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Geomorphology 71 (2005) 3–26
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Geomorphology and American dams: The scientific, social, and economic context

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Received 13 November 2002; received in revised form 11 May 2004; accepted 12 May 2004
Available online 31 May 2005

Abstract

American geomorphologic research related to dams is embedded in a complicated context of science, policy, economics, and culture. Research into the downstream effects of large dams has progressed to the point of theory-building, but generalization and theory-building are from this research because (1) it is highly focused on a few locations, (2) it concerns mostly very large dams rather than a representative sample of sizes, (3) the available record of effects is too short to inform us on long-term changes, (4) the reversibility of changes imposed by dam installation and operation is unknown, and (5) coordinated funding for the needed research is scarce. In the scientific context, present research is embedded in a history of geomorphology in government service, with indistinct boundaries between "basic and applied" research. The federal policy that most strongly influences present geomorphological investigations connected with dams is related to habitat for endangered species, because the biological aspects of ecosystems are directly dependent on the substrate formed by the sediments and landforms that are influenced by dams. The economic context for research includes large amounts of public funds for river restoration, along with substantial private investments in dams; and geomorphology is central to these expensive issues. The cultural context for research is highly contentious and dominated by advocacy procedures that include intense scrutiny of any geomorphologic research related to dams. Advocates are likely to use the products of geomorphological research to make cases for their own positions.

Keywords: Dams; Fluvial geomorphology; Rivers; Environmental management; Restoration

1. Introduction

Geomorphologic researchers rarely conduct their investigations without important connections to the nonscientific world around them. Investigators are subject to a wide array of influences including their cultural backgrounds, the social matrix in which they conduct their investigations, and a host of economic factors. At the same time, investigators have an impact on their social and economic surroundings, sometimes unknowingly but often with forethought. This two-way exchange of influence is particularly important in geomorphologic research related to dams for at least three reasons: knowledge about the effects of dams on geomorphic systems is in a formative

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doi:10.1016/j.geomorph.2004.05.005

stage, managers are required to make decisions that turn on their understanding of the interaction between dams and river geomophology, and enormous social and economic forces are at work in the decision processes. The purpose of this paper is to explore the scientific, social, and economic connections to geomorphologic research related to dams and rivers, and to define the nature and extent of influence between science and this larger context. A clear understanding of the influences among science, society, and the economy related to dams and rivers is significant, because recognition of the connections by researchers can improve the communication of the results of their investigations, create in researchers a greater sensitivity to the limits of their work, and engender a greater general appreciation for their findings.

In building a picture of the context of research for geomorphology and dams, the following sections of this paper address each component of the context in turn. In exploring the scientific context of dams and geomorphology, the sections address the general science of geomorphology, followed by reviews of geomorphology related to dam installation and removal. Subsequent sections evaluate the policy, economic, and cultural interactions with fluvial geomorphologic research for dams.

This paper emphasizes the downstream effects of dams, but considerable research has been conducted on the upstream effects of dam installation, particularly sedimentation of reservoirs. Mapping and explanation of subaqueous sedimentology and geomorphology for reservoir floors is at a relatively advanced, stable state, so that processes, materials, and forms of shallow headwater deltas, deep water fine-grained deposits, and deposits from turbidity currents are well known (McManus and Duck, 1993; Senturk, 1994; Vischer and Hager, 1998). The general rate of sediment accumulation in reservoirs is known for a variety of environments (Bogardi, 1978). Management implications of reservoir sedimentation are also well known, with sedimentation posing problems in about 25% of hydroelectric projects in the United States (Electric Power Research Institute, 2000). Depositional effects of reservoirs upstream from their headwaters via the alteration of river gradients and extension of deposition are well known, though difficult to predict in exact spatial terms (Leopold and Bull, 1979). Despite these difficulties, the general concepts of upstream deposition are well enough known to be part of American case law regarding river management (Vanoni, 1975). This paper emphasizes the downstream effects of dam installation and removal (Fig. 1), because these effects are geographically more far-reaching than the upstream effects, and because the downstream issues are the focus of present debate among researchers and managers. Science, society, and economics for dams interact with each other through mutual influences. Social values ultimate determine which questions researchers investigate, and the availability of financial support determines degree to which questions are not only posed, but examined and answered.

In addition to focusing on downstream effects, this paper deals primarily with the American experience in geomorphology and dams. This restriction reflects the limitations of my own intersection with the subject. I recognize the exceptional contributions of my British, French, Australian, Japanese, Indian, and other colleagues. Their work, ranging from early research in Great Britain (Gregory and Park, 1974) to recent contributions in France (Bravard, 1998) contribute foundational concepts and empirical evidence to support global generalizations.

2. Present research in a historical context

The present geomorphologic research related to dams is within a historical context of a science that, for most of its history, has exhibited a strong association among research, public policy, social values, and financial investment in research by federal agencies. Geomorphology as a named science is barely more than a century and a half old (Tinkler, 1985), with the name "geomorphology" first appearing in the German language in 1858 (Roglic, 1972). A young associate of John Wesley Powell, WJ McGee (whose name was "WJ" rather than "W.J.," as is now often mis-referenced), introduced the term in the English language in 1888 (McGee, 1888a,b). Powell and McGee used their geomorphic insights to address questions about policy related to the federal management of land and water resources.

During the late nineteenth century, American geomorphology was closely associated with policy and management. The first major monograph of the

Fig. 1. The Oachita River downstream from Blakeley Mountain Dam, Ark., showing the effects of the dam on sediment-related processes and forms. This channel is armoured and lacks sand bars, islands, and beaches that characterized the stream in its undammed condition. Photo by W.L. Graf.

fledgling U.S. Geological Survey, for example, was an innovative and powerful exposition of landforms and processes related to the Pleistocene and Holocene history of Lake Bonneville, Utah, by G.K. Gilbert (1890). Now revered as a classic in basic geomorphologic science, the research was initiated by the need of the federal government to determine the variability of climate in the western regions in preparation for expansion of agricultural settlement into the region (Stegner, 1953). In a period when the popular sentiment was that "rain follows the plow" (that is, agricultural settlement stimulated rainfall), Gilbert's work showed the fallacy of such optimism. More germane to the present topic of geomorphology and dams, Gilbert is also known among theoretical fluvial sedimentologists for his flume studies of sediment transport, a multi-year basic research effort with policy and management roots. Gilbert's (1914) work was part of a search for remedies to the problem of stream pollution by mining sediments in central California.

For an extended period in the early twentieth century, American geomorphology diverged from its partnership with public policy as the researchers came to be preoccupied with unraveling the evolution of landscapes on a geologic time-scale as advocated by William Morris Davis and his followers (Chorley et al., 1973). American researchers seemed not to import research trends from Europe, where there was budding interest in environmental change and tectonic geomorphology (Beckinsale and Chorley, 1991). During the mid-1900s, theoretical progress was made in geology (e.g., Mackin, 1948), but fluvial geomorphology related to policy came to be practiced mostly by civil engineers, especially those who were involved in dam building. In the eastern United States efforts at flood control initiated investigations into river basins, flood plains, and potential dam sites, while in the western regions water supply and flood control drove similar efforts.

After World War II, a major paradigm shift among American fluvial geomorphologists ushered into the science a quantitative, dynamic approach that emphasized investigations into phenomena that were operating at human scales. Robert Horton (1945) and Arthur Strahler (1952) built the basis for this new perspective, and geomorphologists at the U.S. Geological Survey (USGS) took up the challenge and developed the paradigm. Although students of geomorphology in the 1960s and 1970s viewed the work of Luna Leopold, M. Gordon Wolman, and other USGS researchers as driven by purely theoretical needs (as outlined by Leopold et al., 1964), in fact it was directly related to water resources management, including making contributions to a growing debate about dams and flood control (Leopold and Maddock, 1954). Another USGS researcher, Stanley Schumm, made substantial contributions to fluvial geomorphology that had theoretical implications, but they were also driven by practical policy considerations (Schumm, 1977). His work on gullies connected directly to management of western grazing lands for example, and his investigations of river channel change was funded by the U.S. Army Corps of Engineers (USACE) in their search for understanding of the enigmatic behavior of partially dammed Great Plains rivers.

Throughout the remainder of the twentieth century, there was an increasingly strong connection between geomorphologic science and its management applications. Funding reinforced this trend among government researchers as well as those in colleges and universities. The USGS and USACE continued to investigate fluvial processes and forms in specific problem-solving situations. On the lower Mississippi River, for example, the USACE struggled with more than two centuries of data to try to develop some understanding of the erosion and sedimentation processes that governed the unpredictable behavior of the channel (Saucier, 1974).

Researchers in academia perhaps had freedom to pursue curiosity-driven research, but by the end of the twentieth century the need to address societal needs in fluvial research had become common in the thinking of most academic researchers in geomorphology. Applied problem solving was a source for funding, ranging from local consulting opportunities to major national-level grants, efforts that increasingly related to river management for endangered species or pollution issues (e.g., Malmon et al., 2002). Recent questions about the downstream effects of dams are a continuation of this policy–geomorphology connection.

3. The scientific context: effects of dam installation

Dams constructed by humans have been part of the American river landscape for at least two millenia, but until the eighteenth century the structures were small and exerted limited influence on river processes. Throughout the eighteenth and early nineteenth centuries, small dams associated with water-powered mills were common in all East-Coast river basins (see Table 1 for size definitions). In the early 1800s, water control structures for canals became common. These transportation-oriented structures were mostly run-of-river dams (simply raising the level of flow for navigation), though additional water storage structures were often required to maintain barge traffic during natural low-flow periods. In the late 1800s and early 1900s, medium and some large structures began to appear, often as part of hydroelectric projects, dryland irrigation, or urban water supply.

Very large dams were not built until the twentieth century, and they began to affect the gemorphic properties of downstream river reaches thereafter. The closure of Boulder Canyon Dam (later renamed Hoover Dam) in 1936, signaled a new era in dam building with very large structures appearing throughout the nation on all the major rivers. As economic development for river resources attracted ever more investment by governments and private interests, the mid-twentieth century became a dam-building era. A quarter of all the presently existing dams in the nation were built in a single decade, the 1960s (U.S. Army Corps of Engineers, 1996). By the time the dam-building era and the twentieth century had ended, more than 80,000 dams existed in the United States, of which 137 were sizable enough be characterized as very large (the total number is an estimate by the Federal Dam Safety Office, Federal Emergency Management Agency). Very large dams now appear in substantial numbers in all parts of the country (Fig. 2).

An understanding that important ecosystem changes are related to the installation of dams has been current knowledge in biology for more than two

Table 1
Size definitions for American dams (modified from Heinz Center, 2002)[a]

Size	Reservoir storage (ac ft)	Reservoir storage (m^3)
Small	10^0–10^2	10^0–10^5
Medium	10^2–10^4	10^5–10^7
Large	10^4–10^6	10^7–10^9
Very large	$>10^6$	$>10^9$

[a] The correspondence between size ranges for ac ft and m^3 is only approximate; 1 ac ft = 1234 m^3.

centuries. As early as 1784, legislators and administrators tried to prevent construction of dams in locations on East Coast rivers that impaired important migratory fish patterns (U.S. Fish and Wildlife Service, 2001). Administrators did not enforce these rules, however, and by about 1825 most East-Coast rivers were blocked by low-head dams. Throughout the 1800s, observers of fish in East-Coast and Pacific Northwest rivers lamented the role of dams in restricting passage of diadromous species. Unregulated fishing was partly responsible for plummeting fish stocks in coastal rivers, but dams almost certainly played a role as well. Based on his observations during the 1830s, Henry David Thoreau concluded that dams in Massachusetts impaired the migration of anadromous fishes, and he advocated the removal of the structures with crowbars (Thoreau, 1849). By 1925, researchers in the Pacific Northwest recognized the role of dams in declining salmon numbers by making large upstream areas unavailable for spawning, and the issue had already become a public issue finding sites for new structures (Lichatowich, 1999).

These early concerns about fish passage, and other later concerns for more extensive biological effects downstream from dams, were not matched by research into the downstream geomorphic changes. Most of the earliest geomorphic work was by engineers concerned about undesirable channel changes downstream from dams in particular locations rather than directed toward more general theory-building. A particularly significant early study, conducted in the late 1920s, focused on downstream geomorphic effects of Elephant Butte Dam on the Rio Grande of southern New Mexico (Fiock, 1931). The dam, closed in 1915, caused channel changes that were of international importance, because downstream from the dam the river formed the boundary between the United States and Mexico. Dam operations and water diversions resulted in the conversion of the channel from a braided system to a single-thread configuration.

Two downstream geomorphic issues that received considerable early attention were localized dam-related channel degradation and armouring. Both processes result from the clear-water discharge from

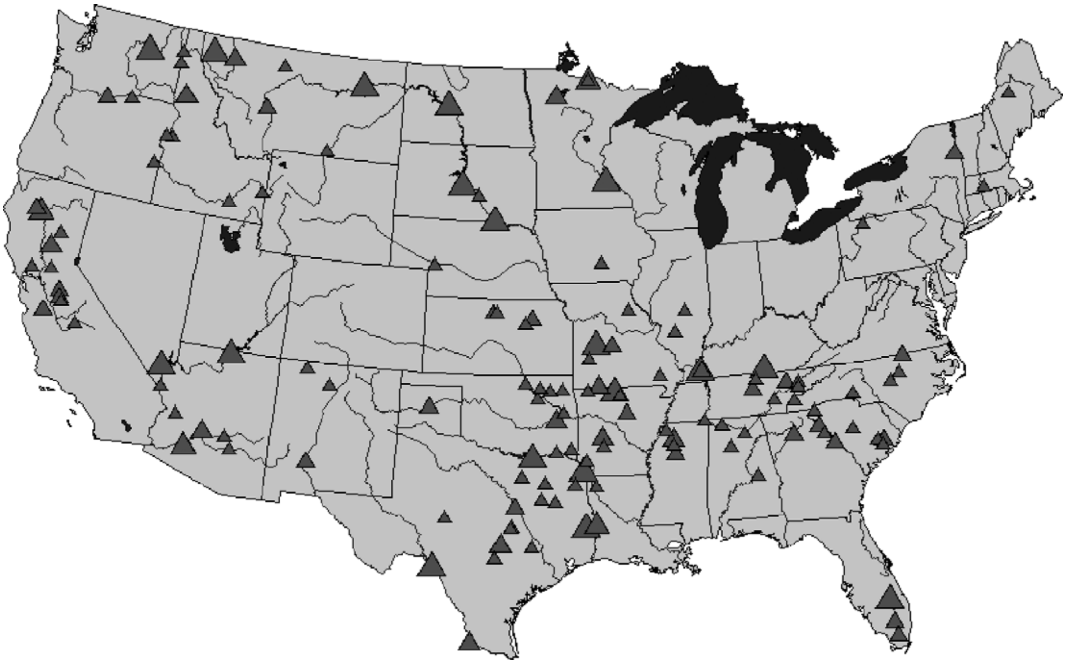

Fig. 2. Map showing the distribution of very large dams (those with reservoir storage equal to or greater than 10^6 ac ft or about 10^9 m^3) in the United States. Symbols graduated in size to show relative magnitude of storage for each structure. Created from original data from U.S. Army Corps of Engineers, 1996.

dams that have trapped sediments in their upstream reservoirs. Erosion by this water of channels downstream from dams could be modeled from an engineering perspective by extending approaches used for the analysis of scour. Gilbert's (1914) work was one of the earliest efforts in the United States that adopted a quantitative modeling approach. Application of general principles of hydraulics including the continuity equation, the Manning Equation, shear stress relationships including the Shields Equation, and various sediment transport functions led to general models of bed degradation that by the 1960s had become standard practice (e.g., Komura and Simons, 1967). Application of these methods provided estimates of the amount of bed lowering at various distances downstream from dams, estimates that were partially confirmed by empirical data from the Middle Loup River downstream from Milburn Diversion Dam, Nebraska (Senturk, 1994).

The winnowing away of fine materials from the bed of the channel immediately downstream from dams that left a pavement of large-caliber debris on the channel floor also lent itself to analysis using classic hydraulic functions. By the mid-twentieth century, these models (based largely on shear stress and various sediment transport equations including the Shields Equation) were widely known and included the ability to estimate the size distribution of the particles in the armour layer (Gessler, 1971).

The downstream *geomorphic* effects (i.e., landscape-scale) of dams received attention only much later than the more site-specific work of engineers. Channel degradation and armouring, for example, were along-profile particle-scale effects that played themselves out in the general form and process of the downstream river, but these geographic- or ecologic-scale changes did not capture much attention until late in the twentieth century (see Petts, 1984, pp. 9–11, for a detailed historical review of dam-related ecological research). One of the earliest general statements about the potentially deleterious downstream geomorphic effects of dams at extended scales was by Turner (1971). Chadwick (1978) and the American Society of Civil Engineers produced one of the earliest books on the issue of environmental effects of dams, including downstream impacts on sediment and aquatic habitat.

Among the earliest features of research interest in studies of downstream impacts were beaches (channel-side accumulations of sand) and rapids in canyon rivers. Dolan et al. (1974) assessed loss of beaches in the Grand Canyon of the Colorado River as a result of sediment trapping by the newly installed Glen Canyon Dam. Their work triggered subsequent analyses of the location, amount, and temporal trends of the sediment losses. Graf (1980) traced the downstream effects of Flaming Gorge Dam on the Green River, Utah, to changes in the dynamics of boulders in rapids of the canyons of Dinosaur National Monument. Reduced flood flows resulted in increasingly stable rapids that gradually enlarged through tributary contributions that were not removed by reduced mainstream floods. Similar effects were noted by Howard and Dolan (1981) in the Grand Canyon. Andrews (1986) further explored fluvial changes downstream from Flaming Gorge Dam.

Alluvial rivers without the confining walls of canyons were also subject to the downstream effects of dams (Fig. 3). Williams (1978) explored the defining characteristic of such streams in his analysis of the shrinkage of braided channels downstream from diversions on the Platte and North Platte rivers of the central Great Plains. For a more complex case, Dewey et al. (1979) connected changes in channel geometry on the Rio Grande in New Mexico to the installation of Cochiti Dam. In the same river, Lagasse (1981) showed that wholesale geomorphic changes ranging from shrinkage to changes in channel planform geometry had occurred as the result of dam installations. Williams and Wolman (1984) produced a national-scale investigation of the downstream effects of dams on alluvial rivers that brought substantial quantitative data to bear on an attempt to generalize the geomorphic changes. Data from 21 cases showed that the changes extended for hundreds of kilometers downstream and that new, stable geomorphic conditions required decades for their establishment.

Why did geomorphologic research on downstream effects of dams emerge in the United States during the 1970s and 1980s? This particular timing was the product of the convergence of two factors: the dams and the geomorphologists themselves. The effects of large dams required at least a few years to become apparent, and in some cases a period of a decade or

Fig. 3. Channel shrinkage from Navajo Dam and water diversions have converted the San Juan River, N.M., from a braided planform to a single thread channel. U.S. Geological Survey aerial photograph, EROS Data Center.

more was required. The effects of many large dams did not become obvious until the 1970s and 1980s, because the 1960s was the primary dam-building decade (Fig. 4). Also, by the 1970s and 1980s fluvial geomorphologists had become more numerous. In American geology, the general geomorphologist had given way to a series of more narrowly defined specialists, and fluvial specialists were particularly sensitive to the role of humans in geomorphic processes. In American geography, fluvial research

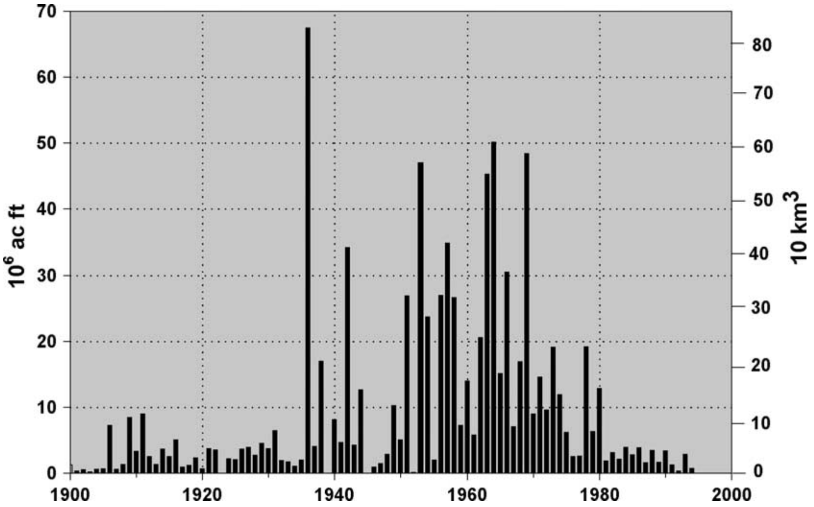

Fig. 4. Graph showing the chronology of increasing potential for hydrogeomorphic disruption from annual additions of reservoir storage behind newly closed dams in the United States. The large increase in 1936 resulted from the closures of Hoover and Ft. Peck Dams. Note the general peak of additions in the 1950s and 1960s. Data from U.S. Army Corps of Engineers, 1996.

became the most common topic in geomorphology, with more practitioners conducting field investigations where the effects of dams were obvious. The convergence in about 1980 of these two trends, one of increasing numbers of dams and the other an increasing number of fluvial geomorphologists, produced the interest in geomorphology and dams we now see 20 years later.

After the initial geomorphologic investigations of the downstream effects of dams, the number and complexity of such studies slowly but steadily increased. Most investigations were focused on a single river: Kircher and Karlinger (1983) on the Platte River of Nebraska, Lagasse (1994) and Hadley and Emmett (1998) on the Rio Grande of New Mexico, Elliott and Parker (1997) on the Gunnison River of Colorado, Graf (2000) on the Salt River of Arizona, and Nislow et al. (2002) on the Connecticut River of New England provide examples. Richter et al. (1996) provided geomorphologists with a standardized approach to describing the changes imposed by dams on downstream hydrology. Chien (1985) and Ligon et al. (1995) provided broad statements about the effects of the installation of dams, and by the end of the twentieth century, a new synthesis of generalizations about the downstream effects of dams was possible. Building on the foundations provided by Lillehammer and Saltveit (1982), Petts (1984), and subsequent detailed investigations, Collier et al. (1996) provided the geomorphologic foundation for the next era of geomorphologic research that was distinctly ecological and management oriented.

At present, two especially large research endeavors assess the downstream effects of dam closures: the Colorado River in the Grand Canyon of northern Arizona and the Everglades of south Florida. The Colorado River at Glen Canyon Dam drains more than 260,000 km^2 (100,000 mi^2) of the Colorado Plateau and portions of the Rocky Mountains. The river downstream from Glen Canyon Dam is probably the most intensively studied river reach in the world with respect to dam effects on rivers (for general reviews see Carothers and Brown, 1991; NRC, 1996). After the dam was closed in 1963, downstream effects slowly became apparent, including the erosion and loss of beaches used by recreational boaters, changes in the distribution of riparian vegetation, and alterations of habitat for endangered native fishes (Fig. 5). Each of these issues connected directly to geomorphic changes caused by the altered hydrologic regime of the river. The Bureau of Reclamation (BOR), operators of Glen Canyon Dam, initiated the Glen Canyon Environmental Studies (GCES) in the early 1980s to provide insights on potential effects of management

Fig. 5. The Colorado River in Marble Canyon, about 10 km (6 mi) downstream from Glen Canyon Dam, illustrating the simplification of the channel and near-channel landforms resulting from release of clear water from the dam and subsequent erosion. Photo by W.L. Graf.

decisions for operation and maintenance of the dam. More than 20 years later, these studies continue; and in sum, they represent a body of literature that provides the most complete ecological view of any such river in the world (NRC, 1996). GCES studies represent exceptionally focused and dense case studies, but they do not lead to the broadest possible generalizations because of necessity they deal with a most special case: the Colorado River in the Grand Canyon. Additional site studies, and more broadly based regional or continental (and thus, probably less detailed) studies are required for the creation of basic generalities.

The outcomes of GCES provided benchmark geomorphic studies for later work in other similar areas. The response of the geomorphic systems to dams in canyon rivers is complex, but GCES provided important predictive capabilities, especially with regard to sediment transport, beach building and erosion, dynamics of rapids, behavior of tributary alluvial fans as they intersect the main river, and general channel change. The most prominent changes resulted from the elimination of large annual floods in the canyon. GCES (supported by the NRC) investigators convinced BOR managers that the dam ought to be operated in such a way that at least occasional, modest-level floods would be beneficial in restoring some of the geomorphic characteristics of the original river. Two floods from managed releases at the dam have restored some aspects of the original geomorphology and ecosystem substrate. The process has been an exercise in adaptive management, with operational strategies tried experimentally and then refined based on monitoring data.

There have been two limitations of the geomorphologic outcomes of the GCES. *First*, the predicted restoration expected from the managed floods is not as great as expected, or may not be workable at all, and the scientific understanding of sediment, hydrologic, and geomorphic processes will require additional fine tuning (Rubin et al., 2002). The experience indicates that adaptive management may be effective, but success also relies on adaptive science. *Second*, as successful and extensive as GCES has been, its general applicability is limited to similar geomorphic settings, specifically bedrock-controlled canyon rivers. The extension of the Grand Canyon experience to rivers on the Great Plains or to eastern Piedmont and Appalachian rivers is not possible, because these alluvial streams operate in wholly different circumstances. Further theory development and empirical investigation will be needed before we have a continental picture of the downstream effects of dams.

The multi-million dollar research effort in GCES was a large investment by any standards, but the investigations related to the downstream effects of dams and water diversions in the Everglades of south Florida represent an even larger investment in restoration science (for general reviews see McPherson and Halley, 1996; Perry, 2001). The south Florida fluvial system operates as a river of unusual proportions (unusual for North America, but similar to many other river distributary systems on a global basis). Water from the 23,000-km^2 (9000-mi^2) drainage basin flows southward along the Florida Peninsula in a slow-moving “river” >100 km (60 mi) wide and <0.5 m deep. Portions of the flow area have hydrodynamically smoothed “islands” a meter or two higher than the surrounding areas, with the entire ecosystem dependent on annual variability of flow (Fig. 6). Over the past century, drainage ditches, water diversions, low dams, and control gates on waterways have resulted in drastic hydrologic changes that have included reductions in the amount of water flowing through the system and a nearly complete reduction of the variability of discharges. Reduction of active channel width is an outcome similar to the channel shrinkage noted in Great Plains rivers, and the reduction in mobility of fine sediment and nutrients in the Florida example has widespread significance for the flora and fauna of the region, just as in other regulated rivers.

In response to these undesired ecosystem changes, the water system managers in south Florida have begun restoration of the system to a conditions more similar to those that existed prior to the installation of water control structures. The USACE and the South Florida Water Management District (SFWMD), with support from Congress, established the Critical Ecosystem Studies Initiative (CESI) in 1997 as a research component of a much larger-scale restoration effort (NRC, 2003). The overall restoration plan calls for the expenditure of more than $15 billion over a 40-year period to re-establish a southward flow of water to the Everglades. During the 1997–2003 period, the federal government spent about $55 million on ecosystem research in direct support of the restoration

Fig. 6. The southern terminous of the Everglades in south Florida, where the low relief of the broad flow zone grades into Florida Bay. Photo by W.L. Graf.

project. The majority of the funding has supported biological research, but the overriding objective of the restoration is to "get the water right," so the work includes extensive topographic surveys at centimeter resolution to provide the basis for hydrologic modeling and fluvial assessments. If research funding continues at the present rate of about $4 million per year, the federal government will invest more than $200 million in environmental research to aid restoration, which in large part focuses on dam removal and re-plumbing of the regional fluvial system.

The more general scientific impacts of the south Florida Everglades restoration project and its science are not yet clear. However, even at this early stage dams obviously play a pivotal role in changing the ecosystem through adjustments in the hydrogeomorphic components that form its foundation. These small dams, many only a few meters high, exert the same sorts of wide-ranging hydrologic and associated geomorphic changes as the very large dams on other rivers.

4. The scientific context: effects of dam removal

The removal of dams may now, at the beginning of the twenty-first century, appear to be a new idea, but Americans have been removing dams for two centuries. Temporary structures in mining areas throughout the nation were intended to last less than a decade, and they rose and fell often. Some dams in logging areas were built with the explicit purpose of collecting water for up to a month, and then being breached to create downstream floods to transport logs (DeBuys, 1985). As water mills ceased operations, their dams occasionally fell into disrepair and were removed, either intentionally or by floods. Records of the structures that were removed from the national inventory of dams are scarce, so that their locations and numbers are not well known.

The most generally available accounting of dams removed prior to the conference where this paper was presented was by American Rivers et al. (1999), (Pohl, 2003). They identified 467 structures removed from the nation's watercourses (whereas Pohl, 2002, identified and confirmed 416), but the data are underestimates because states reporting removals continue to uncover new records and historical evidence. In 2000, Wisconsin's Department of Natural Resources indicated that though they had previously reported 50 dam removals in their state, further investigation revealed at least 120 more cases, with the final total likely to be about 500 (Galloway, 2000). Anecdotal evidence indicates that similar under-reporting has occurred in many other states. Regardless of the reliability of the precise numbers, the removal of dams is accelerating in the United States: in 2002 alone, 63 dams in 16 states are scheduled for removal (Eckl, 2002).

With the under-reporting in mind, some conclusions about dam removal in the United States are nonetheless suggested by the American Rivers et al. (1999) summary. Dam removals became more common in the middle 1990s than in previous decades. Almost all of the dams removed in the past decade have been low head, run-of-river structures that stored small amounts of sediment and that had limited hydrologic effects downstream (Fig. 7). Only a few removed dams had substantial reservoirs, such as Woolen Mills Dam on the Milwaukee River with its 1.5-km (1-mi) long lake. States with the greatest number of removals included Pennsylvania, Ohio, Illinois, Wisconsin, Tennessee, California, and Oregon.

Geomorphological research on dam removal is sparse compared to biological research related to the same subject. In a recent review of ecological impacts of dam removal, Bednarek (2001) outlined water quality, biological, and sediment changes resulting from dam removal, along with the biological outcomes of these changes; but she wrote little about landform and channel form changes simply because the underlying research was absent. A review of a recent special issue of the journal *BioScience* devoted to the effects of dam removal shows that biologists are beginning to amass substantial experience with the issue. Statements by Puzzuto (2002) and Stanley and Doyle (2002) in the same *BioScience* issue update geomorphological interpretations of river channel change resulting from dam removal.

The history and geography of dam removal explain why there is little geomorphologic research published in formal, refereed outlets. Because the removal of significant numbers of structures has occurred only in the last 10 years, little time has been available for the development of mature scientific generalizations about fluvial processes related to dam removal. The geography of removals has also made broad generalizations difficult. The majority of the structures that have been removed are on small rivers of the Upper Midwest in either glaciated plains or other areas of relatively low relief. Experiences from these streams is still too limited to provide geomorphologic generalizations about this restricted region, let alone about a broader continental picture.

Fig. 7. A power shovel operating in the removal of a typical low-head, run-of-river dam: Waterworks Dam on the Baraboo River, Wisc., 1997. Photo courtesy of the River Alliance of Wisconsin.

The published literature has emphasized sediment mobility, and but has devoted little attention to the landform dynamics of rivers downstream from removed dams. Winter (1990) briefly reviewed the sediment transport effects of removing Grangeville (in 1963) and Lewiston (in 1973) dams on the Clearwater River, Idaho, and Sweasy Dam (in 1969) on the Mad River of northern California. Simons and Simons (1991) analyzed and modeled the release of sediment from the removal of Newaygo Dam on the Muskegon River, Michigan. Brief assessments of sediment releases from the removal of Woolen Mills Dam (in 1988) also appeared during the 1990s (Staggs et al., 1995; Kanehl et al., 1997). At the turn of the new century, geomorphologic investigations are becoming more common, exemplified by the work of Stanley et al. (2002). These preliminary studies, along with assessments of analogies to dam removal (Doyle et al., 2003), set the stage for improved theory for sediment mobility and attempts at prediction for structures that are now about to be removed.

The production of useful theory for applied predictions of the geomorphic outcomes of dam removal is most likely to evolve from a series of present research projects that adopt continuous measurement strategies for pre- and post-removal conditions. The empirical data from these studies can inform us not only about sediment transport, but also about the changes in channels and near-channel landforms downstream from the structures. Three examples of such on-going investigations are those related to Elwha and Glines Canyon dams on the Elwha River of the Olympic Peninsula of Washington state; Matilija Dam on a tributary of the Ventura River of southern California, and Manatawny Creek Dam in southeastern Pennsylvania. The potential of these investigations is uncertain, because for the Elwha River there is no interdisciplinary team in place, the effort at Matilija Dam has no clearly defined leader, and the model case of Manatawny Dam involves a relatively small structure. As a result, understanding of long-term changes occurring over decades will continue to be elusive.

One of the most important unanswered geomorphological questions related to dam removal involves the likely course of change. Will post-removal changes simply be a reversal of the changes caused by the installation of the dam, with a similar set (of reversed) intermediate steps? Or will post-removal changes be a new series of processes and forms that do not have direct pre-dam corollaries? New types of adjustments, especially given the altered land uses and land covers in upstream drainage basins since the closure of the dams, are highly likely.

5. Funding for geomorphological research related to dams

The interaction between science and policy in the past 20 years has been barely adequate as a result of structural or institutional barriers. Researchers have responded to the needs of decision-makers mostly on an emergency basis, rather than from a perspective of well-thought-out planned efforts. Decision makers have tended to use scientific outcomes for politically defined goals rather than as guides for decisions. The institutional barriers to improving this situation are related to the decline of in-house research groups in many federal agencies. As the overall federal workforce has become smaller since the 1990s, the numbers of researchers in such agencies as the U.S. Forest Service, National Park Service, Bureau of Land Management, and U.S. Fish and Wildlife Service have declined, and most research is in response to short-term informational demands. The U.S. Geological Survey conducts little basic research, and also responds to primarily either to data needs or requirements of applied investigations. The Bureau of Reclamation and the U.S. Army Corps of Engineers conduct basic geomorphologic research only as it relates to requirements levied upon them by the National Environmental Policy Act or by the Endangered Species Act. State agencies are generally not funded for basic geomorphologic research. These negative influences on geomorphologic research are likely to continue rather than abate.

Despite the pivotal position of dams in controlling the physical, biological, and chemical integrity of rivers, their contributions to problems related to endangered species, and their importance in river restoration, there is no central mechanism for funding geomorphological research related to them. As a result, only uncoordinated patchwork efforts have been possible in building a body of knowledge and theory for prediction of geomorphologic effects of changing dam operations or removing dams. The two most logical agencies to undertake efforts to create new knowledge are a national water commission (which has yet to be established) and the National Science Foundation (NSF).

Several prominent researchers and administrators (including form Secretary of the Interior Bruce Babbitt and form Chief Administrator of the Environmental Protection Agency Bill Riley) have recently called for the formation of a National Water Commission, which might also funnel financial support to research on dams. The most recent expression of the concept of such a commission was at the National Conference on Water and the Environment, hosted by the National Council on Science and the Environment in January 2004. A National Water Commission would identify priorities and orchestrate research and policy efforts for water as a strategic resource system for which dams provide essential control points.

Unlike a National Water Commission, NSF is a reality, and it has already supported some dam-related research. NSF has a 10-year agency-wide initiative to invest in research on complex environmental systems, systems that represent the coupling of natural and human processes. Dam and river processes represent arch-typical examples of such complex systems, and the defining NSF statement concerning the agency's research directions uses the downstream effects of dams as an example of sort of research the agency desires to fund (Graf, 2002). Physical (including geomorphological), biological, social, and economic scientists should pursue integrated funding for dam related research through many NSF programs in association with this complex systems initiative.

6. Policy context

Investigations into the geomorphic effects of dam installation, operation, and removal take place within a policy context of governmental laws, administrative directives, and executive orders, as well as corporation rules and decisions. Social values and the economic investments in research that follow those values have been closely tied to federal law for dams. This policy context is significant for the research, because in many cases policies posed by decision-makers generate research questions and provide research funding for the scientific community. Investigators can maximize the effectiveness of their research if they frame results in ways that improve decisions made within the policy context. Researchers who propose adjustments are most likely to communicate effectively if they frame their proposals within existing policy.

In the United States, public law considers most river courses as "waters of the United States" and treats them as joint federal and state responsibilities. In most policies, the federal government defines overall rules and standards, while states administer rules and monitor compliance. Thus, for the complete picture, researchers must be familiar with federal policy, as well as local applications and practices. The following paragraphs of this section enumerate the most important federal policies and conclude with comments about state-based applications. This review emphasizes policies related to the operation, modification, or removal of dams and does not include the various individual laws authorizing the construction of very large publically owned structures.

Although geomorphologists are most often involved in dam-related research that has environmental quality or restoration implications, the policies that most affect dam operations are ones related to licensing and safety (for a more extended discussion, see Heinz Center, 2002). All dams in the United States are subject to safety regulations, including an important subset of 2600 small to large dams that are privately owned and licensed by the Federal Energy Regulatory Commission (FERC). More than two-thirds of these structures are more than 50 years old. Typical licenses are valid for 30- to 50-year periods, and occasional changes in license operating rules are common, with the proviso that the owner operates the dam in the public interest. The connection to FERC comes about because the regulated structures are hydroelectric producers; and FERC is the successor agency to the Federal Power Commission that originally licensed the dams. FERC derives its initial authority from the Federal Power Act of 1920, and the agency originally tended to emphasize the electrical power aspects of the public interest. The 1986 Electric Consumers Protection Act requires FERC licensing processes to provide equal consideration to power and nonpower values such as environmental quality, recreation, and fish and wildlife. The 1992 National Energy Policy Act provides further protection for parks and recreation areas surrounding dams, and authorizes FERC to charge license holders for studies required under previous laws. Complete ecosystem investigations require geomorphologic research, so that geomorphology is a direct connection to FERC and to its public interest goals.

In addition to licensing, federal programs for dam safety in the Federal Emergency Management Agency, FERC, and the Bureau of Indian Affairs are primary pillars of dam policy. Building on earlier laws, the Water Resources Development Act of 1996 established the National Dam Safety Program in the Federal Emergency Management Agency. The agency is a centralized clearing house for data, expertise, and resources operating through an Interagency Committee on Dam Safety. This committee connects the federal program to programs in almost all states. The dam safety component of FERC includes programmatic capability for episodic inspection of FERC-licensed dams. The dam safety staff also evaluates the potential effects of dam failures on downstream areas, and assists license-holders in preparing required emergency action plans to be implemented in the event of a failure. Finally, the Indian Dam Safety Act of 1994 established a program in the Bureau of Indian Affairs with the mission of maintaining the safety of dams on Indian lands that potentially threaten human life downstream if the dams were to fail. All of these safety programs are connected to geomorphic conditions downstream, primarily in the form of hazard assessment in the case of dam failures.

Among the myriad of federal laws that influences the relationship of dams to environmental quality, three are most important: the National Environmental Policy Act, Clean Water Act, and Endangered Species Act. The National Environmental Policy Act (NEPA) of 1969 generally requires consideration of environmental and (as a result of later executive orders) social consequences of federal actions. With respect to dams, these actions range from the construction of dams to decisions about their operation or removal. NEPA did not establish new substantive rights, but rather created procedures for reaching informed decisions. Thus, destruction of a socially valued ecosystem is entirely legal, but under the precepts of the Act, there must be a public accounting of the anticipated loss before the project goes forward. In political terms, the published accounting triggers public debate about the appropriateness of the proposed action, and the results of this public process may include a modified approach or cancellation of the proposed action. Council on Environmental Quality Regulations 1500–1508 define the procedures for compliance with the Act, including the creation of environmental impact statements. Because the geomorphic and hydrologic systems are the foundation of the more popularly recognized biological systems of rivers. Geomorphologic research may therefore play a required part of NEPA processes (Makenthun and Bregman, 1992).

The Clean Water Act (the results of 1977 amendments to the 1972 Federal Water Pollution Control Act) provides for federally defined water quality goals for uses of public water courses ranging from drinking water to recreational use. Individual states monitor water quality and enforce the standards. Dams and their operations have direct effects on water quality (especially dissolved oxygen content and water temperature), so that management decisions related to the structures often entail consideration of Clean Water Act standards. Some portions of the Act contain policy direction for dam and reservoir planning.

Two aspects of the act are important from a geomorphological perspective: sediment issues and more general ecosystem issues. For sediment, section 404 of the Clean Water Act charges the U.S. Army Corps of Engineers with regulating physical changes to channels and particularly changes in sediment discharges. Sediment issues are especially important when owners consider removing dams, because the deposits behind the structures are likely to become mobile. Predicting the downstream fate of these sediments and their associated contaminants is a hydrologic and geomorphic problem that usually requires investigations and model-based predictions. For more general ecosystem issues, the preamble of the Clean Water Act declares that the general policy of the nation is “to restore and maintain the chemical, physical, and biological integrity of the Nation’s waters” (33 United States Code Annotated, Section 1251(a)). Substantial scientific progress has been made in understanding the concepts of chemical and biological integrity, while physical integrity (well within the purview of the geomorphologist) is at initial stages of intellectual development (Graf, 2001).

The Endangered Species Act of 1973 requires the federal government to preserve species of plants and animals that are threatened with extinction. The application of the law often takes the form of restoring and protecting habitat used by the threatened species (Fig. 8; 16 United States Code Annotated, Section 1531(b)). Species management therefore becomes a problem of the management of geographic space, which inevitably brings into play the requirement for understanding the underlying geomorphology. For rivers, this geomorphological input extends to explanation and prediction of the size and distribution of aquatic habitats for fish and of riparian habitats for plants and animals (e.g., Pitlick and Van Steeter, 1998; Van Steeter and Pitlick, 1998). The federal agency most directly involved in processes related to the Endangered Species Act is the U.S. Fish and Wildlife Service, which usually works in concert with state-level counterparts. Their investigations into threatened river-related species has directly supported substantial amounts of hydrologic and geomorphological research (e.g. Graf et al., 2002).

A complete accounting of all the federal policies with bearing on dams, rivers, and their geomorphology is not possible in the limited extent of this paper, but four policies are most prominent. *First*, each large river in the United States is governed by an extensive collection of laws, treaties, rules, procedures, interstate agreements, and court decisions that are collectively known for each stream as the “Law of the River.” The complex case of the Colorado River is probably best known (Ingram et al., 1991), but other streams such as the Columbia, Missouri, Chattahoochie, Savannah, Tennessee, Ohio, Susquehanna, and many others are subject to similar complexities of governance. *Second,* the Wild and Scenic Rivers Act of 1968 explicitly prohibits dam building in designated river reaches, though dams may be upstream from such reaches and thus exert some control over them. *Third*, the American Heritage Rivers Initiative of 1997 created administrative methods to designate selected river reaches for streamlined federal management with combined goals of environmental, historical, and economic restoration. *Fourth*, the National Historic Preservation Act of 1966 (most recently amended in 2000) confers federal protection for designated structures, including dams and the associated mills, power houses, and other structures. Although none of these policies have direct geomorphological components, they often raise questions related to fluvial geomorphology.

In addition to federal policies, each state has separate and variable policies governing rivers within their borders. In most cases, these state agencies

Fig. 8. Habitat for the southwestern willow flycatcher along the undammed Virgin River, Nev., is dominated by the extensive flood-plain forest of nonnative tamarisk. Photo by W.L. Graf.

cooperate with their federal counterparts; but rules, regulations, and approaches are highly variable from one state to another, and so they defy generalization. With respect to dam removal, for example, the states of Pennsylvania, Ohio, and Wisconsin have state policies that do not mandate dam removal, but that facilitate the process if the dam owner requests assistance in removal. These states view dam removal, particularly of older, obsolete, small structures, as furthering their general aims at improving recreation potential and fish or wildlife habitat. Some states such as Maryland and Massachusetts have relatively little experience with dam removal, and therefore do not have established policies. As a result, opportunities for geomorphological research based on state-level policies is highly variable from place to place.

7. Economic context

Until the 1980s, federal funding for research related to dams was generally commensurate with the size of each project. Large dams such those of the Tennessee Valley Authority and large western storage projects engendered substantial research into river mechanics, flooding, erosion, and sedimentation. Investigations into sedimentation and channel changes on the Colorado River and the Rio Grande triggered geomorphic and engineering research on those streams downstream from large dams. In recent decades, however, such investments in geomorphic research related to dams has been meager, with the only exceptions being related to endangered species issues.

Large and very large dams represent the investment of hundreds of millions of dollars in public funds or from private corporations. The downstream effects of these structures may trigger changes in operations rules that affect the return on these investments, so that the outcomes of geomorphological research can have substantial monetary implications for owners of dams. This is especially true when geomorphological research addresses issues such as habitat for threatened or endangered species that fall under the jurisdiction of the Endangered Species Act, because the act requires (with the force of federal law) sometimes costly actions on the part of dam owners. These high costs may justify significant investment in geomorphological research to support sound management decisions. Direct investments in ecosystem research for management of Glen Canyon Dam have been more than $77 million, with the portion allotted to geomorphology and hydrology amounting to several million dollars.

Modifications of large and very large dams to meet mandated changes for environmental protection often cost many millions of dollars and offer formidable engineering challenges (Anderson, 1993). The removal of small structures costs much less, and in many cases, the cost of removal is less than the cost of repair to meet licensing requirements or to rectify hazardous conditions. Removal costs are acceptable to many private owners who are concerned about liabilities associated with antiquated structures (Ellam, 1976). Data collected by American Rivers et al. (1999) show that in a presumably representative sample of 36 small dam removals, the average cost was $376,000. On an individual basis, these costs are usually not large enough to justify substantial investments in geomorphological research, yet collectively, the small dams represent the most common removal. For this reason, studies of the effects of small structures are likely to receive limited financial support, and the few studies that are funded will have to be generalized to a larger population. Work by interdisciplinary teams including geomorphologists on such examples as Manatawny Creek Dam in Pennsylvania, the Baraboo River in Wisconsin, and Searsville Dam near Menlo Park, California are therefore important precursors to broad generalizations.

As dam removal becomes more common, medium-sized structures and even a few large ones will be removed. These removal projects involving high dams and large reservoirs will require improved geomorphology to assess removal effects, but because the projects are more expensive, they need more support for research than is the case of small structures. The removal of the two dams on the Elwha River will cost up to $200 million. In California, removal of five dams on Battle Creek will cost about $29 million (Friends of the River, 2002), and the dismantling of Matilija Dam will require up to $180 million (U.S. Bureau of Reclamation, 2000). These and similar expensive projects are likely to include funding for geomorphological and other research: the Matilija removal project has already spawned $4.2 million in feasibility investigations (Fig. 9). Extensive geomorphological investigations are under way in these projects, with one of the objectives being the prediction of the fate of reservoir sediments once the dams are removed.

The removal or modification of the water control structures in central and south Florida, upstream from the Everglades, exemplifies the potential magnitude of future projects. Congressional appropriations for ecosystem research related to the 40-year project have funded about \$51 million, with the hydrologic and geomorphologic components totaling about \$7.6 million (National Research Council, in press). As was the case of Grand Canyon downstream from Glen Canyon Dam, investigating the effects of the dams and control structures upstream from the Everglades will expand our knowledge about how partly natural and partly artificial systems operate. The cases call to mind Gilbert's work on California rivers downstream from mining areas, in that large-scale economic and engineering efforts have raised new research questions requiring funds for investigations.

These large-scale projects may change the economics of geomorphology, a science that traditionally has been dominated by "research on the cheap." Geomorphologic research projects during the past two decades often ranged in cost from a few tens to a few hundreds of thousands of dollars. If increasingly large dams are subject to operational changes or to removal, substantially larger investments are likely in geomorphology to support decision-making and adaptive management.

The point at which scientific research interfaces with policy for river restoration occurs in three common types of cases: relicensing of dams by the Federal Energy Regulatory Commission (FERC), changes in operating rules for dams with storage capacity under general public or private ownership, and the removal of dams of a variety of sizes. The presently defined FERC process does not provide funding for geomorphic research, and its process does not include a roadmap for including research in the decision process. However, present (March 2004) procedures allow interveners in relicensing cases, and these interveners sometimes include the U.S. Fish and Wildlife Service operating under the aegis of the Endangered Species Act. State agencies also intervene from time to time, sometimes providing small amounts of research conducted by their own employees. Advocacy groups and nongovernmental organizations also play a part in some cases, with very limited research. The license holder in FERC cases

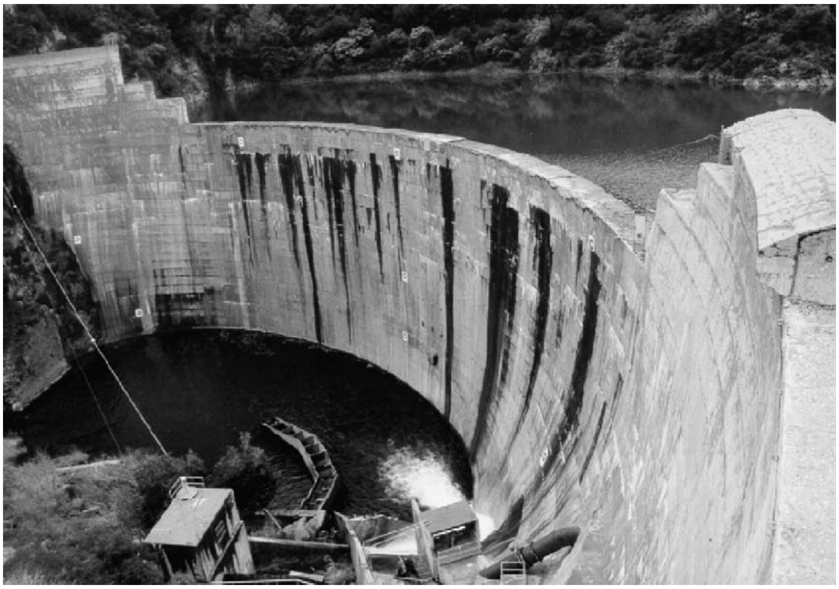

Fig. 9. Matilija Dam has been notched in a partial removal that may be completed by the total removal of the structure. Management of the stored sediments is a major issue. Photo by Sarah Baish, Heinz Center.

often employs researchers to explore various management options, including removal in some cases, but such research is not independent, and it often lacks adequate peer review.

The largest dams in the United States are often the result of federal investment, and the U.S. Army Corps of Engineers (USACE) or the Bureau of Reclamation (BOR) are the primary operating agencies. Under pressure from court rulings or reviews of operating rules that may affect threatened or endangered species as defined by the Endangered Species Act, USACE or BOR (or associated semi-public owners) sometimes conducts research connecting operating rules with downstream effects. Operators of large dams on the Platte River system, for example, are investigating the geomorphic and ecological effects of changing operations that might benefit threatened or endangered fish and riparian birds downstream. Funding for research into the outcomes of altered operating rules is almost always tied to the effects on listed species.

The removal of small run-of-river dams is proceeding apace in the United States, with more than 60 removed in 2003, and a similar number in 2004. In many cases, the removal of these structures does not include geomorphic research of any kind, while in some cases state agencies explore the fate of remobilized sediments but they rarely investigate the geomorphic consequences. Removal of dams in Wisconsin on the Baraboo River and in Pennsylvania on the tributaries of the Susquehanna River are notable exceptions, and extensive projects have received funding in these cases. The ongoing removal of the somewhat larger Matilija Dam in southern California has attracted some attention from researchers, but the effort is not highly organized among the several responsible agencies, and it is underfunded.

8. Cultural context

The practice of geomorphology in connection with dams is within a cultural matrix of local to national dimensions. Cultural perceptions influence the research questions asked by geomorphologists, control the flow of laws and money in the research process, and provide the stage upon which the public receives the results of the research. The river channels and near-channel landforms that are the object of study for geomorphology are often associated with a variety of conflicting social values, so that when researchers present their conclusions about these features in public, research results become part of nonscientific processes. Although these values should not alter the conclusions of researchers, investigators do not operate in a vacuum. Public activists, corporate interests, and the legal community are likely to use research results for their own purposes. Therefore, the most effective scientific results are those that are stated precisely and with an accounting of uncertainty in ways that are understandable for nonspecialists.

Free-flowing rivers are broadly attractive to modern American society that attaches numerous positive social values to natural river landscapes. This appreciation comes at the end of a history of changing values, and is different from previous eras when Americans typically viewed rivers as primarily generators of wealth. In the early 1800s, rivers and their associated canals were *the* major components of the nation's transportation infrastructure. From the early 1800s to the present, rivers have been the means of delivery for resource managers who place an economic value on each cubic meter of water. Beginning in the late 1800s, rivers generated electrical power for public and privately owned distribution systems. Through the middle decades of the twentieth century, rivers were unregulated waste disposal systems for industry, cities, farms, and individuals. The construction of dams throughout most of the twentieth century was taken as a welcome sign of progress, and rivers without dams were considered to be "loafing streams" (Jackson, 1997). By the late twentieth century these values changed broadly in American society to include recreation, wildlife, esthetics, and historical considerations.

The significance of this history is that many of the social values now attributed to rivers are in conflict with inherited values, and dams play a pivotal role in the resulting debates related to management and restoration. Dams made possible much of the economic development of rivers, but the cost of this development has been the degradation of some measures of environmental quality. Many environmental changes associated with dams have two sets of opposing and competing values. Fish species, recreation, and property values are instructive examples. Dams impede some native fish species that depended upon free-flowing rivers in their migration patterns, but dams also make possible the maintenance of introduced sport fishes (one of America's premier trout fisheries is immediately downstream from Glen Canyon Dam). For water-borne recreation, dams also produce mixed outcomes. Dams disrupt white-water recreation in downstream reaches (as in many New England rivers), but make possible flat-water recreation on reservoir waters upstream. Effects on private property values by dams are not obvious in western locations dominated by public land, but the effects are major issues in eastern areas dominated by private land. A reservoir may flood highly valued agricultural property, but create even more valuable lakeshore plots. Removal of an eastern dam may have damaging influences on the monetary value of lakeshore plots that are then left without their primary amenity, the lake.

The conduct of geomorphological research connected with dams is likely to produce results that are of direct interest to individuals and organizations dealing with a broad spectrum of issues from advocacy positions. Monetary values are at the heart of some debates, and landforms that to the geomorphologist have purely scientific implications may for others have dollars and cents implications. Researchers may find the resulting political pressures substantial and uncomfortable, but such pressures are part of the cost of doing scientific business in the public arena.

Social or cultural values also reach expression in nonmonetary ways. Many local cultures resist change as a matter of principle, so that the suggestion that a dam and reservoir be removed, for example, will be likely to engender protest from residents for whom those features have been part of a familiar landscape for a lifetime (Fig. 10). Many dams, canals, and power houses are officially recognized as having historical significance, so that formal laws closely regulate their modification or removal. Landscapes, particularly those associated with rivers, have strongly entrenched non-use values in most local cultures, so that any changes are questioned by many citizens. Geomorphological research is most effective in these debates if it produces understandable explanations for natural change or stability, and if it creates reasonable predictions of the likely outcomes of various alternative public decisions. These services, provided without value judgment, can at least make decisions well-informed and reduce uncertainty.

The case of Rindge Dam on Malibu Creek, California, exemplifies the collision of opposing cultural values concerning a dam whose management has significant geomorphological considerations (Heinz Center, 2002, provides a general review). The Rindge family constructed the dam in 1926 as a

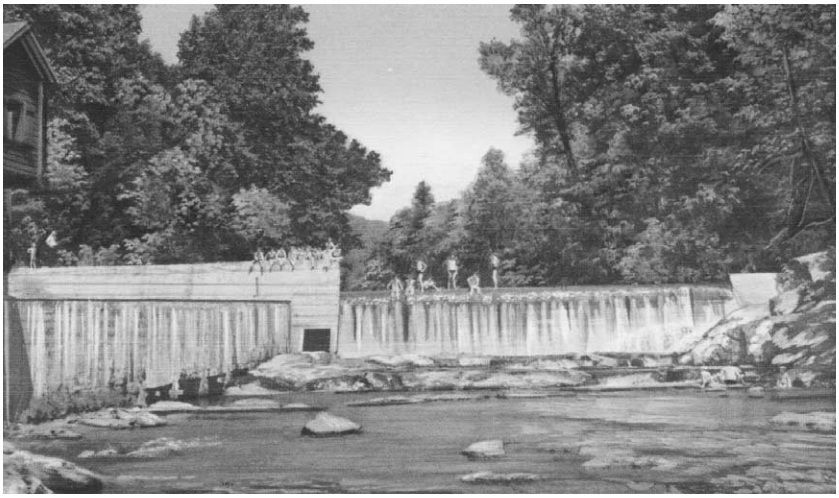

Fig. 10. Post card from the 1920s shows the nostalgic cultural values attached to Patterson School Dam on Buffalo Creek, near Lenoir, N.C. This strong community attachment to historically significant structures is a common value in public debates about the fate of dams. Originally published by the Asheville Post Card Company.

33-m (100-ft) high concrete arch structure to provide water storage for ranching in the western Santa Monica Mountains (Fig. 11). By the 1950s, the reservoir was filled with sediment, and subsequently the dam along with the surrounding watershed became part of the state park system. The California Department of Parks and Recreation proposed removing the structure to allow upstream access for steelhead trout, an endangered anadromous species. On one side of the issue are the Rindge family, who want to retain the dam as a historic structure, and Hollywood celebrities who own property downstream from the dam and who fear increased risks from flooding, debris slides, and disruptive truck traffic if a removal occurs. On the other side are nongovernmental organizations along with state and federal wildlife management agencies who are responsible for managing the dwindling steelhead trout population. Geomorphology plays a significant role in the unresolved debate over the fate of the dam because important issues include the suitability of the stream for steelhead, the amount and fate of the sediments behind the structure, and land use on the various near-channel landforms downstream. The sediments of the reservoir also represent material that has not reached the coast and that might aid in alleviating beach erosion problems at Malibu.

While geomorphology for dams operates within a cultural context, the discipline also has its own internal culture. The majority of geomorphologists in the United States tend to ascribe favorable values to river landscapes characterized by naturalness, stability or equilibrium, and diversity of landforms and ecosystems. As a consequence, many fluvial geomorphologists use language in their writing and public discourse that prejudges values for particular river reaches. Many of the words in this language are also used by ecologists with similar biases: stability, integrity, harmony, balance, healthy, pristine, fragile, recovery, dominance, disruption, collapse, as well as similar pejorative words for nonnative species such as alien, exotic, and invasive (Trudgill, 2001).

The case of invasive species illustrates the issue of values. Generally, geomorphologists and ecologists view tamarisk (or salt cedar, *tamarisk*) as an undesirable alien plant that has crowded out more desirable native vegetation, as well as influencing fluvial forms and processes. Scientific accounts of tamarisk that use negative descriptors for the plant, however, overlook the positive values ascribed to it by some resource users. Game managers view tamarisk tracts as important dove habitat in parts of the Southwest, while these forests of invasive trees also

Fig. 11. Rindge Dam, Malibu Creek, Calif., is a candidate for removal. The dam is 60 m (100 ft) high and has a reservoir filled with sediment. Photo by Sarah Baish, Heinz Center.

provide nesting habitat for the endangered Southwestern willow flycatcher (*Empidonax traillii extimus*), a riparian bird with particular environmental requirements (Finch and Stollson, 2000). These positive values are offset by negative values associated with the reduction in channel flood capacity (hence the connection to hydrology and geomorphology) and pressure on native vegetation resulting from growth of tamarisk. The ultimate choice of how to manage the vegetation and the decision about which values are more important are not scientific questions; rather they are cultural and political issues.

Geomorphologists, faced with complex audiences made up of individuals with a wide range of values, may be most effective in including science in modern public debates by adopting neutral language in reporting scientific results (terms such as change, adjustment, and outcomes, for example). In this way, the results of research can inform the decision process while allowing the appropriate political machinery to sort out conflicting public values that range from materialistic conceptualizations to non-use values based on esthetics. The practice of blind advocacy science ultimately undermines public confidence in research, especially in controversial topics such as river and dam management.

The struggle to produce informative research in an era of conflicting social values is not new to American geomorphology. John Wesley Powell, revered in geography and geology as a scientific pioneer in matters pertaining to rivers and water resources, served two perspectives on western water resources during his tenure as head of the U.S. Geological Survey (Kirsch, 2002). His exploration, mapping, and research opened Colorado River system to the reigning governmental values of the late 1800s: unregulated economic development with control of the resources by engineering structures. At the same time he laid the foundation for later governmental policies directed toward preservation and regulated land use in dryland areas (Powell, 1878).

9. Conclusions

Geomorphologic research focused on issues related to river management and dams takes place within a complicated context, including scientific, policy, economic, and cultural components that influence each other.

(i) In the *scientific context*, present research is embedded in a history of geomorphology for public service, with general theory-building and particular problem-solving strongly linked to each other. Decision-makers need improved river theory from geomorphology that includes the roles of dam installation, operation, and removal. The boundaries between "basic and applied" research are likely to become increasingly indistinct.
(ii) The *policy context* for this research is exceptionally diverse and complicated, with many overlapping policies at federal, state, and local levels. The most important policies now driving geomorphological research are connected to the Endangered Species Act and habitat for federally listed species, because the biological aspects of ecosystems are directly dependent on the substrate formed by sediments and landforms.
(iii) The *economic context* for this research is different from some previous geomorphologic work, because large amounts of public funds are being spent on river restoration, and the public and private investments in dams are substantial. These large investments justify expenditures for geomorphologic research that are larger than in many previous cases.
(iv) The *cultural context* for this research is highly contentious with many competing stakeholders giving intense scrutiny to any geomorphologic research related to dams. Research results are likely to be used in advocacy procedures that highlight conflicting social values, so that objective research and reporting are essential. Geomorphologists can be powerful contributors to debates outside the framework of their science.

A review of American geomorphologic research related to dams shows that there is a growing body of literature reporting on the outcomes of the installation of dams, but very little literature concerning the outcomes of dam removal. Both bodies of literature are likely to advance considerably in the near future, but the outcomes of varying operating rules for large dams remain little studied. Thus far, most of our knowledge about downstream effects of dams is predicated on studies of the installation of large structures. The results of these investigations may not be applicable to dam removal issues because such removals are dominantly of small and medium structures. In all cases, long-term changes remain and the reversibility of the effects of dam installations and operations are reversible are unknown. In dam-related geomorphologic research, new questions for investigation and new results of on-going research are likely to change scientific perspectives, so that adaptive management will need to be matched by equally adaptive science that recognizes and accommodates itself to its social, economic, and cultural contexts.

Acknowledgments

This paper represents the input of many people in addition to the author. On the science side, M.G. “Reds” Wolman, Garnet Williams (USGS), and Bob Hirsch (USGS) have always been sources of information and insight. David Wegner (long-time director of the Glen Canyon Environmental Studies) and Sheila David of the Heinz Center connected science and policy in a team with me in ways that always contributed to my continuing education. Reflections by Bruce Babbitt and Bill Riley based on their cabinet-level service were truly enlightening. To Patty Beyer I am grateful for the opportunity to participate in the Geomorphology Symposium, to Dick Marston for his sage editorial help, and most of all I am grateful to Gordon Grant (U.S. Forest Service) for his review of this manuscript and his many essential inputs to the final product.

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