18 Geomorphology and Policy for Restoration of Impounded American Rivers: What is 'Natural?'

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ABSTRACT

Geomorphology as a natural science is returning to its roots of a close association with environmental resource management and public policy. The science, after an insular period emphasizing mostly basic research questions, has graduated to a more mature phase wherein there is a new emphasis on application of established theory to address issues of social concern. In this new phase, geomorphology must become more interactive with other environmental sciences, and must establish socially relevant paradigms for research and teaching. An example of geomorphology's new directions is the research activity in fluvial geomorphology directed to the restoration of rivers downstream from American dams. The era for construction of large dams is over in the United States, leaving the nation with a fragmented river system and new social values that emphasize restoration through the Federal Power Act, Endangered Species Act, and Safety of Dams Act. The nation's rivers are now divided into segments, with some parts dominated by the direct effects of dams, some by indirect effects, and some in a preserved, unaffected state. To enhance river restoration, policymakers are focusing on dams, modifying them, changing their operating rules (on the Colorado, Trinity, Gunnison, and Kissimmee rivers), and in some cases removing them (on the Elwha, Kennebec, Milwaukee, and Gila rivers). The objective of these measures is to return the downstream landscape to its original, natural condition, yet geomorphic and ecologic changes related to the dams are not completely reversible. The issue of what is natural, and how closely restored systems can approximate natural conditions downstream from dams are challenging policy and scientific questions for fluvial geomorphology. Reaches downstream from the dams have experienced departures from natural conditions by changes in their hydrology (water yield,

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peak flows, low flows, timing of discharge events), sedimentology (sediment discharge, size distribution of sediment), geomorphology (channel and floodplain forms and processes), and biotic systems (riparian vegetation, fish, and wildlife). The underlying geomorphology of the systems helps determine what is natural and how closely restoration can approximate original conditions. Policy analysis by geomorphologists provides predictions of outcomes from a variety of options, whereas basic science seeks general explanation. Geomorphological science can contribute directly to policy analysis by modification of its traditional objectives: (1) defining what is natural by Quaternary studies and historical geomorphology; (2) explaining the operations of the present system by empirical process studies; and (3) analyzing policy options by use of predictive models. To be useful to policymakers, the reductionist, analytic investigations of fluvial geomorphology must evolve into an integrative, synthesizing science.

INTRODUCTION

During its early years as a definable science, geomorphology had a close association with resource assessment and public policy for management of the environment. As economic development connected to the Industrial Revolution stimulated the investigation of the resource potential of landscapes around the globe in the nineteenth century, geomorphology simultaneously emerged as a science to explain surface processes (Tinkler 1985). By the mid-twentieth century, this connection between the practical and the theoretical had broken down, however, and emphasis in geomorphological research had shifted to highly focused theoretical work that sought to exclude the human variable from its analysis of environmental systems. While this work resulted in sophisticated theory for geomorphic systems, the implementation of those theories in problem solving was a low priority, and the connections of geomorphology with other sciences as well as with decision-makers waned. As the functional relationships among various natural systems have become increasingly apparent in the last two decades, geomorphology as a science has partly returned to its historical roots by becoming less insular, by addressing the problems of applying theoretical constructs to problems of interest to decision-makers, and connecting to scientists in other disciplines such as zoology, botany, hydrology, and environmental design.

It would be a daunting task to survey the connections between geomorphology and policy for all the varied branches of the science. Instead, it is the purpose of this chapter to explore how the science is addressing the connection in fluvial geomorphology for the problems associated with the downstream impacts of dams. These problems are instructive because they are typical of the multifaceted aspect of many environmental issues, and they illustrate how geomorphological research can inform decision-makers using empirical evidence supported by theoretical interpretations. Fluvial geomorphology and the downstream impacts of dams is also a suitable venue for exploring science and policy because the issue is a global one of major importance. There are 2357 dams with large reservoirs (those containing more than 108 m^3 or 105 acre-ft), with their waters inundating a surface area the size of California (L'vovich and White 1990). Of the total discharge of the 139 largest river systems of the northern hemisphere, 77% is directly affected by dams (Dynesius and Nilsson 1994).

Downstream geomorphological impacts of dams and associated channelization works are large scale, and include changes in channel sizes, patterns, sinuosity, and hydraulic properties as a result of changes in flow regimes and sediment loads (Brookes 1988). Changes by dams to river systems in Europe, for example, are a legacy of human-induced channel changes that began in Roman times (van Urk and Smit 1989), and that have become progressively more prominent since the Middle Ages (Decamps et al. 1994). Changes in rivers of Spain, France, Italy, and Greece brought about by humans are on a scale of Quaternary-long changes resulting from hydroclimatologic influences (Lewin et al. 1995). Large rivers in Asia, especially China, have an equally long history of the impact of dams with major changes in geomorphology as the result. In the United Kingdom the rivers are generally smaller than those in China, but they experience similar substantial adjustments (Carling 1987; Zhou and Pan, 1994). In Australia, rivers have biological, hydrological, and geomorphological configurations that owe much to the histories of their dams (Warner 1988; Benn and Erskine 1994). Tropical rivers, with their high volume throughputs of water also evidence wide-ranging impacts of dams and their operations (Pickup 1980; Pickup and Warner 1984).

The fluvial system of the United States is not a natural river network. Dams have an impact on flow in every major stream in the conterminous 48 states, and the nation has 87 dams that impound reservoirs of 1.2×10^9 m^3 ($I \times 10^6$ acre-ft) or more (Graf 1993, pp. 36-38). More than 50 000 dams of all sizes have a storage capacity that is more than three times greater than the mean annual runoff of the country's surface (Table 18.1). Channelization, bank stabilization, and artificial works line thousands of kilometres of what were once natural channels (Lagasse 1994; Simons and Simons 1994). By certain definitions, the nation has about 5.1×10^6 km (3.2×10^6 miles) of stream channels (Echeverria et al. 1989), but 17% is under reservoir waters, and of the remainder, human activities have altered all but about 2%. The Wild and Scenic Rivers System permanently protects from development only about 0.3%. The period of large dam construction is now over, but the period of river presentation is just beginning (Figure 18.1). The result of dam construction and piecemeal preservation efforts is a fragmented river system, where segments dominated by engineering works are interspersed with segments that approach natural conditions. Administration as well as physical processes in these systems are

Table 18.1 Reservoirs and dams in the United States

Reservoir capacity (acre-ft)	Number	Total capacity (acre-ft)
> 10 000 000	5	121 670 100
1 000 000-10 000 000	82	186 480 100
100 000-1 000 000	482	136 371 900
50 000-100 000	295	20 557 000
25 000-50 000	374	13 092 000
5000-25 000	1411	15 632 000
50-5000a	50 000[b]	5 000 000
< 50'	2 000 000	10 000 000
Total		508 803 100

[a] Mean reservoir size estimated to be 100 acre- ft.
[b] US Army Corps of Engineers estimates.
[c] Mean reservoir size estimated to be 5 acre-ft.
Source: Data from *US* Army Corps of Engineers, compilation from Graf (1993, p. 17).

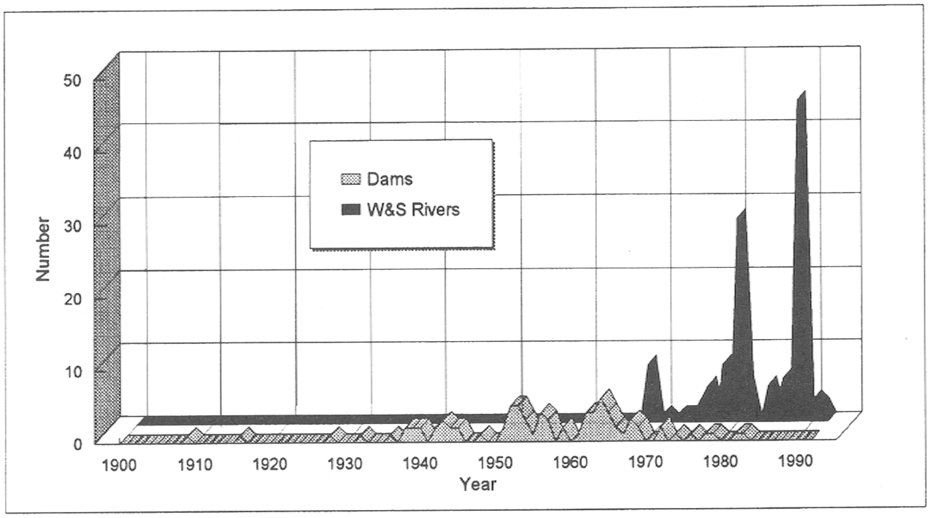


Figure 18.1 The temporal characteristics of policy changes for United States rivers as reflected by the timing of completion of large dams (those with reservoir capacity greater than 1 000 000 acre-ft) and designation of preserved rivers under the Wild and Scenic Rivers Act. Data from Graf 1993, pp. 36-42

poorly integrated, and demand new scientific theory for their understanding, and new policy perspectives for their management.

This artificial system conflicts with current American social values as expressed in laws and regulations to preserve and restore at least some fluvial environments for recreation, aesthetic purposes, and especially wildlife habitat. At the national level, the Wilderness Act (1964), Wild and Scenic Rivers Act (1968), Endangered Species Act (1973), Clean Water Act (1977), and numerous state river preservation systems are expressions of a national ethic emphasizing the desire for natural conditions associated with rivers. While preservation is a matter of legal protection of the resource as it exists, landscape or ecosystem restoration is an active intervention requiring considerable knowledge and expertise. The fundamental question in river resource management in the twenty-first century is likely to be all-encompassing: how can the nation foster economic development while at the same time preserving and enhancing environmental quality? The issue is not limited to water resources, but rather includes all physical, chemical, and biological aspects of the fluvial system (Gregory et al. 1991). The geomorphic and hydrologic components form the foundation of this complex environmental system, and any successful policy designed to manage the system must account for their behavior.

The purpose of this chapter is to explore the opportunities for interaction between science and policy in restoring the nation's rivers to more stable, more natural conditions. The chapter seeks to identify commonalities in research from several rivers, and to bring unity to a group of efforts that often have operated in isolation from each other. The following pages explore three aspects of river restoration related to dams. First, how do science and policy interact with regard to river management to restore river systems? Second, the goal of restoration is a natural system, but what do we mean by 'natural' in this application? Finally, what can we learn from specific applications of restoration science and policy?

INTERACTION OF POLICY AND SCIENCE

Policymakers are legislators, elected executive officials, and agency personnel who have been entrusted by the public to provide overall administrative leadership. They are also administrators of private business concerns, as well as participants in nongovernmental organizations and groups who seek to influence the course of events (National Research Council 1995). The researchers who provide scientific knowledge for policy include private consultants, university faculty, and government employees. The formal contacts between researchers and policymakers are usually in the form of contracts addressing particular applied problems using a body of more general basic knowledge, so that the distinction between basic and applied science is often indistinct. Formal contacts also occur in the form of expert testimony before courts, administrative law judges, or advisory panels.

In the United States, the most important federal agencies dealing with river restoration include the US Army Corps of Engineers, Bureau of Reclamation, Fish and Wildlife Service, Environmental Protection Agency, and the Department of Energy. The Corps of Engineers undertakes projects designed for flood control in a partnership arrangement with other sponsors who may be federal, state, or local agencies (Black 1987, pp. 98-116). The Corps also administers Section 404 of the Clean Water Act, which governs the issuance of permits for altering the channels of the 'waters of the United States', a legal designation that includes most major rivers in the nation. The Bureau of Reclamation is a water resource development agency charged with supplying water to agricultural and urban users (Holmes 1972; Office of the Federal Register 1983). The Fish and Wildlife Service administers the Endangered Species Act, and so is concerned with the protection and enhancement of habitats, particularly wetlands, that support wildlife. The Environmental Protection Agency is responsible for administering the Clean Water Act, a policy that focuses mostly on chemical quality of water, including sediment as a pollutant. The Department of Energy, through its administration of the national laboratories, is concerned with water and sediment pollution associated with the nation's nuclear weapons program.

The geomorphologists who may influence decisions in these agencies fall into one of three categories (Kodras and Jones 1990): researchers outside the state, researchers who are outside consultants to the state, and those directly employed by the state. Those researchers outside government, mostly university-based researchers, derive funding from a variety of sources, but maintain a critical independence from the governmental agency, because their employment does not directly depend on the government. Their agendas may be driven by the availability of funding in various topical areas, but because they have a range of choices for funding sources they adopt research subjects based partly on personal preferences. Their work may subsequently support particular positions adopted by decision-makers. The outside agents enjoy considerable independence, but at the price of relative isolation from the policymakers, and their input is usually indirect. Those researchers who act as consultants provide input for particular cases defined a priori by the funding agency. They have direct access to the decision-makers, but they rarely set their own agendas. Finally, researchers employed by government agencies are agents of the state, and though they lack the independence of other investigators, they are in positions to directly influence decision-makers.

In the past two decades, policymakers and scientists involved in river issues have undergone significant changes in emphasis that are mutually supportive. Policymakers dealing with rivers have reflected the increasing interest among the American public in environmental quality by emphasizing habitat preservation and restoration. The objective of these efforts has been to reduce the impacts of human activities, particularly on wildlife, by maintaining and enhancing entire riparian and fluvial ecosystems, through integrated basins management (Gore and Shields 1995). At the same time, fluvial geomorphology has become increasingly systems-oriented, with more emphasis on the integrative aspects of the science (Hugget 1985). Geomorphological research is now often associated with ecosystem- or watershed-scale investigations rather than isolating a single or a few key components of the river. This trend toward synthesis leads to broader conclusions and results more likely to be of direct use to decision-makers than the reductionist, analytic approaches dominant in the 1960s and 1970s.

PRESENT STATE OF GEOMORPHOLOGY AND POLICY

The rapid increase in demand for geomorphic knowledge with policy implications is especially noticeable in river restoration efforts. Projects presently under consideration for restoration efforts include the removal of the Columbia Falls Dam on Pleasant River, Maine, and modification of operational rules for Sheppard Dam on the Brazos River, Texas; Kingsley Dam on the Platte River, Nebraska; Hawk's Nest Dam on the New River, West Virginia; the San Luis Reservoir system in southern California; and the operation of several dams on the Columbia River in the Pacific Northwest (E. Hunt 1988). Within the next few years, this list may grow with several anticipated additions (Table 18.2).

Heretofore, fluvial restoration has been largely the purview of zoologists, botanists, and engineers, but geomorphology is an important component of any effort to successfully restore rivers to more natural arrangements. Basic geomorphic research, theory building, and application are beneficial in answering three questions facing all river restoration work in reaches affected by dams. *First, what is natural?* Quaternary studies and historical geomorphologic investigations can establish the characteristics of the channel and near-channel processes and landforms before the installation of dams. *Second, how does the system work with dams in place?* Empirical investigations that focus on system operation, integrating the artificially controlled hydrology, landform, sediment, and biotic components can make contributions to understanding the dynamics of the present situation. *Third, what is likely to happen if there are structural or operational changes to enhance restoration?* Predictive studies based on spatially variable, iterative models rooted in basic geomorphic and physical principles can provide improved predictions for decision-makers. Many geomorphologists are already involved in work exemplifying these questions including individuals or groups in the US Geological Survey and at several universities, including Johns Hopkins, Colorado State, University of Wyoming, Utah State University, Arizona State University, and the University of California, Berkeley.

Table 18.2 Dams proposed for removal and requiring FERC relicensing

Dam	River	State	Comments
Gillespie	Gila	Arizona	Breached by 1993 flood
Newport No. 11	Clyde	Vermont	Washed out by 1994 flood
Pine River	Pine	Minnesota	Targeted for removal in FERC relicensing process by American Rivers, Inc.
Stronich	Manistee	Michigan	
Several structures	Manomenee	Michigan–Wisconsin	
No. 160	Genessee	New York	
Condit	White Salmon	Washington	
Savage Rapids	Rogue	Oregon	Removal planned by owners
Elwha	Elwha	Washington	
Glines Canyon	"	"	
Edwards	Kennebec	Maine	Removal likely
Ice Harbor	Snake	Washington	Recommended for removal by the Oregon Resources Council
Lower Monumental	"	"	
Little Goose	"	"	
Lower Granite	"	"	
Hells Canyon	"	Oregon– Idaho	
Brownlee	"	"	
Peton	Deschutes	Oregon	
Gold Ray	Rouge	"	
Windester	North Umpqua	"	
Three Mile Falls	Umatilla	"	
Rodman	Ochlawha	Florida	Under debate in state legislature

Note: List is incomplete, with frequent changes in planning and policy.

Fluvial restoration has become an important component of public policy for rivers. The National Academy of Sciences recently established a philosophical basis for this work (National Research Council 1992). Restoration is often included in legislative directives related to specific streams such as the Trinity and Elwha rivers. In the last Congress (103rd Congress, 2nd Session), representatives introduced four major bills aimed at river restoration, and though they did not pass, they are likely to continue to be considered because they emphasize the federal, state, local, and tribal cooperative approaches presently popular in Congress. Restoration will be a component of policy regarding dams for the foreseeable future, and it represents an important demand for geomorphic knowledge.

WHAT IS NATURAL?

If fluvial restoration has as its goal the re-creation of a predisturbance, natural condition, how does one define that natural condition? More importantly, how does one measure naturalness in the most common cases, those that are partly natural and partly artificial, with a mixture of direct and indirect human influences? The construction of a continuum of natural-to-artificial systems begins with the definition of the end points, followed by the identification of intermediate states. Specification of completely artificial rivers is obvious because they are comprised of engineered or completely disrupted systems. The River

Walk along the San Antonio River in downtown San Antonio, Texas, is a famous example of such a system. With its water flows controlled by gates, its channel defined by cement walls, its vegetation consisting of imported plants, and its built landscape, the River Walk is completely unlike the ecosystem it replaced.

Artificial river reaches are those experiencing the effects of human activities, either directly or indirectly. Built environments in and near rivers obviously impact fluvial processes locally, but other impacts may propagate themselves to distant locations downstream. Modifications of flow characteristics by a dam, for example, affect the geomorphology of the river for a considerable distance, in some larger rivers for more than 100 km (Williams and Wolman 1984). Enhanced or depleted sediment supply has a compound effect downstream by changing the particle sizes and geographic distributions of deposits. The deposits, in turn, exert partial control over biotic distributions and influence the fate of contaminants in the system.

The natural end of the spectrum for ecosystems in general (not limited to rivers) is also relatively easy to define, with some attempts now established in law. Section 2 of the 1964 Wilderness Act defines a natural system (including rivers) in the formal sense of wilderness: 'A wilderness, in contrast with those areas where man and his own works dominate the landscape, is hereby recognized as an area where the earth and its community of life are untrammeled by man, where man himself is a visitor who does not remain' (Public Law 88-577; Hendee et al. 1978, p. 68).

The 1968 Wild and Scenic Rivers Act (Public Law 90-5423) codified definitions of naturalness specifically for rivers. Section 16(a) of the Act defines a river as 'a flowing body of water or estuary or a section, portion, or tributary thereof, including rivers, streams, creeks, runs, kills, rills, or small lakes'. The law contains a scale based mostly on accessibility, degree of disruption, and the presence of control structures (Coyle 1988, pp. 14-16). Section 2(b) of the 1968 Act specifies that a wild river is free of impoundments, is generally inaccessible by trail, and is essentially primitive and unpolluted (Palmer 1993). The completely natural river channel in the classification used in this chapter is analogous to the 'wild' river as defined by the Act, but it is also free from upstream dams that might indirectly alter its hydrology and geomorphology.

By beginning with these extreme conditions of completely artificial and completely natural channels, and continuing with admittedly arbitrary gradations between them, it is possible to develop a formal classification for geomorphic naturalness for rivers (Table 18.3). This classification pertains only to the geomorphology of the rivers, but similar classifications are possible to define departures from natural conditions for any aspect of the river ecosystem, such as hydrology, riparian botanical or zoological communities, or chemical characteristics. Such classifications, used in tandem with the one given here, could address the statistical characteristics of the flow regime, water temperature and pH conditions, ratios of native to introduced fish species, dominance of exotic as opposed to native vegetation, and the concentrations of indicator chemical compounds or elements in water and sediment.

A recent application of the geomorphic naturalness scale in Table 18.3 to central Arizona rivers showed that the majority of the channel reaches were in the range of partly modified to mostly modified, with essentially artificial channels common in urban areas (Graf et al. 1994, a,b). Even in the rivers subjected to extensive engineering, however, there were many segments of channel that were essentially natural. From a naturalness

Table 18.3 Geomorphic 'naturalness' classification for river channels

Channel type	Completely natural	Essentially natural	Partly modified	Substantially modified	Mostly modified	Essentially artificial	Completely artificial
Pattern, X-section shape, materials	No obvious evidence of human activities – same forms and processes as existed prior to human occupation	No obvious evidence of human activities – same forms as prior to human occupation	Altered channel patterns, x-sectional shapes, or sediment characteristics as a result of human activities	Altered channel patterns, x-sectional shapes, or sediment result of human activities	Altered channel patterns, x-sectional shapes, or sediment characteristics as a result of human activities	Altered channel patterns, x-sectional shapes, or sediment characteristics as a result of human activities	Completely engineered and/or built channel with altered processes and sediment
Minor landforms	Same forms and processes as those found prior to human occupation	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply	Altered by human activities or changes in sediment supply
% Channel area engineered or disturbed	0	< 10%	< 10%	> 10% < 50%	> 50% < 90%	> 90% < 100%	100%
Descriptive notes	Completely undisturbed channel, could be a 'wild river' in the Wild and Scenic River System	Minor modifications by human action, sometimes through flow regulation; in other cases, scattered structures on an otherwise undisturbed channel	Obvious modifications by flow regulation of altered sediment supply resulting in channel disturbed by mining, metamorphosis, scattered structures	Major modifications to channel forms and processes, with up to half the channel area disturbed by mining, development, or structures	Major modifications to channel forms and processes, with most of the channel area including dredging; a development, or structures	Largely artificial channel due to engineered bed and/or banks; in some cases including dredging few natural forms or processes remain	Channel completely determined by design and manipulation with no natural forms
Example	Middle Salmon River, Idaho	Colorado River in Grand Canyon, Arizona	Platte River in western Nebraska	Potomac River near Georgetown, Maryland	Santa Cruz River near Santa Cruz, California	Illinois River in central Illinois	Los Angeles River in Los Angeles, California

perspective, the river is segmented into reaches of varying characteristics, with each segment evidencing distinct physical processes and requiring specific policy considerations. Decision-makers (the Corps of Engineers and its partner agencies at the national, state, and local level) used the classification as a basis for selecting channel segments for emphasis in restoration efforts. Generally, they will invest resources in the segments that are partly modified in an attempt to change them to essentially natural. Modifications (direct or indirect) to other channel segments are so substantial that returning them to the more natural end of the scale would be too costly. Similar applications of the naturalness scale are possible in a variety of environments, though it may be much more difficult in forested areas (Gregory and Davis 1992).

The objective of fluvial restoration, the conversion of affected channels to ones that are more natural in morphology and function, is one of the primary purposes of sound environmental management for rivers. Although planners and engineers have a long history of interest in channel design, it has only been in recent years that geomorphologists have begun to apply their scientific understanding to design problems. In an early Binghamton Geomorphology Symposium, for example, Keller (1975) reviewed the significant differences between natural and designed channels, pointing out that design might easily incorporate more natural configurations. Geomorphologists have developed the theme of designing rivers to contain natural roughness elements in arrangements that mimic undisturbed natural streams (e.g. Gregory et al. 1994). Richards et al. (1987), using examples from Scotland, Saudi Arabia, and Honduras, showed how geomorphological perspectives can improve engineering and management solutions in a wide variety of conditions. Newbury (1995) pointed out that restoration efforts are more likely to be successful if traditional engineering tools such as the Chezy equation receive new interpretations to produce more natural and less artificial designs.

SPECIFIC APPLICATIONS OF RESTORATION POLICY AND SCIENCE

Since about 1980, two avenues for change have emerged for dam and river restoration. Each involves substantial policy changes, each produces changes in the fluvial landscape, and each requires new geomorphological research. First, the management of large public dams has begun to include changes in operating rules that enhance downstream restoration. Second, owners of smaller private dams are redesigning their structures or removing them for environmental enhancement in a federal relicensing procedure. Geomorphic research using basic theoretical concepts is a common approach for policy formulation to restore fluvial environments. The following pages provide examples at a variety of scales to illustrate the relationship between geomorphological research and restoration policy. The examples are in two broad categories: operating rules for large public dams, and the removal of smaller private dams.

Operating Rules for Large Public Dams

It has only been in recent decades that the impact of large dams on downstream ecosystems has become apparent. Upstream inundation and loss of riparian habitat is obvious, but the alteration of downstream geomorphic conditions is substantial and far-reaching.

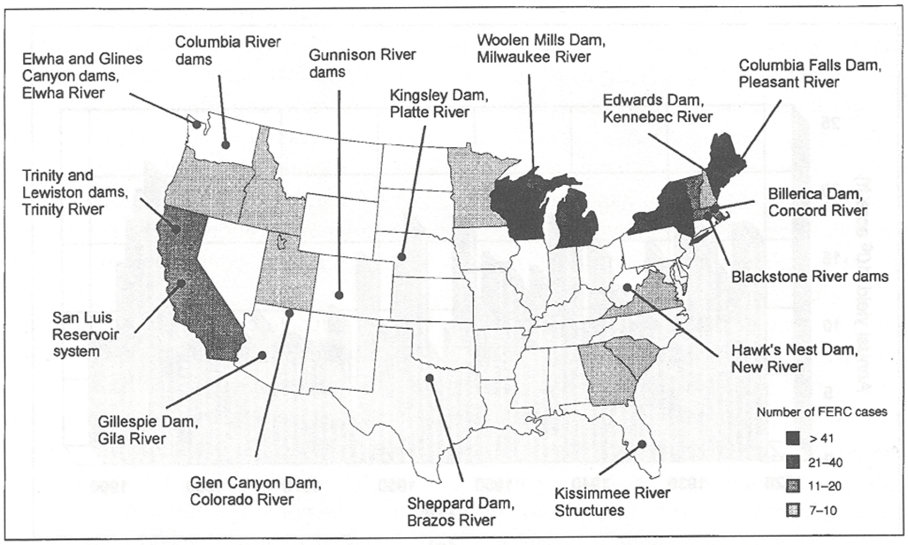


Figure 18.2 Locations of structures discussed in this chapter

Depending on the purpose of the dam and its operating rules, a variety of hydrologic changes occur in downstream flow. Most often, dam operations reduce annual flood peaks, while increasing seasonal low flows in some cases, or eliminating low flows in others. Dams operated for hydroelectric power production introduce short-term flow fluctuations that have no natural counterpart. Some of the most obvious geomorphic changes are channel scour and armoring for a limited distance below the structures, accumulation of tributary sediments in the main channel and valley, conversion of channel patterns from braided to meandering, channel shrinkage, beach and bar expansion, and floodplain expansion (Williams and Wolman 1984; Petts 1979, 1980). These geomorphic changes, in association with the changes in flow regime, result in a new substrate and hydrologic environment for riparian vegetation, with concomitant changes in wildlife populations. Fluvial restoration in these instances depends on changing the operating rules of the dams so that they more closely mimic natural flow regimes. Recent examples of this strategy include operations at Glen Canyon Dam on the Colorado River, dams on the Gunnison River, Trinity Dam on the Trinity River, and structures on the Kissimmee River (see Figure 18.2 for locations).

Glen Canyon Dam

The 1962 closure of Glen Canyon Dam on the Colorado River brought about remarkable changes in the flow of the river downstream through Grand Canyon. The dam impounds the second largest reservoir in the country, Lake Powell, with a maximum storage capacity of 33.7 x 10^9 m^3 (27.3 x 10^6 acre-ft), about two years' mean water yield of the river. The dam eliminated periodic major floods, some as great as 8500 m^3 s^{-1} (300 000 cfs), sustained low flows throughout the year at levels significantly greater than under natural conditions, and terminated the upstream contributions of sediment (Figure 18.3).

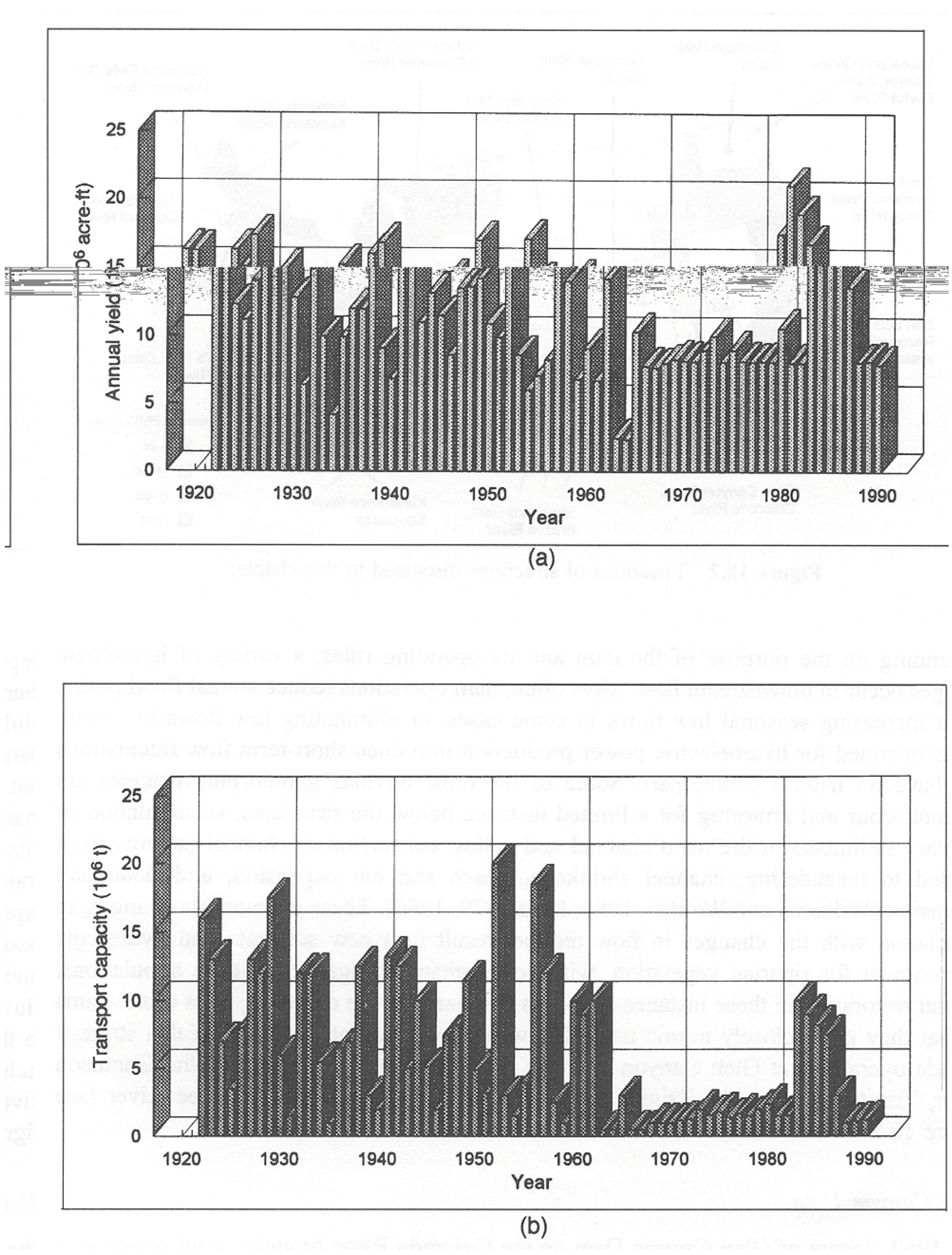


Figure 18.3 Annual water yield and sand transport in the Grand Canyon of the Colorado River below Glen Canyon Dam, Arizona, showing two impacts of Glen Canyon Dam: (a) a regularized annual water yield and (b) a reduced transport capacity as a result of reduced flood flows. Data from US Bureau of Reclamation (1994, pp. 73 and 85)

Operation of the dam for hydroelectric power production introduced the most radical changes in the flow regime. In response to daily variations in demand for electricity in the regional power grid, the dam's penstocks and turbines released as much as 850 $m^3 s^{-1}$ (30 000 cfs) during evening hours, and as little as 28.3 $m^3 s^{-1}$ (1000 cfs) during the morning hours. The result was a daily fluctuation in river stage in the Grand Canyon of up to 4 m (13 ft).

The new regime caused widespread geomorphic and ecologic adjustments in the Grand Canyon, which is part of a national park. The change from warm, silty waters to cold, clear waters released from the dam altered the fish population by creating conditions unfavorable for endangered native fishes such as the humpback chub and razorback sucker (Minckley 1991). Meanwhile, artificially introduced trout flourished. Before the installation of the dam, large-caliber sediment brought down to the main channel by debris flows and floods from tributaries came to rest in the main channel forming rapids, but periodic major floods moved some of these materials into downstream pools (Webb et al. 1987). After the closure of the dam, the highest flows were absent, and debris accumulated in increasingly large rapids. Additionally, the geomorphology of the channel margins changed in response to the lack of large floods. Sand deposits stranded high above the new water levels eroded and desiccated, while eroding beaches and bars near the flow margin lost material to channel pools without the replenishment that would have occurred in natural floods (Schmidt and Graf 1990). Riparian vegetation which depended upon these substrates also changed, and new plant assemblages became common. The invasion of tamarisk, an exotic shrub and tree, had begun before the closure of the dam and accelerated afterwards (Carothers and Brown 1991, pp. 111-128).

These downstream hydrologic, geomorphic, and ecologic impacts were not of concern when the dam was authorized and built. Congress authorized the dam for water storage, sediment control, and power generation, with only minor consideration given to recreation and wildlife (mostly related to the upstream reservoir). By the 1980s, however, the public perceived the downstream changes as a major problem, and the environmental quality ethic had given the geomorphology and ecology of the Grand Canyon new value (National Research Council 1987, pp. 15-20). The beaches were critical to the maintenance of the canyon's $20 million per year whitewater rafting industry, native fishes protected under the Endangered Species Act were declining, and the riparian vegetation supported a variety of desirable wildlife.

Spurred by a lawsuit by river users, the Bureau of Reclamation established the Glen Canyon Environmental Studies (GCES) in 1982. With a budget that has grown to several million dollars per year by 1995, the GCES has investigated the hydrologic, geomorphic, and ecologic processes in the river environment downstream from Glen Canyon Dam. In what was probably the largest-scale geomorphic experiment ever conducted, the operators controlled the dam discharges for a year, testing the hydrologic and geomorphic impacts of various discharge magnitudes, durations, and ramping rates. They have produced hundreds of reports that provide the most extensive knowledge base available for a canyon river. The primary geomorphologic/hydrologic conclusions are that (1) the reduced transport capacity of the river is roughly adequate to carry the available sediment inputs from tributaries below the dam, (2) under normal present conditions, beaches will slowly erode, losing their sediment to nearby pools in the channel, (3) waters below the dam are too cold for a vigorous native fishery

Improved, scientifically based understanding of the canyon river processes has resulted in remarkable policy adjustments for operating the dam in a manner that facilitates the restoration of more natural conditions downstream. The Bureau partially simulates seasonal variation in flows, trying to strike a balance between truly natural discharges and legal requirements for water storage and delivery as outlined in a set of court decisions, treaties, and laws collectively known as the 'Law of the River'. Dam operators may allow an occasional (about once every five years) 'flood' of about 1275 $m^3 s^{-1}$ (45 000 cfs) to scour sediment from pools and deposit it on rebuilt beaches and bars. The agency is also exploring the possibility of a multiple outlet withdrawal structure designed to take water from the reservoir at various depths, a method to increase the temperature of tail waters downstream from the dam (US Bureau of Reclamation 1994). Adaptive management allows operators to change strategy in response to changing conditions downstream as indicated by long-term monitoring.

Glen Canyon Dam is the largest structure to have modified operating rules in favor of extensive restoration, but the modifications are a result of 13 years of intensive geomorphic and other types of research with the expenditure of as much as $100 million. The outcomes of management decisions have a certain degree of predictability in the Grand Canyon. It will never be possible to restore the canyon to the natural conditions that prevailed there before the introduction of exotic species and the installation of the dam. It is possible, however, to move the canyon environment across the naturalness scale to a position less dominated by artificial hydrographs and landforms.

Gunnison River Dams

Dam operations on the Gunnison River in southwestern Colorado are also concerned with the restoration of more natural geomorphic conditions in the river channel of a protected area. Experience there shows the importance of the magnitude and timing of dam releases. The Aspinall Unit of the Colorado River Storage Project includes three dams on the Gunnison - Blue Mesa, Morrow Point, and Crystal - with a combined storage capacity of 1.3 x 10^9 m^3 (1.08 x 10^6 acre-ft), about half the mean annual water yield of the river. Immediately downstream from Crystal Dam is the Black Canyon of the Gunnison, part of a national monument that is under consideration for national park, national conservation area, and wild and scenic river status (US House of Representatives 1993). In 1991, American Rivers, Inc., a private advocacy group, designated the river as the most threatened stream in the nation because of reduced discharges. The operations of the darns have altered the hydrology of the Gunnison in Black Canyon in a manner similar to that described for Glen Canyon Dam. For the Gunnison, the primary consideration is the large flood discharges which in pre-dam conditions (prior to 1966) moved most of the debris in rapids created in the canyon by tributary discharges and debris flows (Figure 18.4). Vegetation evidence suggests that floods large enough to mobilize the rapids (310 $m^3 s^{-1}$ or 10 950 cfs) had a pre-dam recurrence interval of 3.2 years, but a post-dam recurrence interval of more than 20 years (Auble et al. 1991; Elliot and Parker 1992). As a result, considerable buildup of material is occurring in rapids, impeding whitewater recreation and altering fish habitat.

In the early 1990s, the administrators of Black Canyon, the National Park Service, sponsored investigations of the dynamics of the rapids and large-caliber sediment in the

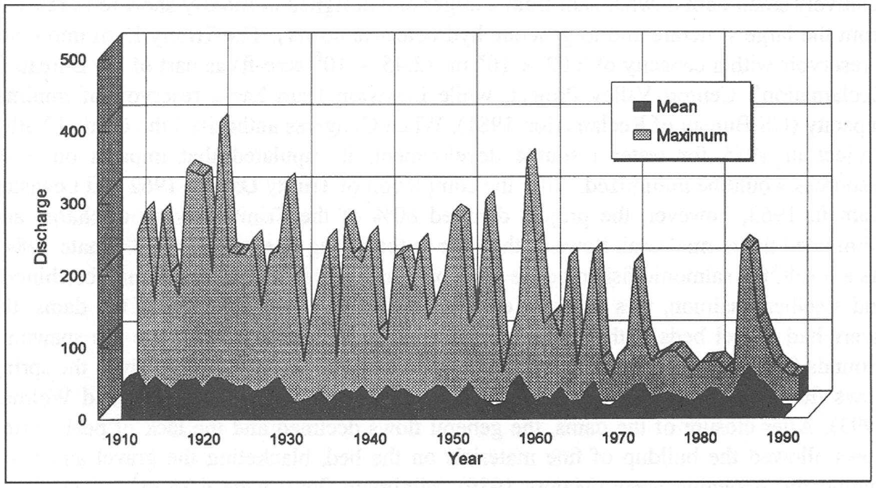


Figure 18.4 Annual flood series and the monthly mean discharges of the Gunnison River, at East Portal, Colorado, below the Gunnison River dams, showing two impacts of dam operations after 1966: more consistent low flows, and generally reduced maximum flows. US Geological Survey data, also given by Chase (1992, p. 75)

canyon with respect to flood discharges. In support of the research, the Bureau of Reclamation manipulated the discharges from Crystal Dam to create artificial 'floods' of 22 $m^3 s^{-1}$ (775 cfs) in September 1990 and 45 $m^3 s^{-1}$ (1500 cfs) in November 1990. Tracking of tagged boulders in rapids showed that at these discharges some debris on the downstream side of the bars was mobilized. Extension of the empirical observations using HEC-2 (a Corps of Engineers computer program) calculations for water surface profiles suggested that at the pre-dam common maximum flows of 310 $m^3 s^{-1}$ all but the largest particles would be mobilized (Chase 1992).

In response to these findings, the National Park Service, Bureau of Reclamation, US Fish and Wildlife Service, and the state of Colorado have agreed to new operating rules for the dams of the Aspinall Unit on a four-year experimental basis (US Bureau of Reclamation 1991-93). During one year, the dams will release a spring 'flood' of 57-142 $m^3 s^{-1}$ (2000-5000 cfs), in one year of 142-283 $m^3 s^{-1}$ (5000-10000 cfs), in one year of greater than 340 $m^3 s^{-1}$ (12 000 cfs), and in one year greater than 424 $m^3 s^{-1}$ (15 000 cfs). The 'floods', released during the naturally occurring peak flow period of May 15 to June 15, will provide a restoration of more natural hydrologic and geomorphic conditions, and return the rapids to a more dynamic state.

Trinity and Lewiston Dams

Experimental discharges and changes in operation rules also play a role in fluvial restoration mandated by Congressional legislation on the Trinity River in northern California, where experience shows the irreversibility of some dam impacts. Two dams are at issue: the Trinity Dam for water storage, and Lewiston Darn, a reregulation structure (a relatively small dam downstream from a larger one designed to modify short-term releases from the large structure and to generate hydroelectric power). The Trinity Dam impounds a reservoir with a capacity of 3.02 x 10^9 m^3 (2.45 X 10^6 acre-ft) as part of the Bureau of Reclamation's Central Valley Project, while Lewiston Dam has a reservoir of minimal capacity (US Bureau of Reclamation 1981). When Congress authorized the Central Valley Project in 1955 for water resource development, it stipulated that impacts on other resources would be minimized. After the completion of Trinity Dam in 1962 and Lewiston Dam in 1963, however, the project diverted 80% of the Trinity River's discharge and eliminated the normal peak flows of the river in the spring of each year (US Senate 1984). As a result, the salmonid fishery, once the most important fishery in California for chinook and steelhead salmon, was virtually eliminated. Before the installation of the dams, the rivers had gravel beds with particular grain-size distributions which were the spawning grounds for the fish (Figure 18.5). Although fine materials occurred in the river, the spring flows flushed them downstream and maintained the gravel beds (Kondolf and Wolman 1993). After closure of the darns, the general flows declined and the lack of peak spring flows allowed the buildup of fine materials on the bed, blanketing the gravel and eliminating the spawning areas (Majors 1989). Minimum flows were 4.25 m^3 s^{-1} (150 cfs) until 1981, when they were increased to 8.5 m^3 s^{-1} (300 cfs) (Cassady et al. 1994). The

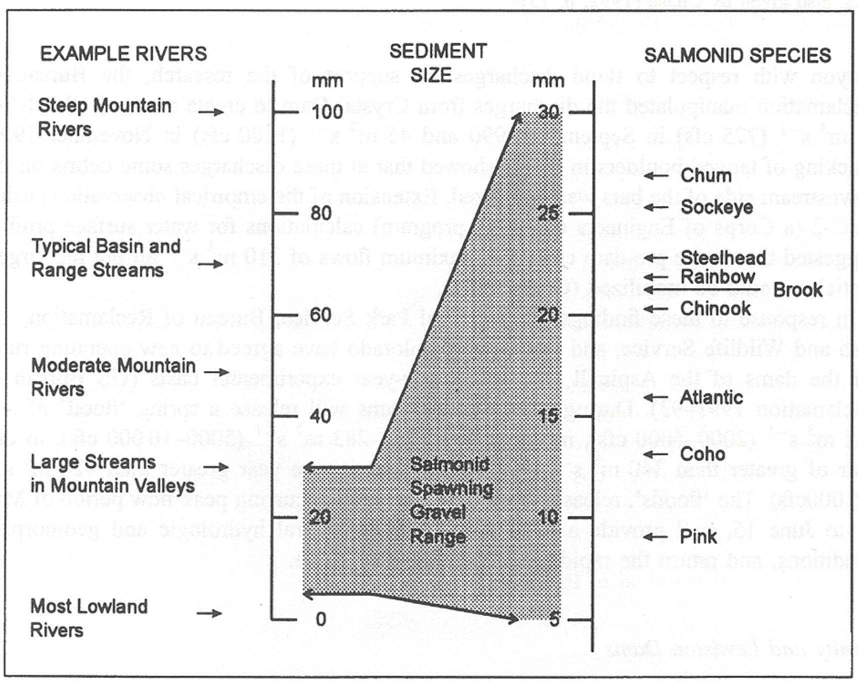


Figure 18.5 Salmonid spawning gravel sizes for various species compared to the natural sediment in groups of representative rivers showing the narrow range of useful sediment sizes. Data for spawning from Kondolf and Wolman (1993), general river data from US Geological Survey information

influx of fine material was further aggravated by logging on steep slopes in the watershed which accelerated slope erosion and increased sediment loading to the streams.

By the early 1980s, an intergovernmental task force had brought about some adjustments in an attempt to restore the fishery. A sand dredging system removed some fine sediment from one of the major sources of fine sediment, the Grass Valley Watershed, and the Bureau of Reclamation restored some streamflows from Lewiston Dam. These efforts did not restore the anadromous fish habitat to an acceptable degree, and recreational, scenic, and wildlife resources were still in a substantially modified condition. In 1984, Congress authorized $33 million to manage and restore the fishery, with another $2.4 million for monitoring (Public Law 98-541, the Trinity River Basin Restoration Act).

From the geomorphic perspective, the Trinity River presented a problem in sediment transport and channel response to changing flow patterns. As the channel became smaller and dominated by fine materials after dam closure, vegetation invaded the channel and near-channel environment. In 1992, an experimental flow of 170 m^3 s^{-1} (6000 cfs) was released from Lewiston Dam in an attempt to flush fine materials from the system and expose the underlying gravel, but the vegetation and altered channel configurations prevented a return to the original, natural conditions. Sediment mobility was indeed increased, but much of the sediment was derived from bank erosion rather than the channel floor. Conversely, many areas were surprisingly resistant to erosion because of their vegetation cover (Pitlick 1992). It thus appears that restoration of the Trinity River to anything approaching its pre-dam natural state is unlikely.

Kissimmee River Structures

Not all adjustments in operations for restoration involve large dams. In the Everglades of south Florida (Figure 18.6), a region of almost imperceptible topographic relief, the restoration of the regional southward flow of water depends on adjustments in operations of low gates and pumps along the Kissimmee River and in the Everglades area south of Lake Okeechobee (Cushman 1994). In the first major civil works project on an American river to be reversed, the Corps will also restore the straightened course of the Kissimmee to its natural meandering configuration, and return water-level fluctuations in lakes and the integrated stream network to more natural timing and ranges. The Corps' operational changes will increase the annual period of inundation for the 41 700 ha (108 000 acres) Shark River Slough addition to Everglades National Park (Figure 18.7), returning the hydrologic portion of the ecosystem to more natural arrangements (US Army Corps of Engineers 1993). The total cost of the restoration project, now under way, will be more than $500 million (US Office of Assistant Secretary of the Army 1992).

Relicensing and Removal of Private Dams

Although the federal government built and manages the largest dams in the United States, private interests have constructed thousands of smaller ones. Most of the private structures completed during the period 1930-60 were primarily for hydroelectric generation. Because the structures use the 'waters of the United States' (rivers administered by the federal government), the Federal Energy Regulatory Commission (FERC, originally the Federal Power Commission) licenses their operation. The Federal Water Power Act of

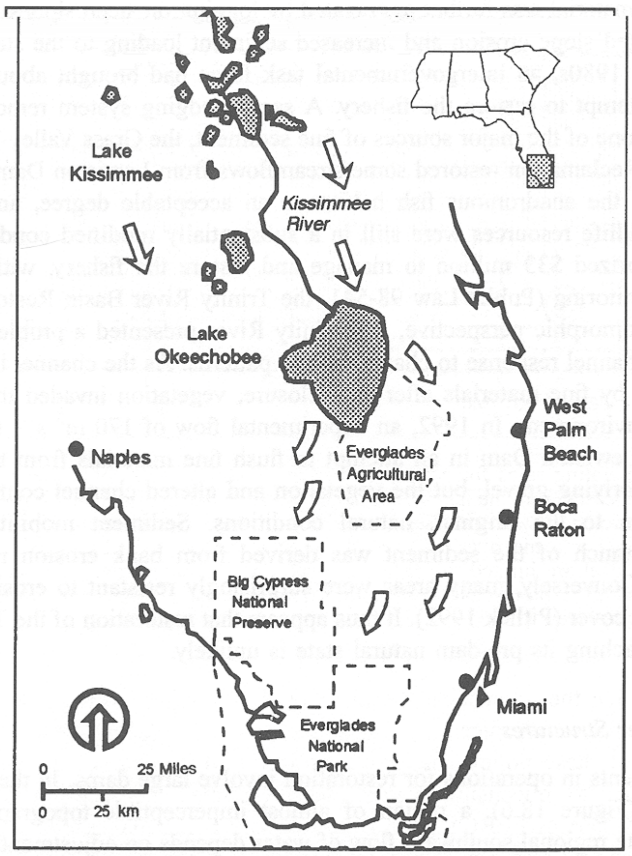


Figure 18.6 The Everglades region of south Florida, showing the regional flow of surface water with respect to Everglades National Park and the critical position of the Kissimmee River in the system. Redrawn and modified from maps by the Audubon Society and the US Army Corps of Engineers

1920 (16 USC 791a *et seq.)* gave FERC the authority to license the private dams for 50-year periods at a time when the darns appeared to be clean, environmentally sound energy sources. By the 1970s it became obvious many of the dams had deleterious effects on fluvial environments, especially on fish habitats and fish migration patterns. By posing obstacles to migrating fish that had become more important as stocks dwindled, the dams took on a central role in efforts to restore the fisheries and the habitats that support them.

During the 1980s, the original licenses of many private dams expired, and their owners began applying for relicensing (Figure 18.2 shows the distribution of FERC relicensing activity). Between 1987 and 2000, some 300 dams worth approximately $10 billion (17% of all hydroelectric projects under FERC authority) require relicensing (R.T. Hunt 1988; Boyd et al. 1990). Initially, FERC renewed licenses with hydropower as the dominant consideration, but changing public ethics placed new social values on natural rivers and the species that used them. The 1986 Electric Consumers Protection Act (Public Law 99-

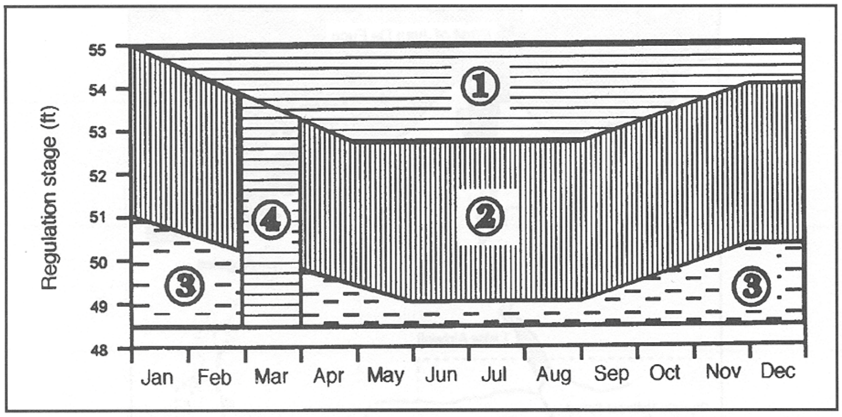


Figure 18.7 Operating rules for control structures related to Kissimmee Lake, Florida: (1) Full discharge, with releases from the lake as rapidly as possible, always preferred if possible; (2) historic stage- discharge relation, with releases from the lake made according to historical averages; (3) minimum discharge into the river maintained from the lake at 250 cfs; (4) March rule, whereby changes in lake level are limited to 0.1 ft per week and discharges are made accordingly. If lake levels fall below 48.5 ft, no discharges from the lake are permitted. Data and figure design from US Army Corps of Engineers (1993)

495) provided that the relicensing process would give equal consideration to power and nonpower uses for each project.

As a result of these policy changes, proponents of restoration successfully mounted serious challenges to relicensing, arguing that the primacy of hydropower in the decision process was not part of FERCs legal authority, and that endangered species, recreation, and aesthetics should also play a part in deciding the future of the dams. Proponents of restoration argued for changes in operating rules for some structures, but they also argued that in some cases the dams should be removed, restoring the natural hydrology and geomorphology of the rivers in question (Echeverria et al. 1989). Although this seemed to be a radical idea in the late twentieth century, it was hardly new. In the early nineteenth century, Henry David Thoreau offered the then outrageous suggestion of using a crowbar to destroy the mill dam at Billerica, Massachusetts, to restore the upstream migration of shad on the Concord River (Thoreau 1849, pp. 40-41). By the 1990s, however, removal of dams for environmental restoration of rivers had become a realistic policy. The cases of four structures illustrate the policy and hydrologic/geomorphic implications of dam removal, and the problems entangled with efforts to restore natural conditions: the anticipated removal of structures on the Elwha River, Washington; the dismantled Woolen Mills Dam on the Milwaukee River, Wisconsin; the debate about removing Edwards Dam on the Kennebec River, Maine; and the breaching of Gillespie Dam on the Gila River, Arizona.

Elwha and Glines Canyon Dams

The Elwha River drains a 818 km^2 (316 mile^2) watershed on the north slope of the Olympic Mountains of Washington (Figures 18.8 and 18.9). The lower 32 km (20 miles)

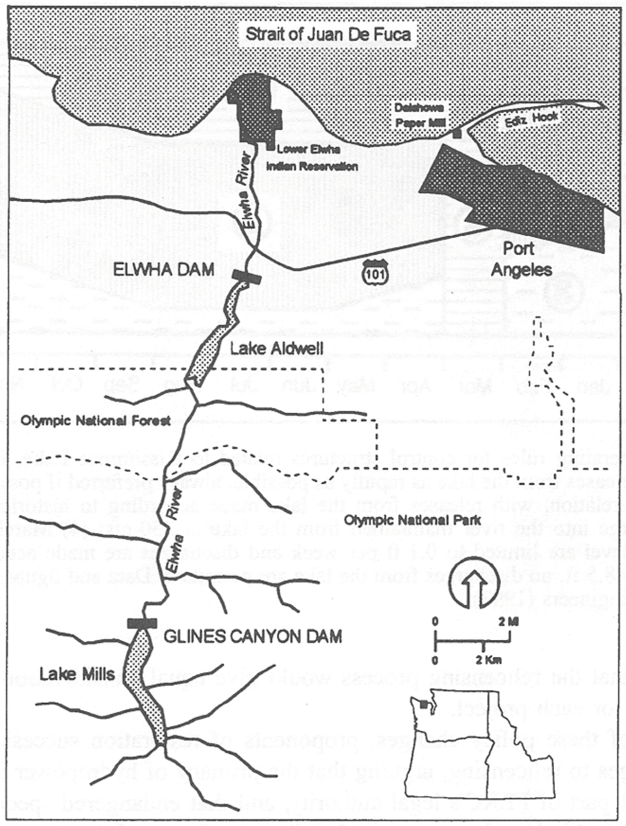


Figure 18.8 Map of the lower Elwha River, Washington, showing the locations of the two large dams with respect to Indian lands, Park Service and Forest Service lands, and the Daishowa paper mill which uses electricity produced by the dams. Based on a map by Federal Energy Regulatory Commission (1991)

of the stream above its mouth at the Strait of Juan De Fuca was once one of the state's most productive fisheries, accommodating six species of salmon as well as a variety of trout. The fish, some weighing as much as 45 kg (100 lb), provided year-round sustenance for the members of the Lower Elwha Klallam Tribe who lived along the lower reaches of the stream (US House of Representatives 1992). In 1911 the closure of Elwha Dam restricted the fishery to the lower 7.9 km (4.9 miles) of the river. While the Elwha Dam and an associated structure, the Glines Canyon Dam, provided hydroelectricity for industrial use, they also decimated the fishery, and Lake Mills, the reservoir behind Glines Canyon Dam, radically altered the river in Olympic National Park (US Senate 1992).

The relicensing application of the private corporation owning the dams triggered wide-ranging consideration of alternatives to the prevailing emphasis on hydroelectric power production. The owners of the structures proposed to partially restore natural hydrologic and biotic conditions by installing a fish ladder, protective screens, and spillway modifications on Elwha Darn, building a trap-and-haul facility at Glines Canyon Dam, and

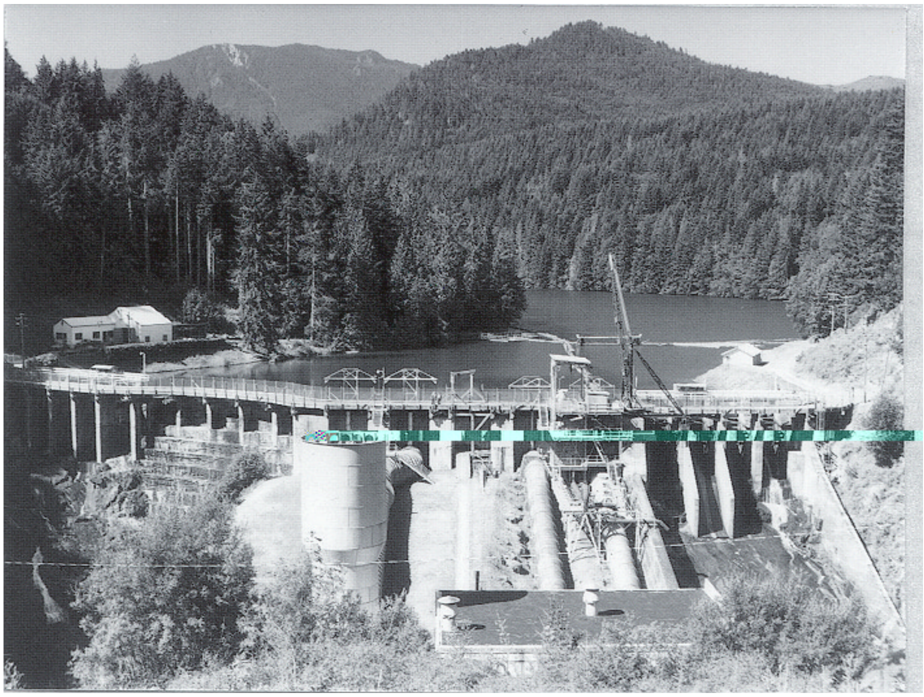


Figure 18.9 Photograph of Elwha Dam and its reservoir, Lake Aldwell, Washington, WL. Graf photograph 124-1, 2 August 1994

initiating annual spills of 2.8 m^3 s^{-1} (100 cfs) from Glines Canyon during the fish out-migration. The total cost of these modifications would be $14.7 million (US General Accounting Office 1991), but the restoration of the native fishery would be limited. Alternatively, after a seven-year analysis of environmental, power, and economic consideration, the two primary federal agencies advising FERC on the relicensing process, the National Park Service and the US Fish and Wildlife Service, recommended that the dams be removed (National Research Council 1992, pp. 219-220). Because FERC is legally bound to follow advice of other federal agencies, it appears that (barring fundamental changes in law) the dams will be removed within the next few years with the objective of restoring natural conditions to the entire length of the river.

FERC (1991, p. xxxiii) has recognized that the principal issue in the Elwha River is reducing uncertainties about the behavior of the large quantities of sediment stored in the two project reservoirs. The draining of the reservoirs and removal of the dams will require five years, with the likely period of adjustment for sediment transport through the system extending another two to five years. FERC estimated that most of the sediment presently stored in the reservoirs would be likely to remain in place, but fine materials would flood downstream areas. In reaches below the darns, presently armored reaches dominated by cobbles would be inundated by silt and sand, creating enlarged floodplains, meandering channels, and more wooded riparian habitats. Park Service and Fish and Wildlife Service personnel hope that within 10-20 years the 'original habitat conditions' would reappear on the lower river and that within the Lake Mills reservoir basin, 'near natural conditions' would be restored in about the same time period. In addition to eliminating about $16.5 million in electricity production per year used by the nearby Daishowa paper mill, the estimated cost of removal of the two structures is $64.3 million (US General Accounting Office 1991).

These prognostications are problematic. There are no formal empirical studies that document and quantify fluvial responses to the removal of large structures like the Elwha River dams, though US Geological Survey researchers are investigating the case. The excavation of previously stored sediment from the reservoirs after dam removal is likely to be a complex, multistage process that has not been widely documented or successfully modeled and predicted. The downstream fate of these sediments in the Elwha system is also more of a guess than a science, because although fine sediments moved through the system before the closure of the dams, they did so on a continuous basis in relatively low annual amounts. The disposition of huge masses of fine materials released into the river during a brief period is largely unknown, and immediate floodplain construction downstream is without historical precedent. Although presently available theory and modeling technology allow some reasonable estimates, it appears that the best experience is that from unintended dam breaches and natural dam failures (Jarrett and Costa 1986). These limited efforts aside, the issue of the geomorphic impact of dam removal remains a largely unstudied aspect of fluvial processes, and increases the uncertainty in managing the Elwha situation.

In addition to the scientific question, the policy considerations in the Elwha case are also at the edge of established practice. The contention that reservoir areas and downstream segments will be restored to natural conditions within two decades is unlikely if strict definitions of 'completely natural' are applied. The large amounts of sediment remaining within the Lake Mills and Lake Aldwell areas will produce channel and bank conditions never before seen in the area, and broad downstream floodplains are probably not natural. The objectives of management on the river are to return natural hydrologic conditions to benefit the fishery, but the fluvial geomorphology will probably be substantially modified (as defined in Table 18.3). Whether or not this partial restoration is acceptable from an ecosystem and landscape management standpoint is an unanswered question.

Edwards Dam

Privately owned low dams in the northeastern United States are also under consideration for removal. The best example is probably Edwards Dam, a run-of-the-river structure on the Kennebec River near Augusta, Maine (American Rivers, Inc. 1994, p. 4; Williams 1993). Constructed in 1837 for sawmill and canal operations, and later modified for hydroelectric production, the dam prevents the upstream migration of Atlantic salmon, and restricts the habitat of shad, smelt, and sturgeon (Egan 1990). Despite the modifications to the dam to improve fish passage, state officials and nongovernmental organizations concluded the changes were inadequate, and the state legislature passed a resolution in 1990 calling for the removal of the structure. In 1994, FERC began investigating of the feasibility and impact of removing the dam, and the issue is not yet settled.

From a scientific perspective, removal of Edwards Dam and other similar structures on New England rivers poses different questions than removal of dams on the Pacific coast.

Because the eastern structures are only a few metres high and are often run-of-the-river, they do not significantly alter the hydrology of the streams, and prediction of the hydrologic effects of their removal is fairly straightforward. The stored sediment and altered channel gradients pose the most important problems. The removal of the structures inevitably produces short-term downstream impacts through remobilized sediment. The masses of sediments themselves may be of only minor concern, but the chemical quality of the materials is a potential pollution problem. New England and the eastern United States was the hearth of American industrialization, and throughout the nineteenth century heavy manufacturing without environmental quality controls dominated the waterways. These industries released to the streams huge (but unmeasured) amounts of heavy metals which became attached to the sediments. Some of these contaminated sediments moved to the long-term sinks of the ocean or Great Lakes, where they now occur as easily defined, but isolated, components of the bottom sediments (Thomas 1972). Large amounts of contaminated sediment also came to rest behind the dams where they have remained interred. Removal of the structures raises the possibility of their remobilization and deposition on floodplains downstream.

An area where this issue is of enough concern to prevent dam removal is the Blackstone River system in central Massachusetts. Low dams have converted the river into a chain of lakes near the old manufacturing town of Worcester. Through the late 1800s, Worcester was a major metal machining center, and at one time was the greatest producer of metal wire in the world. Lead, zinc, copper, cadmium, and a variety of other contaminants from manufacturing are now trapped in sediments behind the dams, which also act as local sinks for runoff from abandoned factory areas. To remove the structures would be to risk hazardous remobilization of the contaminants which are more easily managed in place. In these cases, environmental restoration may be less desirable than containment of contaminated sediments.

Unlike their western counterparts, the streams of the central Atlantic and New England states offer numerous examples of dam removal that might be analyzed for the long-term impact of such efforts. On almost every stream with perennial flow, the eighteenth and early nineteenth century saw the construction of mills and associated dams for the grinding of grain and powering machinery. Between about 1870 and 1930, with the advent of a centralized industrial economy, many of these mills ceased production, and owners removed the dams. Such sites now provide analogs for analysis and prediction of the effects of anticipated additional dam removals.

Woolen Mills Dam

Some empirical evidence regarding removal is available from the case of at least one structure in the Midwest. The Woolen Mills Dam, constructed in 1919, produced a head of 4.2 m (14 ft) and a small reservoir affecting 2.4 km (1.5 miles) of the Milwaukee River in West Bend, Wisconsin (Nelson and Pajak 1990). By the late 1980s, however, the state Department of Natural Resources determined that the dam was unsafe and developed a 10-year plan for its removal. Using suitability models for establishing habitat for smallmouth bass, northern pike, and common carp, administrators restored the channel to emphasize sport fishing in an urban park setting (National Research Council 1992, p.

220). The resulting river is not even essentially natural according the scale in Table 18.2, but it is now closer to the natural side of the scale than it was previously.

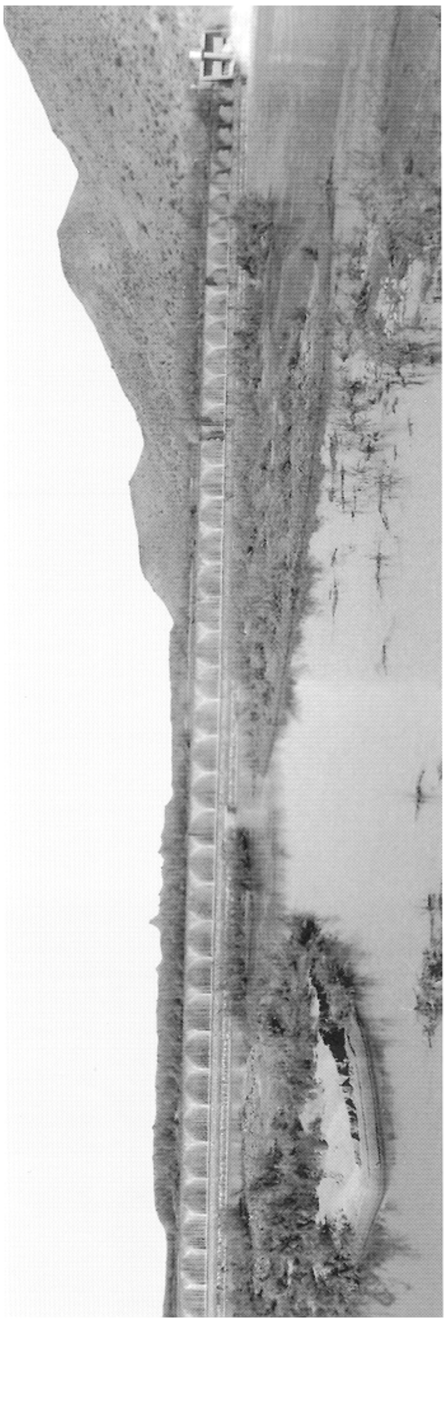
Gillespie Dam

Gillespie Dam on the Gila River of central Arizona provides an unintentional example of the impacts of dam removal. The dam was built in 1921 as a 7.6 m (25 ft) high irrigation diversion structure at a constriction in the Gila River Valley west of Phoenix, Arizona (Lecce 1988). Within two years of its closure, sediment had accumulated to the 485 m (1600 ft) wide crest of the dam, and by the 1980s the wedge of stored sediment extended 11.3 km (7 miles) upstream. During flood events, water passed over the dam, but during most of year, the dam diverted all of the flow into canals. Despite surviving several floods of over 2830 $m^3 s^{-1}$ (100 000 cfs), on 9 and 10 January 1993, the dam breached during a flood of up to 4245 $m^3 s^{-1}$ (150 000 cfs), developing a gap 54.5 m (180 ft) wide and extending from the crest to the base of the structure (Figure 18.10). Within two weeks, channel erosion removed more than half the sediment stored behind the dam, evacuating it through the breach and distributing it along 24 km (15 miles) of the compound channel (a well-defined low-flow invert within a broader, braided high-flow channel) downstream. The deposition of fine sands elevated the bed as much as 2 m (6 ft) in some locations.

The breach caused a virtually instantaneous drop in base level of over 6.5 m (20 ft), but upstream migration of the resulting knickpoint did not produce a confined trench through the accumulated sediments. Lateral migration of the channel within the reservoir area excavated wide swaths of material and left crenelated margins in the remaining sediments. If the breach is not repaired, and restoration of the stream is possible, the long-term stability of the remaining sediments is an unresolved problem (Figure 18.11).

Public policy regarding Gillespie Dam is unsettled. Management options include repairing the dam, removing it completely, or leaving it in its present breached condition (Flood Control District of Maricopa County, Internal Project Review, 17 November 1994). The owners of the dam, a Swiss corporation with investment interests in the 10 100 ha (25 000 acres) irrigated by the water diversions from the structure, are seeking the most cost-effective solution to the problem. Because the owners installed a new pumped withdrawal system to supply irrigation water, they are not likely to repair the dam unless they are forced to do so by regulators.

From the public perspective, there are five major issues, illustrating the administrative complexity associated with fluvial restoration connected with dams: environmental quality, dam safety, flood control, fluvial restoration, and liability. First, any alterations or work in the channel will require a permit from the Corps of Engineers under Section 404 of the Clean Water Act. The Corps is actively pursuing restoration of some segments of the river, and is likely to evaluate any option with that goal in mind. Second, the state Department of Water Resources is responsible for the safety of the structure, and engineering evaluations are required to assess the soundness of the remaining structure, especially its survivability during future floods. Third, the county flood control district is responsible for flood protection downstream from the site, as well as administering the National Floodplain Insurance Program of the Federal Emergency Management Agency. The flood control district is now employing geomorphic studies to assess the effect of channel changes downstream from the dam on flood potential. Fourth, the state



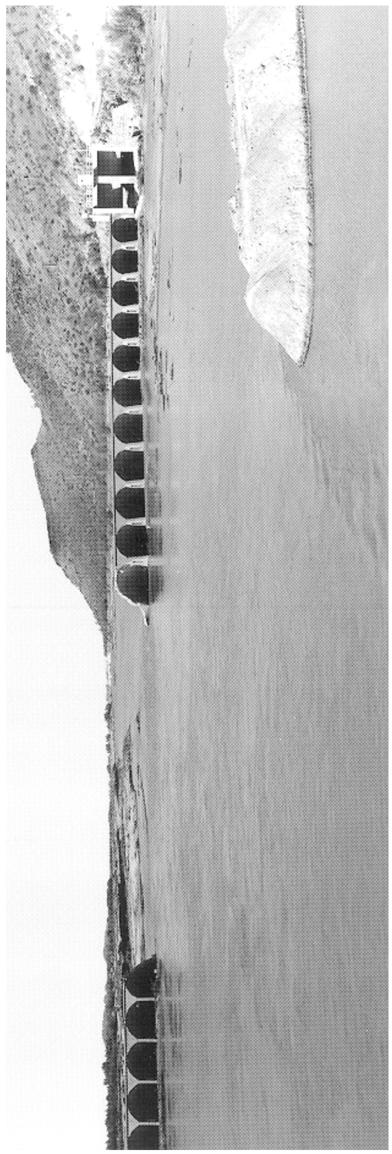


Figure 18.10 Photographs of Gillespie Dam, Gila River, Arizona, before and after its breach in a 1993 flood event. Above, showing the dam intact and operating as a run-of-the-river structure for diversion of irrigation waters, W.L. Graf photograph 51-26, 20 February 1984. Below, showing the breach in the structure, W.L. Graf photograph 110-17, 8 December 1994

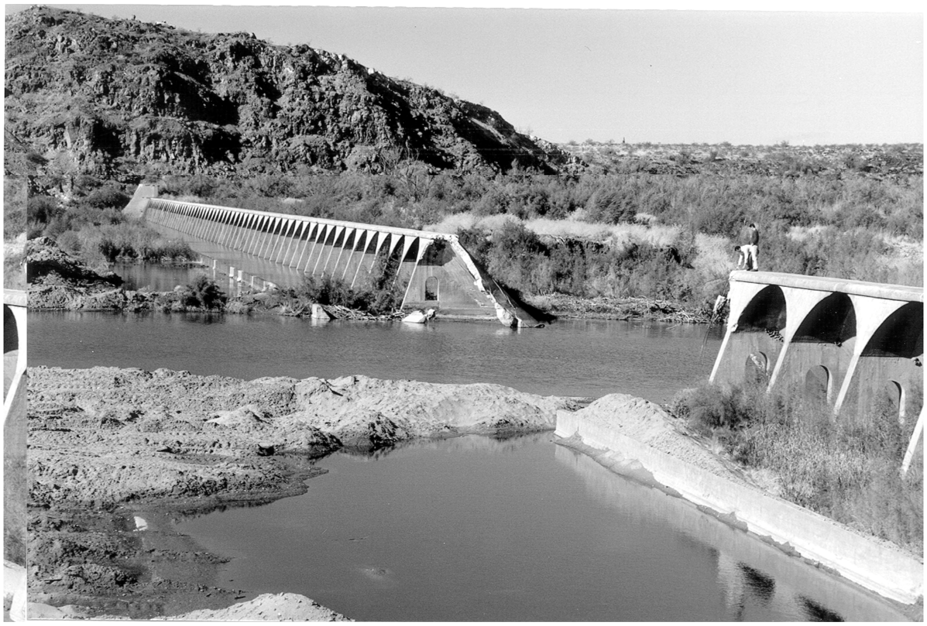


Figure 18.11 Photograph of sediment above and below Gillespie Dam, Gila River, Arizona, with human figures on the dam crest for scale. The sediments behind (to the right) the dam had accumulated to a level slightly above the crest before the breach. WL. Graf photograph 127-22, 8 December 1994

Department of Game and Fish administers an important wildlife area upstream from the dam. Restoration of the original natural river in the reach once part of the reservoir area would augment this wildlife area, but with a mixed blessing. In its natural condition, the river channel was locationally unstable, making its management for any purpose difficult. If restoration is possible, it is likely that a compromise will emerge: a less natural but more stable channel will be the ultimate objective. Finally, landowners downstream from the dam have initiated legal action, charging that mismanagement of the dam and channel led to the breach and has threatened their property with an increased flood hazard.

CONCLUSIONS

A review of science and public policy for restoration of dammed rivers along with several case examples shows that there are several consistent themes that connect science and policy:

1. As industrial societies move into postindustrial stages, social values for rivers are changing from a perspective whereby they are viewed simply as water resources alone to a perspective that is more complex. In addition to serving as water resources, rivers are coming to be viewed as multipurpose ecosystems or landscapes that serve many

objectives. Some of these objectives are compatible with each other, but it is not possible to maximize all the objectives.

2. Social values place increasing emphasis on a particular objective, the preservation or restoration of 'natural' conditions that are conductive to achieving goals related to (in order of established public preference) fish and wildlife management, recreation, and aesthetics.
3. Throughout much of the world, rivers are fragmented or segmented, divided into completely or partially controlled reaches by dams, with each reach exhibiting a geomorphological behavior that is markedly different from other nearby reaches. Theoretical models that view the river system as highly integrated must be modified to account for this segmentation.
4. It is rarely possible to restore truly natural conditions to regulated rivers, and even if dams are removed, the probability of reestablishing original pre-dam conditions is unknown, but it is likely to be variable from one case to another.
5. Dams impose hydrologic and sedimentologic changes on downstream reaches. Dams usually have one or more of the following hydrologic impacts: reduced annual water yield, reduced flood peaks, altered low flows (eliminated, or in other cases, sustained at higher than natural levels), altered seasonality of flow variation. Sedimentologic impacts include reductions in downstream sediment discharges, changes in bed material size, and concomitant upstream storage which is remobilized if the dam is removed or breached, raising problems of sedimentation and contaminant mobility
6. Because of these hydrologic and sedimentologic changes, geomorphic conditions in channels downstream from the structures evolve into distinctly unnatural configurations. These configurations depend not only on the presence of the structures (for which we have some theory), but also on operating rules for the dams (for which we have little theory).
7. Riparian vegetation and zoological communities are intimately related to the hydrologic, sedimentologic, and geomorphic conditions, but our knowledge about these connections is only now evolving into formal understanding.

The primary consideration in establishing policy for river restoration is to address the problem of 'what is natural?' It is unlikely that long reaches of American rivers will ever return to their original, truly natural states, and they are likely to remain in their fragmented condition (Graf 1993; Dynesius and Nilsson 1994), with preserved or restored reaches interspersed with developed and dammed reaches. The rivers are therefore likely to operate as segmented systems, and though effects in one reach are likely to be transmitted downstream, different segments perform different geomorphologic functions and require different policy strategies. But it is possible to make them more natural than they are at present by selective removal of dams and alteration of operating rules for the remaining structures. Policy-making for rivers is often a perceptual issue (Gregory and Davis 1993), but the decision about how far to go in making rivers more natural is partly political (what does society want?), partly scientific (what is possible?), and partly economic (what can society afford?). Based on previously established basic understanding of the systems (e.g. Petts 1984; Williams and Wolman 1984), geomorphologists can ask meaningful research questions with understandable, convincing answers. Management can then proceed confidently on the basis of established and accepted research, with fluvial changes anticipated and taken into account. The science of geomorphology can thus help resolve the dominant philosophical conflict in management of the nation's rivers in the twenty-first century: how to maintain viable economic development of the resource for the present while simultaneously preserving a quality environment for the future.

By addressing questions of interest to policyrnakers, the public, and other sciences, geomorphology returns to its intellectual roots, but to do so, its practitioners must focus their efforts on subjects that others truly care about rather than on topics only of interest to a limited number of geomorphologists. Geomorphologists must more often participate in the evolving complex interactions among Earth and life scientists to address issues of ecosystem quality and restoration (Naiman et al. 1995). The recent experiences of geomorphologists as outlined in this chapter show that such interactions can be fruitful on an administrative as well as scientific basis. Whether they like it or not, the scientist and policyrnaker are destined to be partners.

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