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Undamming Rivers: A Review of the Ecological Impacts of Dam Removal

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ABSTRACT / Dam removal continues to garner attention as a potential river restoration tool. The increasing possibility of dam removal through the FERC relicensing process, as well as through federal and state agency actions, makes a critical examination of the ecological benefits and costs essential. This paper reviews the possible ecological impacts of dam removal using various case studies.

Restoration of an unregulated flow regime has resulted in increased biotic diversity through the enhancement of preferred spawning grounds or other habitat. By returning riverine conditions and sediment transport to formerly impounded areas, riffle/pool sequences, gravel, and cobble have reappeared, along with increases in biotic diversity. Fish passage has been another benefit of dam removal. However, the disappearance of the reservoir may also affect certain publicly desirable fisheries.

Short-term ecological impacts of dam removal include an increased sediment load that may cause suffocation and abrasion to various biota and habitats. However, several recorded dam removals have suggested that the increased sediment load caused by removal should be a short-term effect. Preremoval studies for contaminated sediment may be effective at controlling toxic release problems.

Although monitoring and dam removal studies are limited, a continued examination of the possible ecological impacts is important for quantifying the resistance and resilience of aquatic ecosystems. Dam removal, although controversial, is an important alternative for river restoration.

Dams are pervasive features of the world's river systems. There are more than 75,000 dams above 5 ft tall in the United States and 40,000 dams over 50 ft tall worldwide (National Research Council 1992, Dynesius and Nilsson 1994, McCully 1997). Smaller dams (i.e., below 5 ft tall) in the United States likely number in the thousands (American Rivers and NPS 1996). Nearly 80% of the total discharge of large rivers in the northern third of the world is impacted by river regulation (Dynesius and Nilsson 1994). This large number of dams worldwide can be attributed to the variety of services they provide: inexpensive and efficient power generation, effective flood control, navigation, water supply, irrigation, and recreational opportunities.

Nevertheless, the presence of dams is problematic for many aquatic ecosystems. Dams impact ecosystems in a number of ways: altering the natural cycle of flow, transforming the biological and physical characteristics of river channels and floodplains, and fragmenting the continuity of rivers (Petts 1984, Chisolm 1994, Yeager 1994, Ligon and others 1995, Ward and Stanford 1995, Stanford and others 1996, Poff and others 1997). Lateral exchanges of sediment, nutrients, and organisms between aquatic and terrestrial areas may be limited by fewer overbank floods in a dammed river (Junk and others 1989, Naiman and others 1993). Coastal areas may lose valuable habitat and shift biotic composition when they are deprived of sediment because of dammed rivers upstream (DOI 1995). The physical obstruction of both dams and reservoirs impedes and delays the migration of various organisms (Drinkwater and Frank 1994, Staggs and others 1995, Stanford and others 1996). The turbines of a hydropower operation harm fish and other biota as they attempt to pass (Dadswell 1996). The change from a river to a reservoir ecosystem often shifts species composition. Unnatural timing of flow releases for power production and the altered temperatures of those releases can confound emergence or growth cues (Petts 1984).

Recognition of these impacts has led to a search for solutions. For example, in the United States, the Federal Energy Regulatory Commission (FERC) relicensing process for hydropower operations is critically examining the environmental impacts of dams (American Rivers and NPS 1996). FERC issues 30- to 50-year licenses to dams owned by nonfederal entities, such as utility companies, municipalities, and independent

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power producers. Over 450 dams are scheduled for relicensing between 1999 and 2001, representing approximately half the power produced at FERC-licensed dams (American Rivers and NPS 1996). Through the relicensing process, FERC has mandated new operating conditions to meet environmental concerns, including increased minimum flows, added or improved fish ladders, periodic high flows, and protection measures for riparian land (Auer 1996). Federally owned, non-FERC-regulated dams have also had operational changes implemented (Collier and others 1996, 1997, Higgins and Brock 1999).

Regardless of operational changes or installations of advanced equipment and technology, however, some ecological impacts of dams may not be remediated with mitigation tools. For example, the Edwards Dam in Maine contributed to a serious decline in numerous fish species within the Kennebec River by blocking migration and diminishing suitable spawning habitat (Dadswell 1996). Researchers determined that adding fish passages to the dam did not significantly improve fish populations because several species were either too large or too small to use the devices (Dadswell 1996). Based on this and other socioeconomic factors, FERC ordered Edwards Dam to be removed in July 1999.

In fact, over 100 small dams have been removed so far within the United States (Born and others 1998, American Rivers and others 1999) and many others are being considered for removal (Wood 1999). Internationally, Denmark has removed several small dams from its highly impacted river systems and has succeeded in improving habitat and fish passage on many of its rivers as a result (Iversen and others 1993). In addition, some larger dams in both Europe and the United States have been removed and many more are either slated for removal or are under consideration (Lovett 1999). For example, France removed two large dams in the Loire Valley in the summer of 1998 in an effort to restore the sole stock of Atlantic salmon on the European Atlantic Coast, and there are plans to remove others (Arnould 1997, Bowman personal communication).

With increasing attention on dam removal as an ecological restoration tool, enumerating the ecological benefits and costs of removal is crucial. There can be a variety of socioeconomic reasons for removing a dam, such as economically inefficient power production or a risk of structural failure of old, unsafe, or abandoned dams (American Rivers and others 1999). Regardless of the socioeconomic or environmental motivations, however, it is important to understand the ecological impacts of removals, since these may influence what can be expected of a river after removal.

Unfortunately, there are only a small number of peer-reviewed ecological studies available on completed dam removals. Although there have been a few reviews concerning the environmental and socioeconomic effects of dam removals (see Shuman 1995), so far none have fully addressed the impacts on crucial ecosystem components. These can include the flow regime, habitat, sediment transport, and connectivity of a river, some of the most important factors for healthy river ecosystems (see Poff and others 1997).

This paper surveys the available literature on the ecological impacts of prospective and completed dam removal and restoration attempts, as well as some of the environmental effects of dams, in order to outline the ecological implications of dam removal. The intent of this review is not to produce an exhaustive list of removals, since more and more dams are being removed or proposed for removal on a regular basis (see American Rivers and others 1999, for a list of completed dam removals). Instead, the major impacts of dams and dam removal on flow regime, reservoir displacement, temperature alterations, sediment transport, and connectivity are examined, using various examples from the literature to address how and when removal influences key components of ecosystem health (Table 1). These ecological impacts are divided into possible long-term and short-term impacts to distinguish between the effects due to dam removal that may take an extended period of time to appear and those more immediate ecological impacts of dam removal most likely brought about by the removal process itself.

Long-Term Ecological Impacts of Dam Removal

Flow

Individual rivers can vary widely in the fluctuations and magnitudes of flows they experience (Junk and others 1989, Heiler and others 1995, Poff and others 1997). These spatial and temporal variations in frequency, magnitude, duration, and regularity of flow determine the characteristic physical environment of a river, as well as the biotic community (Poff and others 1997). By physically blocking the river, storing excess runoff, or releasing water according to human needs, dams alter natural flow regimes (Poff and others 1997). Large or infrequent floods, such as 10- or 100-year floods, may no longer occur in some rivers. Regulated streams can experience dampening of large or seasonal floods and an elevation of low flows, with high flows corresponding to times of peak power consumption or navigational needs (Malmqvist and Englund 1996, Collier and others 1996). This leads to a decreased diversity of fauna, although an increased density of certain spe-

Table 1. Case studies of completed or proposed dam removals

Dam	Location	Removal status	Ecological impact of removal addressed by study	Reference
Dead Lake Dam	Chipola River, Florida, USA	Removed December 1987	Improved fish passage; increased flow fluctuations; Number of fish species increased; Improved water quality	Hill and others 1993, Estes and others 1993
Edwards Dam	Kennebec River, Maine, USA	Removed July 1999	Sediment changes (improved spawning habitat); Improved fish passage	Dadswell 1996
Elwha Dams (Elwha and Glines Canyon)	Elwha River, Washington, USA	Not yet removed	Change in coastal sediment transport; Return of native species	DOI 1995
Enloe Dam	Similkameen River, Oregon, USA	Not yet removed	Improved fish passage	Winter 1990
Fort Edwards Dam	Hudson River, New York, USA	Breached in 1973 (not intentionally removed)	Released PCBs	Shuman 1995, Chatterjee 1997
Fulton Dam	Yahara River, Wisconsin, USA	Removed 1993	Change in community composition; Loss of reservoir species	ASCE 1997, Born and others 1998
Grangeville Dam	Clearwater River, Idaho, USA	Removed 1963	Improved sediment movement	Winter 1990
Lewiston Dam	Clearwater River, Idaho, USA	Removed 1973	Improved sediment movement	Winter 1990
Little Goose Dam	Snake River, USA	Not yet removed	Improve fish passage	Wik 1995
Newaygo Dam	Muskegon River, Michigan, USA	Removed 1969	Sediment release	Simons and Simons 1991
Rodman Dam	Oklawaha River, Florida, USA	Not yet removed	Improved mammal and waterfowl habitat;	Kaufman 1992, Shuman 1995
Sallings Dam	AuSable River, Michigan, USA	Removed 1991	Temperature changes	Pawloski and Cook 1993
Stronach Dam	Pine River, Michigan, USA	Undergoing removal	Improved sediment and fish movement	American Rivers and others 1999
Sweasey Dam	Mad River, California, USA	Removed 1969	Reservoir silted in; improved fish passage	Winter 1990
Woolen Mills	Milwaukee River, Wisconsin, USA	Removed May 1988	Sediment release; Improved organism movement	Nelson and Pajak 1990; Staggs and others 1995, Kanehl and others 1997
Washington Water Power Dam	Clearwater River, Idaho, USA	Removed 1963	Improved fish passage and habitat for chinook salmon	Shuman 1995

cies may also occur. With more constant flows, organisms that would have otherwise been displaced by higher flows or flooding increase in abundance and come to dominate the community, overwhelming organisms that are unable to tolerate the other altered conditions of the regulated rivers, such as changes in temperature or dissolved oxygen.

Although maximum and minimum flows are dampened in some dammed rivers, regulated rivers may actually experience a greater degree of weekly, daily, or hourly fluctuations than unimpounded rivers because flow conforms to variations in power or water consumption (Gillilan and Brown 1997). For example, the Ocoee River, in the southeastern United States, alternates between a surging, white-water stage, allowed for recreationalists and rafters, and an extremely low-flow period, when the Tennessee Valley Authority (TVA) empties the river and redirects flow through a flume to the powerhouse for power production (Devine 1995). These changes can cause physical scouring of organisms and leave these riverbeds devoid of many fauna (Camargo and Voelz 1998). Frequent dewatering can also strand insects, fish, and bird nests (Stanford and Hauer 1991, Nilsson and Dynesius 1994) or decrease riparian vegetation growth (Nilsson and others 1997).

Some mitigation efforts have focused on the impacts of these erratic flows or water levels. For example, for the Flaming Gorge Dam on the Green River in Utah, flow management operations were changed in 1985 to help protect endangered fish, pursuant to the Endangered Species Act (Collier and others 1996). Spring floods were allowed and daily fluctuations were diminished to protect fish habitat and encourage spawning. The Thurlow Dam on the Tallapoosa River in Alabama had also previously released highly fluctuating flows (Travnichek and others 1995). The shoreline of the river surrounding the dam experienced irregular periods of extremely low water, dominated by a low diversity of fish species, with generalist species the most abundant. Higher flow through the dam increased the water level on the shoreline surrounding the dam, allowing specialist fish species to repopulate the river. This increased the diversity of the fish assemblage to more closely resemble an unimpounded section of the river.

These various attempts have successfully mitigated the effects of a dam on flow in a number of rivers. However, aquatic systems exhibit intense variation in flow patterns (Gillilan and Brown 1997). At certain times, some rivers are dominated by organisms that thrive in habitat created by large floods, while other species require more constant flows (Poff and others 1997). If restoration, rather than partial mitigation, is the goal, attempts to simulate large flows may not always provide the correct magnitude or frequency of flow or level of water necessary to truly mimic an unimpounded riverine flow regime.

Instead, restoring a natural flow regime through dam removal can work to increase biodiversity. For instance, the Dead Lake Dam on Florida's Chipola River produced a more constant flow than was typical of the preimpounded river. Following its removal, fluctuations in flow increased, along with the diversity of fish species, which expanded from 34 to 61 (Hill and others 1993). Although the mechanisms behind the heightened diversity are unclear, many of the fish species in the area may have benefited from a habitat restored by increased fluctuations in flow. For instance, the drying and compaction of the substrate during periods of low flow in this river restored macrophyte growth, such as alligatorweed, to the littoral zone (Hill and others 1993, Estes and others 1993). These areas of cover are often attractive spawning habitat for fish such as largemouth bass. Preferred spawning areas, such as backwater areas at certain depths, were also created by increased water level fluctuations after dam removal (Hill and others 1993).

A goal and possible result of dam removal is the reconnection of riparian and aquatic habitats by returning flows that inundate terrestrial areas. For example, studies for the removal of Rodman Dam in Florida emphasized this need (Shuman 1995). If the dam is removed, the riparian areas will be flooded more often, restoring riparian vegetation and some wetlands. Many wide-ranging terrestrial species that require abundant riparian vegetation, such as black bears and panthers, will benefit (Kaufman 1992). Small, ephemeral ponds, which are used as nurseries by aquatic organisms, will also return (Kaufman 1992).

For coastal rivers, the interactions of cyclical freshwater flooding and marine tides will be affected by dam removal. Anadromous adult fish and shrimp often use spring floods to carry them to coastal breeding regions (Dadswell 1996). Small, weak-swimming fish utilize the tidal surge to move them upstream from estuaries and coastal regions towards spawning habitat (Ouellet and Dodson 1985, Dadswell 1996). Dams prevent the tidal surge from moving upstream very far and dampen the floods that help carry fish downstream. Dam removal should eliminate this obstacle to migration and movement.

Shift from Reservoir to Free-Flowing River

The creation of a reservoir through damming turns the impounded section of the river into a slow-moving, lakelike habitat and alters the species composition of the river (Yeager 1994). Lake-adapted (i.e., lentic) species may begin to flourish and riverine (i.e., lotic) biota may become more susceptible to displacement. For example, in the Snake River in Oregon, the slow-flowing reservoir habitat has encouraged salmonid predator densities to increase (Wik 1995). A related issue for regulated rivers is the associated risk of displacement of native organisms by exotic species with the shift from lotic to lentic habitats (Moyle 1976, Meffe and Minkley 1987).

It is possible to mitigate some of these impacts in a dammed river through operational changes. However, most dams still block a river and create a slower-moving body of water. Here, dam removal may be an important restoration option. For example, after the removal of the Woolen Mills Dam in Wisconsin, there was a decrease in the high densities of the invasive and undesirable common carp, well-suited to the slow-moving conditions of the regulated river, and a return of native species, such as smallmouth bass (Staggs and others 1995, Kanehl and others 1997).

However, dam removal can also decrease the diversity or density of desirable organisms that prefer the slower, open water of the impounded reservoir or the existing wetlands. For example, retirement of the Fulton Dam on the Yahara River in Wisconsin has caused a replacement of cattail and sedge by wet meadow grasses (ASCE 1997). In addition, the duck and muskrat populations were negatively affected by the dam removal because of the loss of the reservoir habitat. On the other hand, several other species that utilized the reservoir area prior to removal, such as turtles, amphibians, mink, raccoon, and skunk persisted after the drawdown of the reservoir.

Temperature

By pooling or slowing flow behind a dam, there are temperature changes both within the reservoir and downstream (Ward and Stanford 1979, Petts 1984, Yeager 1994). Temperature stratification usually occurs in the reservoir because of the change to a more lakelike habitat, characterized by larger surface areas and slower moving water. The top layer of the reservoir (the epilimnion) warms and decreases in density, while cooler water remains on the bottom layer of the impoundment (the hypolimnion). In many reservoirs, these layers of varying densities do not mix, retaining a stratified temperature pattern. Since many dams draw water from the bottom of the reservoir (i.e., the cool hypolimnion), temperatures in the tailwaters decrease (Yeager 1994). This can change the biotic composition to coolwater fisheries in the tailwaters, many of which are highly valued by the fishing community (Gillilan and Brown 1997). However, hypolimnetic releases are also often very low in dissolved oxygen (DO) due to a lack of mixing with well-oxygenated upper layers, no photosynthesis, and high biological oxygen demand. These low dissolved oxygen levels are insufficient to maintain the density of some organisms in the tailwaters. Whether warm or cool water is released, changes in temperature downstream eliminate or shift the composition of species adapted to the natural water temperatures. If the dam releases warm, epilimnetic water, warm-water species often thrive downstream. For migrating cold-water fish, however, such as salmon and trout, warm temperatures act as a thermal barrier to movement (Gillilan and Brown 1997). The fish may instead choose cooler, unimpounded tributaries, altering migration routes, and decreasing the chances of reaching appropriate spawning grounds.

Mitigation for temperature changes has involved modifying the structure of the dam (Long and others 1997). Such modifications may include changes to the penstocks that allow withdrawal at different levels of the reservoir to achieve desirable temperatures in the tailwaters (Long and others 1997). Furthermore, weirs may be added downstream that increase temperature by pooling water in small reservoirlike accumulations and slowing its movement (Long and others 1997).

Although few studies have examined the changes in water temperature associated with dam removals, eliminating a stratified reservoir should return the natural range of temperatures of unregulated rivers. For example, Pawloski and Cook (1993) studied the immediate effects of the 1992 removal of the Sallings Dam on the AuSable River in Michigan. These researchers predicted that water temperatures would continue to decrease in the years following the removal by up to 3°C in the former reservoir area.

Sediment Transport

Sediment transport is also affected by damming (Petts 1984, Kondolf 1997, Poff and others 1997). Obstruction by dams disrupts the movement of sediment in rivers and changes a river's structural habitat (Kondolf 1997, Wood and Armitage 1997). Storage dams slow the water velocity of the river, causing sediment to settle in the inflow of the reservoir. Where the river no longer has the power to transport boulder, cobble, and other large particles, it results in an aggradation (raising) of the streambed upstream of the dam (Petts 1984, Fan and Springer 1990). Finer particles, such as sand and silt, settle closer to the dam itself and can ultimately fill the reservoir, limiting hydropower generation or water storage (Petts 1984). These fine particles also fill in valuable cobble and boulder habitat, rendering it unusable for many organisms. Changes in sediment transport can decrease biotic diversity. Fish can have physical habitat requirements that fluctuate seasonally or by their age class (Rabeni and Jacobson 1993). Salmonid fish depend on a variety of sediment types for spawning (Kondolf 1997). The size of the sediment needed can vary with the size of each type of fish and its strength in moving sediment with its tail (Kondolf and Wolman 1993).

Retention of sediment by the reservoir can also cause sediment-low water to be released downstream of the dam, limiting the sediment and nutrients available for organisms (Church 1995, Kondolf 1997). These "clear-water" releases can also cause erosion downstream of the dam as the river attempts to regain sediment equilibrium (Kondolf 1997). The channel becomes coarse, or armored, riffle–pool sequences vanish, and bank collapses and riparian losses may result (Dietrich and others 1989, Quinn and Hickey 1990, Sear 1995, Kondolf 1997). Channel incision also occurs, lowering groundwater tables and affecting riparian zones by limiting access to water (Gillilan and Brown 1997). The altered habitat may be inhospitable for some organisms, causing changes in biotic community composition to occur (Quinn and Hickey 1990, Staggs and others 1995, Kanehl and others 1997). A reduction in the amount of transported sediment that is deposited in coastal areas can result in a loss of shoreline and habitat. Alternatively, sediment inputs from tributaries below a dam, unmoved by the slower water velocities in the tailwater, can also cause changes in habitat (Schmidt and others 1998). For example, the Glen Canyon Dam on the Colorado River blocks 95% of the sediment moving down the river in the reservoir (Collier and others 1996). However, the limited amount of sediment present below the dam due to tributary inputs stayed in the river channel rather than in the sandbars that were common in the unimpounded river.

Remediation efforts to return sediment transport to regulated rivers have often involved prescribed flooding or higher releases of water through dams (Collier and others 1996). These high flows have been planned to match natural peak flows, rather than to match peaking hydropower operations. The release of high flows through the Glen Canyon Dam was partly an effort to rebuild degraded, incised beaches and sandbars downstream of the dam (Collier and others 1996, 1997). Some sediment was redeposited further downstream following the managed high flow, and sandbar restoration was observed. However, this sort of episodic high flow may not be able to simulate continuous sediment transport or restore habitat complexity because the river, its natural flow regime, and the bulk of the sediment load are still blocked.

Dam removal is an alternative technique for returning active sediment transport to a river. When a dam is removed, fine sediment is mobilized from the slow-moving reservoir and redistributed, exposing gravel, cobble, and boulders within formerly impounded areas. For example, following the removal of the Woolen Mills Dam on the Milwaukee River in Wisconsin, the percentage of rocky substrate in the previously impounded area of the river increased by nearly two times. The impounded area had formerly consisted of mostly silt and mud (Kanehl and others 1997). Fish, such as the native smallmouth bass, increased in number following the dam removal, perhaps because their preferred habitat is gravelly substrate (Nelson and Pajak 1990). Elsewhere, the Stronach Dam on the Pine River in Michigan is currently undergoing a multiyear removal (D. Hayes and K. Klomp personal communication). This dam has caused fine sediment, particularly sand, to fill approximately 4 km of the river upstream of the dam. Removal of the dam is expected to return the preferred habitat of the native trout and lead to increases in trout population densities.

Dam removal may also restore sediment to coastal beaches. Two dams on the Elwha River in Washington state, the Elwha Dam and the Glines Canyon Dam, are blocking fine sediment transport to near-shore areas, resulting in eroded beaches and shoreline with a preponderance of rocky, armored substrate (DOI 1995). Sand obstruction by these dams has enabled nonnative species of kelp and barnacles to dominate near-shore regions of the Strait of Juan de Fuca, displacing native organisms (DOI 1995). It has also contributed to the loss of estuaries, which often serve as nurseries for fish and shrimp, because sediment bars separating estuarine or brackish water from the ocean are no longer deposited (DOI 1995). The restoration of fine sediment to the coastal regions is expected to return native biota, including economically valuable species such as hardshell clams (DOI 1995). Removing only the dam closest to the ocean, the Elwha, might restore some sediment to the coastal region. However, because the Glines Canyon Dam would still block much of the sediment upstream, releasing sediment-low, potentially erosive water, restoration of estuarine habitats would occur at the expense of upstream habitats (DOI 1995). Both dams on the Elwha River are currently slated for removal.

Connectivity

Connectivity is an important component of nearly all aspects of a functioning riverine system, including the maintenance of flow, water quality, temperature, and sediment transport (Taylor and others 1993, Ward and Stanford 1995). However, connectivity is also important for enabling organisms to travel throughout a riverine system. Continuous passage through a river enables organisms to migrate up and downstream, search for optimal sediment sizes and water levels for spawning, or find areas of greater food availability or lower predation.

Dams fragment the corridor of the river in several ways: they isolate populations and habitats, create physical and thermal obstructions for migrating and drifting stream organisms, and disrupt interactions between freshwater, terrestrial, and coastal systems (Winston and others 1991, Chisholm and Aadland 1994, Dynesius and Nilsson 1994, Stanford and others 1996). For instance, blocked migration of diadromous fish has been an issue for numerous dammed rivers. Many migratory fish are not euryhaline (i.e., they do not have mechanisms to adapt their physiology to different salinities required for movement between fresh and saltwater) (McDowall 1992). The delays in migration time from encountering dams cause energy needed for migration or reproduction to be expended while fish are pooling above or below the dam. For example, the American shad reabsorbs its gonads when returning to the ocean if it is delayed, without releasing eggs or sperm (Dadswell 1996). In addition, predation often increases in pooling areas, where many fish accumulate waiting to pass the dam through fish ladders.

Dam removal may eliminate several problems associated with fish passage for migration or movement within the river channel. First, where a dam has no fish passage structures, removal eliminates mortality due to the inability to pass around the dam and allows organisms to inhabit previously impounded areas. For example, removal of small dams (in Denmark) has resulted in salmonids and other fish being able to reach optimum spawning grounds, enhancing their chances of survival (Iversen and others 1993). Second, where a dam has some form of fish passage, dam removal eliminates death or injuries to riverine organisms caused by passage mechanisms, such as turbine entrainment and fish ladder mortality (Travnicheck and others 1993, Dadswell 1996). Third, where a dam has some form of fish passage, dam removal eliminates delays such as waits at crowded upstream passage devices and downstream delays from swimming through the slow-moving reservoir. Since fish passage structures can not usually accommodate large numbers of fish at the same time, removal will speed fish movement and increase the odds of successful reproduction (Winter 1990, Drinkwater and Frank 1994, Wik 1995). Analyses of fish passage versus dam removal for the Enloe Dam on the Similameen River in Oregon, for example, suggested that added fish passage would not successfully accommodate the large number of migrating fish attempting to pass (Winter 1990).

Removal might also impact organisms that have never been observed using up- or downstream fish passages or that are too large or small for it (Dadswell 1996). For example, there are no records of smelt or Atlantic sturgeon utilizing fish passages on the North American East Coast (Dadswell 1996). Small fish, such as rainbow smelt, might not be able to maneuver through a passage designed to enhance salmon migration, a much larger and stronger swimmer (Dadswell 1996).

The success of efforts to restore river continuity also depends significantly on the extent of the regulation throughout the river. If only one dam is removed on a river that has several, the continued presence of upstream or downstream obstructions limits the extent of the restoration process (Tyus and Winter 1992). One of the first recorded dam removals, the Washington Water Power Dam on the Clearwater River in Idaho in 1963, has improved habitat quality and fish runs of chinook salmon (Shuman 1995). However, the fish runs are not completely restored because of additional dams on the Snake and Columbia rivers through which the fish must maneuver (Shuman 1995).

Short-Term Ecological Impacts of Dam Removal: The Dam Removal Process

The process of dam removal itself has various short-term impacts on the riverine ecosystem. Some of the most significant impacts include sediment mobilization, contaminated material, and an increase in the threat of supersaturation.

Sediment Release

The full or partial removal of a dam results in sediment movement downstream. In most cases, the impoundment above the dam will have been accumulating sediment for many years and, in some, the impoundment may be almost completely filled (Kondolf 1997). This sediment is usually fine silt and sand because coarser rock is likely to have settled in the inflow of the reservoir (Kondolf 1997). Dam removal produces disturbance and resuspension of this sediment during the transition from a reservoir to a free-flowing river (Doeg and Koehn 1994).

Increased sediment loads can damage spawning grounds for various organisms such as fish and mussels (Bogan 1993). The roots and stems of macrophytes are damaged through abrasion (Wood and Armitage 1997). Algae and insects are scoured as sediment moves downstream and are unable to attach to substrate covered in fine silt or sand (Newcombe and MacDonald 1991, Wood and Armitage 1997). Food quality is diminished as fines accumulate within matrices of algae (Wood and Armitage 1997). Some types of invertebrate habitat or food sources, such as leaf packs, can be completely covered so that they are unusable (Doeg and Koehn 1994).

The increased turbidity from dam removal, however, should be mostly a temporary effect. Several completed dam removals have demonstrated that sediment eventually flushes out of a turbid river channel (see Winter 1990, Kanehl and others 1997). Recovery time depends on factors such as the length of time sediment has been accumulating, the velocity of the river, the gradient of the riverbed, and the techniques of removal. For example, when the Grangeville and Lewiston dams on the Clearwater River in Idaho were removed, the wave of silt and sediment moved downstream within one week even though the reservoir of the Lewiston Dam had been completely filled with sediment (Winter 1990). The flushing of the river following removal of the Woolen Mills Dam in Wisconsin took only six months to move much of the fine material downstream (Nelson and Pajak 1990). The amount of sediment released from the removal of the Sweasey Dam in California was estimated to be the same amount as that released by a two-year storm (Winter 1990). At the other extreme, flushing of sediment from removal of the Newaygo Dam on the Muskegon River in Michigan is expected to take 50–80 years, depending on how many high flows occur during that time (Simons and Simons 1991).

This range of recovery is wide, but is consistent with natural variations in the sediment levels of a river. Despite the lengthy projected flushing time of the Muskegon River, engineers have determined that the sediment released is within the natural range of variation for sediment levels in the river (Simons and Simons 1991). Certain rivers are able to flush large amounts of sediment relatively rapidly. For instance, the eruption of Mount St. Helens released 3 billion cubic yards of sediment into part of the North Fork Toutle River basin and 50 million cubic yards of sediment and debris into the South Fork Toutle River basin, burying approximately 90% of available stream habitat for salmon and nearly all riparian vegetation (Lucas 1985). Although the habitat was nearly wiped out, fish began to reappear only three months after the mudslides and influx of sediment.

The timing of dam removals significantly alters the effects of sediment movement. If removal occurs during a period of low flow, the river may not have enough power or force to transport sediment downstream, aggravating turbidity (Kondolf 1997). Conversely, release during very high flows, such as spring run off, may have detrimental effects because of already heightened sediment loads from normal spring runoff. The Grangeville Dam removal in Idaho was timed to be removed before spring runoff to minimize silt impacts (Winter 1990). A week later, the river was clear of the extra sediment from the removal.

Other techniques to reduce the adverse impacts of excessive sediment suspension include gradual drawdown of the reservoir, sediment screens and traps, and/or immediate stabilization of reservoir sediments following drawdown (ASCE 1997). If sediment impacts from a dam removal are predicted to be severe, dredging of the sediment from the reservoir can be conducted (ASCE 1997).

Contaminated Sediment

Contaminated sediment is another important consideration for dam removal (Murakami and Takeishi 1977, Stone and Droppo 1994, Chatterjee 1997). Because small-size sediments tend to sorb (attach) relatively more contaminants than coarse sediments due to their large ratio of surface area to volume, a release of fine sediment impounded behind a dam may constitute a major hazard to the river (Stone and Droppo 1994, Wood and Armitage 1997). Thus, toxics released upstream are both more likely to settle out of the water column within a slow-moving reservoir and to accumulate in the fine sediments located therein. Contaminated sediments can also become enmeshed in algal mats, or in some cases, attach to algal cells and eventually accumulate in higher trophic levels.

If precautions are not taken, dam removal can result in a resuspension of the contaminated sediments behind an impoundment. For example, the removal of the Fort Edwards Dam on the Hudson River in New York in 1973 resulted in a release of PCB-contaminated (polychlorinated biphenyl) sediments (Shuman 1995, Chatterjee 1997). Predam removal studies and monitoring will reveal the extent of sediment contamination and the hazard it poses to the ecosystem. Options for dealing with contaminated sediment include capping sediment with concrete or employing appropriate dredging techniques that minimize resuspension (Cooke and others 1993).

Supersaturation

Supersaturation could also be a concern with some dam removals. A rapid drawdown of a reservoir during removal will produce short-term increases in velocity and pressure, which increase chances for gas-bubble disease in fish (Weitkamp and Katz 1980, Wik 1995). During a 1992 drawdown test on the Little Goose Dam (on the Snake River in the Pacific Northwest), dissolved gas supersaturation increased, along with turbidity and loss of reservoir fish and insects (Wik 1995). However, these losses and changes were short term and did not affect overall populations (Wik 1995). If the removal is gradual, sharp increases in velocity may be avoided, lessening the chances of supersaturation.

Discussion

Measures to mitigate the negative impacts of a dam, such as initiating or increasing minimum flows, enhancing fish passages, or improving dissolved oxygen levels, have been implemented through the relicensing process at FERC-regulated dams, as well as at federally operated dams, and have been successful in restoring some river segments. For example, the Tennessee Valley Authority (TVA) has the Reservoir Release Improvement Program, which is aimed at implementing and improving minimum flows and water quality throughout the TVA system (Higgins and Brock 1999). In some cases, mitigation techniques have successfully returned habitat or native fish species (Auer 1996, Collier and others 1996, 1997, Higgins and Brock 1999). There may be many instances in which dam retention, accompanied by continuing mitigation efforts, may be a reasonable approach to reducing the ecological impacts of dams.

In order to evaluate fully the ecological impacts of the various alternatives (i.e., mitigation or removal), however, the ecological effects of dam removal need to be documented and quantified. Unfortunately, many recorded dam removal studies thus far have been brief and mostly descriptive (e.g., Winter 1990, Hill and others 1993, Estes and others 1993, ASCE 1997). For example, the state of Wisconsin has removed approximately 61 dams since 1965, yet there has been little long-term monitoring before the removal or extensive follow-up studies because such studies were not included in the dam removal plan or funding package (American Rivers and NPS 1996). This general absence of preremoval sampling may also be due an increasing urgency to remove dams for various ecological or economic reasons. However, characterizing the ecosystem before a large change occurs (such as a removal) can also be important for understanding the processes involved in the river's response to the removal and subsequent recovery process.

Another factor complicating the process of documenting the impacts of dam removal is a lack of monitoring programs at privately owned dams. For example, a survey given to owners of hydroelectric facilities showed that only 54% had monitoring programs after a dam was constructed (Lewis and Mitchell 1995). Those companies and projects that do have monitoring programs provide little detailed information. Much of the data involves just a few characteristics of the river, such as fish species. None of the companies surveyed monitor the changes in the physical environment that result from flow alterations at the dam. This condition may change now that FERC has begun to require monitoring technology at many hydroelectric dams as a condition of the relicensing process (Hancock 1995).

The importance of dams worldwide affects the progress of dam removal itself. Dams continue to be built and highly valued throughout the world, making removal difficult to document or champion in some places. Developing countries often have inefficient methods of power production (and high levels of greenhouse gas emissions), as well as a need for cheap sources of power, improved flood control, and water supply (Edmunds 1991). For example, the Three Gorges Dam currently under construction in China will purportedly serve these functions (Edmunds 1991, Chau 1993). China hopes to reduce its dependence on coal-fired plants, reduce its greenhouse gas emissions, and improve flood control, electricity supply and standard of living for numerous rural villages with this dam (Edmunds 1991). Conversely, there are many controversial environmental and social issues associated with the project, such as the flooding of the gorge, blocked dolphin and fish movement, massive resettlement, and loss of cultural artifacts (Dai 1991, Edmunds 1991). However, China's socioeconomic needs are powerful and dam removal is not likely to be a viable option for existing dams there or in many other developing countries. Instead, dam removal has mostly occurred in developed countries.

Although dam construction has waned in developed countries, proposed removal of large dams (i.e., greater than 5 ft tall) continues to generate controversy. Four dams on the Snake River in the United States are currently under consideration for removal to improve salmon migration. Those opposed to removal cite numerous costs to dam decommissioning in the Snake River. For example, water wells could be affected by the drawdown of the reservoirs that use surface water and discharge wastewater into the river (Tatro 1999). Drawdown will also expose 8100 ha of land, leaving mudflats and undesirable riparian lands (Tatro 1999). Thirty of the thirty-three recreational sites in the area would be affected by the removal (requiring some sort of modification to remain usable), with 11 sites requiring demolition (Tatro 1999). Other opponents of proposed dam removals in the United States cite recreation, flood control, water supply, and reliance on hydropower as an efficient and inexpensive source of power as objections to removal. These socioeconomic issues are important considerations for decisions about whether or not to remove a dam.

Continued dam construction and defense of existing dams currently confines removal to small, defunct, or underutilized dams (American Rivers and NPS 1996, American Rivers and others 1999). Indeed, understanding how dam removal will generally impact river ecosystems may be limited until a wider range of sizes and types of rivers worldwide are undammed. However, despite the limitations of current data for dam removals, lessons from past removals serve as important guides for future ones. The case studies used in this review illustrate that removals have influenced some of the most crucial ecosystem components. The effects of dam removals should be considered an important element of research programs if paradigms and models are to be developed to predict the effects of human manipulations of ecosystems. Studies of restoration following dam removals may provide valuable evidence of the resistance or resilience of different populations, communities, or ecosystems. Although dam removal continues to be contentious (Tatro 1999, Wood 1999), a critical examination of all the benefits and impacts of dam removal should lead to better restoration for all rivers.

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