is removed is becoming increasingly important. Because few detailed geomorphic studies of dam removal have been conducted, however, there is little direct observational basis for predicting the geomorphic effects of dam removal. Furthermore, rivers are complex and fluvial processes often occur over decades or centuries, so predictions are inherently uncertain.

Fortunately for researchers, the processes associated with dam removal also occur naturally. For example, after dam removal the sediment fill in an impoundment is likely to become incised, and an equilibrium channel with a new floodplain is likely to form as sediment evacuated during incision increases the sediment supply to downstream reaches. Natural processes related to incision, floodplain formation, equilibrium channel development, and increased sediment supply have been widely studied by geomorphologists and engineers, providing useful conceptual models for evaluating the geomorphic effects of dam removal (Doyle et al. in press). These models can rarely be quantified, however, and in many cases the appropriate model for a particular situation may not be apparent before dam removal. Thus future research will need to concentrate on discriminating among the myriad possible geomorphic responses to dam removal and improving the quantitative basis for predictions.

> ALTHOUGH MANY WELL-ESTABLISHED CONCEPTS OF FLUVIAL GEOMORPHOLOGY ARE RELEVANT FOR EVALUATING THE EFFECTS OF DAM REMOVAL, GEOMORPHOLOGISTS REMAIN UNABLE TO FORECAST STREAM CHANNEL CHANGES CAUSED BY THE REMOVAL OF SPECIFIC DAMS

## *Geomorphic effects of different engineering strategies*

The engineering design and implementation of dam removal plans can profoundly influence the subsequent geomorphic evolution of the impoundment, as well as the extent and nature of sediment impacts downstream of the dam. Important design considerations include strategies to stabilize or remove sediment fill above the dam, the timing and nature of the actual dam removal, and the extent to which the removal follows engineering design criteria.

A variety of strategies exist for minimizing erosion of the sediment fill above dams. Although it may be expensive, removing sediment fill behind the dam may be useful in some instances (Smith et al. 2000). Removing sediment is a particularly attractive alternative when dam fill sediments present an extreme hazard, or when other exceptional factors can justify the expense involved. Furthermore, the sediment that makes up the fill may consist of sand and gravel (Egan and Pizzuto 2000, Wilcox et al. 2000) that could be sold as aggregate for concrete or for construction fill (assuming that sediments are not contaminated). Regrading, revegetating, and riprapping (i.e., strengthening with a layer of stones) of the exposed dam fill have also been proposed as means of reducing the extent and rate of erosion (Harbor 1993, Kanehl et al. 1997).

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The engineering design of the actual dam removal may have a significant influence on sediment-related impacts. In many cases, dams are breached only over short sections to allow the reservoir to drain before removing the remainder of the dam (Egan and Pizzuto 2000). Drawing down the reservoir before removal can achieve the same effect, in addition to allowing fine-grained reservoir sediments to consolidate and strengthen (Kanehl et al. 1997). To minimize the potential impacts of eroded reservoir sediments downstream of high dams on the Elwha River in Washington, Harbor (1993) advocated "controlled lowering" of the dams on the Elwha River in Washington, in which removal would occur in stages.

It is also important for engineering designs to be specific and for the removal process to be monitored by qualified inspectors. When the Manatawny Dam in Pottstown, Pennsylvania, was removed in August 2000, the contractor was simply directed to remove the dam: No detailed specifications for removal were given to the contractor, and the dam removal process was not monitored by suveyors. After the dam had been "removed," surveys revealed that the contractor had removed only half of the 2-meter (m) height of this dam. The remaining 1 m of the dam consisted of large blocks that could not be transported by the stream. These blocks made erosion at the dam site impossible, in addition to controlling the elevation of the streambed above the dam. As a result, the channel upstream did not change initially. In November 2000 the remaining half of the dam was removed, and by June 2001 sand and gravel had accumulated in the streambed above the dam and finer-grained sediments had been swept downstream to expose gravel riffles (steep, rocky sections of the channel with shallow, fast-moving water) (Egan 2001).

Such problems may not necessarily be caused by a contractor's negligence. Rather, the desired elevation of the dam site following dam removal may not be explicitly defined or discussed. Indeed, it is an easily neglected concept: What could be simpler than just "removing" the dam? At the Manatawny Dam, the problem was clearly illustrated only following a detailed survey of the longitudinal profile over the dam site. Ideally, the design should have included a target longitudinal profile for the postdam channel, which, when projected over the dam site, would have indicated the appropriate elevation to which the contractor should have excavated.

## Geomorphic processes above the dam

Upstream from the dam, geomorphic processes should follow a coherent sequence (figure 1). First, the channel will incise through the sediment fill. Bank failures will occur if the channel depth increases above a critical value that depends on the strength of the soil and the detailed geometry of the stream. The additional sediment supplied by bank failures could be used to build floodplains and, ultimately, a new equilibrium channel. The complete sequence will probably require at least a decade and will depend greatly on the mass and grain size of the sediment stored behind the dam.

***Incision processes.*** The sediment fill in the impoundment could be incised by a variety of processes that will probably depend on the height of the sediment fill and its grain size (figure 2). In cohesive silt and clay sediments, a vertical headcut (an eroding vertical face in the stream bed) is likely to migrate upstream through the fill (Doyle et al. forthcoming). Sandy fills could be subject to sapping as groundwater emerges at the base of a headcut. Other mass wasting processes related to liquefaction of sandy sediment could also occur, particularly when the reservoir fill is thick. Otherwise, a knickpoint (an abrupt increase in slope) could migrate upstream through a sandy fill. Fills composed of sand or cohesive silt and clay are likely to erode even during low flows, but fills composed of gravel may be incised only during high-flow events that are competent to move coarse sediment (Egan 2001, Doyle et al. forthcoming). For this reason, gravel fills are labeled as "event-driven" in figure 2.

Incision rates for removing dam fill sediments are poorly documented. Gerrits (1994) documented 300 m of knickpoint migration in the year following the removal of Musser Dam in Pennsylvania, a 10-m-high run-of-river dam (a small dam that does not significantly influence the water discharge into the stream). Doyle and colleagues (forthcoming) describe the migration of knickpoints following the removal of two low-head dams in Wisconsin, but they do not provide quantitative results.

***Development of a stable channel morphology.*** As noted in considerable detail by Doyle and colleagues (forthcoming), field studies of the development of incised channels provide a useful conceptual model of how channels could respond to dam removal (Schumm et al. 1984, Harvey and Watson 1986, Simon 1989a, 1989b, Simon and Hupp 1992). Harvey and Watson (1986) developed a six-stage conceptual model for the evolution of Oaklimiter Creek in northern Mississippi (also summarized by the Task Committee on River Width Adjustment [TCRWA 1998b]) (figure 3). The six stages may be observed at any time along the longitudinal profile of an incising channel, but they also indicate the evolution of individual cross-sections through time. In stage I, the channel slope is steepened above its equilibrium value, but incision has not yet occurred and the banks are stable. During stage II, the channel incises. Stage III is characterized by extensive bank erosion. The additional supply of sediment from the banks causes aggradation of the bed (stage IV), which gradually becomes vegetated (stage V) and ultimately develops into a mature floodplain with an equilibrium channel (stage VI).

Monitoring studies of incised channels indicate that the complete sequence occurs over several decades. Because comparable observations of dam removals are lacking, the appropriate time scale for incision and recovery following dam removal is undocumented. However, when describing the geomorphic response of the removal of two small low-head dams in Wisconsin, Stanley et al. (2002) observed "relatively small and transient geomorphic changes in downstream reaches, and apparently rapid channel development to an equilibrium form within the impoundment." In this case, dam sediments were composed of readily transportable sand, and extensive floodplain development was apparently not required to form an equilibrium channel.

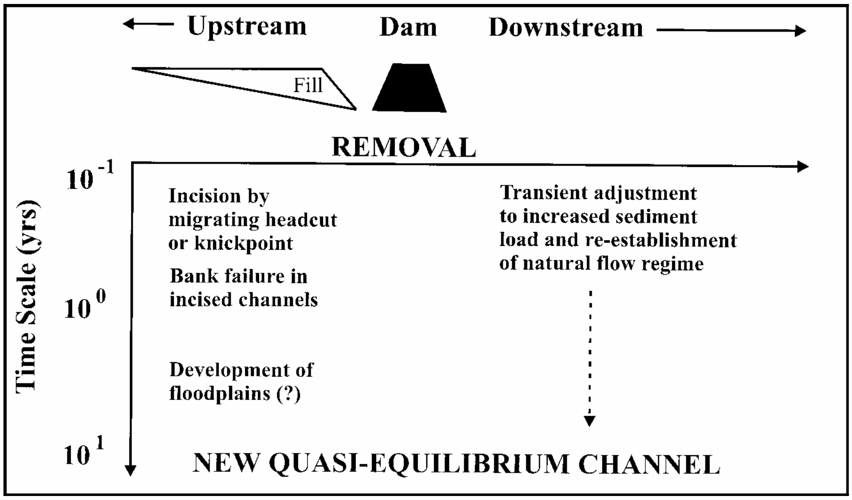


*Figure 1. Schematic illustration of geomorphic processes above and below removed dams. The time scale is highly speculative and will vary considerably from site to site, depending on the size of the dam, the mass of sediment impounded, and other variables.*

If the sediment fill in the impoundment is thin, incision may not occur (figure 2). Draining a wide impoundment may create extensive flat areas upstream with a wide, shallow channel (Egan and Pizzuto 2000). To develop a narrower, deeper equilibrium channel, floodplains may have to form by vertical accretion as sediment is deposited from overbank flows. These processes are well documented in the geomorphic literature (Schumm and Lichty 1963, Allred and Schmidt 1999, Moody et al. 1999). For example, Moody and colleagues (1999) described floodplain development and channel narrowing following a large flood on the Powder River in southeastern Montana. The floodplain, which grew over approximately 20 years, was built by the deposition of decimeter-thick layers of sand and mud when annual or biannual floods overtopped the growing floodplain.

After the Manatawny Dam was removed, extensive gravel bars formed. These probably represent the initial stages of floodplain development required to narrow the channel by about 10 m (Egan 2001). The deposition required to accrete the gravel bars far exceeds the volume of erosion at Manatawny Dam, indicating that the primary response to dam removal in this case was deposition rather than erosion and incision. Thus sediment budgets for downstream reaches may need to be reconsidered depending on whether incision or floodplain development is expected to dominate at a particular site.

***Predicting morphology of the equilibrium channel.*** It is often desirable to be able to predict the size and shape of the equilibrium channel that will ultimately form upstream from the dam. Channel width and depth are needed, for example, to design river restoration projects. However, making such predictions is very difficult. Although the dimensions of undisturbed reaches upstream can provide a useful guide (Egan and Pizzuto 2000, Egan 2001), the banks of the channel within the former impoundment will likely have a different sediment type and different riparian vegetation from any reach upstream. Thus even empirical methods may not provide an accurate assessment of the equilibrium channel width and depth in the impoundment. Furthermore, empirical methods "cannot predict either the rate of change or intermediate widths attained during dynamic adjustment of channel morphology" (TCRWA 1998b). The American Society of Civil Engineers' Task Committee on River Width Adjustment provides a useful review of these issues (TCRWA 1998a, 1998b).

## Geomorphic processes downstream from the dam

***Overview.*** Downstream from the dam, the channel will respond to the increased sediment load from the eroding fill, as well as to the reestablishment of a natural flow regime.

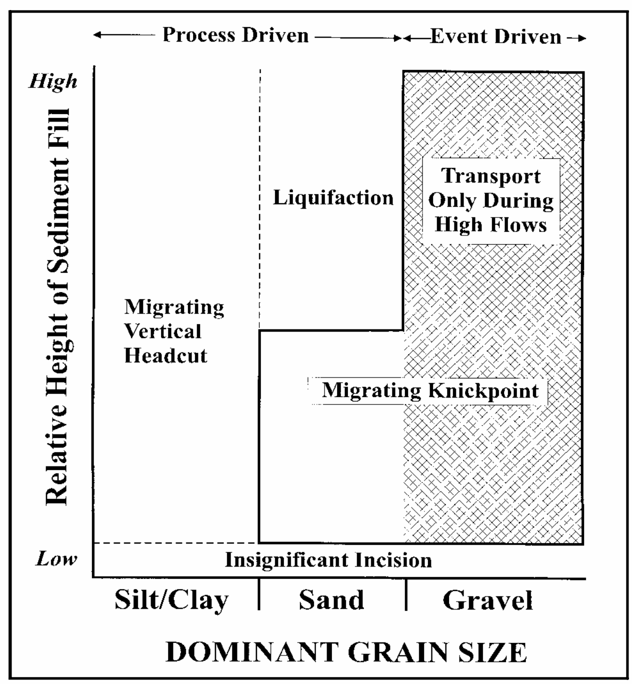


*Figure 2. Speculative relationships between the height of a reservoir sediment fill, the dominant grain size of the fill, and different processes of incision. Erosion of gravel depends on high-flow events; therefore these incision processes are "event-driven." Incision of sand and of silt and clay do not depend on high-flow events, but rather on the mechanism of incision; therefore, removal of fills of sand and of silt and clay are "process-driven."*

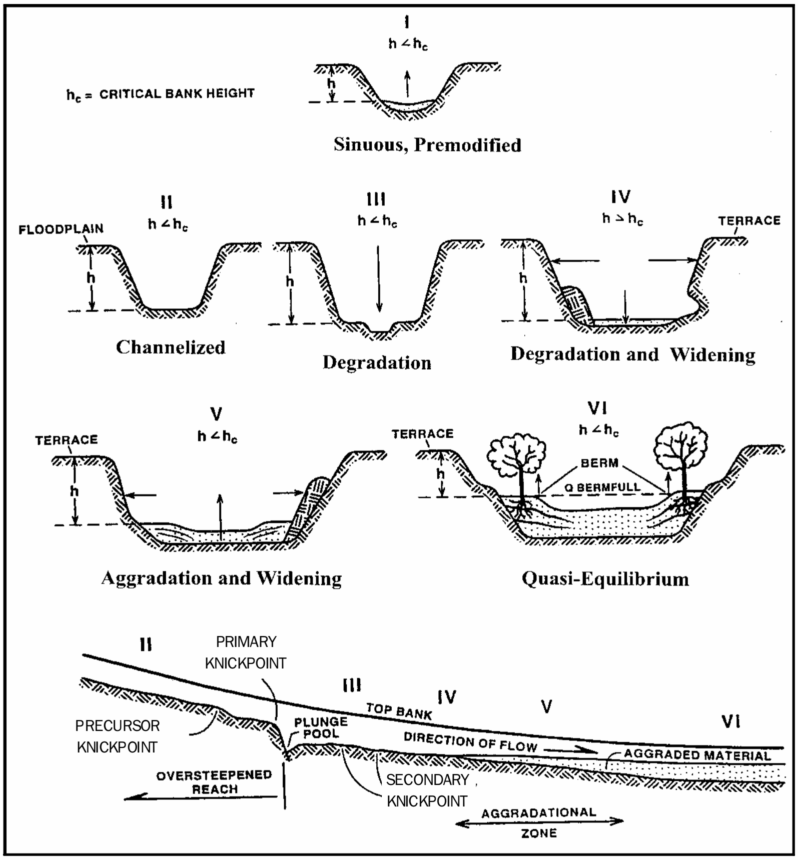


***Figure 3. Six-stage sequence of incised channel evolution (from Doyle and Stanley forthcoming, after Simon and Hupp 1992, Harvey and Watson 1986, and TCRWA 1998b). The variable* $h_c$ *is the critical height at which bank failures occur.***

Because the volume of sediment supplied by channel incision will vary with time (Simon 1989), and because channel responses to changes in sediment supply are time-dependent, the morphology and sediment character of the channel downstream will be highly transient. Gradually, as the fill upstream is removed and stored sediment moves downstream, a stable equilibrium form should develop.

Geomorphologists and hydraulic engineers have developed at least two distinct conceptual models to explain patterns of bed elevation changes and sediment transport following a one-time increase in the supply of bed material to a stream channel (figure 4). In one case, the initial pulse of sediment (as represented, for example, by the accumulation of sediment behind a dam) decays in place, a process called dispersion by Lisle et al. (2001). Sediment in transport above the pulse is trapped on its upstream side, and sediment eroded from the crest of the pulse is deposited downstream, resulting in a pattern of bed evolution that resembles a classical diffusion process (e.g., decay of heat from a point source or transport of a dissolved substance by Brownian motion). Dispersion is contrasted with *translation,* in which a wave of bed material travels downstream without a decrease in amplitude. A combination of both processes is also possible (figure 4).

Although many geomorphologists have suggested that sediment inputs translate as waves (Gilbert 1917, Madej and Ozaki 1996), recent experimental (Lisle et al. 1997, 2001), theoretical (Cui and Parker 1997), and field studies (Ball et al. forthcoming) suggest that dispersion should predominate. For example, Lisle et al. (1997) introduced a pulse of sediment into an experimental equilibrium gravel channel. The pulse essentially decayed in place, evolving almost entirely by dispersion (figure 5). Lisle et al. (1997) were able to explain their observations using a relatively simple mathematical model of hydraulics and sediment transport. More extensive flume experiments and modeling results partly reported by Lisle et al. (2001) also emphasize the importance of dispersion. The erosion of a landslide dam on the Navarro River in California also was almost entirely dispersive (Ball et al. forthcoming).

Determining the relative importance of dispersion and translation is significant because the two models have different implications for downstream sediment impacts following dam removal. If a bed material wave translates without decreasing in amplitude, then serious sediment impacts could propagate downstream. Dispersive bed material waves, on the other hand, create sediment impacts that decrease in severity both with time and distance downstream.

Ecological impacts could also vary in response to these two contrasting processes. For example, translation might have larger short-term impacts at a particular location, but then the sediment wave would pass that location and have no further effect. By contrast, a dispersive process might have a smaller effect per unit time at a particular location, but impacts at that site could last much longer.

The results described above that emphasize the importance of dispersion apply primarily to gravel-bed rivers and do not take into account factors such as floodplain processes and width adjustment. Nonetheless, they suggest that impacts from bed material following dam removal will not influence the channel far downstream. Doyle et al. (forthcoming) and Stanley et al. (2002) disagree, however, and suggest that downstream translation of sediment waves can be significant under certain circumstances following dam removal.

***Reach-scale changes in bed texture and morphology.*** An increase in sediment supply downstream caused by dam removal could have significant impacts at the reach scale, where a reach is defined as a length of stream that contains several pool and riffle sequences or meanders, or that is 10 to 30 channel widths in length (Leopold et al. 1964). These impacts include destruction of pools and riffles, burial of coarse-grained riffles by finer-grained sediment, and modification of bedforms and armor.

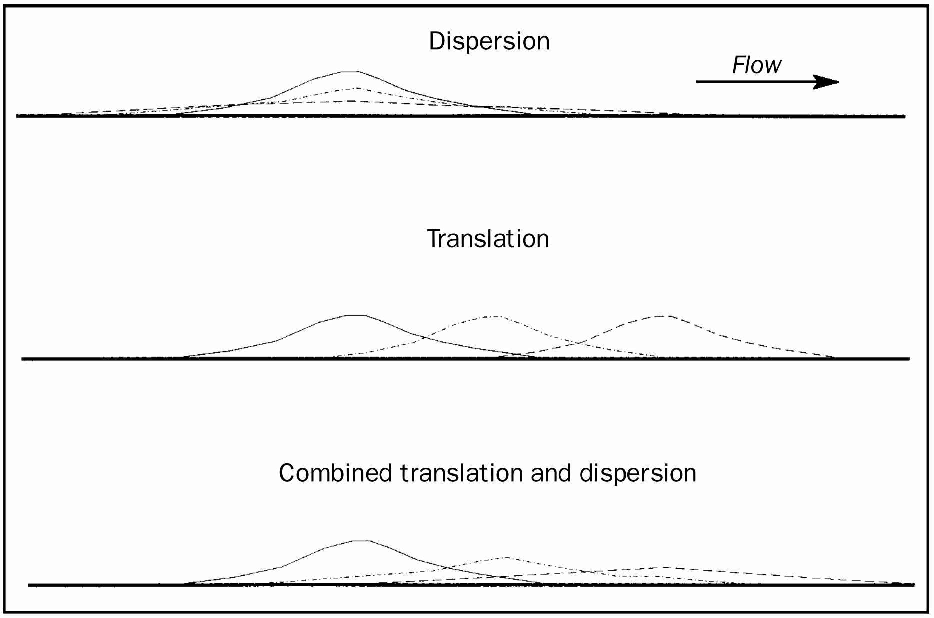


*Figure 4. Dispersion, translation, and combined translation and dispersion of bed material waves illustrated in profile. The solid line represents the initial bed topography. The dashed and dotted line represents the second position of the bed, and the dashed line represents the final position of the bed (after Lisle et al. 2001).*

dam fill had migrated at least 25 m downstream, destroying both the pools and riffles created by alternate bars and the armored bed. A bed with scattered sandy patches replaced the preexisting armored bed. After 5.2 hours, the armored bed was reestablished, but the alternate bars had not reappeared. Finally, after 8.5 hours, the same pattern of alternate bars and pools and riffles that characterized the initial equilibrium channel had reappeared.

These observations suggest that the sediment supplied by dam removal could rapidly destroy the structure of the bed at the reach scale.This conclusion is supported by many field studies demonstrating a decrease in surface grain size in gravel bed rivers that is caused by an increased supply of finer grained sediment (Montgomery et al. 1999). During the ensuing recovery, as the extra sediment

Flume studies are particularly effective for investigating bed processes in gravel-bed rivers. Analyses of scaling laws and the relevant fluid mechanical principles indicate that small-scale flumes are excellent physical analogues for real gravel-bed rivers (Shvidchenko 1998).

Observations from flume studies suggest that changes in bed texture and morphology resulting from an increase in sediment supply may occur in a predictable sequence (figure 6). The experiments described by Lisle et al. (2001) involved (a) creating an equilibrium channel with an armored gravel bed and well-developed alternate bars (the uppermost map in figure 6), (b) introducing a pulse of sediment that could represent a dam fill (figure 6), and (c) observing the response of the channel downstream as the pulse was eroded. In these experiments, the pulse was approximately 15 channel widths long and 3.5 centimeters (cm) high—about the same height as the equilibrium depth of flow. The transient evolution of the "dam fill" and the reach downstream was observed for 8.5 hours. After 0.6 hours, the sediment from the

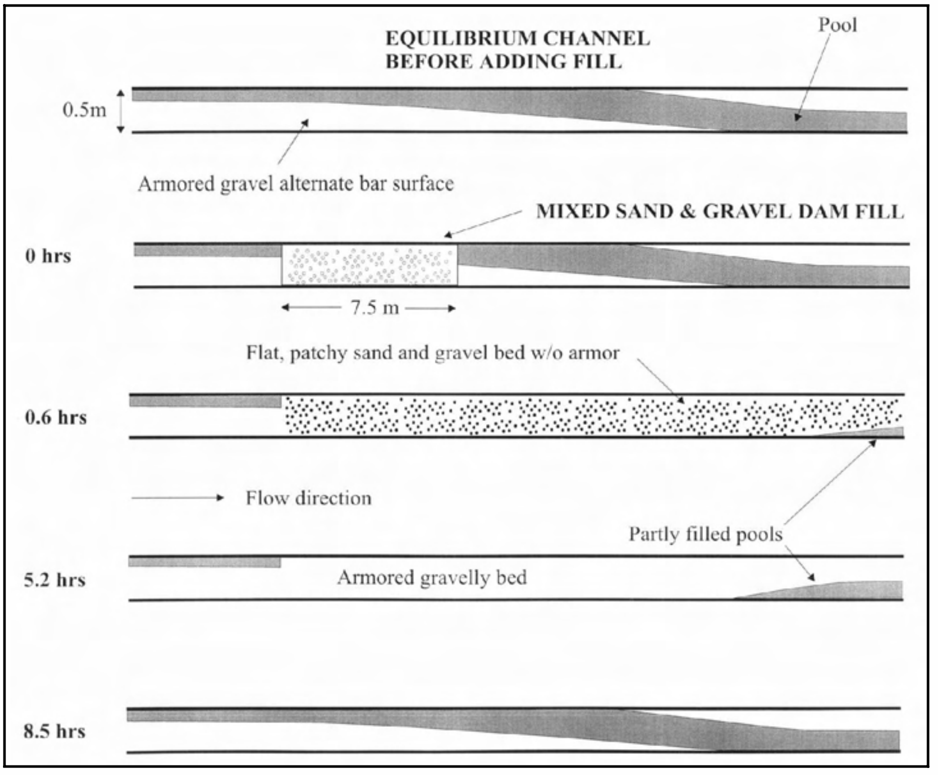


*Figure 5. Evolution of a sediment wave in an experimental channel. The horizontal axis represents the longitudinal distance down the flume. The vertical axis is the thickness of sediment above the sloping base of the flume. At 0 hours (hrs), an equilibrium channel is illustrated. After 0.75 hrs, a pulse of sediment 3 cm high and 20 meters long was introduced into the channel. This pulse essentially decayed in place. The "observed" data have been smoothed, and the solid line represents predictions from a mathematical model (after Lisle et al. 1997).*

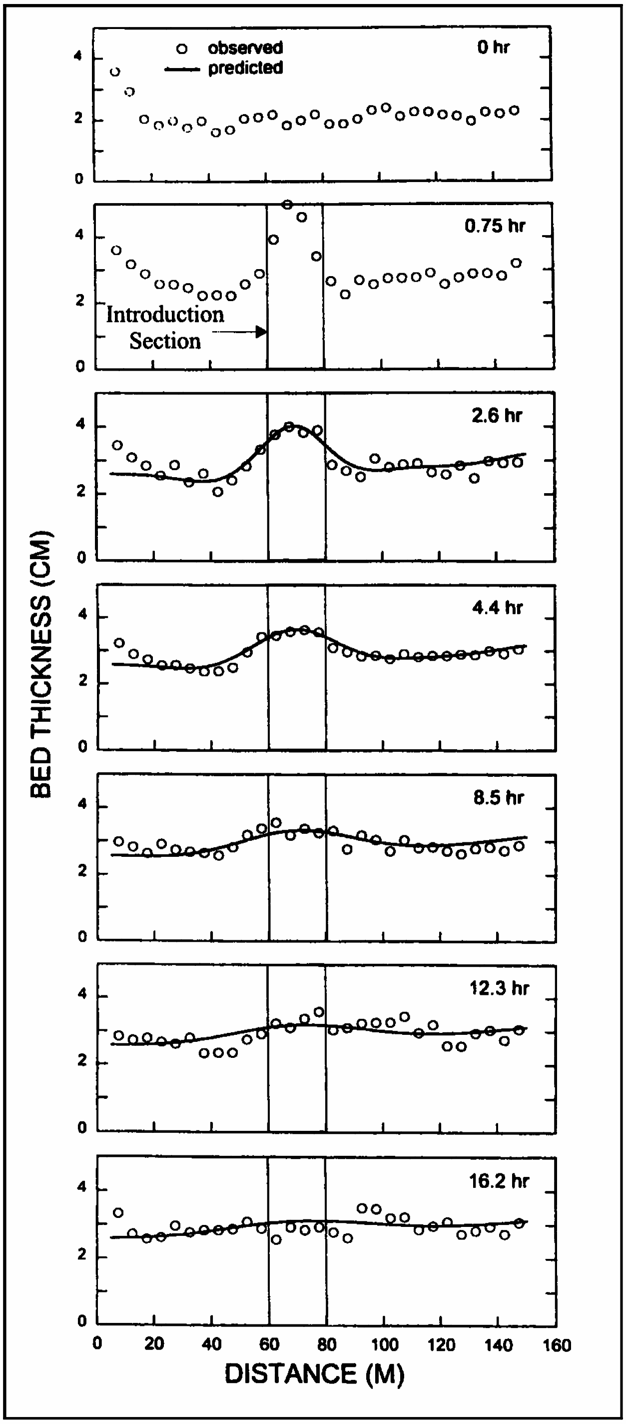


*Figure 6. Map views of a laboratory flume experiment modeling the erosion of a sand and gravel dam fill. The uppermost drawing illustrates an equilibrium channel with armored alternate bars. A pulse of sand and gravel (possibly representing a dam fill) was then added; this pulse was equal to the flow depth in height and approximately 15 channel widths long. Three maps illustrate the recovery of the channel to its initial condition after 8.5 hours. These observations were made during run two of experiments at St. Anthony Falls Laboratory by Lisle et al. (2001).*

is removed, the armored bed is reestablished first, followed by alternate bars and pools and riffles. Although these changes were observed in a matter of hours in a laboratory flume, the time scale for equivalent changes in a field situation is difficult to specify precisely, but it is likely to be at least several years (Madej 2001).

Observations at the reach scale by Egan (2001) following the removal of Manatawny Dam provided some information on the nature of the evolution of alternate bars and pools and riffles. Downstream from the dam, cobble riffles were buried by a mixture of sand, pebbles, and granules eroded from the dam fill upstream. (Buried riffles following dam removal were also noted by Kanehl et al. 1997 and Stanley et al. forthcoming, documenting aggradation downstream of removed dams.) After 11 months of monitoring, these riffles remained buried. In the impoundment itself, incipient pools and riffles and a midchannel bar formed during a 2.5-year flood (a flood that, on average, will be equaled or exceeded only once every 2.5 years) that occured 5 months after the dam was removed. After 11 months, however, the spacing of the pools was relatively incoherent compared with a control reach upstream, in which pools and riffles exhibited fairly regular spacing of five channel widths. Pools were also deeper in the control reach than in the impoundment area. These observations suggest that complete development of pools and riffles in a gravel-bed channel following dam removal could take at least several years, depending on the frequency of discharges competent to move the bed sediment.

Other, more complex responses at the reach scale are also possible. Gerrits (1994), for example, documented sediment storage in backwater areas and on the floodplain following the removal of Musser Dam. Stanley and colleagues (2002) observed similar deposits following the removal of small dams in Wisconsin. Sediment could also be stored in areas of low current velocity close to stream banks (Stanley et al. 2002).

## *Numerical models of geomorphic response*

Numerical models are commonly used to evaluate sediment transport and hydraulic processes associated with dam removal. These models predict the average velocity and water surface elevation for a reach, and use these hydraulic data to estimate reach-averaged rates of sediment transport and changes in bed elevation.

At a symposium on "Rehabilitation and Decommissioning of Aging Dams" at the 2000 fall meeting of the American Geophysical Union, five of ten presentations emphasized predictions based on numerical models (the abstracts are published in the 2000 fall meeting supplement of EOS and are also available at *www.agu.org).* How robust are these predictions?

The impacts of most dam removal projects are likely to extend far enough downstream to require the use of one-dimensional models, rather than more complex two- or three-dimensional models, because of limitations in computer information storage capacity and computational power. For

*Table 1. Studies that could lead to improved forecasting of dam removal effects.*

| Type of study | Benefit |
|---|---|
| Semi-quantitative observation of many dam removal projects | Develop conceptual models that could be used to forecast controlling processes following dam removal |
| Improved numerical modeling | Improve quantitative forecasting; assist engineering design |
| Physical modeling | Test conceptual and numerical models under widely varying controlled conditions |
| Integrated modeling of geomorphic, hydrologic, and ecological processes | Develop physical models that are useful for predicting biotic and biogeochemical effects |
| Comprehensive, quantitative, multidisciplinary studies of selected dam removal projects | Rigorous testing of physical and biological predictions. |

example, Wilcox et al. (2000) modeled approximately 45 kilometers of the Sandy River in Oregon to predict the potential impacts of the proposed removal of Marmot Dam. Although it would clearly be impractical to represent meter-scale spatial and temporal variations in hydraulics, morphology, and sediment transport over such distances, this is precisely the resolution required by two- or three-dimensional models.

One-dimensional models can predict only changes in grain size and bed elevation in the downstream direction, and all results are averaged across the width of the channel. Furthermore, predictions in the downstream direction are typically associated with a computational grid that is widely spaced relative to channel width. As a result, one-dimensional models predict single, reach-averaged values of grain size and bed elevation. Predictions of smaller scale or multi-dimensional features such as alternate bars or grain-size patches cannot be obtained from one-dimensional models.

One-dimensional sedimentation models are, however, relatively well-established tools in river engineering. Useful reviews of older models were presented by Dawdy and Vanoni (1983) and the National Academy of Sciences (1983). More up-to-date reviews will be available with the publication of the American Society of Civil Engineers Manual 54, *Sedimentation Engineering,* which will contain chapters on "Sediment Transport Mechanics," "Transport of Gravel and Sediment Mixtures," and "1-D Computational Modeling of Sedimentation Processes." One-dimensional models have been used in thousands of field studies (Ball et al. forthcoming provide an excellent example) and laboratory studies (Cui et al. 1996), often with useful results.

Nonetheless, many of the processes represented by current one-dimensional sediment transport models are not well understood. For example, methods for computing transport rates of sand and gravel mixtures are in their infancy (Wilcock 1997). Methods for computing transport processes of silt and clay are also rudimentary (Packman 2001). Mixtures of sand and gravel are very common in nature, and most of the sediment load of rivers is represented by the transport of silt and clay. Furthermore, these processes are only selected examples. Nearly all existing models neglect many other important processes, including upstream propagation of knickpoints and headcuts; changes in width due to bank erosion or deposition (TCRWA 1998a, 1998b, Doyle et al. forthcoming); processes associated with floodplains, including overbank flows and associated sediment transport; and the influence of vegetation on sediment transport processes.

An additional impediment to the development and use of improved numerical models is the poorly developed state of conceptual models that identify controlling geomorphic processes (Grant 2001). As a result, the processes that should be included in a quantitative model forecast at a particular site are not well constrained. Empirical observations are also needed to better define the processes that will probably occur during particular dam removal projects (Grant 2001). It is difficult to provide accurate, quantitative forecasts of the effects of dam removal using a numerical model if the processes represented by the model cannot be identified *before* a dam is removed.

## Toward improved forecasting of dam removal effects

Improving our ability to forecast the effects of dam removal will require a concerted, well-designed effort. Table 1 outlines some components of a research program that could help achieve this goal.

Our greatest need is to improve the ability to develop and test conceptual models that will indicate the relevant processes controlling the evolution of the river following dam removal. This will require observations from dam removal projects under a wide variety of conditions, with varying dam heights, fill sediment types, impoundment sizes, and a host of other variables. Because it is impractical to study a large number of dam removal projects in detail, geomorphologists, engineers, ecologists, and others will need to develop rapid protocols for semi-quantitative documentation of dam removal processes through a multidisciplinary effort.

Researchers should also develop improved numerical models to quantify the relevant processes identified by improved conceptual models. Although current models do not include many relevant processes, the rapid development of computing power and the widespread availability of modeling expertise should allow development of useful predictive models. The current widespread use of numerical models indicates that models will always be needed to provide quantitative predictions to guide management decisions. If models are to be used, then both researchers and managers should have confidence in them.

Studies using flumes or other physical models could be extremely useful for improving our conceptual knowledge of dam removal processes and testing numerical models under rigorously controlled conditions. Physical models have provided extremely useful results in many areas of fluvial geomorphology, including landscape evolution (Hasbargen and Paola 2000), the development of drainage basins (Parker 1976), watershed-scale sediment routing (Parker 1976), the evolution of localized sediment inputs (Lisle et al. 1997, 2001), the development of armor in gravel bed rivers (Parker et al. 1982), and the evolution of bedrock channels (Wohl and Ikeda 1997).

Physical models could provide a cost-effective means of studying dam removal processes under controlled conditions that cannot be duplicated by field studies. Scaled physical models have significant limitations, however. Sedimentary processes involving clay, silt, or fine sand often cannot be effectively scaled because of the surface chemistry of the finest grain sizes. Varying discharges are difficult to create and scale in the laboratory, and scale models cannot represent important effects caused by vegetation in the field. Finally, the geometry of scale models does not always correspond to field conditions.

Developing improved conceptual and numerical models of hydrodynamic and geomorphic processes will not suffice. Ecologists also need predictions of changing river morphology and sediment transport processes to predict changes in ecological processes following dam removal. However, the nature and scale of geomorphic predictions that are most useful to ecologists are not necessarily those that geomorphologists are most likely to produce. For example, a one-dimensional model used by an engineer or geomorphologist might predict the mean grain size of the bed material or even the extent of bed armoring. Ecological processes might be linked more strongly to the percentage of silt and clay in the bed—a quantity that has received little attention from geomorphologists and engineers. To maximize the utility of geomorphic predictions for ecologists, a coordinated multidisciplinary effort is needed to develop integrated geomorphic and ecological models. This will require a conscious, planned collaboration between ecologists and geomorphologists throughout entire projects, from initial study design to final model development and testing.

To gain confidence in the reliability and precision of improved predictive models, comprehensive, quantitative, multidisciplinary monitoring studies are needed. A coordinated study of the removal of a dam on Manatawny Creek in Pottstown, Pennsylvania, provides a useful example (Johnson 2001). These studies will be expensive and difficult, and therefore only a small number of such efforts can be funded. However, they represent the only means of thoroughly evaluating our forecasting ability and of understanding the effects of dam removal on fluvial and biological processes.

## Conclusions

Previous research on fluvial processes provides many useful models for evaluating the geomorphic effects of dam removal. Studies of the evolution of incised channels, knickpoint and headcut migration, floodplain formation and channel narrowing, bank erosion and channel widening, the movement of sediment waves, the formation of alternate bars, the origin of patches of differing grain sizes in gravel bed rivers, and the development of armored beds all provide insights into potential trajectories of channel evolution following dam removal.

Upstream from the dam, geomorphic processes should be dominated by evolution of the channel as it incises into the sediments trapped in the impoundment. Case studies of the evolution of incised channels suggest several stages that will ultimately lead to development of a new equilibrium channel. The initial stages involve downcutting, followed by bank erosion and aggradation of the bed and floodplain development. If the impoundment contains relatively little sediment and is significantly wider than equilibrium channels upstream and downstream of the dam, then the primary processes above the dam are likely to be deposition and floodplain construction (Egan 2001) rather than erosion and incision.

Downstream from the dam, geomorphic processes should be dominated by fluvial responses to temporally varying sediment supply. Observations in the field and in laboratory flumes suggest that the dam fill will not migrate downstream as a coherent "sediment wave," but is more likely to disperse in place, leading to sediment impacts that decrease with the time since removal and the distance from the dam. Increased sediment supply at the reach scale could destroy alternate bars, pools and riffles, and armored beds. Enhanced sediment storage on floodplains, in backwater areas, and along the banks is also likely. The time scale for recovery from downstream transient sediment impacts is currently difficult to predict, but the available evidence suggests that years or decades may be required.

Although a variety of useful models exist for predicting the geomorphic effects of dam removal, site-specific forecasts are unlikely to be reliable. Coordinated research is needed to define the geomorphic processes that are most likely to dominate under different conditions, develop improved conceptual and numerical models, couple geomorphic and ecological models, and monitor selected dam removal projects in sufficient detail to evaluate both qualitative and quantitative forecasts.

The geomorphic effects of dam removal can be significantly influenced by different strategies of design, management, and construction. The removal process can potentially be scheduled and manipulated to minimize undesirable impacts. A variety of methods are available to control erosion of the sediment fill and therefore to minimize the effects of increased sediment supply downstream. Well-conceived restoration strategies could potentially increase the rate of recovery both above and below the dam. Future research programs should be designed to provide the scientific knowledge to guide management decisions so that informed choices can be made as to whether dams should be removed, and if so, how, when, and where.

## Acknowledgments

This paper would not have been written without Dave Hart's encouragement and enthusiasm. Helpful reviews were provided by Dave Hart and Thomas Johnson of the Patrick Center of the Academy of Natural Sciences and three anonymous reviewers. I would particularly like to thank The Pew Charitable Trusts for providing support that helped me complete this paper.

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# A Special Section on Dam Removal and River Restoration

DAVID D. HART AND N. LEROY POFF

**Human activities have degraded many of the world's** ecosystems, which has created an urgent need for strategies that can restore their ecological integrity. This need is accompanied by many scientific challenges, however. In particular, ecosystems are among the most complex entities in the hierarchy of life, and the successful repair of damaged systems will require a deep understanding of the processes that determine their structure and function. Biologists have a critical role to play in creating this knowledge because of their expertise in such varied phenomena as the role of microbes in detoxifying anthropogenic contaminants, the effects of disturbance on population persistence, and the factors influencing competitive interactions between native and exotic species.

By itself, however, biological knowledge is not sufficient for restoring degraded ecosystems. Two other types of expertise are also needed for developing integrated restoration solutions. First, because ecosystems are composed of many interacting abiotic and biotic components, biologists must collaborate with their colleagues in the physical sciences to learn how these systems work. Second, because humans are such strong interactors in these complex systems, we need to work with experts who can help us understand how human attitudes, institutions, and technologies influence the condition and management of ecosystems. Such enhanced interdisciplinary dialogue and unified approaches are essential for creating public policies that can sustain the planet's life support systems (Lubchenco 1998, Covich 2000, Ludwig et al. 2001).

Proposals to restore rivers via dam removal raise many issues that require broad discussion and teamwork. This approach to river restoration derives from the growing recognition that dams often disrupt the structure and function of river ecosystems by modifying flow regimes, disrupting sediment transport, altering water quality, and severing their biological continuity (Ward and Stanford 1979, Petts 1984, Collier et al. 1996). Future dam removal decisions can be enhanced by developing a more complete scientific understanding of the processes that determine how rivers are affected by different types of dams and how they respond to dam removal. There is an equally important need to understand the social, economic, engineering, and legal factors that influence dam removal decisions. Assembling a diverse array of experts to explore these different facets of dam removal was an exciting challenge for us. Listening to and participating in the dialogue that took place when those experts gathered at the annual meeting of the Ecological Society of America in August 2001 was even more rewarding.

This special section of *BioScience* brings together those diverse authorities, and a few others, to examine the potential utility of dam removal as a method of river restoration. Our goal is not just to explore the many different scientific and social aspects of this topic but also to consider how these components can and should be connected. Bruce Babbitt, former secretary of the US Department of the Interior during the Clinton administration, is intimately familiar with the subject matter, having been present—sledgehammer in hand—at many dam removals across the United States. His passionate essay (Babbitt 2002) clearly frames both the scientific and human dimensions of the subject. In particular, he emphasizes the critical need for strong science, not just to predict what will happen when dams are removed but also to monitor dam removal outcomes so that we learn how to maximize the effectiveness of this restoration method.

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The next six articles focus on various scientific facets of dam removal and river restoration. Poff and Hart (2002) provide an overview of the ways in which dams impair river ecosystems, and they highlight the conceptual and data needs for creating a more systematic and robust science of dam removal. They quantify variation in such important dam characteristics as size and operation at a national scale and describe how this variation can form the basis of an ecological classification system that distinguishes the environmental effects of different dam types. Hart and colleagues (2002) review alternative methods for predicting ecological responses to dam removal, emphasizing that knowledge of dam effects and removal responses is far from complete. They develop and have begun to implement an ecological risk assessment framework for determining how potential effects of dam removal vary as a function of dam and river attributes.

Dam removal can cause dramatic changes in fluvial processes and channel morphology, which will in turn affect many other ecosystem components. Pizzuto (2002) examines the challenges involved in predicting the effects of dam removal on sediment transport and channel evolution; he also suggests a range of studies (including collaborations between geomorphologists, engineers, and ecologists) that could lead to improved forecasting. One example of the benefits of such collaboration is the work by Stanley and Doyle (2002), which examines links between geomorphic processes and nutrient dynamics. They describe how nutrient cycling is influenced by various impoundment processes (e.g., sedimentation, denitrification) and show how geomorphic models can help predict changes in nutrient retention after dam removal.

The removal of very large (> 30 meters high) dams has been proposed as a method for restoring endangered anadromous salmon in the Pacific Northwest, but no dams of this size have yet been removed in the United States. Gregory and colleagues (2002) focus particular attention on the complex web of direct and indirect pathways by which large dams modify ecological interactions in major rivers. They illustrate many of the scientific uncertainties associated with large dam removal through case studies of dams in the Elwha and Snake Rivers, and they explore various options for making prudent decisions in the face of such uncertainty. The removal of dams affects not only aquatic biota, but also the riparian habitats associated with river margins and floodplains. Shafroth and colleagues (2002) examine how riparian vegetation is likely to respond to various geomorphic and hydrologic changes stemming from dam removal; they also discuss how sediment management and vegetation planting strategies can be used to enhance restoration outcomes.

The final three articles focus on the economic, social, and legal dimensions of dam removal. Cost-benefit analysis has been proposed as an important economic tool for evaluating the potential consequences of dam removal. Whitelaw and MacMullan (2002) present a conceptual framework for estimating the costs and benefits of dam removal and examine the way such analyses have been performed for dams on the Lower Snake River. They argue for a balanced approach to cost-benefit analysis, one that accounts for all subsidies and externalities and places both costs and benefits in a realistic economic context.

Economic issues are not necessarily the primary determinant of stakeholder attitudes and behaviors regarding dam removal, however. For example, Johnson and Graber (2002) have found that communities are often reluctant to consider the removal of old and obsolete dams, even when removal costs much less than dam repair. They describe some of the social and psychological barriers that prevent individuals and communities from considering dam removal as an option and propose creative methods (e.g., community-based social marketing, diffusion of innovations) for encouraging the adoption of management practices that can restore river ecosystems.

Environmental laws might also be expected to provide a powerful tool for removing dams that impair river ecosystems, but Bowman (2002) shows how laws designed to protect ecosystems can actually be an impediment to ecological restoration. Specifically, environmental laws are often designed to protect the environment by maintaining the status quo (i.e., by preventing degradation), which can inadvertently discourage restoration activities because they also cause a deviation (albeit positive) from the status quo. Bowman suggests that regulatory modifications within existing laws might provide decisionmakers with greater flexibility to approve projects with restoration objectives, although she emphasizes that project outcomes must be assessed carefully to avoid creating loopholes that result in environmental degradation.

Ultimately, the benefits of this collection of articles may be twofold. First, we hope that it succeeds in calling attention to the potential utility of dam removal in restoring rivers and in focusing research on specific scientific, engineering, and socioeconomic questions that can enhance the effectiveness of this innovative restoration method. Second, it may highlight the need for greater dialogue and closer interaction among a diverse array of experts and stakeholders. Many environmental problems would benefit from broader discourse about the best ways to create sound environmental policies, effective management practices, and adaptive institutions that can restore and protect the ecosystems on which all life depends.

## Acknowledgments

We thank the authors for their dedication and enthusiasm, Matt Greenstone for his broad perspective and unflagging optimism, and Robin Davis for capable editorial assistance. We are also grateful to the Aquatic Section of the Ecological Society of America and its officers (Steve Kohler, Craig Osenberg, and Margaret Palmer) for sponsoring our symposium ("Dam removal and river restoration: Linking scientific, socioeconomic, and legal perspectives") at the 2001 annual meeting of the Ecological Society of America. The Pew Charitable Trusts provided support to help participants attend the symposium and prepare manuscripts for publication.

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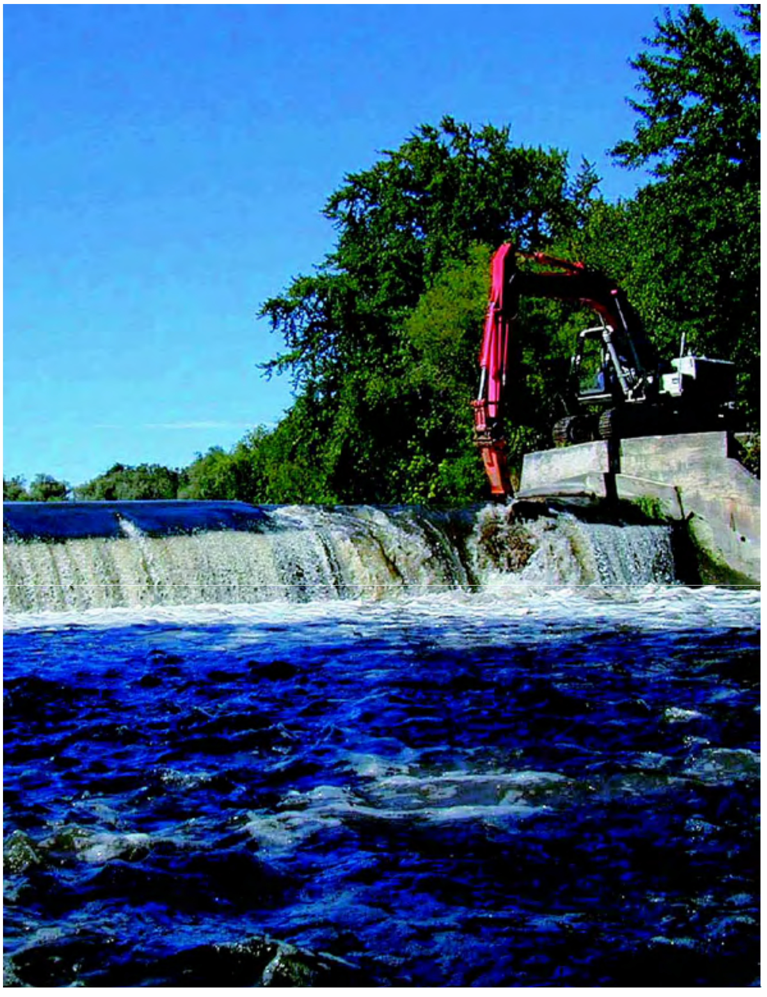

# Potential Responses of Riparian Vegetation to Dam Removal

PATRICK B. SHAFROTH, JONATHAN M. FRIEDMAN, GREGOR T. AUBLE, MICHAEL L. SCOTT, AND JEFFREY H. BRAATNE

**Throughout the world, riparian habitats have been** dramatically modified from their natural condition. Dams are one of the principal causes of these changes, because of their alteration of water and sediment regimes (Nilsson and Berggren 2000). Because of the array of ecological goods and services provided by natural riparian ecosystems (Naiman and Decamps 1997), their conservation and restoration have become the focus of many land and water managers. Efforts to restore riparian habitats and other riverine ecosystems have included the management of flow releases downstream of dams to more closely mimic natural flows (Poff et al. 1997), but dam removal has received little attention as a possible approach to riparian restoration.

The riparian vegetation that grows in post–dam removal environments interacts strongly with other factors that are generally given more direct consideration in dam removal efforts. For example, riparian vegetation can stabilize sediments in former reservoir pools, perhaps reducing downstream sediment transport that can harm aquatic ecosystems (Bednarek 2001). Vegetation that occupies new surfaces downstream and within the former reservoir pool will influence use by wildlife and for human recreation (AR/FE/TU 1999).

Vegetation response to dam removal is highly dependent on changes to the physical environment. Vegetation at the interface between a water body and the surrounding uplands is dominantly structured by the hydrologic gradient. Sites along this gradient differ in the duration, frequency, and timing of inundation (generally referred to as *hydroperiod).* Species differences in hydroperiod tolerances and requirements produce zonation and pattern in species composition and general cover types along the hydrologic gradient (figure 1). Dam removal may change aspects of the hydrological regime that structure riparian vegetation, including flood and low-flow regimes and associated water table dynamics. Further, dam removal will generally result in the creation of two classes of bare sediment that can be colonized by riparian plants: (1) downstream deposits transported from the former reservoir pool and upstream sources and (2) surfaces within the former reservoir pool (figure 1).

> DAM REMOVAL GENERALLY CAUSES CHANGES TO ASPECTS OF THE PHYSICAL ENVIRONMENT THAT INFLUENCE THE ESTABLISHMENT AND GROWTH OF RIPARIAN VEGETATION

The distribution and character of new bare substrates will vary tremendously across sites. Removal of small dams in systems with low sediment transport may result in few downstream changes and relatively simple upstream changes associated with vegetation colonization and succession on the former lake bottom. Removal of dams that have trapped large quantities of sediment could result in erosion of those deposits and transport of sediment downstream. The physical (e.g., particle-size distribution) and chemical (e.g., macronutrient and micronutrient status) character of sediments may be different from conditions that existed before dam removal, potentially affecting species composition of

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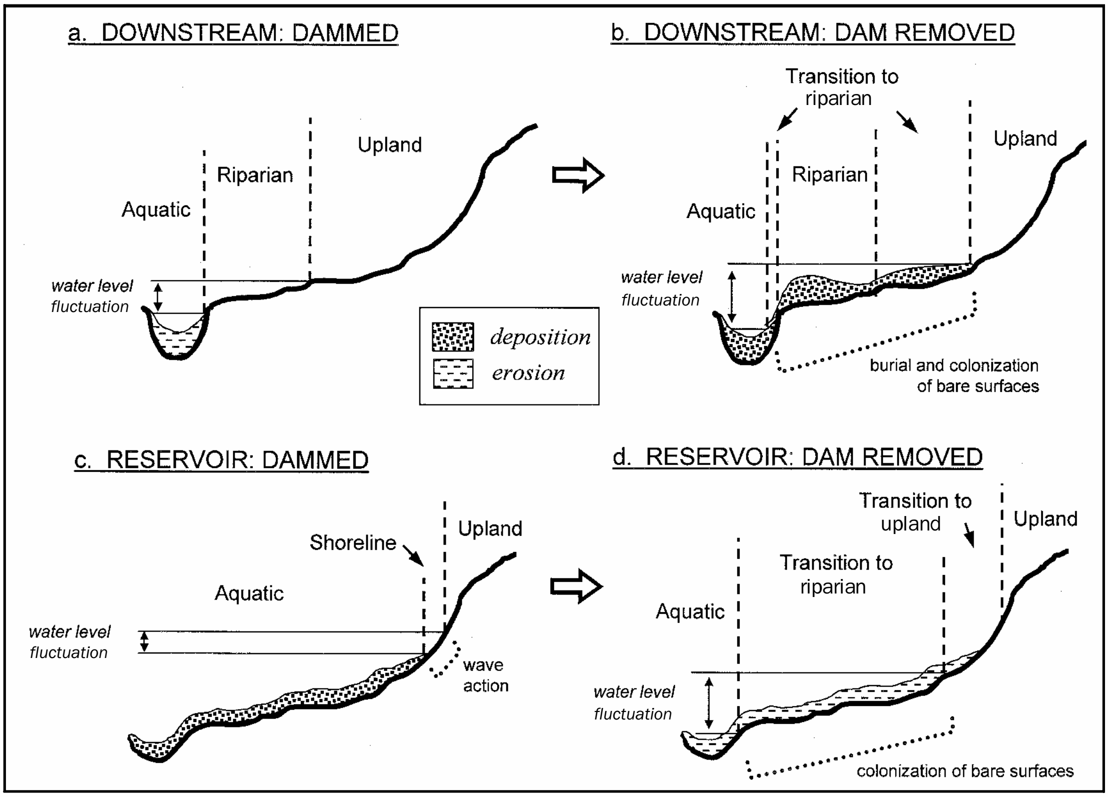


***Figure 1. General changes to key physical environmental factors and vegetation following dam removal. (a) During the dammed period, the downstream river may experience some channel degradation, a decrease in flow variability (depicted as water-level fluctuation), and a narrowed riparian zone. (b) Following dam removal, transport of upstream river sediment and sediment trapped in the reservoir may lead to a pulse of sediment deposition, which, combined with increased flooding, may both stress existing vegetation and create sites for the colonization and establishment of new vegetation. (c) During the dammed period, vegetation along the reservoir shoreline is often confined to a narrow band, and its composition is driven largely by fluctuations in the reservoir water level and wave action. (d) Following dam removal, large areas of former reservoir bottom are exposed and may be colonized by riparian or upland plants. Trapped sediments behind the dam may be subject to erosion.***

plants colonizing substrates within the former reservoir pool or downstream deposits. For example, invasions of exotic plants are sometimes associated with increased nitrogen availability (Dukes and Mooney 1999), and soils containing high micronutrient or heavy metal levels may support only plants tolerant of these ions (Marschner 1995).

The character of the new flow regime may also influence vegetation development following dam removal. Where dam removal results in a return to a natural flow regime, benefits to native plants and communities may accrue over time (Poff et al. 1997, Stromberg 2001). On rivers with multiple dams, a dam removal may result in only spatially limited or partial restoration of natural flows. Along rivers in which reservoir capacity has been severely reduced by sedimentation, flow regimes may no longer be substantially different from natural flows, and dam removal will have little effect on the downstream flows.

Riparian plant communities are often part of primary successions, with colonizing plants becoming established on bare, moist, alluvial sediments like those expected to be present following dam removal. Life history characteristics of plants can have an important effect on the trajectory of a riparian primary succession (Walker et al. 1986). Initial colonization of bare sediment in riparian environments is accomplished primarily through a combination of wind and water dispersal, although animal dispersal may bring a more diverse set of propagules to a site over time (Kalliola et al. 1991, Galatowitsch et al. 1999). Dam removal should increase the efficiency of long-distance transport of seeds by water (Jansson et al. 2000), which may enhance riparian restoration efforts. The timing of viable seed dispersal (Walker et al. 1986), substrate characteristics (Krasny et al. 1988), and soil moisture influence which species are able to successfully colonize a site. Soil seed banks contribute to vegetation dynamics along lake or reservoir shorelines and along margins of confined rivers (Keddy and Reznicek 1986) and, following dam removal, would be expected to play an important role in primary succession on newly exposed sediments upstream of the dam. Seeds of some emergent wetland species buried by sediment and submerged in water have been estimated to remain viable for between 45 and 400 years (Leck 1989). Vegetative reproduction can also be an important strategy for expansion of remnant or founder populations (Krasny et al. 1988, Kalliola et al. 1991).

In this article, we review the scant information documenting responses of terrestrial vegetation to dam removal and derive expected responses both upstream and downstream of the former dam on the basis of empirical and theoretical relationships between riparian plants, stream hydrology, and fluvial processes. We evaluate case studies from North America of planned or completed dam removals, natural analogs of dam removal, and alternative strategies of releasing and exposing water and sediment. We consider transient and equilibrium responses and the effects of different dam removal strategies on native and exotic plants. We focus on the natural establishment of vegetation following dam removal, although we also discuss active measures such as planting.

*Figure 2. (a) Pioneer riparian vegetation colonizing a new sediment deposit. Fresh alluvial deposits such as these would be expected to occur on river reaches downstream of a dam removal. (b) Tree mortality associated with burial by sediment transported and deposited following a dam failure in Rocky Mountain National Park, Colorado. Photographs by Patrick Shafroth.*

## Downstream responses

***Effects of a downstream sediment pulse.*** Dams generally trap and store sediment, often depleting reaches downstream (Williams and Wolman 1984). Dam removal may result in the downstream transport of stored sediment, which is usually seen as a potential problem (Simons and Simons 1991, Hotchkiss et al. 2001). For example, the sediment may kill fish, clog spawning gravels, or damage neighboring property. However, this transient pulse of sediment provides an opportunity for channel change and the creation of new surfaces suitable for the reproduction of riparian pioneer species (figures 1, 2a). Such surfaces may have been scarce following dam construction; thus, from the perspective of riparian vegetation, sediment released upon dam removal may be a benefit (Semmens and Osterkamp 2001).

Most dam removals to date have involved small reservoirs with small amounts of sediment, and few data are available concerning the effects of the downstream pulses of sediment on channel morphology and vegetation (Hotchkiss et al. 2001). There are, however, better-described cases of sediment pulses resulting from other causes, including hydraulic mining (Gilbert 1917, James 1989), timber cutting (Madej and Ozaki 1996), volcanic eruption (Major et al. 2000), large floods (Jarrett and Costa 1993), and dam maintenance (Wohl and Cenderelli 2000). Several generalizations may be drawn from this literature. As the sediment pulse travels downstream, its amplitude decreases and its wavelength increases over time (Gilbert 1917, Simons and Simons 1991, Pizzuto 2002). At a point along the stream, the pulse may be observed as a transient increase in bed elevation or in the rate of sediment transport. Because fine particles are transported more easily than coarse particles, the sediment pulse may be sorted over time, with finer particles moving downstream more rapidly. The trailing limb of this pulse can take the form of exponential decay, and it may take decades for sediment loads to return to prepulse conditions (James 1989, Simons and Simons 1991). The sediment pulse may partially or completely fill channels, resulting in temporary or permanent channel avulsion. Avulsion and fluctuations in bed elevation often leave behind terrace deposits (James 1989) that may persist for centuries or more. Vegetation may colonize these terrace deposits, as with some valley oak *(Quercus lobata)* forests in California's Central Valley. Other surfaces associated with temporally and spatially variable aggradation and degradation of the sediment pulse will be colonized by vegetation, as has been described for mudflows associated with volcanic eruption (Halpern and Harmon 1983).

In addition to creating new alluvial surfaces, sediment deposition downstream of a removed dam could bury existing vegetation (figure 2b). Riparian species vary in their tolerance of high sedimentation rates (Hupp 1988). If vegetation downstream of dams has succeeded to late seral stages (Johnson 1992), then dominant species in these communities are likely to be less tolerant than pioneering species of burial by sediment. In 1982, a dam breach in Rocky Mountain National Park resulted in a large flood that deposited a 0.18 square-kilometer ($km^2$) alluvial fan that was up to 13.4 meters (m) thick (average thickness = 1.6 m; Jarrett and Costa 1993). Some vegetation died immediately because of complete burial (Keigley 1993), while many trees succumbed over a period of years, probably because of the effects of anoxic soils and accumulations of toxic levels of micronutrients (figure 2b; Barrick and Noble 1993).

***Effects of a naturalized downstream flow regime.*** Along rivers, the hydrologic regime interacts strongly with the geomorphic setting to influence the establishment and growth of riparian plants. Dam removal could restore natural hydrologic regimes, which can contribute to the rehabilitation of native plant communities (Poff et al. 1997, Taylor et al. 1999, Stromberg 2001). Regulated flow regimes are generally less variable than unregulated flows, and some vegetation downstream of dams is more competitive under relatively homogenous flow regimes. The timing, magnitude, and duration of flood, flood recession, and baseflows strongly influence riparian vegetation (Rood et al. 1998, Friedman and Auble 2000, Nilsson and Berggren 2000). For example, cottonwood *(Populus* spp.), willow *(Salix* spp.), and many other riparian species native to North America are pioneers that colonize bare sites produced by flood disturbance. By reducing flood magnitude and frequency, dams decrease establishment opportunities for such species (Johnson 1992) and can improve the competitive ability of shade-tolerant exotic species that do not depend upon disturbance, such as Russian-olive *(Elaeagnus angustifolia;* Katz 2001). However, even if dam removal reduces available habitat for seedlings of exotic species, established adults may persist for decades until a flood, drought, age-related factors, or some other agent kills them. Persistence of large woody plants established under the former regulated flow regime could indefinitely impede the resumption of channel movement after dam removal because of their stabilizing influence on channel banks.

***Case study: Elwha River, Washington.*** Large quantities of sediment are predicted to be transported downstream following the proposed removal of the Elwha Dam and Glines Canyon Dam on the Elwha River, Washington (Hoffman and Winter 1996). Results of current sediment modeling efforts (USDOI 1996) predict that 15% to 35% of the coarse sediment (sand, gravel, and cobbles) and about half of the fine sediment (silt- and clay-size particles) would be eroded from the two reservoirs following dam removal. The remaining sediment would be left along the reservoir margins as a series of terraces. Fine-sediment concentrations released from the reservoirs would be high during periods of dam removal, typically 200 to 1000 parts per million (ppm) but occasionally as high as 30,000 to 50,000 ppm. After the dams are removed, fine sediment concentrations would be low during periods of low flow and high during flood flows that erode channels in the reservoir areas. Within 2 to 5 years, concentrations would return to natural levels. Coarse sediment would aggrade in the relatively steep reaches of the river up to 15 centimeters (cm). Sediment aggradation in moderate-gradient alluvial reaches would promote natural patterns of lateral channel migration, especially near the river's mouth. Over the short term (up to 5 years), this could potentially increase river stages during the 100-year flood up to 1 m. Over the long term (50 years), aggradation could continue and increase existing river stages during the 100-year flood up to 1.5 m with an average increase of 0.75 m. Coarse sediment would enlarge the delta at the river's mouth to a size and character similar to that of predam conditions. As sediment modeling of this basin advances over the years, estimates of the magnitude and timing of sediment transport will become more refined. Yet current results provide an effective framework for predicting vegetation responses to dam removal.

Currently, red alder *(Alnus rubra)* is much more prevalent than black cottonwood *(Populus trichocarpa)* and native willows *(Salix* spp.) along the Elwha River downstream of the dams (figure 3). On the basis of predicted changes in fluvial geomorphology following dam removal, it appears that *Populus* and *Salix* would be favored in the colonization of alluvial reaches of the Elwha River. The life history, ecology, and physiology of these genera are well adapted to the natural flow regimes and sediment–deposition patterns predicted for the Elwha River (Braatne et al. 1996). The relatively high volumes of sediment transport and deposition in alluvial reaches subsequent to dam removal will not favor red alder. Several studies have shown that red alder is vulnerable to hypoxic conditions arising from sediment deposition or extended periods of inundation (Harrington et al. 1994). Therefore, a decrease in red alder and an increase in black cottonwood and willow would be expected in alluvial reaches following dam removal. Additional evidence for these changes in riparian vegetation can be found in the extensive cottonwood forests of the Dungeness River, an adjacent, undammed basin on the Olympic Peninsula of Washington (Dunlap 1991).

## Upstream responses

***Vegetation within the former reservoir pool.*** Upstream of the dam, dam removal exposes areas of bare ground that were formerly under water, and river discharge (rather than reservoir storage) controls water stages. This will generally produce shifts from the always inundated aquatic zone to mostly inundated and occasionally inundated wetland and riparian vegetation zones, and from inundated or groundwater-affected zones to upland vegetation (figure 1). Thus dam removal may lead to mortality of vegetation along the former reservoir margin, especially if it is sensitive to water table declines associated with the drawdown. The distribution and location of changes in hydroperiods will depend on the topography and stage–discharge relations that develop following dam removal. In many cases, accumulation of sediment behind the reservoir will have altered the topography. If the new stream channel downcuts to near its previous elevation faster than the overall area erodes, then the distribution of hydroperiods in the reservoir pool may be drier following dam removal than before the dam was constructed (Lenhart 2000). On the other hand, partial dam removals in which a lowered control structure is left in place will yield a new storage capacity and effective stage–volume relation and could produce a new set of hydroperiods that may be wetter than those of the predam river.

***Figure 3. Young red alder trees* (Alnus rubra) *line the channel and midchannel bars of the Elwha River, Washington, while older black cottonwoods* (Populus trichocarpa) *occupy older, higher surfaces. Conditions resulting from proposed dam removals on the Elwha River could lead to a decrease in red alder and an increase in black cottonwood. Photograph by Patrick Shafroth.***

Initially, vegetation is unlikely to be in equilibrium with the new distribution of hydroperiods. Rather, there will be a transition phase involving colonization of extensive bare areas or mud flats uncovered as water stages decline with the draining of the reservoir (figure 4). Dense, natural revegetation of these areas during the growing season has been observed within weeks in humid regions (AR/FE/TU 1999), while vegetation cover can take years to recover in less productive settings, such as subalpine reservoir margins in the Rocky Mountains (Mansfield 1993). Propagules of early colonizing plants may be present in seed banks or may be dispersed from adjacent areas. The initial colonizing plants can have a substantial long-term influence on plant composition through the persistence of long-lived individuals, vegetative reproduction, relatively higher seed production of those species, and alterations of the physical environment (Mansfield 1993). Initial plant colonists of sites characteristic of former reservoir bottoms (bare, moist, nutrient-rich, with a depauperate seed bank) tend to be weedy plants with typical ruderal traits such as rapid growth, high levels of seed production, and effective dispersal mechanisms. This group of plants may include a relatively high fraction of invasive, nonnative species (Galatowitsch et al. 1999, Lenhart 2000).

***Case study: Removal of small dams in Wisconsin.*** Many small dams in the northeast and upper Midwest were built between the mid-1800s and early 1900s to power lumber and flour mills. Because of abundant water resources and the early development of dams for mechanical and small-scale hydroelectric energy, the state of Wisconsin has more than 3600 dams. Safety and economic reasons (i.e., where repair costs greatly exceeded removal costs) have led to the removal of more than 70 dams since 1950 in Wisconsin (Born et al. 1998, AR/FE/TU 1999).

Lenhart (2000) performed a retrospective analysis of natural vegetation recolonization in five former impoundments in Wisconsin. Two sites represented long-term (more than 40 years) recovery periods, whereas three sites had recovered in 3 to 5 years. Across all sites, high-nutrient sediments, ranging in depth from 25 to 200 cm, had been deposited over predam soils. Vegetation at the three younger sites had low species diversity and were dominated by large, monotypic stands of pioneer species like stinging nettle *(Urtica dioica)*, reed canary grass *(Phalaris arundinacea)*, and rice-cut grass *(Leersia oryzoides)*. The plant communities observed on the

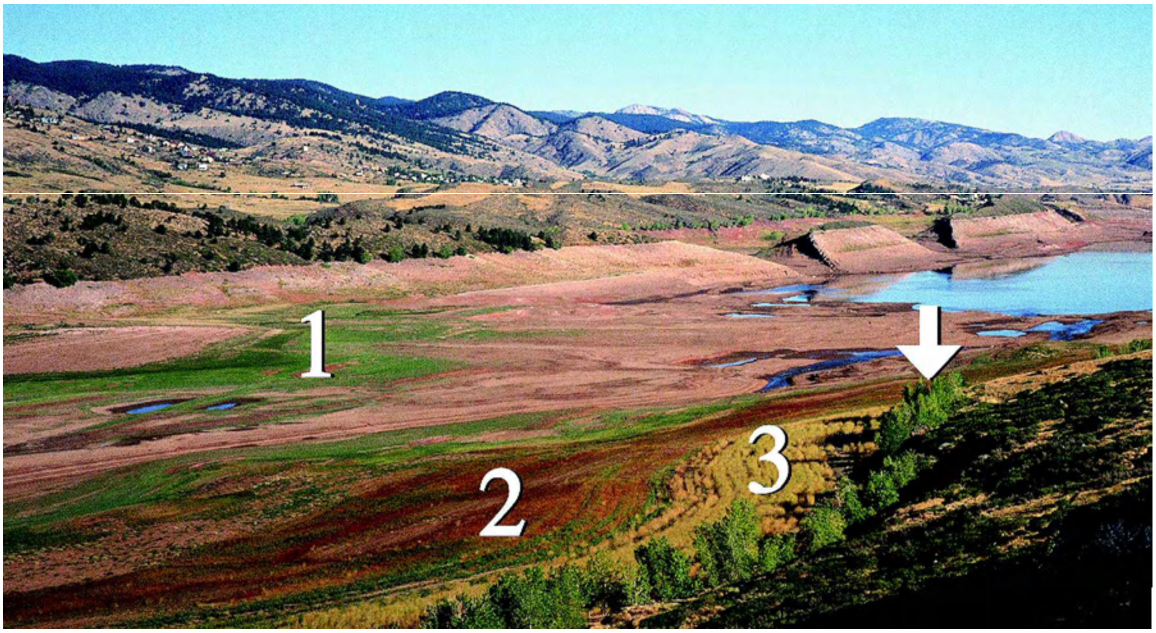


*Figure 4. Vegetation colonization on the exposed bottom of Horsetooth Reservoir, Colorado. Between January 2000 and October 2001, water was drawn down 32 meters to enable dam repairs, reducing the water surface area from 621 to 77 hectares. Numbers refer to bands of vegetation dominated by the following nonnative species: (1) goosefoot* (**Chenopodium glaucum**), *(2) smartweed* (**Polygonum lapathifolium** *and* **P. persicaria**), *(3) sweet clover* (**Melilotus** *spp.). The arrow points to mature cottonwood trees* (**Populus deltoides**) *that approximate the high water line. Photograph by Patrick Shafroth.*

younger sites did not resemble any native communities. Young sites tended to be composed of a high fraction of wetland plants, which colonized the moist surfaces that were exposed following dam removal. Over time, sites became drier and were dominated by more xeric species. The two older sites had higher species diversity but included a higher percentage of nonnative species.

## Management considerations

***Restoration potential.*** Dam removal should not always be expected to restore riparian ecosystems to their predam condition (figure 5). A spectrum of outcomes is possible, given the variability in predam conditions, the responses of the system to the dam, and the responses to dam removal (Zedler 1999). Ecological systems frequently exhibit hysteresis and time-lagged responses, the details of which are not clear with respect to riparian vegetation, although a transient phase of 50 to 100 years has been observed when systems respond to dam construction and operation (Petts 1987, Johnson 1998). Legacies of flow regulation such as altered channel morphology, species composition, and age structure may result in a delayed response of the system to naturalized flows. Even if dam removal restored the natural flow regime, effects of dam removal would vary regionally with factors such as climate, flood regime, geology, and fluvial processes associated with riparian vegetation establishment (Friedman and Auble 2000). Other anthropogenic impacts to a river system, such as adjacent groundwater pumping, channel stabilization, and agricultural and residential development, could prevent a return to predam conditions (figure 5). Effects of extreme events that occurred before but not during the dammed period (Katz 2001) or climate differences in the predam and postdam removal periods could also influence the response. Despite these possible limitations, dam removal has the potential to restore valuable components of riparian ecosystems, and some management actions could enhance this potential.

***Managing for a beneficial transient sediment pulse.*** In some dam removal situations, relatively small pulses of sediment could promote enough channel change to create surfaces suitable for the establishment of riparian forest, without greatly damaging other resources. It could be argued that there is little value in managing for a transient benefit, because eventually trees established as a result of the sediment pulse would die. However, this view underestimates the importance of transient events in structuring populations of disturbance-dependent, long-lived species. For example, the cottonwood gallery forests along the Platte River system are a product of an adjustment in channel size following water management (Johnson 1998). Establishment of these forests was a transient event, not an equilibrium expression of the predam or postdam flow or sediment regime. Once established, such forests exist for more than a century, which is longer than the life of many dams. Given the persistent effects of transient events in these ecosystems, managing the sediment pulse following dam removal could be an efficient conservation strategy.

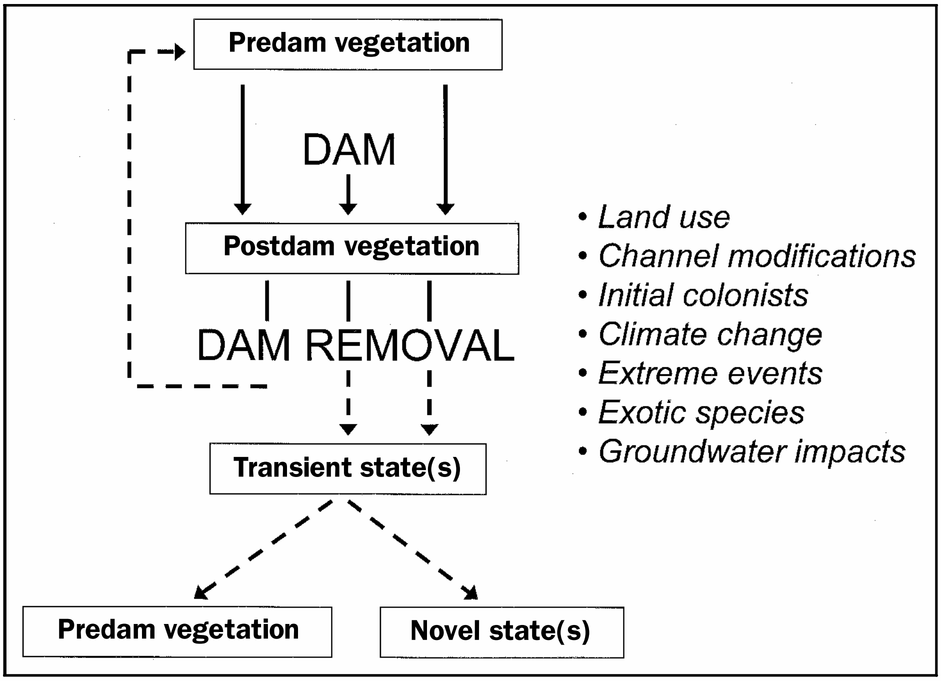


***Figure 5. Multiple pathways of riparian vegetation change from unregulated conditions through postdam removal states. Riparian vegetation may respond to dam construction and operation in various ways, and multiple trajectories are possible following dam removal, depending on initial conditions and the nature of hydrologic and geomorphic change. Other factors, including those listed next to the flow diagram, also influence riparian vegetation response. As a result, in many cases, riparian vegetation is unlikely to quickly return to its predam condition.***

***Controlling the reservoir drawdown.*** The timing and pattern of drawdown heavily influences the species composition of bare, moist areas by exposing sites at times that do or do not match the life history characteristics of various species with respect to germination and early seedling establishment requirements. Much practical experience with manipulating drawdowns to achieve desired mixes of herbaceous species is embodied in the wildlife–management strategy of "moist soil management" (Fredricksen and Taylor 1982). Many refuges and waterfowl management areas actively manipulate drawdowns in shallow constructed impoundments or moist soil units to grow specific species with desired food and cover value for wildlife. Similar approaches have been effectively employed in riparian restoration efforts to encourage natural establishment of desired native trees and shrubs (Roelle and Gladwin 1999). In arid and semiarid landscapes, where seedling establishment requirements for native riparian trees are often much wetter than the conditions they require as adults, the plants established during the transition or drawdown phase may persist and dominate the drier postdam regime for many decades. Recruitment of cypress *(Taxodium distichum)* and tupelo *(Nyssa aquatica),* after extended drawdown of a large impoundment in the southeastern United States suggests that natural establishment of bottomland hardwood forest could be expected following dam removal, assuming there are upstream sources of seed, that large numbers of seeds were produced the previous season, and that subsequent water levels do not exceed average seedling height for extended periods (Keeland and Conner 1999). Few dam removal projects have attempted to manipulate the timing and pattern of drawdown during the transition phase so as to produce desired vegetation. Where the reservoir pool can be lowered by draining and pumping before any work is done on the dam structure, there is tremendous potential for effective, even multiyear control over the plant community by managing water stages during the transition phase (ASCE 1997).

***Invasive species.*** Although dam removals represent a significant opportunity for riparian habitat restoration, they also provide opportunities for invasion of undesirable, nonnative species (figure 4; Galatowitsch et al. 1999, Lenhart 2000). High levels of physical disturbance result in significant proportions of exotic species in many riparian floras (Planty-Tabacchi et al. 1996, Tickner et al. 2001). The extensive, bare, nutrient-rich sediments of the former impoundment provide a substrate that may favor weedy, nonnative plants (Dukes and Mooney 1999). Once established, nonnative weeds may inhibit the establishment of native species, thus reducing plant and animal species diversity (Galatowitsch et al. 1999, Middleton 1999) and influencing succession (Hobbs and Mooney 1993). Where the risk of nonnative vegetation establishment is high, a more managed approach to vegetation establishment following dam removal may be warranted.

***Active revegetation.*** Dam removal plans may include broadcast seeding or limited tree planting aimed at precluding the establishment of undesirable nonnative species or stabilizing sediments in the former reservoir pool (ASCE 1997, AR/FE/TU 1999). Additional reasons for active revegetation following dam removal include creating habitat diversity and improving recreational use. Secondary measures such as installation of structures to slow or reduce bank erosion, construction of fenced exclosures to manage livestock, and multiyear irrigation of plantings have been necessary elements of revegetation efforts in arid and semiarid regions of the United States (Briggs 1996). Active revegetation of riparian shrubs and trees in the western United States has often failed because of insufficient understanding of establishment and survival requirements of native species and continued livestock grazing following planting (Kauffman et al. 1995, Briggs 1996).

Plantings of early successional native species with relatively high growth rates may be an effective means of minimizing the establishment of exotic plant species and initiating natural successional processes. Dense stands of native woody plants, such as cottonwood and willow, may effectively shade out and thus exclude many exotic herbaceous annual and perennial plants. In contrast, planting slow growing, late-successional or climax species following dam removal may provide exotic weeds with an initial advantage. In the midwestern United States, plants such as smartweeds *(Polygonum* spp.), rice-cut grass, barnyard grass *(Echinochloa crus-galli),* and sod-forming sedges *(Carex* spp.) often naturally recolonize disturbed prairie wetlands. Other species, which may effectively compete with aggressive weeds, have been suggested for planting as potential native cover crops. These include late-season grasses such as *Spartina pectinata* and forbs such as *Coreopsis* spp. and *Ratibida* spp. (Galatowitsch and van der Valk 1994). Cover crops may quickly occupy sites, stabilizing the soil surface and usurping space that might otherwise be taken by less desirable species. In subsequent years, more slowly growing species may gradually replace the annuals. In the southwestern United States, attempts to actively restore native riparian understory species by planting, removal of nonnatives, and use of commercial soil amendments were ineffective, largely because of the rapid regrowth or establishment of nonnative species already on site (Wolden and Stromberg 1997). Recommendations for future efforts suggested that (a) seeding should be done over several years to accommodate climatic and hydrologic variability, (b) seed mixes should include species reflecting a diversity of life-history traits so species can sort out across the range of fine-scale environmental conditions that may exist at the restoration site, and (c) some weedy native annuals may compete well initially with nonnatives.

The assumption that a diverse set of species will naturally disperse to and become established on a site following the planting of a few of the dominant species is not always valid—such planting has produced stands of relatively low diversity in reforested bottomland hardwood forests (Allen 1997). Experimentation can make seed selection more efficient by helping to determine which species will recruit well naturally versus which need to be planted and which and how many species are necessary to develop desired ecosystem functions (Zedler et al. 2001).

Ultimately, a fundamental goal of any attempt to actively reestablish self-sustaining wetland and riparian vegetation should be to restore or reestablish key physical processes such as natural flow variability and channel change (Middleton 1999, Stromberg 2001). Such physical processes integrate terrestrial and aquatic elements of the watershed, producing spatially and temporally distinctive patterns of vegetation establishment (Scott et al. 1996). Restoration of key physical processes, in concert with active revegetation, enhances long-term success. The displacement of native wetland and riparian vegetation by invasive, nonnative species is typically associated with alteration of the natural hydrologic regime and land use practices that reduce flooding, lower water tables, and alter soil properties (Briggs 1996). Efforts aimed at actively revegetating herbaceous (Wolden and Stromberg 1997, Middleton 1999) and woody (Briggs 1996) vegetation have benefited from natural flooding.

## Research needs

There is a strong need for more quantitative studies of the response of vegetation to dam removal. This should include rigorous monitoring of new or recent dam removals or retrospective analyses of older sites. Long-term studies will be necessary to elucidate potentially complex pathways of vegetation change. The potential for the generation of novel plant communities associated with the unusual physical conditions that may follow dam removal represents an intriguing topic of ecological research. Manipulative experiments could be used to test different management techniques, including controlled drawdowns and various planting approaches. Given the well-documented importance of fluvial geomorphic and hydrologic conditions in structuring riparian vegetation, botanists and plant ecologists should seek collaborations with physical scientists and couple plant response models to models used to estimate water and sediment dynamics following dam removal.

## Acknowledgments

Thanks to David Hart and LeRoy Poff for organizing the dam removal symposium at the 2001 annual meeting of the Ecological Society of America and to The Pew Charitable Trusts for providing support that helped us to complete this article. Thanks also to those who shared their experiences with dam removal, including Madeline Fisher, Jeff Connor, and Chris Lenhart. The comments of David Hart and three anonymous reviewers improved the manuscript. This manuscript was prepared by employees of the US Department of the Interior, US Geological Survey, and therefore may not be copyrighted.

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# Enlisting the Social Sciences in Decisions about Dam Removal

SARA E. JOHNSON AND BRIAN E. GRABER

**Ecologists and conservationists share the desire to** have healthy and sustainable ecosystems. But many of our society's ecological management activities and policies thus far have not resulted in sustainable ecosystems, and ecologists and conservationists recognize that considerable change in human behavior will be required to achieve that goal. It would stand to reason, then, that ecologists and conservationists would also share a desire for decisionmaking that considers alternatives, such as selectively removing dams, that could result in outcomes beneficial to ecosystems.

Experience, however, shows that decisions on ecological issues often do not include alternatives that could benefit ecosystem health. When they do, such alternatives are often dead on arrival and are not given serious consideration or adequate review. Experiences with local decisions concerning old and obsolete small dams (for discussion purposes, dams 7.6 meters high or less) highlight this problem. Unlike decisions regarding larger dams, which are typically made in a court of law and are based on expert testimony, decisions affecting the future of small dams are usually made in a local "court of public opinion" and involve many stakeholders and decisionmakers, including private citizens and citizen groups, elected officials, government resource agency personnel, and local business interests. While certain individuals or bodies, such as the private dam owner, agency personnel, or elected officials, may have actual legal authority to make the final decision, public support, or lack of it, can make or break a restoration opportunity.

Research shows that this kind of decisionmaking about the future of dams and rivers is often poor. Born and colleagues (1998) looked at 14 dam removal cases in Wisconsin and found that decisions were commonly made with incomplete and inaccurate information and in emotionally charged and divisive atmospheres. These findings support our experiences that the divisiveness of decisionmaking is exacerbated

THE APPLICATION OF SOCIAL SCIENCE CONCEPTS AND PRINCIPLES TO PUBLIC DECISIONMAKING ABOUT WHETHER TO KEEP OR REMOVE DAMS MAY HELP ACHIEVE OUTCOMES LEADING TO SUSTAINABLE ECOSYSTEMS AND OTHER GOALS IN THE PUBLIC INTEREST

when one or more of the following situations exists: when the idea of removal is new to the community; when the dam poses public safety concerns, thus forcing a quick decision; and when outsiders (e.g., state agency personnel or conservation organizations with representatives not from the area) are involved in the decision process.

Faced with the uncertainty that such circumstances are likely to produce and the need to make decisions, humans commonly resort to psychological shortcuts to help make those decisions (Cialdini 2001). Such shortcuts include accepting the prevailing social norm as one's own position, adopting the opinion of someone who is similar to oneself and

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is well liked, or simply digging in one's heels to remain consistent with one's earlier actions or words. These and other psychological principles direct human behavior, generally without an awareness that they are being used.

We are not suggesting that dam removal is always the best alternative; indeed, in some cases, removal of a dam could cause long-term harm to the ecosystem. But because dams can have a profound and often negative impact on water quality, river function, and ecology (Baxter 1977, Graf 1980, Petts 1980, Petts and Pratts 1983, Williams and Wolman 1984, Chien 1985, Andrews 1986, Ligon et al. 1995, Power et al. 1996, Hadley and Emmett 1998, Brandt 2000, Graf 2001, Magilligan and Nislow 2001), decisionmaking about dam removals should be improved. In an improved process, alternatives (such as selective dam removal, where it might benefit the ecosystem) should be considered and informed by scientific findings about potential outcomes (social, economic, and environmental), so that alternatives may be accepted or rejected on their merits (AR/TU 2002).

Social science principles and practices have long been used to encourage societal change in the areas of public health and safety, but their use to encourage beneficial change in the health of the ecosystem has been slow to take hold. However, if fundamental social and psychological principles such as these decision shortcuts are understood and factored into the design of public information efforts and decisionmaking, they may hold substantial potential to influence social change concerning dams and rivers, such that "win-win-win" outcomes may be achieved that benefit not only the ecosystem but also dam owners and the local community.

We look briefly at the changing socioeconomic context in which public decisions around dams and rivers are being made, explore the use of social science concepts and principles to improve such decisions, and discuss potential roles of scientists in public decisionmaking that affects the sustainability of ecosystems. The use of concepts and principles discussed here is not limited to decisions about dams and rivers; they could be helpful in any decisionmaking that could lead to improved ecosystem health or other public benefits.

## *What's the big deal about small dam removal?*

A number of social, economic, and environmental factors are converging in a manner that is raising public awareness of dams and their impacts on rivers and streams. A brief discussion of some of these factors provides a societal context for decisions about dams and rivers.

Societal values (and associated economic values) regarding dams and rivers have changed over time. Changing societal needs and technological changes over the past century, for example, have left many dams, especially smaller structures, no longer useful for their original purpose and in need of extensive and potentially costly repairs. Estimates of the total number of dams in the United States range from 76,000 (NID 2001) to 2.5 million (Johnston 1992); one reason for this disparity is that many smaller dams are not included in national databases or even in some state databases. The American Society of Civil Engineers recently rated the safety of America's dam infrastructure with a grade of "D," citing 61 reported failures over the past two years (ASCE 2001). Many smaller dams, built over 100 years ago and no longer used for their original purpose, such as grist milling or raising water levels to float logs to timber mills, have deteriorated to the point that they pose public safety hazards, which has led states to order repairs or removal to alleviate the hazard.

Dams have a finite life expectancy, often stated to be on the order of 50 years (FEMA 1999, ASDSO 2001), and even many of those built more recently than the old grist mills have reached or are approaching the end of their useful lives, although repairs can maintain a structure for longer periods. But costs to repair or rebuild a deteriorating small dam are typically high—from hundreds of thousands to even millions of dollars in some cases (Born et al. 1998, AR/FE/TU 1999, TU 2001). The high cost of maintaining old dams, especially obsolete ones, is forcing dam owners (often municipalities) to look for solutions.

As small dams have become less critical to the US infrastructure and the financial costs of maintaining them have become greater, society's understanding and appreciation of the values of healthy waters in general have grown. The growth of water-based outdoor recreation, for example, coincided with water quality improvements after passage of the Clean Water Act in 1972; annually, more than 35 million people fish (Fedler 2000) and 25 million canoe or kayak (ACA 2000). Scientists in recent decades have enabled greater understanding of the vital role of naturally functioning river systems in the context of ecosystem health and sustainability; resource agencies have even reorganized by watershed boundaries rather than by political boundaries.

Experience and some research show that selective removal of small dams is one method for river ecosystem restoration that can be in the public interest. Documented public benefits of selective dam removal include cost-effective water quality improvements; cost-effective and permanent removal of a public safety hazard; cost-effective restoration of fish and wildlife habitat for endangered species or sport fisheries (or both); recreational improvements; aesthetic enhancement, such as restoration of waterfalls or riffles; and opportunities for community economic revitalization and associated quality-of-life enhancements (AR/FE/TU 1999, TU 2001).

It is within this changing socioeconomic context that more and more local communities are facing decisions concerning their dams. The difficulty of deciding may in part be a reflection of these changing "bigger picture" factors running up against local communities with strong attachments to their dam and its impoundment and a strong preference for the status quo. In some cases, removal of the dam, even an obsolete structure, is not even considered to be an option.

More and more small dams are being removed nonetheless, primarily to relieve the economic burden of deteriorating structures and to eliminate public safety hazards, but also to meet concerns about the environment and conservation, especially to improve water quality or restore native or sport fisheries (AR/FE/TU 1999). Many deliberations about small dam repair or removal still result in a decision to repair old and sometimes obsolete structures. In some cases, economic, historical, environmental, or other factors may warrant repairing a dam. But in many cases, such decisions to keep the structure are made at great expense to the river when the water quality and fisheries continue to degrade; to the dam owners, who are often the taxpayers of the local community; and to local businesses, which might have capitalized on opportunities for economic revitalization with a restored river, especially in urban or downtown settings. Furthermore, the opportunity for restoration of that stretch of water and habitat in a larger ecosystem context may be lost for decades, perhaps even a lifetime.

The issue of dams continues to be pushed higher on the public agenda. In recent years, some elected officials have been attempting to bring dam-related laws into the 21st century; several states (e.g., Pennsylvania, Wisconsin, California) have changed or have attempted to change legislation and policies governing dams and their host rivers in recent years. With dams increasingly in the news, every dam removed for purposes of river system restoration has the potential to make the next one easier or more difficult.

Removing dams is not a new idea; more than 500 dams have been removed in the last century (AR/FE/TU 1999, AR 2001). Nonetheless, it is a new idea to many community members who face a decision about the future of their dam. If river ecosystem restoration is a goal, and selective dam removal is a potential method to achieve that goal, experience suggests that an effective strategy would be to first increase public support for dam removal as a viable tool for river restoration—in short, to influence social change concerning dams and rivers. An efficient approach to social change is necessary to reduce strife in local communities, to avoid unnecessary and expensive financial obligations to dam owners and taxpayers, and to reduce the number of lost opportunities for ecosystem restoration.

## *Drawing on the social sciences to effect changes in human behavior*

The social science literature recognizes important differences between activities that result in increased awareness and understanding and those that result in behavior change. Most public information efforts that are designed to foster change inform to some extent, but seldom are they successful in effecting desired behavior change (Andreasen 1995, Rogers 1995, McKenzie-Mohr and Smith 1999). Not surprisingly, programs thoughtfully and strategically designed to achieve behavior change are more likely to result in actual behavior change.

Following is an overview of some social psychology principles and practices that could be pertinent to efforts to effect changes in human behavior regarding sustainable ecosystems, especially relative to dams and rivers. We look at how people tend to make decisions when uncertainty is high, how new ideas often spread through communities, and techniques for encouraging acceptance of new ideas at the individual and community levels.

***Shortcuts for decisionmaking.*** Psychologists have long known that when people are asked to make a decision but do not have the desire or the ability to analyze information carefully, they are likely to fall back on psychological "shortcuts." When these shortcuts are used, the decision to comply or not comply with a request is made on the basis of a single piece of information, such as agreeing if they know their friends or colleagues agree. Cialdini (2001) identifies a number of such triggers for compliance with a request, a few of which we think are especially pertinent to decisions regarding dams and rivers. As is the case with stereotypes, over time an individual judges decision shortcuts to be timesaving and reliable, and he or she is usually unaware of using them.

**Social norms as a psychological shortcut.** Although researchers have varying definitions of social norms, the term generally refers to what is most often done or approved of in society at large or in a particular setting, such as a local community. In short, people tend to do what others like them are doing. Cialdini (2001) notes that people especially look to see what others are doing when two factors are present: when uncertainty is high and when others exhibiting the behavior are similar to oneself or well liked.

Few programs designed to foster sustainable behavior have taken into consideration the powerful effects of social norms (McKenzie-Mohr and Smith 1999). In many small communities, current social norms concerning dams and rivers appear to support the status quo (that is, keeping the dam) and often preclude the consideration of removal as an alternative. If social norms could be changed to be supportive of healthy and naturally functioning river systems, the alternative of selective dam removal would more likely be considered and then accepted or rejected on its merits.

A practical way to encourage the acceptance of social norms that support dam removal as an alternative, for example, would be to pay close attention to "messengers." If the aim is to have the support of local business leaders in community A, one approach would be to invite a business leader from a similar community where a river was successfully restored through selective dam removal (community B) to speak to the business leaders of community A. Better yet would be to arrange for community A business leaders to take a field trip to community B to talk with leaders and see the restoration for themselves. This alone would be unlikely to change social norms among the business leaders of community A, but it could be a key component of a successful public information program.

**Commitment and consistency as a psychological shortcut.** Securing a commitment from someone to do something can be a powerful technique for behavioral change. Written commitment is a stronger motivator than oral commitment, but both can and have resulted in desired behavior change (Katzev and Wang 1994, McKenzie-Mohr and Smith 1999, Cialdini 2001).

Consistency is closely tied to commitment. Psychologists have recognized for more than 50 years that the desire to be (or to be seen as) consistent is a central motivator of behavior and, therefore, is also a potent component of efforts to influence behavior change (Cialdini 2001).

With the so-called foot-in-the-door technique (Freedman and Fraser 1966) commonly used in sales, commitment to comply with an initial small request leads to a greater likelihood of compliance with a larger request. This marketing technique has also proven effective in energy conservation efforts: Citizens who complied with a request to complete a written survey had a higher rate of compliance when later asked to reduce energy consumption at home (Katzev and Wang 1994). One reason for this greater compliance is that once a person has committed to do something, his or her support for that activity is internalized and therefore becomes even stronger (Cialdini 2001).

Currently, commitment and consistency principles appear to be working against considering dam removal as an option, but they could be used to encourage support of dam removal as an alternative. Finding common ground is important in divisive situations like dam repair or removal decisions. Decisionmakers, business leaders, and other concerned citizens, if asked, are all likely to agree that having a healthy river running through their community is desirable. After agreeing that a healthy river is good, commitment and consistency theories suggest that these same individuals would be more likely to later agree to consider options that could result in a healthier river, such as potentially removing the dam. Again, this exercise alone would not change social norms or ensure compliance with later requests, but it could play an important role in a successful effort to influence change toward support for sustainable ecosystem practices.

***How new ideas are spread: Diffusion of innovations.*** In fields that have a long history of scientific outreach, such as agriculture, researchers and practitioners have spent much more time than in other fields learning how to influence the potential for adoption, and rate of adoption, of effective resource management practices, and there is a much greater acknowledgment of the role of social systems (e.g., communities) in decisionmaking. Diffusion is the spread of ideas through social systems; diffusion of innovations is the diffusion of ideas that are new, or new to the target audience (Rogers 1995). Diffusion theory grew out of rural sociology in the 1940s and has since been at the core of many university extension efforts to effect social change in agriculture, as well as behavioral change in human health and safety.

One of the most valuable contributions of diffusion research has been the identification of the different roles of individuals in encouraging adoption of new ideas. The first adopters of new ideas, so-called innovators, are typically too far ahead of the rest of the community to be helpful in encouraging change among many others. Rogers's "early adopters," however, are an integral part of the social community and are the people many others look to before using or accepting a new idea (for example, elected officials, leaders in the business community, or community elders). Early adopters help set social norms for the community. Therefore, targeting information and change efforts first to community members who have been identified (through formal or informal surveys, perhaps) as early adopters, rather than to the entire community, is an efficient method for facilitating the diffusion of information that is supportive of healthy rivers and ecosystems, because targeting saves money and speeds the process.

***Social change: Techniques for changing human behaviors.*** Following are social science principles and concepts that hold significant potential to help change behaviors at the individual and community levels to support alternatives that could improve ecosystem health.

**Social marketing.** Social marketing applies marketing principles and practices to address social problems through behavioral change. It involves the marketing of a product, service, or idea where the benefit accrues not to the "seller" but to the targeted individual or society (Andreasen 1995). In social marketing, the basic means of achieving improved social welfare is to effect a change in behavior. It is much more outcome-based than many current public information and education efforts, where goals are simply to increase awareness and understanding.

Social marketing can be extremely efficient at influencing change. The individuals whose behavior one desires to change—those who have control over the outcome—are the ones who will play the primary role in the social marketing process. Unlike many other change efforts, all actions in social marketing are based on a thorough understanding of the needs, wants, and perceptions of that target audience. Social marketing begins by understanding real and perceived barriers to the desired change and then strategically delivers to key target audiences programs designed to address these concerns and to influence change (Andreasen 1995).

Social marketing practices have typically focused on individuals as the ultimate target for behavior changes such as stopping smoking, adopting certain health practices, recycling, or conserving energy, thus effectively bringing about social change, one person at a time. Social marketing practices could also hold great promise for influencing change in decisionmakers and early adopters, the opinion leaders in local communities, toward support of sustainable ecosystems.

**Community-based social marketing.** Community-based social marketing (CBSM) is an emerging field that is also based on psychological principles. An important distinction, however, is that CBSM makes the larger community the focus of attention, rather than individuals. It is therefore an even more efficient method for effecting social change in some cases (McKenzie-Mohr 2000).

At the heart of community-based social marketing is the identification of barriers to adopting the desired behaviors. CBSM encourages practitioners to ask three basic questions:

**Box 1. Questions for researchers:**
**What are the potential economic impacts associated with aging dams?**

**Understanding the potential economic impacts associated with keeping or removing dams is an increasingly important issue. Private and public dam owners, mayors, governors, legislators, and elected officials at all levels of government wrestle with decisions about how local communities and this country can and should deal with costs associated with aging dams. Scientific research could inform individual decisions and larger policy decisions by addressing the following questions:**

- **What will happen to my property value if the dam is removed? A common assumption is that property values surrounding an impoundment will decline following dam removal. Preliminary Trout Unlimited (2001) studies at one site, however, show that predicted decreases in property value had not occurred 10 years following dam removal and river restoration. Independent, scientific, peer-reviewed studies are needed to understand what short- and long-term economic impacts are associated with small dam removal, for private and public property, including businesses.**
- **What is the potential economic liability associated with aging dams throughout the country (or in one watershed or county)? What portion of this cost would likely be borne by taxpayers and what part by private dam owners?**
- **What are the costs of mitigating water quality, fisheries, and other environmental impacts associated with dams? To whom do these costs accrue, e.g., are they public or private? To whom do the benefits accrue?**
- **What is the cost of eliminating public safety hazards posed by dams? Who currently pays those costs, and who is likely to in the future? Considering that some states do not have dam safety programs, how accurate are assessments of dam safety costs?**

What is the potential impact of the behavior? What barriers exist, real and perceived, to engaging in the desired activities? And do the resources exist to overcome identified barriers (McKenzie-Mohr 2000)?

McKenzie-Mohr's questions are used below as a framework for suggesting topics of scientific research that would be useful for informing decisionmakers (and those who influence decisionmakers) and influencing social change toward more ecologically sustainable practices.

**What is the potential impact of the behavior (i.e., removing the dam in my community)?** Community questions about what will happen after dam removal are wide ranging; they are societal, economic, environmental, technical, and legal in nature and would benefit from research by both natural and social scientists. The following questions, which are representative of those frequently asked by members of a community facing dam repair and removal decisions, indicate a lack of understanding of both dams and natural river systems. Will the stream dry up if the dam is removed? Will we be stuck forever with stinking mudflats? Will flooding increase without the dam (even when the dam is not a flood control structure)? Who will own the new land? Doesn't this dam have historical value? Won't the best fishing spots be lost? Won't dam removal introduce exotic or diseased species? And perhaps the most common and complex question of all is, How will keeping the dam affect my pocketbook? Our community's pocketbook? (RAW/TU 2000).

Although some of these questions may appear simple, there are no simple answers to them. The need for interdisciplinary and multidisciplinary collaboration to provide answers, or at least reasonable expectations, is evident by looking more closely at just the last question, about the economic impacts of keeping a dam or removing a dam (see box 1). While natural science research is needed to answer many questions about potential outcomes, there is a clear need for social science research to better understand the human dimensions of dam removal.

**What barriers exist, real and perceived, to engaging in the desired behavior?** Identifying potential barriers calls for social science research. Experience with multiple small dam repair or removal situations suggests that barriers include lack of understanding of the values of a healthy river and how the dam may be harming the river and river life, concern about property values adjacent to the impoundment, misinformation about costs of repair and of removal, and aesthetic concerns about what the former impoundment will look like after drawdown and dam removal. These concerns represent potential barriers that could be surmounted through dissemination of scientific research findings that address the topics identified in McKenzie-Mohr's first question.

Experience repeatedly shows that other, less obvious barriers to accepting dam removal as an option also often exist; such barriers include a profound sense of loss and a sense of fear or helplessness, especially if the impetus for removal is coming from outside the community. McKenzie-Mohr (2000) and Hudson (2001) caution, however, that program planners working to effect change often mistakenly think they know what these barriers are and act accordingly, even though the perceived barriers may not reflect the actual barriers.

Social science researchers can conduct empirical research in this area and provide valuable insight into the real and perceived barriers that dissuade local community members from embracing dam removal as an alternative.

**Do the resources exist to overcome identified barriers?** Scientific information is needed about the resources and about the people involved, or potentially involved, in dam removal decisions before the barriers to accepting dam removal as a viable alternative can be fully understood. Only when those barriers are identified can it be ascertained whether the human and financial resources exist to overcome them.

## Role of scientists in decisions regarding dams and rivers

Typically, ecologists and other scientists conducting research on sustainable ecosystems focus on developing scientific principles of natural systems and practical management methods, understanding cause-and-effect relationships, and assessing environmental outcomes. Unfortunately, much of the resulting scientific information is seldom or never seen or used beyond the academic community (Doppelt 1993, Aumen and Havens 1997, Firth 1998, Lubchenco 1998).

In the case of dam removal, the problem thus far has been not so much a lack of dissemination or interpretation of scientific findings as a lack of usable scientific research findings. Although the scientific community has recognized the effects of dams on rivers for decades (Baxter 1977, Graf 1980, Petts 1980, Williams and Wolman 1984), only a handful of peer-reviewed research papers have been published on the effects of dam removals (Shuman 1995, Kanehl et al. 1997, Born et al. 1998, Bednarek 2001, Stanley et al. 2002). Only Stanley and colleagues (2002) and Kanehl and colleagues (1997) analyzed actual ecological data, and only Born and colleagues (1998) analyzed sociological data following dam removals.

As aging dams and their impacts on rivers continue to be pushed higher on the public agenda, scientists have the potential to influence whether society responds to this emerging issue as a problem or as an opportunity. Researchers today are playing a crucial role by increasingly providing data and analysis on what happens after a dam is removed. But if the goal is to have dam removal and river restoration (or other practices that lead to sustainable ecosystem health) accepted as a viable option, simply providing information may not be enough. Many citizens presume that publicly funded research will be used to benefit society, for example, to develop technology for public use and benefit. Increasingly, they also expect publicly funded research to inform public management and policy decisions—not to determine the outcome but to help understand the consequences of potential outcomes—in a manner that will benefit society (Aumen and Havens 1997, Lubchenco 1998, Norton 1998, Bjorkland and Pringle 2001, Hudson 2001). In Wisconsin, for example, there is a long history of interaction between university researchers and decisionmakers for the purpose of informing public policy. The "Wisconsin Idea" is well known in that state, where, historically, such interactions are strongly encouraged and facilitated (University of Wisconsin–Extension 1981).

Human behavioral change is central to the notion of ecological sustainability, and high levels of public support for such sustainability—which are not currently present—will be needed (Orr 1992, McKenzie-Mohr 2000, Bjorkland and Pringle 2001). Ecologists and other scientists who want their research to result in healthier ecosystems hope for change. Such change will require elected officials and other decisionmakers, including resource agency personnel, industry representatives, and private citizens, to step outside their comfort zone to accept new ideas. Scientists who want to help facilitate social change to benefit ecosystem health may need to stretch the boundaries of their own comfort zones as well.

We are not suggesting by any means that all scientists forgo conducting "pure" research. Objective information is critical to the credibility of public education efforts regarding natural resource issues, especially controversial ones (Johnson and Jacobs 1994). We are suggesting, however, that some scientists consider using their knowledge to address practical management challenges and to inform public policy on dams and rivers by ensuring that their scientific findings are interpreted and disseminated beyond the academic community (see figure 1). We hope that yet others will offer their technical expertise directly to resource agencies and change agents, such as university extension and resource agency personnel, as well as to conservation organizations and dam owners themselves. It is possible to inform without advocating (Blockstein 2002).

***Figure 1. Potential roles of scientists in influencing social change around dams and rivers.***

**Conduct pure research**

Conduct pure research on the environmental, economic, and societal impacts of dams and dam removal, and publish findings.

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**Conduct applied research**

Allow practitioner needs to shape research agendas. Address research topics that could directly assist dam repair or removal decisions and dam removal management.

↓

**Disseminate findings**

Actively facilitate the interpretation and dissemination of scientific information to resource agencies, communities, decisionmakers, conservation organizations, and dam owners, through presentations and publications outside the academic community.

↓

**Provide technical expertise**

Provide professional technical expertise on potential outcomes of various alternatives through public comment processes or as a technical advisor to a resource agency, conservation organization, or professional association.

↓

**Actively promote findings**

Write letters to the editor, elected officials, agency heads, and other decisionmakers and influential leaders.

Scientists who believe that science should inform public management and policy decisions, and who agree that societal change toward more sustainable ecosystem practices is necessary, are the best candidates for successfully moving from conducting pure research to actively promoting their findings.

## Conclusion

Significant changes in human behavior are required to achieve sustainable ecosystem practices. A key component in achieving desired ecological outcomes will be to improve the process of decisionmaking so that alternatives that could improve ecosystem health, such as selective dam removal, are considered and accepted or rejected on their own merits. Scientists, especially social scientists, can play important roles in enabling such social change by conducting applied research and working to interpret and disseminate findings to decisionmakers.

## Acknowledgments

The authors would like to thank David Hart of the Academy of Natural Sciences for recognizing the value of human dimensions in dam removal issues and the value of practitioner expertise, and for his encouragement and comments on earlier versions of this paper. Thanks also to two anonymous reviewers for their suggestions. Finally, we extend our thanks to The Pew Charitable Trusts for support of this research.

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