

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 (Babbitt 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,

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

(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.

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

ivers 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 techni-

cal 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 (m³); or (3) a low hazard potential but height exceeding about 1.8 m and storage exceeding 61,700 m³. 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 × 10⁶ m³ 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.

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 m³ to 3.7 × 10¹⁰ m³. 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;

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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

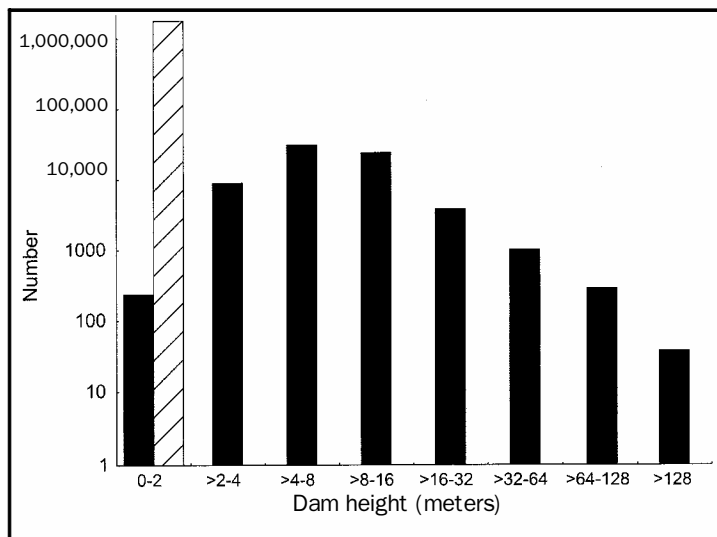


Figure 1. Distribution of US dams by structure height. Data are from the National Inventory of Dams (solid bars; USACE 2000) and estimated by USACE for dams less than 2 meters in height (diagonally hatched bar; Graf 1993).

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.,

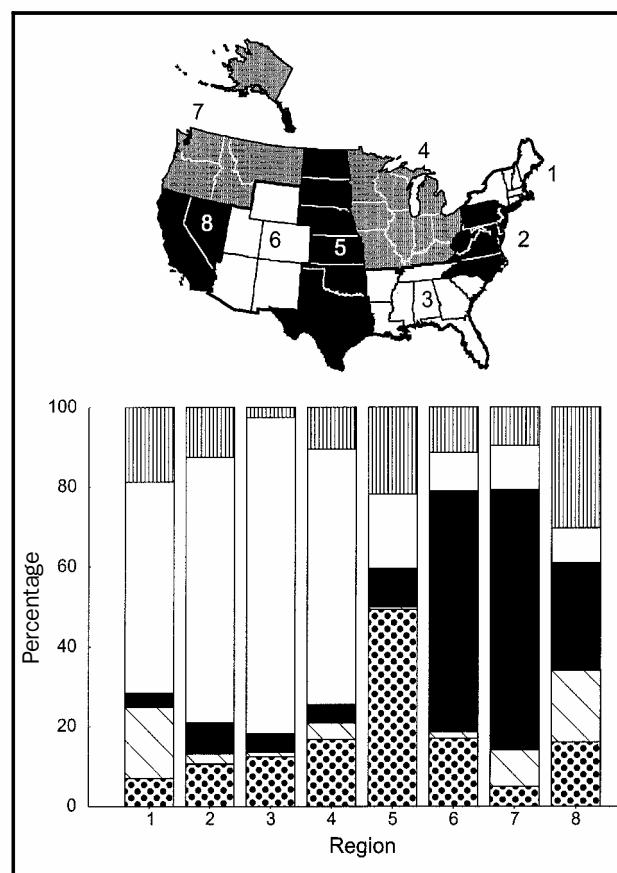


Figure 2. Percentage distribution by geographic region of dams falling into five categories of primary operational purpose, as defined in the national inventory of dams (USACE 2000). Dam uses are defined as flood control (stippled), hydropower (diagonally hatched), irrigation (solid black), recreation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

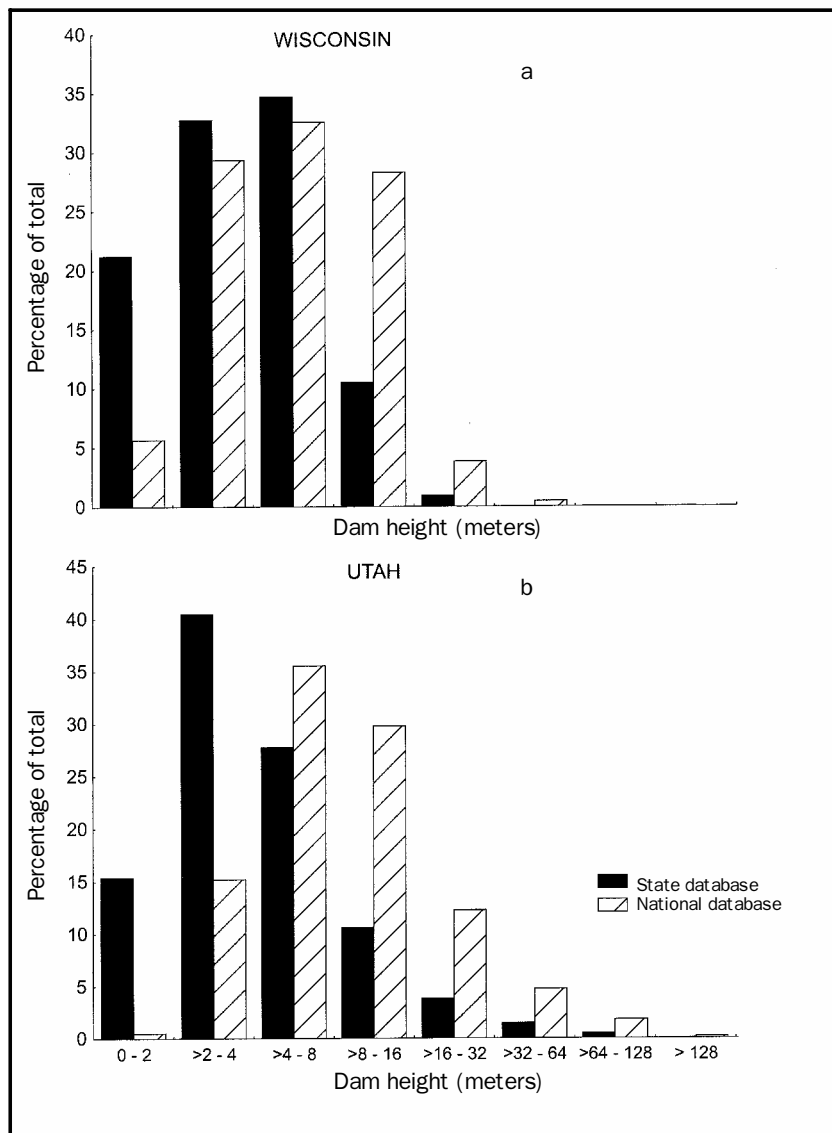


Figure 3. Percentage distribution by dam height for dams in state databases (solid black) and the National Inventory of Dams (diagonally hatched; USACE 2000) for (a) Wisconsin and (b) Utah.

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 plank-

tonic 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.

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.

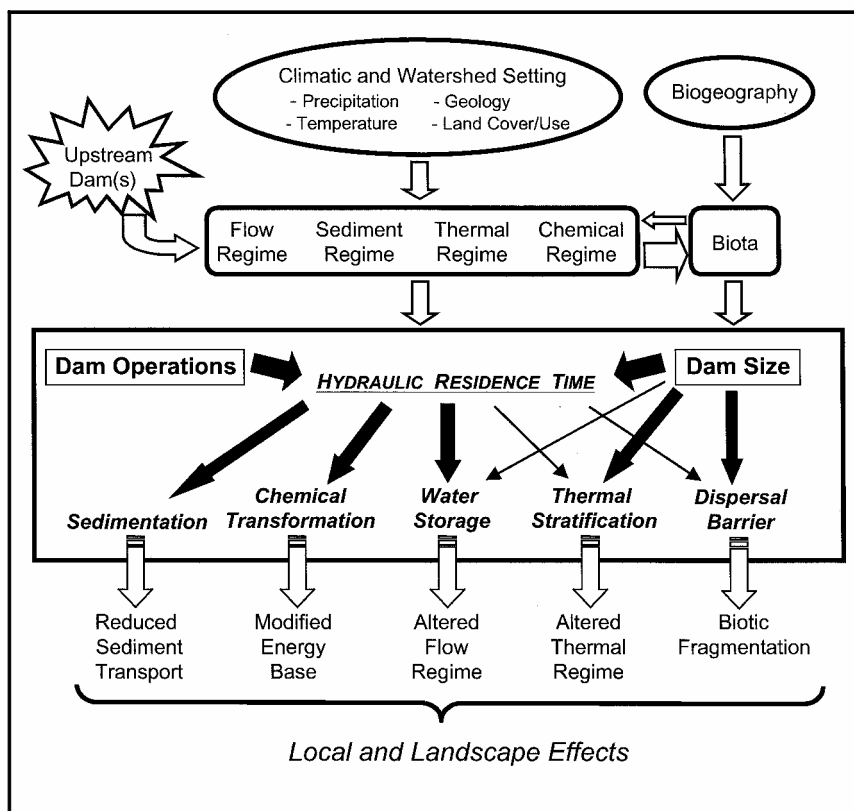


Figure 4. Flow chart illustrating how attributes of dam-reservoir systems, especially dam size and operations, modify fundamental riverine biophysical processes to cause alterations with local and landscape environmental effects.

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 asso-

ciated 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 1.2×10^6 and 12×10^6 m³ 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.

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 6.2×10^4 m³ 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

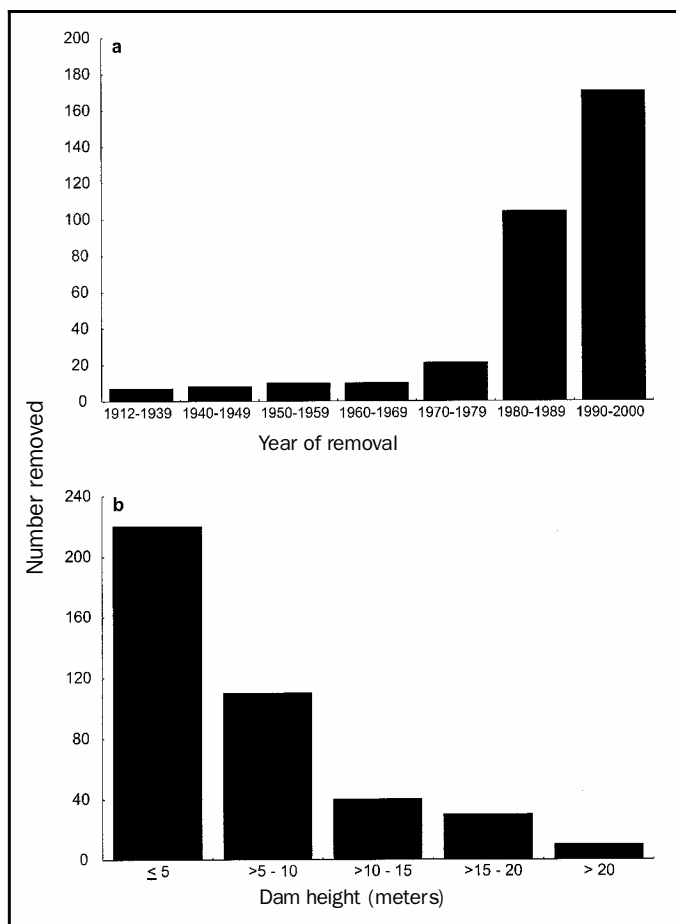


Figure 5. Dam removal in the United States by (a) decade and (b) structure height. (Data taken from AR/FE/TU 1999 and Doyle et al. 2000.)

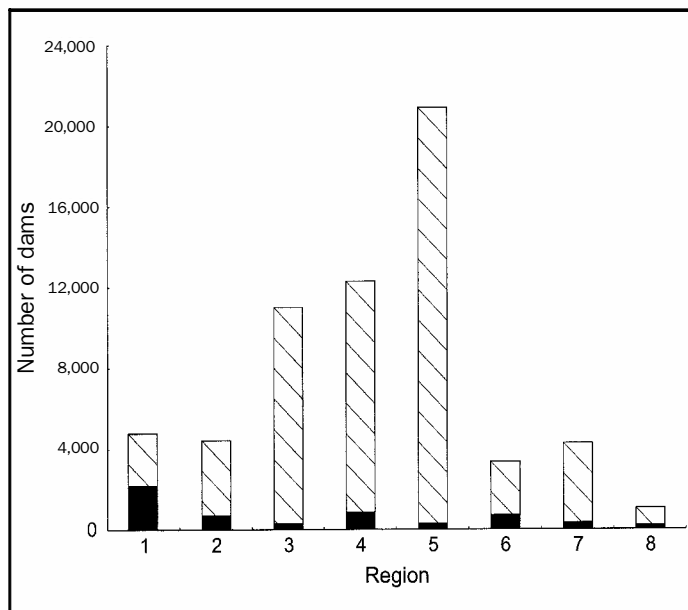


Figure 6. Number of dams by geographic region in the National Inventory of Dams database (USACE 2000) with estimated average time to half-filling with sediment being 91 years or less, on the basis of reservoir storage volumes. Dams are divided into those constructed before (solid black) and after (diagonally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

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References cited

- [AR/FE/TU] American Rivers, Friends of the Earth, Trout Unlimited. 1999. Dam Removal Success Stories: Restoring Rivers through Selective Removal of Dams That Don’t Make Sense. Washington (DC): AR/FE/TU.
- [ASCE] American Society of Civil Engineers. 1997. Guidelines for retirement of dams and hydroelectric facilities. New York: American Society of Civil Engineers.
- . 2001a. Web Pages about Dam Infrastructure Report Card. Reston (VA): ASCE. (5 October 2001; www.asce.org/reportcard/index.cfm?reaction=factsheet&page=8)
- . 2001b. Web Pages about Issue Brief on Dams. Reston (VA): ASCE. (12 November 2001; www.asce.org/news/reportcard/issbrfdm.cfm)
- Babbitt B. 2002. What goes up, may come down. *BioScience* 52: 656–658.
- Baron JS, Poff NL, Angermeier PL, Dahm CN, Gleick PH, Hairston NG, Jackson RB, Johnston CA, Richter BG, Steinman AD. 2002. Meeting ecological and societal needs for freshwater. *Ecological Applications* 12. Forthcoming.
- Bayley PB. 1995. Understanding large river–floodplain ecosystems. *BioScience* 45: 153–158.

- Benke AC. 1990. A perspective on America's vanishing streams. *Journal of the North American Benthological Society* 9: 77–88.
- Born SM, Genskow KD, Filbert TL, Hernandez-Mora N, Keefer ML, White KA. 1998. Socioeconomic and institutional dimensions of dam removal: The Wisconsin experience. *Environmental Management* 22: 359–370.
- Chao BF. 1991. Man, water and global sea level. *EOS, Transactions, American Geophysical Union* 72: 492.
- Collier M, Webb RH, Schmidt JC. 1996. Dams and rivers: Primer on the downstream effects of dams. Reston (VA): US Geological Survey. Circular no. 1126.
- Dendy FE. 1968. Sedimentation in the nation's reservoirs. *Journal of Soil and Water Conservation* 23: 135–137.
- Dendy FE, Champion WA, Wilson RB. 1973. Reservoir sedimentation surveys in the United States. Pages 349–357 in Ackermann WC, White GF, Worthington EB, eds. *Man-Made Lakes: Their Problems and Environmental Effects*. Washington (DC): American Geophysical Union. Geophysical Monograph 17.
- Doyle MW, Stanley EH, Luebke MA, Harbor JM. 2000. Dam removal: Physical, biological and societal considerations. Paper presented at the American Society of Civil Engineers Joint Conference on Water Resources, Engineering and Water Resources Planning and Management; 30 July–2 August; Minneapolis, MN.
- EnergyIdeas. 2001. Energy glossary: Hydroelectric. Washington State University Cooperative Extension Energy Program, Energy Ideas Clearinghouse. (1 July 2002; www.energyideas.org/glossary/terms.cfm?vcategor y ID=7)
- [EPA] US Environmental Protection Agency. 2001. Dams management measures. EPA Office of Water. (1 July 2002; www.epa.gov/nps/MMGL/Chapter6/ch6-3a.html)
- Fausch KD, Torgersen CE, Baxter CV, Li HW. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. *BioScience* 52: 483–498.
- [FEMA] Federal Emergency Management Agency. 2001. National Dam Safety Program. FEMA Federal Insurance and Mitigation Administration. (1 July 2002; www.fema.gov/mit/damsafe/about.htm)
- Gleick PH. 1998. *The World's Water: The Biennial Report on Freshwater Resources*. Washington (DC): Island Press.
- Graf WL. 1993. Landscapes, commodities, and ecosystems: The relationship between policy and science for American rivers. Pages 11–42 in *Water Science and Technology Board, National Research Council. Sustaining Our Water Resources*. Washington (DC): National Academy Press.
- . 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* 35: 1305–1311.
- Grant G. 2001. Dam removal: Panacea or Pandora for rivers? Invited commentary. *Hydrologic Processes* 15: 1531–1532.
- Hart DD, Johnson TE, Bushaw-Newton KL, Horwitz RJ, Bednarek AT, Charles DF, Kreeger DA, Velinsky DJ. 2002. Dam removal: Challenges and opportunities for ecological research and river restoration. *BioScience* 52: 669–681.
- Joseph P. 1998. The battle of the dams: Those who think some of our rivers are a dammed shame argue for the structures to come down. *Smithsonian* (November).
- Kalff J. 2002. *Limnology: Inland Water Ecosystems*. Upper Saddle River (NJ): Prentice Hall.
- Ligon FK, Dietrich WE, Trush WJ. 1995. Downstream ecological effects of dams. *BioScience* 45: 183–192.
- Matilija Coalition. 2000. Matilija Coalition. (1 July 2002; www.rain.org/~pjenkin/matilija)
- McCully P. 1996. *Silenced Rivers: The Ecology and Politics of Large Dams*. London: Zed Books.
- Meade RH, ed. 1995. *Contaminants in the Mississippi River, 1987–1992*. Reston (VA): US Geological Survey. Circular no. 1133.
- Morris GL, Fan J. 1998. *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watershed for Sustainable Use*. New York: McGraw-Hill.
- Muth RT, Crist LW, LaGory KE, Hayse JW, Bestgen KR, Ryan TP, Lyons JK, Valdez RA. 2000. Flow and Temperature Recommendations for Endangered Fishes in the Green River Downstream of Flaming Gorge Dam. Lakewood (CO): Upper Colorado River Endangered Fish Recovery Program. Final Report, Upper Colorado River Endangered Fish Recovery Program Project FG-53.
- Naiman RJ, Turner MG. 2000. A future perspective on North America's freshwater ecosystems. *Ecological Applications* 10: 958–970.
- Nilsson C, Berggren K. 2000. Alterations of riparian ecosystems caused by river regulation. *BioScience* 50: 783–792.
- [NRC] National Research Council. 1996. *Upstream: Salmon and Society in the Pacific Northwest*. Washington (DC): National Academy Press.
- Pejchar L, Warner K. 2001. A river might run through it again: Criteria for consideration of dam removal and interim lessons from California. *Environmental Management* 28: 561–575.
- Pennsylvania Fish and Boat Commission. 2001. Hazards on the water. Commonwealth of Pennsylvania Fish and Boat Commission (1 July 2002; http://sites.state.pa.us/PA_Exec/Fish_Boat/damhaz.htm)
- Petts GE. 1984. *Impounded Rivers: Perspectives for Ecological Management*. New York: John Wiley and Sons.
- Poff NL. 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology* 36: 71–91.
- Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: A paradigm for river conservation and restoration. *BioScience* 47: 769–784.
- Postel SL. 2000. Entering an era of water scarcity: The challenge ahead. *Ecological Applications* 10: 941–948.
- Pringle CM, Freeman MC, Freeman BJ. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the New World: Tropical–temperate comparisons. *BioScience* 50: 807–823.
- Pyle MT. 1995. Beyond fish ladders: Dam removal as a strategy for restoring America's rivers. *Stanford Environmental Law Journal* 14: 97–143.
- [RAW/TU] River Alliance of Wisconsin, Trout Unlimited. 2000. *Dam Removal: A Citizen's Guide to Restoring Rivers*. Madison (WI): River Alliance of Wisconsin.
- Rosenberg DM, McCully P, Pringle CM. 2000. Global-scale environmental effects of hydrological alterations: Introduction. *BioScience* 50: 746–751.
- Sahagian D. 2000. Global physical effects of anthropogenic hydrological alterations: Sea level and water redistribution. *Global and Planetary Change* 25: 39–48.
- Schnitter NJ. 1994. *A History of Dams: The Useful Pyramids*. Rotterdam (The Netherlands): A. A. Balkema.
- Scott ML, Friedman JM, Auble GT. 1996. Fluvial processes and the establishment of bottomland trees. *Geomorphology* 14: 327–339.
- Shuman JR. 1995. Environmental considerations for assessing dam removal alternatives for river restoration. *Regulated Rivers: Research and Management* 11: 249–261.
- Smith N. 1971. *A History of Dams*. London: Peter Davies.
- St. Louis VL, Kelly CA, Duchemin E, Rudd JWM, Rosenberg DM. 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. *BioScience* 50: 766–775.
- [USACE] US Army Corps of Engineers. 2000. National inventory of dams. CD-ROM Federal Emergency Management Agency. (1 July 2002; <http://crunch.tec.army.mil/mid/webpages/mid.cfm>)
- [USBR] US Bureau of Reclamation. 2001. Web pages about definition of technical terms. (1 July 2002; www.usbr.gov/cdams/glossary.html)
- Ward JV, Stanford JA, eds. 1979. *The Ecology of Regulated Streams*. New York: Plenum Press.
- Ward JV, Stanford JA. 1983. The serial discontinuity concept of lotic ecosystems. Pages 29–42 in Fontaine TD, Bartell SM, eds. *Dynamics of Lotic Ecosystems*. Ann Arbor (MI): Ann Arbor Science.
- [WCD] World Commission on Dams. 2000. *Dams and Development: A New Framework for Decision-making*. London: Earthscan Publications.
- [WDNR] Wisconsin Department of Natural Resources. 1995. Wisconsin's Biodiversity as a Management Issue: A Report to the Department of Natural Resources Managers. Madison (WI): WDNR.
- Wootton JT, Parker MS, Power ME. 1996. Effects of disturbance on river food webs. *Science* 273: 1558–1561.