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DAM REMOVAL: PHYSICAL, BIOLOGICAL, AND SOCIETAL CONSIDERATIONS

Martin W. Doyle (1), Emily H. Stanley (2), Michelle A. Luebke (2), and Jon M. Harbor (1)

(1) Grad. Student and Assoc. Prof., respectively. Dept of Earth and Atmospheric Sciences, Purdue University, W. Lafayette, IN 47907. (PH: 765-494-0258, FAX: 765-496-1210, email: mdoyle@purdue.edu, jharbor@purdue.edu)
(2) Asst. Prof. And Undergrad Student, respectively. Center for Limnology, Univ of Wisconsin, 680 N. Park St., Madison, WI 53706 (PH: 608-263-2567, FAX: 608-265-2340, email: ehstanley@facstaff.wisc.edu, maluebke@students.wisc.edu)

INTRODUCTION

The American environmental movement is currently witnessing significant changes in accepted approaches to river management. Rivers once developed and altered for human benefits are being restored in a variety of manners and magnitudes, often with the sole intention of environmental enhancement. River restoration to date has primarily consisted of enhancement of geomorphic and habitat features along a specific reach of a river, or the enhancement of water quality via regulation of point and non point source pollution. However, such measures are only partially capable of accomplishing the goal of restoration: to return an ecosystem to an approximation of its pre-disturbance condition (Schmidt et al., 1998). Dams remain a significant limitation to overall restoration efforts, as there are fewer than 60 rivers with 100 km or more of free-flowing channel in the contiguous U.S. Hence, the recent realization of dam removal represents a significant development for the potential restoration of riverine environments.

Historical and Regulatory Context

Federal and local dam licensing regulations make the current time period one in which dam removal is a realistic option. The Federal Energy Regulatory Commission (FERC) requires relicensing of dams every 50 years, and during the 1990’s hundreds of existing have come up for relicensing. In addition, there are regulations for nonfederal dams and those not licensed by FERC. For instance, the state of Wisconsin’s Dam Safety Inspection Program requires dam inspection every 10 years by the state’s Department of Natural Resources (WDNR); dams failing to meet safety criteria must be repaired to WDNR standards or removed (Born et al., 1998). Similarly, under Pennsylvania law, upon written order of the Pennsylvania Fish and Boat Commission, any newly constructed or existing dam that requires state permits for construction or modification must include provisions for fish passage as a permit requirement (S. Carney, Pennsylvania Fish and Boat Commission, pers. comm.).

The cost of repairing a dam is often significantly greater than the cost of removal, particularly when fish passage must be provided. For example, the average cost of repair was 3.4 times greater than the cost of removal in cases analyzed by Born et al. (1998). Because almost 75% of all dams are privately or locally owned, the least costly option for dealing with a dam is often the de facto choice of most communities and individuals.

The combination of deteriorating dam conditions, the timing of FERC and other dam relicensing programs, and the recent increased public acceptance of environmentally focused river management, has created circumstances in which dam removal is a realistic alternative in a rapidly-growing number of cases throughout the U.S. (Figure 1, Table 1). Whether the current attitudes toward dam removal represent a fundamental change in the way rivers are viewed, or is a unique environmental window of opportunity (sensu Haeuber and Michener, 1998) remains to be seen.

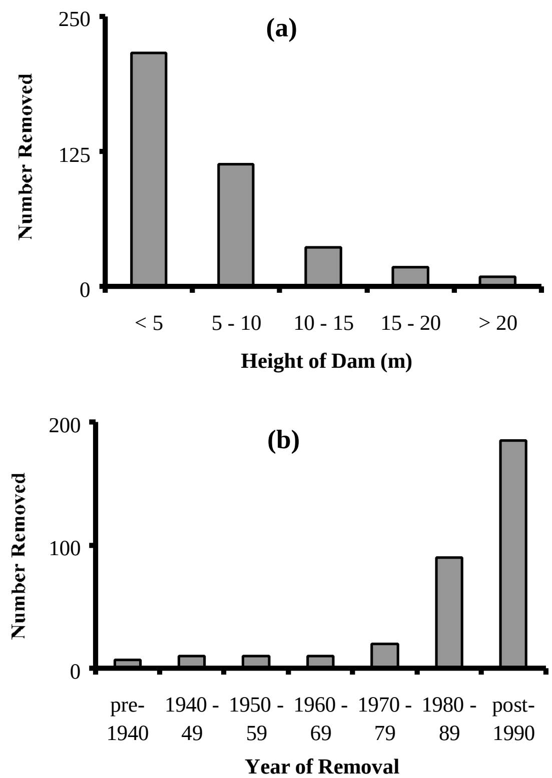

Figure 1. Number of dams removed as a function of (a) dam height, and (b) year of removal (adapted from American Rivers et al., 1999).

Table 1. Number of dams removed per state (American Rivers et al., 1999). States with less than 5 dams removed are not listed.

State	Number of dams removed
WI	73
CA	47
OH	39
PA	38
TN	26
WA	19
IL	17
CT	16
ID	13
TX	12
SD	11
KS	10
CO	9
ME	9
MI	9
MN	9
VA	9
NJ	9
VT	8
WY	8
MD	7
MT	7
NE	6
OR	5
SC	5

Current State of Dam Removal

While there are more than 75,000 inventoried dams in the U.S. (greater than 1.8 m (6 ft) high with at least 0.2 km^2 (50 acres) impoundment), there are also an estimated 2 million smaller dams (Shuman, 1995). As such, the majority of dams that have been removed and are currently being considered for removal are relatively small, non-hydroelectric dams, particularly run-of-river structures (Figure 1). While the majority of media attention, design, and research efforts have focused on large hydroelectric dam removal projects, such structures represent less than 3% of the dams in the U.S. (ASCE, 1997), making them exceptional cases. The greatest number of dams removed to date, as well as the greatest number which will be removed in the future, are less than 5 meters tall. This trend has two ramifications: (1) small dam removal offers the greatest source of information for research and testing of removal techniques, and (2) technical guidance in removing small dams is particularly urgent because of the incredibly large number of small dams slated for retirement in the immediate future.

The removal of dams is becoming an increasingly realistic and preferred option in river management. The task remaining for engineers and scientists is to develop a base of knowledge from which to guide decisions surrounding dam removal. Unfortunately, virtually no data exist on pre- and post-removal conditions. Hence, project managers and local communities faced with the decision to remove or repair a dam have only grey literature, unpublished reports, and anecdotal information for guidance. The need for a peer-reviewed, scientific foundation will become even greater as the need for formal policy relating to dam removal develops. Herein, we discuss three facets constituting pivotal issues in dam removal: physical effects, ecological effects, and societal issues.

PHYSICAL EFFECTS

Shuman (1995) and the ASCE Task Committee (1997) stated that the primary concern in most, if not all dam removal cases is the fate of sediment stored in impoundments and the subsequent physical changes in the river channel that occur following removal. While the impacts of dam construction on river morphology are well documented in the literature and are based on high quality data extending over several decades, the impacts of dam removal have yet to receive scientific attention, even though a significant number of dams have already been removed (Figure 1). The limited number of studies of dam removal that do exist provide an insufficient description of pre- and post-removal sediment storage and movement (Shuman, 1995). Because of this lack of data from which to form a summary of the 'state of the science,' we will examine available geomorphic data from dam removal projects as well as modeling studies conducted, and then assess these studies based on established knowledge of geomorphic systems.

Previous Dam Removal Studies: Case Studies and Modeling

Of the few cases in which sediment movement has been documented, the most consistent observation is that drastic morphologic changes occurred immediately following dam removal. At the 1969 removal of the Newaygo Dam on the Muskegon River, Michigan, approximately 40% of the stored sediment moved downstream immediately in the form of an elongating sediment wave, travelling at a rate of approximately 1.6 km per year (Simons and Simons, 1991). At the Fort Edward Dam on the Hudson River (removed in 1973), approximately 33% of the stored sediment moved downstream within a year of removal, and was highly publicized due to the presence of PCB's in the transported sediment (Shuman, 1995). Following the removal of the Woolen Mills Dam from the Milwaukee River, Wisconsin in 1988, most of the impounded sediment was transported within 6 months. Similarly, preliminary results from the recently removed Oak Street Dam on the Baraboo River, Wisconsin, show channel cross section area increasing from 15 to 23 m^2 within 2 months of removal (Figure 2). While not a complete removal of a dam, Wohl and Cenderelli (2000) document a reservoir sediment release on the North Fork Poudre River, Colorado. And estimated that 70–80% of the sediment supplied by the reservoir release was transported downstream within one year.

Several studies have taken modeling approaches to examine sediment transport during dam removal. HEC-6, the Army Corps of Engineers' 1-dimensional sediment transport model, is frequently used due to its wide acceptance by federal agencies and its familiarity to many engineers. HEC-6 was used to develop removal options for the Elwha (34 m high) and Glines Canyon Dams (64 m high) on the Elwha River, Washington and the Condit Dam (38 m high) on the White Salmon River, Washington. Based on modeling results of the Elwha River, sediment transport following rapid (<2 year) dam removals was predicted to cause bed aggradation and flooding, which in turn would require an increase in downstream flood-control levee heights of 0.3 to 1.5 meters and cause severe impacts to aquatic resources (Harbor, 1993). Stoker and Harbor (1991) describe an alternative removal scenario of incremental drawdown and suggest that such a procedure would produce a final channel closely replicating the pre-dam river shown on historical maps. Based on a HEC-6 analysis similar to the Elwha study, Beck, Inc. (1998) predicted that removal of the Condit Dam would result in 4.0 x 10^5 m^3 of the 6.2 x 10^5 m^3 (65%) of reservoir sediment being transported within the first year, and cause fish kills due to extremely high sediment concentrations within the first several months following removal. Like the Elwha study, Beck, Inc. (1998) also predicted that following removal, the river channel through the reservoir would return to pre-dam conditions within a year.

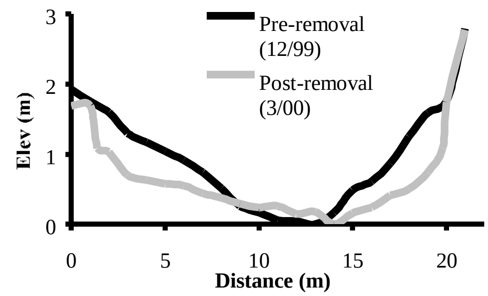

Figure 2. Changes in channel cross section caused by removal of Oakdale Dam, Wisconsin (removed in 1/00).

Accuracy and Limitations of Previously Used Methods

Because the aforementioned modeling studies comprise the bulk of well-documented, quantitative analysis and research to date of dam removal projects, it is important to assess, at least on a cursory level, the potential accuracy of such modeling methods. Unfortunately, the empirical data from dam removal studies do not necessarily support many of the modeling results. To begin, Wohl and Cenderelli (2000) suggest that standard bedload transport equations are not applicable under conditions where the original channel bed downstream of the dam is largely immobile in comparison to the finer reservoir-derived sediment being transported on the surface of the bed (i.e., as a veneer). In channels similar to their study site, models using standard bedload transport equations are based on tenuous premises and remain untested for the conditions that exist in dam removal situations. Similarly, the Bureau of Reclamation recently conducted a reservoir drawdown experiment to test ability of available models to forecast effects of dam removal and found that no existing models could simulate the processes observed. Consequently models are now being developed using these newly available data (T. Randle, Bureau of Reclamation, pers. comm.).

Further discrepancies exist between assumed post-removal channel conditions and field observations from sites where dams have been removed. Among five streams in southern Wisconsin, bankfull discharge of channels corresponded to flood recurrence intervals of < 2-, 7-, and 31-yrs for sites in which dams had been removed 6 years ago, while channels where dams were removed more than 40 years ago had bankfull discharges corresponding to 6- and 15-yr recurrence intervals (Lenhart 2000). These channel geometries contrast with natural, stable channels, in which bankfull discharge typically corresponds to a recurrence interval of 1 to 5 years. These data suggest that the assumption that post-removal channels will return to pre-dam conditions may not be valid, or that while much geomorphic change occurs immediately following removal, the recovery time to a stable channel configuration may be much longer than the 1-yr predicted by the aforementioned modeling studies. In addition to channel shape, predicting and/or controlling the alignment and location of the post-removal channel in the reservoir sediment is also difficult. Surveys and soil coring data from Lenhart's (2000) study indicated that in four of five cases, post-removal channels did not follow the pre-dam channel alignment, but rather developed a new course in the pre-dam floodplain. Similar problems have been encountered by the WDNR, who found channel avulsion in former impoundments to be a significant problem, particularly when trying to stabilize channels with bank protection (S. Josheff, WDNR, pers. comm.). Such observations are in stark contrast to the assumption that the post-removal channel will return to pre-dam conditions within a year of removal.

Geomorphic Analogies

Valuable insights into the problem of dam removal may be gained from geomorphic analogies. Two specific geomorphic phenomena are analogous to observed conditions in post-dam removal channels, and bring to light geomorphic processes that have not been previously addressed. First, Simon (1992) documented the geomorphic adjustments of the North Fork Toutle River (gravel and cobble-bed) following a massive debris avalanche and showed that channel adjustments were most dominant in the first two years following disturbance. Similar rates of adjustment occurred along sand-bed channels of western Tennessee as rivers responded to channelization (slope increase), although through different mechanisms of channel adjustment (Simon 1992). Channel widening was much more important in the high-energy, coarse-bedded North Fork Toutle River in comparison to the low-energy, fine-bedded channels of western Tennessee, where vertical degradation followed by widening was dominant. These results suggest that one-dimensional models not accounting for channel widening processes (e.g., HEC-6) may be misleading in various riverine environments. Second, in their study of channel development following the avulsion of Little Grassy Creek, Illinois, Ritter et al. (1999) found that the development of the longitudinal profile, as well as other channel features, was governed by the upstream migration of a knickpoint. Knickpoints have been observed as a significant geomorphic process following dam removal (L. Wildman, Milone and MacBroom, Inc., pers. comm.), and thus may be a further complication to the prediction of channel response to dam removal.

The physical changes to a river system induced by dam removal are critical concerns that remain, for the most part, unknown. Over twenty years ago following the Ft. Edwards Dam removal, the Federal Power Commission decided that pre-dam removal studies must not only address sediment transport, but also be precise and unambiguous in determining whether a dam removal should be authorized. To date, most dam removal cases remain ambiguous with respect to sediment and physical changes expected to occur. Further, the methods used to address sediment redistribution in dam removal cases (numerical models) deserve considerable attention as to their applicability and relevance to the conditions imposed by dam removal. Geomorphic analogies provide insight into possible channel responses to dam removal, although quantitative prediction and engineering design will ultimately rely upon numerical models.

ECOLOGICAL EFFECTS

As is the case for the physical environment, there is a rich literature describing the ecological effects of dams on rivers (e.g., see Baxter 1977, Ward and Stanford 1979). These effects occur at all levels of ecological organization, are often profound, and are generally viewed negatively by biologists. And again, similar to research on channel and sediment processes, few publications exist that describe ecological effects of dam removal, although it is widely assumed that changes are substantial, relatively rapid, and positive. As a result, ecological considerations are the major driving factor of dam removal in the U.S. (Table 2).

Table 2. Factors leading to dam removal (American Rivers et al., 1999). Reasons for removal are given for 119 of 467 cases, and more than one reason for removal was given for 4 of these 119 cases.

Reasons for removal	Percentage of cases
Environmental	43
Safety	30
Economics	18
Failure	6
Unauthorized Dam	4
Recreation	2

Rates and Patterns of Change

There is little solid evidence upon which to build generalizations regarding rates of biotic recovery following dam removal. Some preliminary results suggest that changes can be extremely rapid. For example, striped bass returned to previously inaccessible sections of the Kennebeck River within 3 months of breaching of the Edwards Dam in Maine (American Rivers et al. 1999). Similarly, invertebrate communities in the Baraboo River, Wisconsin changed from a characteristically lentic community to a more diverse mixture of taxa that included a large representation by obligate riverine species within 1 year of dam removal (Figure 3). In contrast, modeling results from studies of western dam removals suggest a period of decades to centuries will be required for complete recovery of fish and riparian plant populations (National Park Service 1996). These general patterns of relatively rapid recovery of short-lived taxa (invertebrates), and slower return of longer-lived taxa (fish) can be expected if the dam removal itself is not a particularly large or disruptive event. However, given the profound physical changes that occur

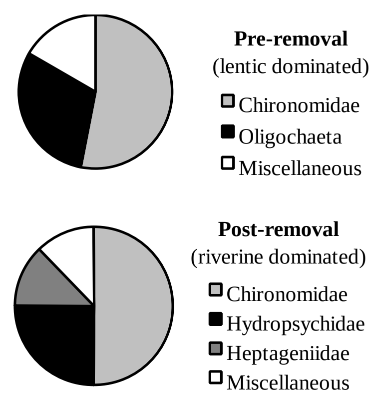

Figure 3. Composition of major invertebrate groups within the impoundment above the Waterworks Dam, Baraboo River, Wisconsin one year before and one year after dam removal. Heptageniidae and Hydropsychidae are obligate riverine families of mayflies and caddisflies, respectively.

during dam removal, the possibility of threshold effects and alternative recovery patterns must be considered.

We suggest a two-phase model of ecological response to dam removal. In the initial phase, the river experiences rapid and highly variable changes in several physical, chemical, and biological parameters. The period of transition from reservoir back to a river is a particularly vulnerable period for organisms, and events and circumstances occurring during this initial phase may determine the pattern of ecological recovery. The potential exists for ecosystems to return to conditions similar to the pre-dam state, or alternatively to a new and unfamiliar state. Massive changes in the physical structure of the river open the door to dramatic ecological changes that may have long-term effects on the nature of the recovery sequence in years to come.

Two examples demonstrate the potential for an ecosystem to undergo different successional pathways following dam removal, resulting in ecological conditions distinct from the pre-removal state. Floral communities at former impoundment sites in southern Wisconsin were dominated by monocultures of weedy pioneer species (e.g., stinging nettles) 5-6 years after dam removal (Lenhart 2000). Plants that initially colonized exposed sediments were able to persist for several years and prevent other species from becoming established in the area. Further, plant communities in these former impoundment sites did not resemble naturally occurring Wisconsin plant assemblages. In this case, the riparian community was shifted to an alternate state due to extreme habitat alteration (i.e., the sudden availability of extensive amounts of nutrient-rich sediments for colonization) and the ability of an individual species to colonize these sediments.

Salmon response to dam removal provides an excellent example of a population that could potentially show discrete recovery patterns, depending on the nature of the disturbance and fish responses during the initial transition phase. An evaluation of the potential impacts of the removal of the Elwha Dam, Washington concluded that dam removal would have "major adverse short-term impacts on salmon attempting to return or spawn in the river." Suspended sediment loads associated with breaching are expected to reach lethal levels during some phases of the removal, consequently, the removal schedule will be designed such that sediment releases occur when salmon are not in the river. If scheduling is successful, then it is reasonable to expect populations to recover to pre-impoundment densities. However, mismatches between expected time of fish runs and the removal schedule, or an unanticipated flood that mobilizes large amounts of sediments could potentially devastate remaining populations. In this case, timing of the dam removal plays a critical role in dictating the subsequent recovery pattern of the fish. Other similar scenarios can be generated. For example, if fine sediments that prevent successful spawning persist in gravel beds for long periods (e.g., due to a drought), then spawning failure would lead to further population declines. In sum, we expect that critical changes occurring during the relatively short period of time following dam removal have the potential to dictate trajectories of longer-term ecological recovery.

Some Final Caveats

As is stated above, there is a general sense that dam removal will result in positive environmental change, and an abundance of anecdotal evidence supports this assumption (e.g., see American Rivers et al.1999). However, we urge a degree of healthy caution. The evidence in hand typically deals with short term (1-3 year) responses to dam removal, is often qualitative, and in the few quantitative cases, firm conclusions regarding effects of the dam removal alone may be confounded by other processes. For example, significant improvements in the Milwaukee River fishery following the removal of the Woolen Mills dam were enhanced by extensive habitat improvements and, a fortuitous change in fishing regulations that went into effect the year the dam was removed (Kanehl et al. 1997). We expect that recovery following small dam removal should be relatively predictable in most cases, however, because patterns of recovery are likley sensitive to events that occur during and soon after the removal, the potential exists for a shift to a state that is structurally and functionally different from the original ecosystem.

SOCIETAL CONSIDERATIONS

Schmidt et al. (1998) suggest that effective environmental restoration, in addition to being based on sound science, must be based on a clear definition of the value of riverine resources to society. Discussion to this point has shown that the scientific foundation for dam removal is far from sound, and unfortunately, societal values as they relate to dams and reservoirs add a further significant complication to this issue.

Differences in values are especially pointed in dam removal because the removal option is one that is most often introduced and advocated by non-local parties. As such, dam removal can place the values and concerns of communities (Table 3) against those of non-local environmentalists, scientists, and government agencies (Table 2). Nostalgic and aesthetic value, while difficult to quantify in cost-benefit analyses (which often drives dam removal), is one of the more consistent reasons voiced by local stakeholders in opposition to dam removal. Many of the small dams removed to date were built before 1900, meaning that they have historical value to the local community. In addition, riparian landowners and businesses often have purchased land or developed businesses based on the reservoir and thus rely on high water levels. Hence, property value can change dramatically, either positively or negatively, as a result of dam removal.

Table 3. Critical issues to community of LaValle, WI, site of LaValle Dam (slated for removal winter, 2001)

Issue	Percentage Expressing Concern
Wildlife habitat	42
Fate of millpond	16
Aesthetics	14
Historic/community value	12
River fishery	11
Economic value	2

On a more basic level, communities often view natural resources in a fundamentally different light compared to non-local groups. It is important for scientists and engineers involved in dam removal to bear in mind that many communities have a strong sense of environmental ethics, although these ethics are based on a land-based appreciation of environmental quality (Rhoads et al., 1999). That is, rather than being based on a set of ideals, as is the case in traditional environmental ethics, land-based environmental ethics are strongly based on the everyday interaction of local communities with the environment (note contrast in first concerns in Tables 2 and 3). This fundamental difference in the way the environment is viewed is the basis for many of the disagreements regarding the value of a dam to the river between non-local groups and local communities. While nonlocal environmentalists view dams as a non-natural disturbance to a river ecosystem, many communities see instead the wetlands, wildlife habitat, and fishing opportunities created by dams.

The result of these differences in environmental views and values has been the development of 'top-down' decision-making in many dam removal cases, similar to that described by Rhoads et al. (1999) for stream naturalization. Based on dam removals in Wisconsin, Born et al. (1998) found that in every case studied, some citizens were opposed to dam removal, and that even though other alternatives were preferred by the community, dam removal was usually chosen. In addition, in half the cases studied, stakeholders felt that their concerns were not considered seriously and that there was intentional bias of the involved non-local parties toward dam removal. This latter situation is a common point of discrepency during interactions between scientists and communities, as nonscientists often perceive that they are being cast as ignorant. Rhoads et al. (1999) suggest that the main reason for such discrepancies is because scientists and many environmentalists often do not fully respect the knowledge, experiences, and interests of the local communities, and that scientists and environmentalists often fail to distinguish between their knowledge and their values.

In all, there are significant discrepancies between dam removal advocates and communities where dams are located. The reason for such discrepancies is based on differences in views and values of the various groups, which are rarely identified or dealt with appropriately in many dam removal cases. Future cases should adopt the model for interaction developed by Rhoads et al. (1999), or at least a similar approach towards dealing with societal issues associated with dam removal.

CONCLUSIONS

Dam removal has become a realistic option in environmentally focused river management. However, the practice of dam removal has outpaced the building of a scientific foundation, leaving a gap in applicable knowledge from which to approach the act of dam removal. Dam removal is advocated as an environmental restoration tool, and while preliminary anecdotal data offer some support for this assumption, sufficiently quantitative and/or long-term studies of physical and biological responses do not exist even though a significant number of dams have been removed. To date, the interactions of scientists and engineers in dealing with communities faced with the decision to remove a dam has not always been ideal. Without giving credence to the values and views of community stakeholders, dam removal will continue to be a highly contentious issue. Two specific suggestions are made with respect to the immediate future of dam removal: (1) research focused on dam removal is currently increasing dramatically, but it will be critical for scientists conducting this research to disseminate their results to practicing engineers faced with a drastically increasing number of dam removal cases; (2) there is a great need to improve interaction between non-local dam removal scientists/advocates and local communities, and this can only be accomplished through developing a cooperative approach to decisions related to the removal of a dam rather than the top-down currently used in most dam removal cases.

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