components of the river. Dam removal results in the remobilization of sediments once stored in reservoirs, and some of these sediments may be high in nutrients or contaminated by pollutants. Therefore, planners and researchers need to undertake wide-ranging assessments of likely outcomes of dam removals that account for anticipated changes in water, sediment, landforms, vegetation communities, and fish and wildlife.

- **Conclusion:** Sediment processes are the most fundamental aspects of dam removal issues that are poorly understood. Water quality is important because of its human health and environmental dimensions; it is governed by extensive policies, yet outcomes of dam removal on water quality are poorly understood. Empirical data are lacking on river channel change downstream from removed structures.
- **Recommendation:** The panel recommends that the scientific community of river researchers provide (1) improved understanding of sediment quality and dynamics to provide a scientific basis for evaluating contaminated sediments, (2) improved understanding of the roles that dams and their potential removal play in water quality models, (3) empirically derived explanations of river channel change upstream and downstream from removed dams; and (4) a knowledge base of the likely fate of sediments and their contaminants downstream from removed dams.

- **Conclusion:** There is a glaring need in the science and decision-making communities for a geospatial database that provides accurate, readily accessible data about the segmentation of the nation's rivers by dams.
- **Recommendation:** The panel recommends that U.S. Environmental Protection Agency, and/or U.S. Geological Survey should consider augmenting the existing national stream reach geographical data to include the location of dams and to allow better analysis and understanding of the segmented nature of the nation's streams and rivers.

- **Conclusion**: The quantity of sediment discharged is available from the U.S. Geological Survey as part of its stream gaging efforts. However, the number of gages producing sediment data is only a portion (1,600) of the total national gage system (6,600).
- **Recommendation**: The panel recommends that the U.S. Geological Survey maintain and extend its network of sediment measurement statistics throughout the total national stream gauging system.

5

Biological Outcomes of Dam Removal

AQUATIC ECOSYSTEMS include components ranging from an entire watershed to one-celled bacteria that are responsible for primary decomposition. Rivers are dynamic entities that undergo change and evolution, continuously creating, evolving, and realigning new aquatic habitats. An aquatic ecosystem is a complex continuum of habitats that include production zones, spawning areas, refugiums for various life stages of fish and metapopulations (Figure 5.1), migration corridors, feeding stations, and a plethora of unique microhabitats. The physical and biological processes of the river system define each ecosystem component.

This chapter explores the biological aspects of rivers that are relevant to decisions about dam removal. As is evident with respect to the physical and hydrologic aspects of rivers, scientists know a great deal more about the biological changes effected by the installation of dams than about those induced by dam removal. The chapter begins by providing a framework of levels of change and response and then discusses the fundamental contexts for restoration: spatial, temporal, and ecosystem contexts. Finally, this chapter reviews the various factors that affect restoration.

Aquatic ecosystems are the products of the dynamic relationship between the watershed and the biological resources that live in the river system. A river is the sum of its parts and often has been referred to as a continuum of ecosystems and processes (Figure 5.2) (Vannote et al., 1980). Rivers and reservoirs are shaped by inputs from the upstream watershed. Rivers and reservoirs exhibit different trophic relationships due to modified hydraulic dynamics and variables. A trophic hierarchy exists in rivers, building from the primary sources of energy, the algae and macrophytes; to the primary consumers; to, ultimately, the fishes and the

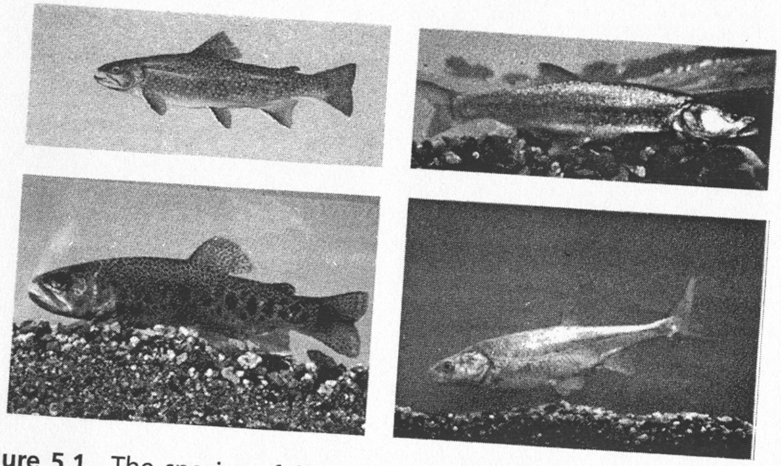
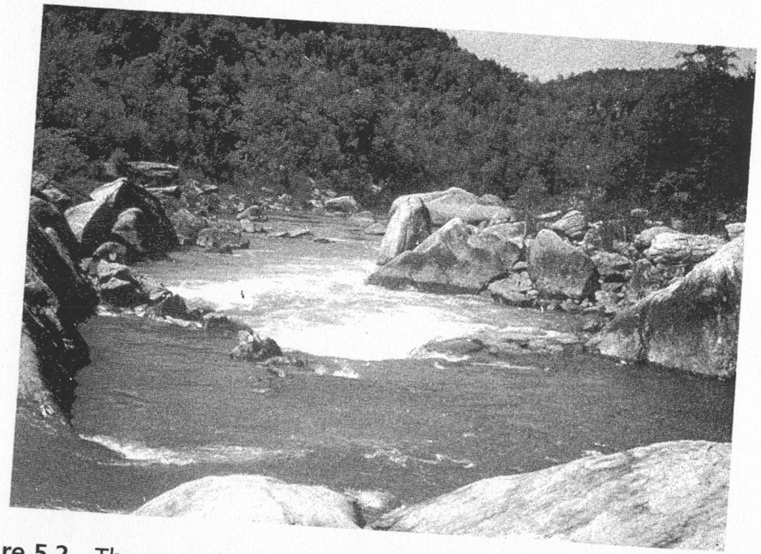


Figure 5.1 The species of fish that live in rivers include brook trout (top left); pike minnow (top right, an endangered species); Gila trout (bottom left, also endangered); and Virgin River chub (bottom right, endangered). Courtesy of the U.S. Fish and Wildlife Service, photographs by Duane Raver Art.



igure 5.2 The aquatic environments on the free-flowing South Fork f the Cumberland River in Tennessee range from rapids to tranquil ools. A dammed river, in comparison, has less varied habitats. Photo ourtesy of the U.S. Army Corps of Engineers.

issues associated with their distribution and abundance, life-history adaptation, and management. In river systems without dams, changes are often subtle unless a large, river-reshaping event occurs, such as a flood or massive land change (Poff et al., 1997; Richter et al., 1996).

The shape and size of a river is a function of the flow, quantity and character of the sediment in transport, and character and composition of the materials that make up the bed and banks of the river (Leopold, 1994). By affecting quantity and timing of water flow, flow velocities, water chemistry and biogeochemical cycling, dams change the dynamic relationship between the watershed and river and, consequently, affect the species that depend on the river and riparian area for their survival (Ligon, Dietrich, and Trush, 1995; Power et al., 1996). According to a recent report by the Wisconsin Department of Natural Resources, dams are among the most significant obstacles to restoring the biodiversity and integrity of riverine systems (Born et al., 1998).

A watershed perspective is especially helpful in visualizing and understanding the physical systems of rivers, as outlined in Chapter 4. However, watersheds also can be viewed as ecosystems, functioning collections of organisms and their inorganic support systems (Meehan, 1991). Ecosystem boundaries are difficult to map and interpret, but watershed boundaries are usually clearly defined, and they make useful margins for biological analyses involving water-related resources. Scientists and policymakers involved in dam removal decisions will find the recently published *Freshwater Ecoregions of North America: A Conservation Assessment* (Abell et al., 2000) especially helpful in this regard, because it focuses largely on biological resources and is compartmentalized according to watersheds and river basins. The maps and diagrams in the report are helpful in placing dam decisions in both a physical and a biological context.

POTENTIAL IMPACTS OF DAM REMOVAL ON AQUATIC ECOSYSTEMS

The placement of a dam and a reservoir on a river modifies the biogeochemical cycles both in the reservoir and downstream (Stanford and Ward, 1979). Dams immediately fragment the river system, leading to modified flows (i.e., water quantity, timing, and quality) and, subsequently, changes in the movement patterns, process times, available habitats for fish and macroinvertebrates, and ultimately has resulted in losses of biodiversity. The modification of a natural flow regime has direct, indirect, cumulative, and specific watershed-level impacts on an aquatic ecosystem (Poff et al., 1997)

Changes in the river's aquatic ecosystem responses are defined and controlled by the limnological events occurring in the upstream reservoir and further modified by the discharge regime from the dam (American Fisheries Society, 1985; EPA, 1989; Tyus, 1999; U.S. Department of Energy, 1994). To predict the effects of dam removal, it is necessary to understand how dams have influenced the downstream and upstream environments. The key aquatic ecosystem characteristics that can be used to assess the influence of dams as the downstream environment include the following:

- Modified substrates associated with the armoring of the streambed downstream and the subsequent reduction in the amount and availability of spawning habitats
- Loss of small-grained sediments necessary for transferring nutrients and for providing substrate for riparian and aquatic plants (Wilson, Gendhe, and Marston, 1988; Gresch, Lichatowich, and Schoonmaker, 2000)
- Loss of the ability to support nutrient and energy flow (Larkin and Slaney, 1997; Cederholm et al., 1999)
- Modified thermal regimes in terms of timing, ecological cues for life cycles, and total number of degree days necessary for development (Collier, Webb, and Schmidt, 1996; Vinson, 2001)
- Modified downstream aquatic saprophyte assemblage due to changes in sediment delivery, thermal conditions, seasonal floods, etc. (Voelz and Ward, 1991; Stevens, Shannon, and Blinn, 1997; Andrews, 1986)
- Modified macroinvertebrate species diversity associated with changed thermal cues, habitats, and timing of life history strategies (Vinson, 2001; Lehmkuhl, 1972)
- Modified fish assemblages associated with changes in habitats, introduction of non-native species, changing food bases, and modification of thermal and other water quality and quantity cues necessary to initiate specific life history cycles; these effects cause changes in the reproductive cycles and growth of young fish and result in the loss of effective migration ability among adult and juvenile fish (National Research Council, 1992, 1996; Petts, 1980)

Just as constructing a dam alters the natural environment of a river, removing a dam also alters the aquatic ecosystem below and above the structure. The changes are variable on both temporal and spatial scales. The ecological changes depend on the size of the structure and amount of water that it impounds; quantity and quality of sediment trapped in the reservoir; season and timing of the draining of the reservoir; native and non-native fish and invertebrate species that inhabit the reservoir; limnological conditions in the reservoir; and stability of the downstream river channel (Burns, 1991; Dynesius, Nilsson, 1994).

Dams create reservoirs, which are artificial bodies of water that create modified hydrologic, physical, and biological environments that differ from those provided by rivers. Depending on the size, watershed, and management of the reservoir, wetland habitats may be temporarily formed at the low area of the reservoir and the number of species may temporarily increase. Problems with reservoirs arise, however, as water levels fluctuate, resulting in direct impacts to wetland habitats (Bolke and Waddell, 1975; Heiler et al., 1995).

The removal of a dam has both short-term and long-term effects on a river's aquatic ecosystem and biodiversity. Biodiversity, short for biological diversity, is defined by the National Research Council (1997) as the variety of life found on the planet. Although dams can have some positive ecological effects (e.g., creating additional wetland habitat), removing a dam may increase the abundance and diversity of aquatic insects, fish, and other organisms (Doyle et al, 2000; Ward and Stanford, 1995; Malmquist and Englund, 1996; Doeg and Koehn, 1994; Camargo and Voelz, 1998). Wetlands surrounding the reservoir may be lost, but wetlands and riparian areas along the banks of the rivers may be restored. In addition, although water quality often is degraded immediately following a removal, the restoration of a river's natural flow may eventually result in improved aquatic habitat. Once a dam is removed and crucial upstream habitat becomes accessible, migratory fish populations (including endangered or threatened species) often rebound (American Rivers et al., 1999). The removal of a dam has a lasting impact, however, on some game species of fish (Shuman, 1995) (Figure 5.3). Dams usually change rivers from a state of constant flow to a more lake-like condition with standing water.

Different species of fish use specific habitats. Panfish, catfish, and largemouth bass are typical of the fish assemblages that are supported by reservoirs. Native fish species have evolved specific life history characteristics that allow them to survive and flourish in a flowing water environ-

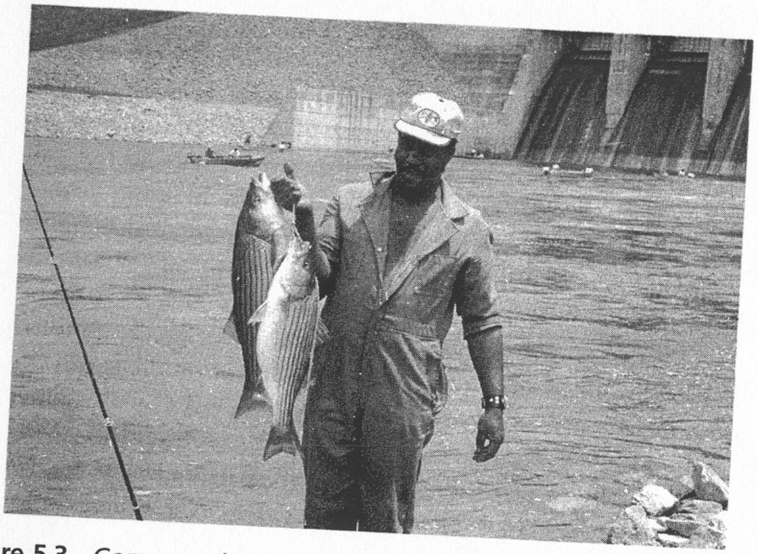


Figure 5.3 Game species, such as these striped bass, may be affected by the removal of a dam. Courtesy of the U.S. Army Corps of Engineers.

ment, such as a river. With the removal of a dam, the fish assemblages supported by the reservoir are forced to change (Jennings, Forem, and Karr, 1995). Studies conducted on the fish assemblages on the Baraboo River in Wisconsin showed that the communities changed rapidly as the river reclaimed its natural flow dynamics (Catalano et al., in press). Within eighteen months after the removal, the number of fish species upriver from the former dam site increased from 11 to 24, according to a Wisconsin Department of Natural Resources survey. The number of smallmouth bass species, which cannot tolerate poor water quality, increased from 3 to 87 (American Rivers et al., 1999; Kennebec Coalition, 1999).

The response of an aquatic ecosystem following a dam removal may result in a different aquatic community than existed before dam construction (Wik, 1995; Travnicheck et al., 1995; Shuman, 1995). The pre-dam community may reappear only through active restoration activities, such as non-native fish eradication, habitat and substrate restoration, and watershed management. (In some cases, the pre-disturbance species may have been eliminated and upstream watershed processes modified.) The bottom line is that the pre-dam aquatic community likely has changed, through development and successional processes, in response to the natural and modified physiochemical environment, watershed, and habitat changes. These changes seldom are related directly to the dam in question, so dam removal by itself is unlikely to restore the exact ecological conditions that existed before human occupation of the floodplain (Box 5.1). It is possible to reach limited restoration goals with dam removal, especially in the reestablishment of fish passages (Box 5.2).

Box 5.1 The Unanticipated Impacts of Removing Fort Edward Dam in New York

The experience of removing Fort Edward Dam shows how complicated true river restoration can be. The project also demonstrates the need for comprehensive pre-removal environmental assessment studies. Constructed in 1898, Fort Edward Dam was a 586-foot-long, 31-foot-high hydroelectric dam on the Hudson River in New York. Its owner, the Niagara Mohawk Power Corporation, removed the dam in 1973 after a study concluded that it was a public safety hazard.

Although several studies and analyses were conducted before the removal, they were inadequate with respect to determining the full impact on surrounding areas, aquatic ecosystems, and navigation. Soon after the dam was removed, unanticipated water quality and navigational problems appeared, some of which continue to this day. For instance, the quality of the sediment trapped behind the dam was not analyzed sufficiently to discover the presence of polychlorinated biphenyls (PCBs) that had been accumulating from an upstream chemical manufacturing plant. The sudden release of these contaminants was catastrophic for the river's ecosystem, causing New York State to close the Hudson River to fishing in 1976 and the U.S. Environmental Protection Agency to declare a portion of the river a federal Superfund site in 1983. In addition, the sediment moved downstream and effectively blocked a large portion of the Hudson River navigation channel, a marina, several industrial sites, and other downstream areas. The channel's reduced capacity and restricted water flow also increased the flood hazard for the town of Fort Edward and created a public health hazard when untreated raw sewage released into the river began to stagnate.

These unanticipated impacts resulted in several lawsuits and millions of dollars in lost revenue (mainly for fisheries and navigation) in addition to the clean-up and restoration costs. Lessons from the Fort Edward dam removal have been incorporated into more recent dam removal decisions. The lessons include the importance of testing and analyzing both the quantity *and* quality of the accumulated sediment and determining the potential impacts of the sediment release and decreased water flow on the entire upstream and downstream environment.

Box 5.2 The Restoration of Butte Creek in California

Dam removal can be an effective part of a more comprehensive river restoration program. The 1998 removal of four water diversion dams and 12 unscreened water diversions on Butte Creek in Sacramento Valley, California, was the result of a decision based on both agricultural and ecological values. Rice farmers bordering Butte Creek traditionally eliminated rice stalks from the previous year's crop in their fields by burning. In 1991, air pollution from this activity became so problematic that an alternative had to be found, and the rice farmers turned to the river. By flooding their fields, they could accelerate the decomposition of the rice stalks. However, the California Department of Fish and Game was concerned that the unscreened water diversions might further harm Butte Creek's already threatened salmon population.

In 1987, only 14 spring-run chinook had been found spawning upriver of the dams in Butte Creek. Once California's most abundant salmon species, the spring-run chinook was listed as threatened under California's Endangered Species Act and was being considered for listing under the federal Endangered Species Act. If the chinook were listed, not only would the rice growers not be able to flood their fields, but commercial fishermen would not be able to fish on Butte Creek, and pumps on the creek, which supply Southern California with water, could be shut down. The California Department of Fish and Game, Western Canal Water District (which owned two of the dams), U.S. Department of the Interior, and California Urban Water Agencies worked collaboratively to remove the four dams and 12 diversions. The project's total cost was $9.13 million. Removing the dams and diversions restored 25 miles of Butte Creek to a free-flowing condition, and more than 20,000 adult chinooks spawned in Butte Creek in 1998.

Source: American Rivers et al., 1999.

AQUATIC ECOSYSTEM RESTORATION PLANNING

All restorations are exercises in approximation and in the reconstruction of naturalistic rather than natural assemblages of plants and animals with their physical environments (Berger, 1990). In some cases, rehabilitation may be a more descriptive term, because the management goals may be to repair damage to river processes and forms resulting from a dam or its operation. The removal of a dam provides an opportunity for a river to partly reconnect its watershed. Predicting what will happen to the aquatic ecosystem when a dam is removed is more complex than simply taking down a dam and letting "nature" take its course. Whether a dam removal project is judged a success or not will depend on the goals and objectives of the removal. As discussed in Chapter 3, these goals and objectives of dam removal need to be articulated as the first step in the decision-making process regarding dam removal. Legal considerations may force a decision to remove a dam for safety reasons, while the restoration of habitat for legally protected species may be the primary factor. The removal of Savage Rapids Dam in Oregon is one of many such cases (Box 5.3).

"Restoration" of rivers is a commonly stated goal in dam removal decisions, so decision makers need to be clear on the implications of using the term (National Research Council, 1992). Restoration is defined by the National Research Council (1992) as

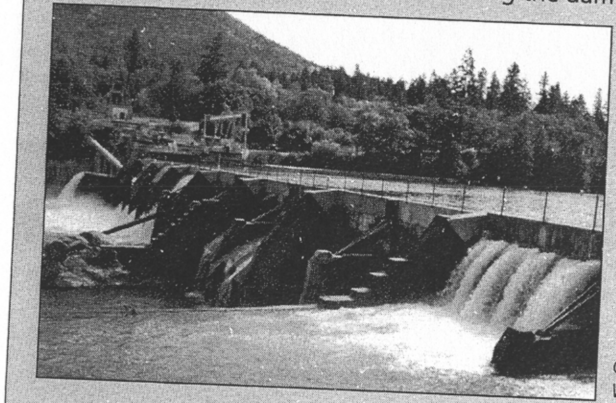
> The return of an ecosystem to a close approximation of its condition before disturbance. In restoration, ecological damage to the resource is repaired. Both the structure and the functions of the ecosystem are recreated. Merely recreating the form without the functions, or the functions in an artificial configuration bearing little resemblance to a natural resource, does not constitute restoration. The goal is to emulate a natural, functioning, self-regulating system that is integrated with the ecological landscape in which it occurs. Often, natural resources restoration requires one or more of the following processes: reconstruction of antecedent physical hydrologic and morphologic conditions; chemical cleanup or adjustment of the environment; and biological manipulation, including revegetation and the reintroduction of absent or currently nonviable native species.

The National Research Council (1992) also notes that no restoration can ever be perfect. It is impossible to replicate the exact biogeochemical and climatological sequence of events over geologic time that led to the creation and placement of even one particle of soil, much less to restore an entire ecosystem. In developing restoration strategies, the recovery of an ecosystem to an approximation of its natural predisturbance condition needs to be pursued as the first goal. In many situations, this ideal may not be practical, physical, and biological as illustrated in Figure 5.4.

The shaded area represents an "envelope" in which the morphology and function of the ecosystem are considered acceptable and achievable under existing social, political, economic, and engineering constraints (NRC, 1992). The goal in this restoration scenario would be to transform

Box 5.3 Legal Considerations in the Removal of Savage Rapids Dam in Oregon

The decision about whether or not to remove Savage Rapids Dam, located on the Rogue River in Oregon, is an example of a process driven by concern for an endangered species and habitat restoration. This concrete diversion dam, which stands 39 feet high and 460 feet wide, was constructed in 1921 to divert water to farmers. The dam's owner, the Grants Pass Irrigation District (GPID), has known for years that the dam impedes the upstream and downstream passage of salmon and steelhead trout. Moreover, the dam no longer provides any flood control, storage, or power generation benefits. Twice, in 1994 and 1997, the GPID Board of Directors voted in support of dam removal, thus agreeing with the National Marine Fisheries Service (NMFS) to improve passage for the endangered fishes. In 1995, the U.S. Bureau of Reclamation completed a study that estimated the cost of refitting the dam to be less lethal to salmon could run as high as $21 million. In contrast, removing the dam and meeting local water needs with modern pumps was estimated to cost only $13 million (Waterwatch, 2001).



The Savage Rapids Dam in 1999.

Courtesy of Waterwatch

Box 5.3 continued

The GPID did not remove the dam when new board members were elected. In response, the NMFS brought suit against the irrigation district under the federal Endangered Species Act (ESA) in 1998, because one of the salmon species affected by the dam is the ESA-listed coho. Several conservation, sportfishing, and commercial fishing organizations have joined the federal government in the pending lawsuit. Despite efforts by the GPID to save it, Savage Rapids Dam may be removed because of legal actions under Oregon water law and the ESA. Dam removal and replacement with pumps is the only permanent solution to the problem and the only solution that eliminates the GPID's ongoing liability for fish losses at the dam. It is also the only solution that guarantees that the GPID will receive an incidental take permit under the ESA and allow settlement of the ongoing litigation with the federal government. This permit is needed to ensure the GPID's continued right to operate its diversion system.

In October 2001, the governor of Oregon signed a consent decree that dissolved the state and federal lawsuits against the GDIP over the harm the dam has caused endangered coho salmon. The agreement calls for a new pumping system that will divert water into irrigation canals without disturbing the fish in the river to be installed by 2005, followed by dam removal by 2006 (Olson, 2001). However, the agreement depends on the U.S. Congress approving at least some funding for the project, estimated at $22.2 million. U.S. Senator Ron Wyden (D-Oregon) introduced the Savage Rapids Dam Act of 2000 (S. 3227) in the 106th Congress. However, there was insufficient time to pass the bill in the last session and no comparable bill has been reintroduced. Initial removal study funding of $500,000 has been appropriated (Grants Pass Irrigation District, 2001).

the ecosystem, by the time the project is complete, from its present state to some point within the achievable envelope.

SPATIAL AND TEMPORAL CONTEXTS

From a spatial perspective, rivers operate within a specific arrangement of the earth's surface that is delimited by watersheds (National Research Council, 1999). Watersheds are areas of land surface that contribute runoff—including water, sediment, and chemicals—to confined channels (Williams, Wood, and Dombeck, 1997). Small basins are nested within larger ones in a topographically defined arrangement, culminating in the watershed that constitutes the areas and supports river basins. The aquatic resource is organized, supported, and defined according to watersheds. The dams and their effects are best understood in a watershed context (Dynesius and Nilsson, 1994; Stanford and Hauer, 1991; Ward and Stanford, 1995). The removal of a dam strongly influences its immediate site and reservoir area and is likely to have effects far downstream. Removals

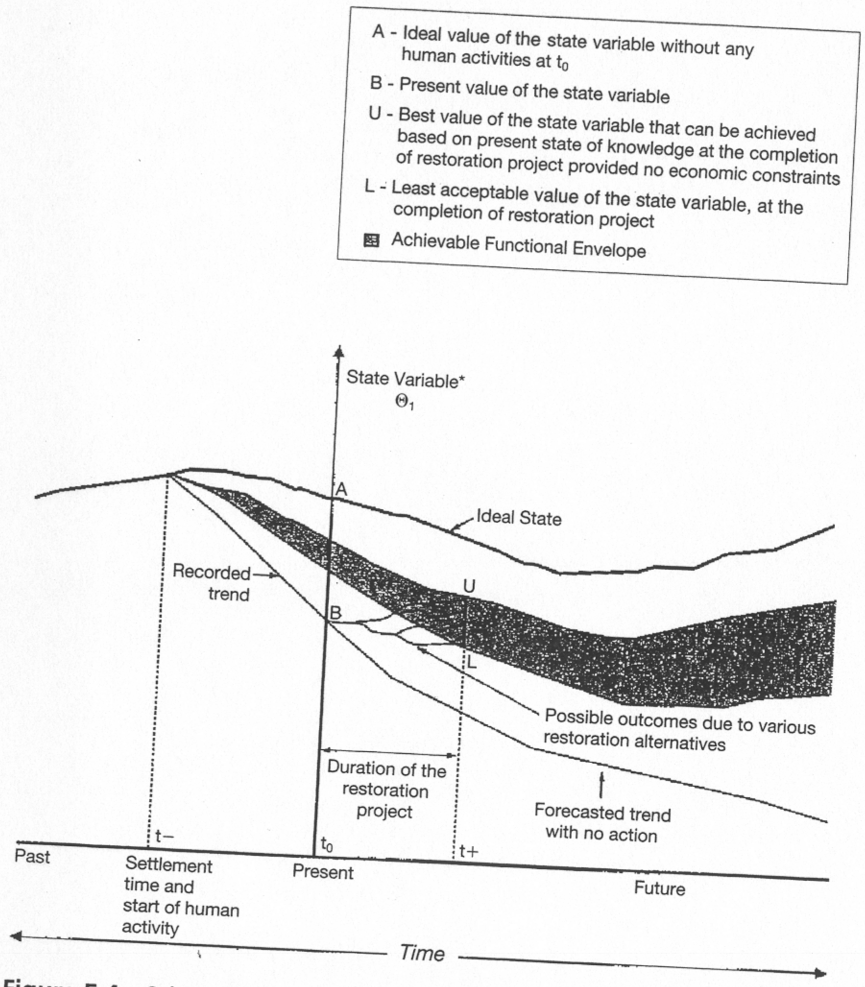


Figure 5.4 Schematic representation of a restoration scenario. *Source:* Reprinted with permission from National Research Council (1992).

of dams also may propagate effects upstream of the impounded reach by reconnecting headwater areas to aquatic organisms that can migrate upstream without an impeding structure and reservoir in place. Reconnecting the river's ecosystem will allow for retrieval and energy exchange (Hall, 1972; Wood and Armitage, 1997; Camargo et al., 1998; Hughes and Noss, 1992), sedimental redistribution (Petts, 1980; EPA, 1989; Tyus, 1999), and fish passage (AFS, 1985; Raymond, 1988; Burns, 1991;

Bates, 1993). Because dam decisions affect watershed-scale processes, the decisions often should be made within the same watershed context. The Conestoga River dams of Pennsylvania exemplify this approach (Box 5.4).

Restoration can involve passive or active processes or both. Passive restoration uses the natural river processes following their own timetable. Active restoration involves direct actions and management to assist in the restoration effort.

AQUATIC ECOSYSTEM INDICATORS OF RESTORATION

Determining what an aquatic ecosystem restoration will look like is an essential first step in developing and implementing a credible dam removal program. The determination of ecosystem responses to restoration actions is complex and a criterion of immense importance in the dam removal process.

Evaluating of recovery patterns of aquatic ecosystems requires the selection and use of indicators that are characteristic of the specific aquatic ecosystem and that include the appropriate spatio-temporal scale of observation (Kelly and Harwell, 1990). Biotic and abiotic indicators commonly are used to evaluate aquatic ecosystem responses (Ward and Stanford, 1979; Shuman, 1995; Karr, 1981; Auble, Friedman, and Scott, 1994). Figure 5.5 is a graphic representation of possible functional end points.

An aquatic ecosystem's biotic response following dam removal needs to be evaluated at both structural and functional community levels. Most common macroinvertebrates and fish species are used as indicators of aquatic community responses. Structural criteria include the composition of the community assemblages in terms of attributes such as density, number of species, and species diversity, along with indicator and keystone species (Milner, 1994). Criteria typically include a comparison to pre-disturbance times or a reference community. Functional criteria refer to the response of the community as indicated by production, trophic and species equilibrium, and the existence of keystone species. A common methodology used to evaluate community function is the concept of biological integrity, which is described well by Karr (1994).

A biotic response includes both habitat and water quality. Physical habitat quality may include the amount of gravels for spawning, heterogeneity of the substrate, and complexes of useable and available habitats. Water quality criteria include dissolved oxygen levels, thermal characteristics, pH, total suspended sediment, heavy metal concentration, and nutrient levels.

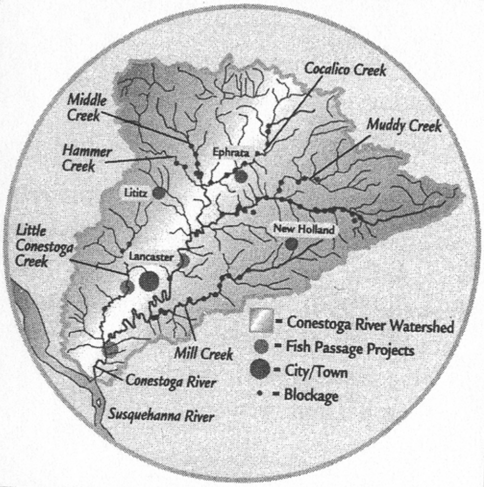
Rivers exist in a dynamic equilibrium and, as a result, the species that inhabit these aquatic ecosystems continuously respond to changes (Vannote et al., 1980). Ultimately, an aquatic ecosystem may not recover to a pre-disturbance condition unless a self-sustaining community based on natural reproduction, succession, and adaptation is attained (Cairns, 1990).

Box 5.4 Dam Removals in the Conestoga River Watershed in Pennsylvania

Decisions about dam removal on the Conestoga River demonstrate the value of a watershed perspective in the decision-making process. The Conestoga River and its tributaries in southeastern Pennsylvania include approximately 114 stream miles. The system drains approximately 477 square miles and is part of the Chesapeake Bay watershed. The Conestoga River system historically supported breeding and rearing habitat for migratory fish species, including American shad (*Alosa sapidissima*), alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), and American eel (*Anguilla rostrata*). However, the 28 artificial blockages (including 23 dams) on the Conestoga River and the 45 artificial blockages (including 44 dams) on its major tributaries made much of the watershed inaccessible to migrating species.

The 1987 Chesapeake Bay Agreement included a commitment that the states that were signatories provide for fish passage at dams and remove stream blockages whenever necessary to restore migratory fish. Since that time, efforts have been undertaken to restore fish passage along the Conestoga River and its tributaries. The Pennsylvania Fish and Boat Commission, through its Consultation and Grant Program for Fish Passage and Habitat Restoration, has been involved in the design and funding of some 20 fish passage projects. In addition, numerous dams have been removed, including four along the Conestoga River (Rock Hill, Eden Paper Mill, Wenger Mill, and Hinkleton Mill dams) and five along its tributaries (Maple Grove, Millport Roller Mill, Lititz Run Intake, East Petersburg Intake, and Martin's dams). All were obsolete run-of-river dams originally built to power mills or supply water to navigation canals. Seven dams removed between 1997 and 1999 varied in height from 3 to 13 feet and in length from 10 to 300 feet, and they cost between $1,500 and $110,000 each to remove (American Rivers, 2001a).

All together, these restoration efforts have reopened more than 28 miles of the Conestoga River to migratory fish. In June 2000, American shad were collected at Lancaster Intake Dam for the first time in decades. In addition to dam removals, efforts are under way to improve water quality in the Conestoga River and its tributaries. Siltation and nutrients have been identified as the two most prevalent causes of quality impairment in the basin. The continued efforts of watershed groups, nonprofit organizations, and government agencies to restore the water quality and integrity of tributary stream channels will have a positive impact and contribute to anadromous fish restoration in the Chesapeake Bay watershed.



Map of the Conestoga River watershed.

Courtesy of Ted Walke, Pennsylvania Fish and Boat Commission

Box 5.4 continued

Factors Affecting Restoration Rates

The rate of recovery in an aquatic ecosystem after the removal of a dam is difficult to predict due to the large number of controlling factors and the cumulative affects related to integrating ecosystem components (American Rivers et al., 1999; Carmago et al., 1998; Church, 1995; Dadswell, 1996; Iversen et al., 1993). All aquatic systems respond differently to changes and impacts (Table 5.1).

These variables need to be addressed when discussing whether to use an active or passive approach to restoration. The simplest approach is

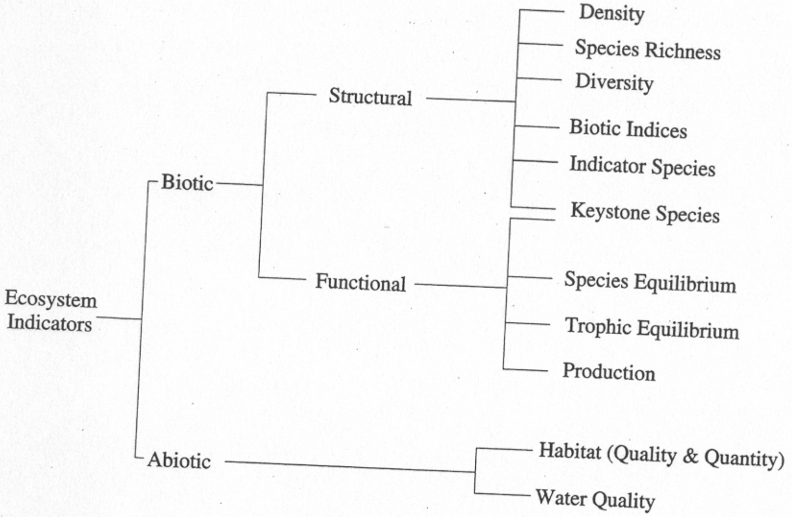


Figure 5.5 **A variety of indicators may be used to evaluate aquatic ecosystem recovery.** Adapted from Milner, 1994.

a passive one. This approach allows the river system to restore itself with little to no input from stakeholders or managers. The rate of restoration may be considerably slower than that of an active program, and the process may not reach specific objectives and expectations expressed by stakeholders. Small-scale recovery efforts are likely to occur faster than larger-scale efforts. Upstream watershed conditions, riverine inputs, and existing ecosystem dynamics dictate the rate of passive restoration (Iversen et al., 1993; National Research Council, 1992; Nelson and Pajak, 1990; Rabeni and Jacobson, 1993; Shuman, 1995; Staggs, Lyons, and Visser, 1995).

Conversely, an active restoration approach includes collaborators working together and identifying critical ecosystem processes that may need to be jumpstarted to initiate the rehabilitation process. These actions may include the stabilization of sediments, revegetation of exposed sediments, restoration and seeding of specific fish and other species, stabilization of riverbanks, and upstream flow and sediment control. The degree of success depends on how well the restoration group understands the watershed dynamics, timing, finances, personal commitments, and luck required for restoration to occur (Milner, 1994).

Table 5.1 Variables Affecting Rates of Aquatic Ecosystem Response to Dam Removal

Variable	Response
Level of impact (small, medium, or large)	Small systems react more quickly.
Location of dam in watershed	Systems higher in watershed are typically smaller and show faster response to physical restoration.
Hydrologic regime	Higher flow conditions mobilize sediments faster and reset system to new base level.
Time of year	Removal during winter elicits different rates of response than restoration begun in spring.
Expectations of community	High expectations require more active approaches.
Size of watershed	Large watersheds usually have larger repopulation source and consequently may show faster restoration rate.

In many situations, a combination of passive and active approaches provides the best mix and is most acceptable. Stakeholder groups and managers need to work cooperatively to address the issues, identify critical ecosystem relationships, and identify specific actions that will have the highest potential for jumpstarting and guiding the restoration effort.

Physical Habitat

The size of the dam, the reservoirs, and its location in the watershed influences the rate and potential restoration capacity of the river. Dams affect the physical habitat by reducing the amount of sediments downstream, removing the woody debris, causing loss of heterogeneity of the river bed substrate, reducing seasonally dynamic flow patterns, eliminating diversified flow patterns in the river channel, and reducing the heterogeneity of aquatic habitat. These effects influence the colonization times of macroinvertebrates, availability of the suite of aquatic habitats needed by native fish species, and seasonal availability of unique aquatic habitats for spawning and juvenile rearing.

Restoration of Terrestrial and Riparian Vegetation

An aquatic ecosystem is defined by the watershed, the terrestrial, and riparian vegetation that it supports (Williams, Wood, and Dumbeck, 1998). The restoration of the physical and biological components of an aquatic ecosystem depends on the recovery of the riparian corridor along the river (NRC, 1998; Shuman, 1995). The riparian and watershed community provides organic input in the form of carbon necessary for aquatic food production, woody debris for microhabitats, and shade and cover in the aquatic ecosystem (Newcombe and MacDonald, 1991; Nilsson and Dynesius, 1991; Nilsson, Jansson, and Zinko, 1997). A less-disturbed riparian corridor may allow the restoration of the aquatic ecosystem to occur at a faster rate.

Size of Disturbed Area and Upstream Sources of Drift

The size of an aquatic ecosystem and its location in the river's watershed influences the recovery rate (Shuman, 1995; American Rivers et al., 1999). If the area affected by the dam is large, the distances upstream and downstream to likely sources of colonizing macroinvertebrates and fish are likely to be great. Drift from upstream sources and migration of downstream sources are the two primary mechanisms for the natural colonization of the aquatic ecosystem.

Continued Disturbances

Continued disturbances in the form of upstream watershed effects (land use practices) slow or restrict the successional pathways and limit the potential success of a restoration effort. Disturbances may take the form of short-term, limited duration events or longer-term events that affect the whole watershed (Williams et al., 1998). Examples of the latter are increased sedimentation due to logging, mining impacts, upstream water quality impacts, and upstream flow control. Shorter-term disturbances many include localized impacts such as vehicular transport, seasonal livestock movement, and site-specific meteorological events.

Frequency of Previous Disturbances

An aquatic community that historically has experienced frequent disturbances may be restored more quickly than an ecosystem that has a long history of stability (Carmago et al., 1998; Church, 1995; Iversen et al., 1993). Many aquatic ecosystems have a long history of frequent disturbances because of watershed and localized events. In these types of ecosystems, a networked series of metapopulations typically exist in the stream networks that readily supply a new source of colonizing creatures (Peacock et al., 2002). This is analogous to a prairie system that experiences periodic fire. River ecosystems are dynamic; those in diverse environments evolved with the capability to handle varying levels of disturbance. In fact, it is the annual disturbance regime, ranging from floods to low flows, that dictates the productivity of the aquatic ecosystems in many river systems (Allan, 1995).

Presence and Proximity of Refugiums

The farther a refugium is located from the source of recolonizing individuals, the longer it takes for recovery to occur. A natural aquatic ecosystem is composed of a multitude of complex habitats, including microhabitats, migration corridors, unique reaches, riparian vegetation, floodplains, hyporheic zones, production areas, spawning areas, and refugiums (NRC 1992; Shuman, 1995). The refugiums may be in unique areas populated by biota that are sources for the recolonization of rivers following disturbances that reduce biomass or distribution (Sedell et al., 1990). Location of a refugial population necessary for aquatic ecosystem recovery should be identified prior to dam removal.

Flushing Capacity and Persistence of Disturbance

The persistence of the effects of a dam and the sediments in the reservoir has a major influence on the ability and rate of recovery of an aquatic ecosystem. Sediment storage behind dams is often a major issue that needs to be dealt with in any recovery scenario. Sediments in reservoir basins, especially the delta ones, are eroded quickly; these sediments are not extensively consolidated and protected by the roots of riparian vegetation or protective cover (Staggs et al., 1995). Active erosion of these exposed sediments into the river leads to an initial surge of sediment until a level of equilibrium is reached. The erosion of sediments and its movement into the river requires a thorough review of the hydrologics of the river

(Wood and Armitage, 1997). If an aquatic ecosystem experiences periodic (i.e., seasonal) flushing flows, the rate of recovery is enhanced. If, on the other hand, sediments cannot be flushed from the system quickly, recovery is delayed.

Watershed Characteristics and Land Use

Watershed stability and land use influence the rate of recovery, transport of contaminants, and magnitude and frequency of water and sediment disturbances (Williams et al., 1998). Watersheds with extensive and intensive agriculture, logging, mining, or other disturbances have increased amounts of sediment and flashier flow regimes (Williams et al., 1998). Such watersheds are unlikely to reach the objectives for ecosystem recovery after dam removal.

Timing of Disturbance and Life Cycles of the Biota

The time of year when an aquatic ecosystem changes is very important in a determination of the ability and the rate of the species and ecosystem's response (American Rivers et al., 1995; Winter, 1990). The timing of dam removal determines which life stage of an organism is present. Some life stages may be, at crucial times, better able than others to recolonize or survive. The sequence of colonization, succession, and possible end-point community may be influenced significantly by which species are part of the recolonization pool at the time the dam is removed.

Nutrient Input and Recycling

Disturbances that affect autotrophic production or allochthonous inputs to an aquatic ecosystem influence recovery rates of macroinvertebrates and fish. The combined processes of nutrient cycling and transport occur at various rates depending on the productivity of the aquatic ecosystem (Ward and Stanford, 1979; Ligon et al., 1995). The recovery of an aquatic ecosystem following the removal of a dam depends largely on nutrient cycling and retention (Heller et al., 1999; Camargo 1998). In aquatic ecosystems with low nutrient inputs and low turnover and cycling of nutrients, resilience is low and recovery takes longer. Recovery times are reduced if nutrients can be retained in the aquatic system (Kline et al., 1997).

Location of Disturbance in Stream Course and Stream Order

River systems are composites of tributaries and larger rivers. The location of a dam to be removed in a river system has bearing on the timing and restoration potential of the aquatic ecosystem (American Rivers et al., 1999; Iversen et al., 1993). Dam removal lower in the river system offers access to a larger base of recolonization organisms.

Rivers begin a modification process immediately after the removal of a disturbance as flows begin to support the reestablishment of the physical and biological processes that define a dynamic river system (Kinsolving and Bains, 1993). The rate at which rivers modify themselves is a factor of the watershed; flow regimes; time of year; and access to resupply of critical chemical, biological, and physical components (Petts, 1984). Modification or restoration rates are determined by the many factors outlined above, which may be quite variable. Recovery rates associated with dam removal depend on the size of the dam and reservoir located above it, location of the dam in the river basin, upstream watershed disturbances, channel modifications, hydrology, and water quality impacts (Iversen et al., 1993; NRC, 1992; Nelson and Pajak, 1990). In the case of Edwards Dam in Maine, significant signs of a modified river were seen only three months after the dam was removed (Box 5.5).

Water Quality

The water quality of the reservoir basin and upstream watershed can play a very important role in the recovery rate of an aquatic ecosystem. An understanding of watershed dynamics upstream of the restored reservoir and river area is essential to the effective management of dam removal and the prediction of potential for success. Specific water quality components that need to be evaluated include upstream watershed integrity, temperature, dissolved gases, sediment, heavy metal mobilization, and organic matter transport (Murakami and Takeishi, 1997; Newcombe et al., 1991; Shuman, 1995). It is essential that an understanding of watershed dynam-

Box 5.5 Signs of Recovery: The Removal of Edwards Dam in Maine

The removal of Edwards Dam in Maine was followed by a rapid ecosystem response. Edwards Dam was a rock-filled, timber crib structure, 24 feet tall and 917 feet wide, built on the Kennebec River in 1837 for navigation and later used for hydropower generation. In 1993, the dam owner, a small, privately held company, submitted an application to the Federal Energy Regulatory Commission (FERC) to renew its license. A series of studies showed that restoring passage for several migratory fish species would cost 1.7 times more than removing the dam. Moreover, removing the dam would open up 17 miles of historical upstream spawning habitat. FERC denied the dam owner's petition, and in 1999, Edwards Dam was removed.

Signs that the Kennebec River changed in response to the dam removal appeared just a few months later. Bird species such as bald eagles and the great blue heron, once rarely seen, became a common sight along the Kennebec. Less than three months after the removal, schools of striped bass were seen feeding on alewife upstream of the former dam site, and anglers 19 miles upstream caught stripers up to 40 inches long. Populations of 10 migratory fish, once rare in this stretch of the Kennebec, are expected to continue rebounding over the next 20 years (American Rivers et al., 1999).

ics and reservoir basin conditions be developed before initiating dam removal. The timing and management of dam removal needs to take into consideration water quality conditions at the time of removal and how this may affect the watershed.

Upstream Watershed. Decision makers need to understand the watershed dynamics upstream and downstream of the project area, or else the aquatic system recovery may be compromised. Important watershed relationships to evaluate include inflow hydrology and water management; groundwater and sediment supply, quality, and transport; water quality conditions (affected by upstream dams or watershed conditions); riparian well-being; upstream aquatic assemblages (source for replenishment); and upstream land use (intact or fragmented) (Williams et al., 1998). If the upstream integrity of the watershed is high, then the aquatic restoration probably will succeed. If the upstream watershed is heavily affected, the potential for success may be reduced significantly.

Temperature. As reservoirs are drained, the reservoir water body is transformed back to the conditions of the river system. Fish and insect species that have adapted to reservoir conditions are likely to be affected as dynamic river conditions begin to be reestablished. Thermal regimes defined by the upstream watershed, groundwater, and seasonal ambient conditions become a primary factor defining the aquatic assemblage (Vinson, 2001; William and Hynes, 1976). Specific evaluations need to be made of the presence and impact of upstream dams and reservoirs and the potential thermal regime supplied to the recovery area.

Sediment. As reservoirs are drained, sediment deposits trapped behind the dam are subjected to hydraulic forces. Local mobilization of sediments occurs as a reservoir drops in elevation and the inflowing river begins to migrate across and through the deposited sediment. Initially the delta area will be eroded and the process will continue downstream (Shuman, 1995; Dadswell, 1996; Department of the Interior, 1996). The mobilization of sediment is likely to lead to increased sediment and turbidity levels in the reservoir basin and immediately downstream of the removed dam. This increased turbidity and sediment transport may affect the eggs of fish species that have been deposited in cobbles and gravels downstream, and insect species that depend on clear water conditions (Kondolf et al., 1993; DOI, 1996; Newcombe and MacDonald, 1991). The level of impact depends on the season of drawdown, the rate of reservoir drawdown, and the upstream watershed dynamics. The potential impacts related to sediments are large and need to be evaluated carefully in terms of timing and the management of dam removal.

Heavy Metal Mobilization. Reservoirs located in watersheds where mining occurs or historically has occurred may accumulate mining waste and heavy metals, which may become trapped in the sediments behind the dam (Murakami et al., 1997). The sediment composition and quality, and the potential for remobilization and transformation of the metals and mining wastes, need to be considered before dam removal is initiated. The rate of timing of the reservoir drawdown combined with on-site stabilization and upstream watershed dynamics may be necessary to avoid water quality impacts downstream (DOI 1996; American Rivers et al., 1999).

Dissolved Gas. Dissolved gases occur naturally in all water bodies. Supersaturation of the water column with dissolved gases can result from both natural and human-induced conditions. Dams often exacerbate the effect of dissolved gases on the downstream aquatic environment. Water released through dams may increase the levels of total dissolved gases in the water column and negatively affect the health and survival of young-of-the-year, juvenile and adult salmonids, and aquatic insects (Weltkamp and Katz, 1980; NRC, 1992; Ligon et. al., 1995). Careful timing and management of dam removal and subsequent water releases are essential to avoid unnecessarily modifying the water quality and affecting the downstream aquatic biota.

Organic Matter Transport. Organic matter in the form of materials that have been trapped in reservoir basins may be mobilized as dams are removed and water bodies drained. Specifically, sunken trees, wastewater treatment residue, aquatic plants, and terrestrial vegetation may be mobilized and may generate a spike in organic matter and carbon supply downstream of the removed dam (Shuman, 1995; DOI, 1996; Dadswell, 1996).

CONCLUSION AND RECOMMENDATIONS

One way to learn about the potential effects of dam removal is to review what is known about the effects of dam installation on a river system. Although the changes brought about by installation may not be completely reversible, they do help predict the various consequences of removal. Changes in the physical system of a river imposed by a dam, and partly reversed by dam removal, cause associated adjustments in the biological components of the ecosystem. These biological changes, particularly among fish and macroinvertebrates, include altered movement patterns, residence times, species assemblage, and general habitat opportunities. These biological ecosystem changes are variable in time and space. The extent and intensity of the changes depend on the size of the dam (i.e., storage capacity), quantity and quality of sediment in the reservoir, timing of reservoir level fluctuations, limnological conditions in the reservoir, and stability of the downstream river reach. Non-native exotic species also affect native species in both rivers and reservoirs.

Dam removal has increased the abundance and diversity of aquatic insect, fish, and other populations, but long-term data and numerous "before and after" tests of population trends are not available.

Reservoirs create wetland areas in some cases; the removal of a dam and draining of a reservoir may create some wetlands downstream, but at the expense of some wetlands upstream. Dam removal often results in the replacement of one aquatic community with another that is partly natural and partly artificial. The most significant biological effect of the removal of small structures is the removal of physical obstructions and increased accessibility of upstream habitat and spawning areas for migratory fishes.

- **Conclusion:** Decisions to remove dams have far-reaching implications both upstream and downstream in a complicated physical and biological system. The consideration of a limited scope of outcomes is likely to have unforeseen consequences.
- **Recommendation:** The panel recommends that dam removal decisions take into account watershed and ecosystem perspectives as well as river reach perspectives and the more limited focus on the dam site.
- **Recommendation:** The panel recommends that the U.S. EPA and/or appropriate state or local government agencies conduct a monitoring and evaluation program following dam removal. This program should be developed and implanted so that vital data on the natural and enhanced restoration of habitats is collected and made available in public datasets for use in adaptive management.