Science and Values in River Restoration in the Grand Canyon

There is no restoration or rehabilitation strategy that will improve the status of every riverine resource

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Restoration of riverine ecosystems is often stated as a management objective for regulated rivers, and floods are one of the most effective tools for accomplishing restoration. The National Research Council (NRC 1992) argued that ecological restoration means returning "an ecosystem to a close approximation of its condition prior to disturbance" and that "restoring altered, damaged, or destroyed lakes, rivers, and wetlands is a high-priority task." Effective restoration must be based on a clear definition of the value of riverine resources to society; on scientific studies that document ecosystem status and provide an understanding of ecosystem processes and resource interactions; on scientific studies that predict, measure, and monitor the effectiveness of restoration techniques; and on engineering and economic studies that evaluate societal costs and benefits of restoration.

If flooding is crucial to the recovery of flood-adapted species but the absence of floods is crucial to the conservation of terrestrial endangered species in new habitats, then managers face an intractable dilemma

In the case of some large rivers, restoration is not a self-evident goal. Indeed, restoration may be impossible; a more feasible goal may be rehabilitation of some ecosystem components and processes in parts of the river (Gore and Shields 1995, Kondolf and Wilcock 1996, Stanford et al. 1996). In other cases, the appropriate decision may be to do nothing. The decision to manipulate ecosystem processes and components involves not only a scientific judgment that a restored or rehabilitated condition is achievable, but also a value judgment that this condition is more desirable than the status quo. These judgments involve prioritizing different river resources, and they should be based on extensive and continuing public debate.

In this article, we examine the appropriate role of science in determining whether or not to restore or rehabilitate the Colorado River in the Grand Canyon by summarizing studies carried out by numerous agencies, universities, and consulting firms since 1983. This reach of the Colorado extends 425 km between Glen Canyon Dam and Lake Mead reservoir (Figure 1). Efforts to manipulate ecosystem processes and components in the Grand Canyon have received widespread public attention, such as the 1996 controlled flood released from Glen Canyon Dam and the proposal to drain Lake Powell reservoir.

The importance of the river and the dam

The Grand Canyon is the most famous and extensive canyon in the world; approximately 5 million people visit Grand Canyon National Park each year. Whitewater recreation on the Colorado River is internationally renowned, and 25,000 people travel the river through the Grand Canyon annually. This segment of the Colorado River is a federally designated critical habitat for two endemic endangered fish: the razorback sucker (*Xyrauchen texanus*) and the humpback chub (*Gila cypha*). Riparian vegetation along the Colorado River in the Grand Canyon is a federally proposed critical habitat for the endangered Kanab ambersnail (*Oxyloma haydeni kanabensis*) and the southwestern willow flycatcher (*Empidonax traillii*). The

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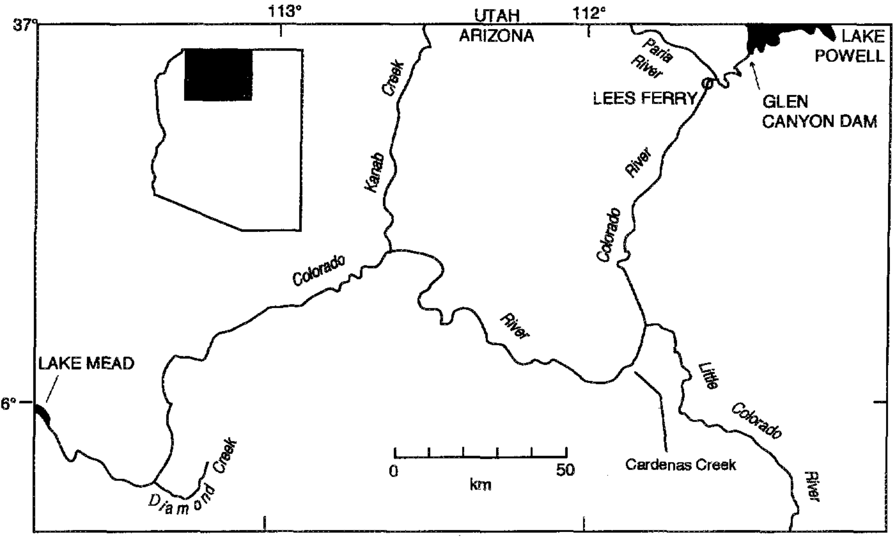

Figure 1. The Grand Canyon region.

25 km reach between Glen Canyon Dam and Lees Ferry is a blue-ribbon trophy fishery for non-native rainbow trout (*Oncorhynchus mykiss*).

The river provides essential water for humans as well. Water from the Colorado River has been diverted to southern California for 90 years and is being increasingly diverted to cities in the Wasatch Front in Utah, the Front Range in Colorado, southern Nevada, and central and southern Arizona. The discharge of the Colorado River is relatively small for the basin's size: The mean annual discharge at Lees Ferry was only 505 m^3/s ($15.9 \times 10^9\ m^3/yr$) between 1912 and 1963, before the dam was built (USGS 1996). Therefore, large reservoirs have been constructed to assure water availability, and the Colorado River has the largest reservoir storage capacity in relation to annual discharge of any major watershed in the United States (Hirsch et al. 1990). The potential for flood control and sediment retention by these reservoirs is nearly complete, and restoration or rehabilitation can be achieved only by changing the dams or their operations.

Many aspects of water-release policy from Glen Canyon Dam are controlled by statutory or administrative rules that are related, directly or indirectly, to the seven-state Colorado River Compact of 1922 that allocated water use among the states. Water released from Glen Canyon Dam constitutes a delivery of water from the upper basin to the lower basin because the division point between the basins is near Lees Ferry. Glen Canyon Dam is the largest dam of the Colorado River Storage Project (CRSP); its power plant produces approximately 75% of the total CRSP power for a six-state region. Lake Powell holds 80% of the upper Colorado River basin's stored water supplies.

Table 1. Controlling factors and ecological processes of the Colorado River in the Grand Canyon that can, and cannot, be manipulated by Glen Canyon Dam.

Relation to the existence or operations of Glen Canyon Dam	Controlling factors	Ecological processes
Unrelated	Regional climate; regional geology and geomorphology; human activities (prehistoric settlement, spatial patterns of water use, growth in water demand, regional land-use changes, recreational demand); non-native species invasions	Regional land use; tributary floods and debris flows; stage-discharge relations of the Colorado River; solar insolation and downstream rate of water warming; regional expansion of some native and non-native species
Related	Discharge; water temperature; sediment; nutrients; woody debris; non-native species introductions	Lake Powell limnology and mainstem sediment transport; stratification; sediment accumulation on river bed; transfer of sediment to eddies and sediment accumulation in eddies; sandbar stability; ice formation and transport; dissolved load transport; woody debris transport and decomposition; aquatic and terrestrial productivity

The management of that portion of the Colorado River that flows through the Grand Canyon reflects the interests and values of many management and regulatory agencies. The federal agencies that manage or monitor Glen Canyon Dam and the ecological resources of the Colorado River include the US Bureau of Reclamation, the National Park Service, the US Fish and Wildlife Service, and the Grand Canyon Monitoring and Research Center. The Western Area Power Administration markets the power produced by the CRSP and partly determines the daily releases from each CRSP dam. The Arizona Game and Fish Department manages the sport and native fish populations. Approximately 200 km of the left side of the river (facing downstream) forms the reservation boundaries for the Navajo and Hualapai tribes, and five additional Native American tribes have vested interests in Grand Canyon river management. Other interested parties include numerous municipalities and agricultural organizations that use water and electrical energy, national and regional environmental groups, commercial river-running companies, and professional trout-fishing guides.

The Colorado River ecosystem in the Grand Canyon

The Colorado River ecosystem in the Grand Canyon is sustained by the flow of water and nutrients released by Glen Canyon Dam, but other controlling factors are unrelated to the dam, such as regional geology and geomorphology, climate, tributary inflows of water and sediment, and human activities (Table 1). Changes in these factors have caused adjustments in channel geomorphology, alterations in riparian vegetation and fish assemblages, decreases in habitat availability for endangered fish, and changes in water temperature and quality. Deciding whether to restore or rehabilitate the Colorado River ecosystem requires an understanding of the role of Glen Canyon Dam, in relation to other factors, in causing ecosystem change and the potential to reverse these changes.

Water discharge and sediment transport. The construction and operation of Glen Canyon Dam reduced the frequency, magnitude, and duration of floods through the Grand Canyon. Before the dam was constructed, peak discharge occurred in late spring following snowmelt in the Rocky Mountains (Figure 2). The magnitude of the two-year recurrence flood for the period 1921–1962 was 2150 m^3/s, and flows that exceeded 1250 m^3/s were typically sustained for 30 days or more (Table 2). Short-duration floods occurred in September and October.

Since the dam's completion in 1963, the magnitude of annual high flows is determined by the magnitude of inflows and the elevation of the reservoir when these inflows occur (Figure 3). Lake Powell did not fill to capacity until 1980, and dam releases were always less than the capacity of the Glen Canyon Dam power plant, which is approximately 891 m^3/s. Large-magnitude dam releases occurred in 1980, and annually between 1983 and 1986, because the reservoir elevation was high and inflows were large. The two-year recurrence flood at Lees Ferry was 679 m^3/s for the period 1963–1996; flood flows of 1250 m^3/s or more now occur less than 1% of the time (Garrett and Gellenbeck 1991). The 1996 controlled flood of 1272 m^3/s was much smaller than typical pre-dam floods (Figure 2). Dam releases between 1964 and 1990 were characterized by large, hourly flow fluctuations resulting from load-following hydroelectric power production in response to regional demand.

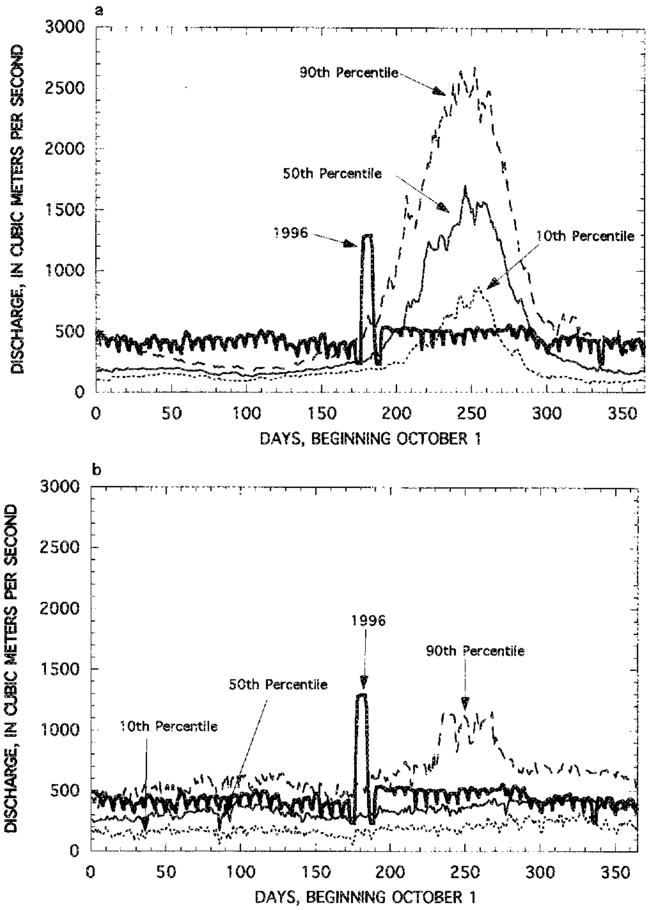

Figure 2. Hydrograph of water year 1996 compared to pre-dam and post-dam hydrographs for the Colorado River at Lees Ferry, Arizona. (**a**) Pre-dam (1922–1962). (**b**) Post-dam (1963–1995). The heavy black line is the hydrograph for 1996 and is the same on both panels. The dashed, solid, and dotted lines connect the mean daily discharge values for each date below which 90%, 50%, and 10% of the years, respectively, occur.

The average suspended-sediment load of the Colorado River at Lees Ferry was approximately 6.0×10^{10} kg/yr before construction of the dam. An average additional 1.8×10^{10} kg/yr is contributed by tributaries downstream from Lees Ferry; 70% of that amount comes from the Paria and Little Colorado Rivers (Andrews 1990). The magnitude of this annual sediment resupply varies greatly. In 1964 and 1965, after the dam was completed, the average annual suspended-sediment load of the Colorado River at Lees Ferry was only 0.000013×10^{10} kg/yr because Lake Powell traps all the sediment transported from the upper Colorado River basin.

River corridor geomorphology. Restoration options are determined in part by the geomorphic attributes of the river corridor. The width of the Colorado River in the Grand Canyon is constrained by bedrock, talus, and debris fans (Howard and Dolan 1981). Debris fans, which are composed of coarse debris supplied from steep tributaries, partially constrict the channel and create rapids (Webb et al. 1989). Before the completion of Glen Canyon Dam, mainstem floods reworked debris fans and removed all but the largest boulders from the rapids (Howard and Dolan 1981, Kieffer 1985, Webb et al. 1989, 1996). Debris fans have increased in volume and thus narrowed adjacent rapids because the magnitude of post-dam floods has been too small to transport the coarse debris delivered to the river since the dam was completed. As rapids narrow, they potentially become more difficult to navigate and pose safety hazards. Thus, high dam releases might be used to rework accumulating coarse debris. Releases at maximum power-plant capacity rework parts of recent debris-flow deposits; larger dam releases, such as those that occurred between 1983 and 1986 and during the 1996 controlled flood, caused substantial debris-fan reworking, but they still did not entirely reverse the narrowing trend (Kieffer 1985, Webb et al. 1996).

Unvegetated sandbars were a distinctive landscape feature of the unregulated river. Sandbars form in eddies that occur downstream from most debris fans (Schmidt 1990, Schmidt and Rubin 1995). These eddies have relatively low velocity and turbulence and are prominent sites of sand accumulation. Sandbars are dynamic features subject to deposition during floods and ero-

Table 2. Comparison of pre- and post-dam Colorado River resources downstream from Glen Canyon Dam. Changes occurred on widely differing time scales. Whereas physical changes (in flow, sediment load, and temperature) occurred rapidly after closure of the dam in 1963, geomorphic (e.g., debris-fan reworking and sandbar erosion and deposition) and biotic (e.g., trophic patterns and non-native species invasion) changes occurred more slowly and are ongoing.

Riverine feature	Before Glen Canyon Dam	After Glen Canyon Dam
Hydrologic regime	Variable; two-year flood was caused by regional snowmelt that averaged 2150 m^3/s between 1921 and 1962[a]	Regulated; two-year flood of 679 m^3/s is less than the power-plant capacity of 940 m^3/s; large hourly fluctuations are associated with load-following power production
Sediment load	Variable; mean annual suspended sediment load at Lees Ferry was 6.0×10^{10} kg[a]	Virtually zero in dam releases; mean annual contribution of 1.8×10^{10} kg from tributaries downstream from Lees Ferry[a,b,c]
Debris fans	All but largest boulders from rapids frequently reworked[b,d,e]	Debris flows continued, with consequent aggradation of rapids[d,e]
River temperature	Varied seasonally, from near freezing in winter to 25–30 °C in summer[f,g]	Nearly constant 8–10 °C because water is drawn from below thermal discontinuity in Lake Powell in summer; there is slight year-to-year variation in the temperature of the winter isothermal period[f,g,h,i,j]
Unvegetated sandbars	Common; distinctive features associated with eddies downstream from debris fans[k,l,m]	A near-river riparian zone has been established that consists of a marsh zone within the range of river stages regulated by power-plant operations[l,n,o,p]
Trophic structure	Thought to be heterotrophic because high sediment loads diminished light availability	Autotrophic in dam tailwater and in nearshore or cobble-bars downstream[i,j]
Fish assemblage	Eight native endemic species; 74% level of endemism is highest among North American rivers; heavily dependent on terrestrial food sources; some species extirpated, others endangered[f,q]	Warm-water fishes introduced to Lake Mead and trout to the tributaries by the 1930s; tailwater trout fishery is highly valued

[a] Andrews (1990).
[b] Howard and Dolan (1981).
[c] Randle et al. (1993).
[d] Webb et al. (1989).
[e] Webb et al. (1996).
[f] Valdez and Ryel (1997).
[g] Marzolf et al. (1996).
[h] Stanford and Ward (1991).
[i] Stevens et al. (1997a).
[j] Stevens et al. (1997b).
[k] Schmidt (1990).
[l] Schmidt et al. (1995).
[m] Webb (1996).
[n] Turner and Karpiscak (1980).
[o] Johnson (1991).
[p] Stevens et al. (1995).
[q] Miller (1959).

sion after flood recession (Rubin et al. 1990). Before the dam's completion, both the size of the sediment-comprising eddy bars and the shape of these bars reflected the characteristics of sediment transported during recession from the annual spring peak as well as from lower-magnitude late-summer floods. Thus, pre-dam deposits that still exist in the Grand Canyon are typically very fine sand mixed with silt and clay.

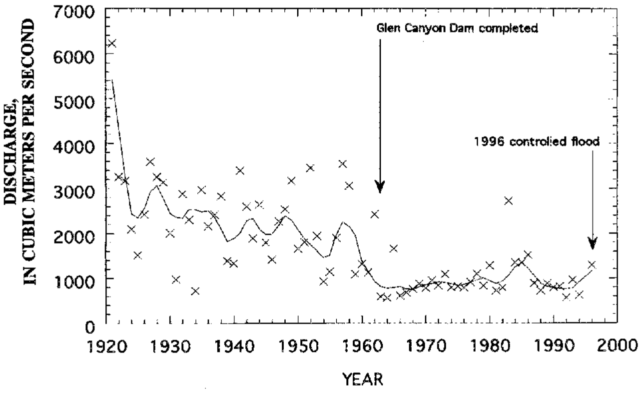

Figure 3. Annual peak discharge of the Colorado River at Lees Ferry, Arizona. Solid line is a weighted average. The year of completion of Glen Canyon Dam (1963) and the magnitude of the 1996 controlled flood are indicated.

A sediment budget calculated for a 141 km reach immediately downstream from Lees Ferry indicates that fine sediment accumulates in the Grand Canyon despite the fact that no sediment is released from Glen Canyon Dam (Randle et al. 1993). Accumulation occurs because the undammed Paria and Little Colorado Rivers continue to contribute significant amounts of fine sediment to the Colorado River. This sediment accumulates on the channel bed and in eddies because the bars along the river's margin have typically eroded, not aggraded. At least 30% of all large, high-elevation sandbars in the Colorado River decreased in size between 1965 and 1973; 32% decreased in size between 1973 and 1991 (Kearsley et al. 1994). These decreases were caused by degradation and invasion by riparian vegetation.

Although high discharges of water in 1983 caused a number of sandbars to increase in size, almost all of these bars had decreased to pre-1983 sizes by 1991. River runners use large sandbars as campsites, and decreases in sandbar size cause decreases in campsite carrying capacity (Kearsley et al. 1994). Net post-dam erosion of sandbars may decrease with distance downstream from the dam (Webb

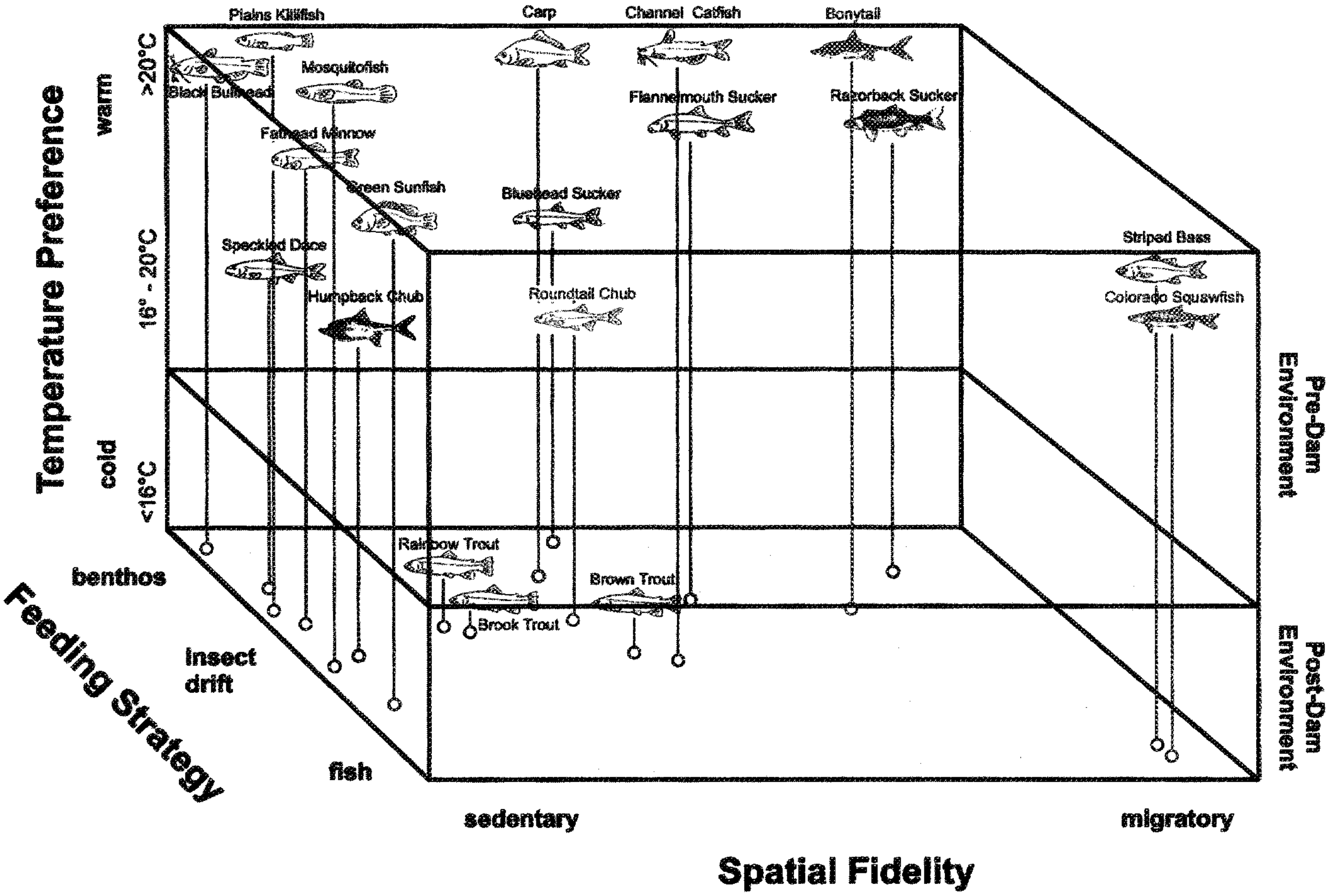

Figure 4. Guild box of spatial fidelity, feeding strategy, and temperature preference for the eight native fish species and 11 principal non-native fishes of the Colorado River in the Grand Canyon. Extirpated native species are shown in red, endangered native species in blue, and non-native species in green. Circles indicate location with respect to spatial fidelity and feeding strategy, and vertical placement of fish symbols indicates temperature preference.

1996). Different types of sandbars vary in their susceptibility to erosion (Schmidt et al. 1995); erosion may be greatest in the narrowest parts of the Grand Canyon (Schmidt and Graf 1990, Kearsley et al. 1994).

Biological processes. Fish assemblages native to the Colorado River evolved in an environment of highly variable discharge, large annual temperature fluctuation, high turbidity, large input of organic material, and the opportunity for basinwide fish migration (Valdez and Ryel 1997). These conditions have all changed. For example, annual river temperatures before the construction of Glen Canyon Dam ranged between approximately 0 and 29 °C. River temperature no longer varies seasonally; it is now determined by the temperature of the reservoir at the level at which water is withdrawn into penstocks that lead to the power plant.

The penstocks are at a fixed elevation of 1058 m above MSL (mean sea level), so the depth of withdrawal depends on how much water is in the reservoir. The reservoir is full at 1128 m above MSL. In most summers, water comes from beneath a thermal discontinuity less than 20 m below the surface. These waters have a relatively constant temperature of between 8 and 10 °C. Isothermal conditions prevail in winter, when the reservoir surface is lowest. The heat content of the reservoir is highest in early autumn, when temperatures from the surface to depths of between 15 and 20 m are as high as 30 °C (Stanford and Ward 1991). These seasonal changes in the reservoir's thermal regime provide the opportunity to increase summer river temperatures by decreasing the depth from which water is withdrawn through the construction of multilevel intake structures on the penstock intakes.

Water quality in the Grand Canyon is controlled primarily by processes in Lake Powell, although photosynthesis by benthic algae and submerged aquatic vegetation determines daily changes in oxygen concentration and pH in the 25 km of the river immediately downstream from the dam (Marzolf et al. 1996); tributary contributions of sediment and salt affect water quality farther downstream (Taylor et al. 1996). Because water chemistry in Lake Powell is controlled by temperature, the chemistry of water released from the dam depends on the region in the reservoir from which the water is drawn. Warm surface waters have lower concentrations of nutrients (carbon, nitrogen, and phosphorus) and salts, whereas cold water, which is withdrawn from greater depths, contains higher concentrations of these nutrients.

Releases of cold, clear water and reduced transport of organic material from the upper Colorado River basin have dramatically changed conditions for the aquatic macroinvertebrates downstream from the dam (Stevens et al. 1997b). Thus, the food supply available for native fish in the Grand Canyon has changed greatly. Observations made in the less regulated upper Colorado River basin indicate that high densities of aquatic insects currently exist on gravel bars and that native fish feed on a variety of terrestrial and aquatic invertebrates (Dill 1944, Vanicek 1967, Tyus and Minckley 1988). Predam river runners in the Grand Canyon described large accumulations of woody debris in eddies, and the decomposition of this wood probably supported a suite of aquatic and terrestrial invertebrates.

The Colorado River benthos in the Grand Canyon is productive but depauperate in species. Chironomids, simuliids, oligochaetes, and an introduced amphipod, *Gammarus lacustris*, are the most common macroinvertebrates. More than 65% of the aquatic plant and invertebrate standing biomass of the entire Grand Canyon is produced upstream from Lees Ferry (Stevens et al. 1997b). The occurrence of terrestrial macroinvertebrates in adult humpback chub stomachs increases downstream because of resupply from unregulated tributaries. Since construction of the dam, decomposition of woody debris has a minor effect on the invertebrate communities because relatively little of this matter is stored on the channel banks and none is resupplied from upstream.

Fish assemblage. The fish assemblage of the Colorado River through the Grand Canyon has altered dramatically during the past century, but this change is related only partly to dam-caused variations in discharge, sediment transport, temperature, nutrients, and food base. Before the late 1800s, 74% of the 35 fish species native to the entire Colorado River basin were endemic, the highest percentage among North American river basins (Miller 1959). Eight of these species once lived in the Grand Canyon (Miller 1959). The eight native warm-water fishes differed little in their temperature preferences but had different feeding strategies and spatial fidelities (Figure 4).

Three of the native fish species, Colorado squawfish (*Ptychocheilus lucius*), bonytail (*Gila elegans*), and roundtail chub (*Gila robusta*), were extirpated from the Grand Canyon by the 1970s (Minckley 1991). Razorback suckers are currently rare in the Grand Canyon; only ten specimens were reported between 1944 and 1990 (Valdez and Ryel 1997). By contrast, the humpback chub population in the Grand Canyon is the largest of six extant populations in the Colorado River basin.

Cold water releases impede reproduction of native fish. Native speckled dace (*Rhinichthys osculus*), bluehead sucker (*Catostomus discobolus*), and flannelmouth sucker (*Catostomus latipinnis*) continue to reproduce in several tributaries in the Grand Canyon, but there is very little reproduction by any of the native species in the mainstem. For successful spawning, these fish need a minimum temperature of about 16 °C, and in the Colorado River these temperatures occur only immediately upstream from Lake Mead for a short time in the summer.

At the same time that reproduction of native fish has been reduced, competition and predation by non-native fish have increased (Minckley 1991, Douglas et al. 1994). There had already been a marked decline in populations of many native fishes by the late 1950s (Miller 1959), presumably because of pressure from non-native fish and blockage of fish migration caused by the first mainstem dams. Non-native carp (*Cyprinus carpio*) and channel catfish (*Ictalurus punctatus*), which are warm-water species, were introduced to the basin in 1890 or so and were dominant in the lower Colorado River by 1911. Cold-water species, such as rainbow trout, brown trout (*Salmo trutta*), cutthroat trout (*Oncorhynchus clarkii*), and brook trout (*Salvelinus fontinalis*), were introduced after 1919. Warm-water centrarchid game fishes were introduced into Lake Mead in the 1930s, and other non-native species gained access as incidentals or bait fish.

Currently, there are 11 principal non-native species—three cold-water and eight warm-water—in the Grand Canyon (Valdez and Ryel 1997). Each of these species was already in the Grand Canyon at the time the dam was completed. Non-native warm-water fishes fill ecological niches similar to those filled by the remaining native species, and the non-native cold-water species occupy new thermal niches (Figure 4). Niche overlap has increased selection against native fishes, further threatening their existence.

The cold temperatures of the regulated Colorado River in the Grand Canyon restrict the distribution of non-native warm-water species. Channel catfish and carp are less abundant than in the upper Colorado River basin, where summer river temperatures are warm. These species presently spawn only in the Little Colorado River, because they require temperatures of over 20 °C. Populations of fathead minnows (*Pimephales promelas*), black bullhead (*Ictalurus melas*), and green sunfish (*Lepomis macrochirus*) are also low in the mainstem and occur primarily downstream from the Little Colorado River. Few of the warm-water fishes that are common in Lake Mead, such as striped bass (*Morone saxatilis*), ascend into the Grand Canyon.

The trout fishery between the dam and Lees Ferry is maintained by periodic releases of hatchery-reared fish. There is considerable natural reproduction in this fishery, although water temperature during spawning between December and February is usually 10 °C, below the optimum for trout. Trout upstream from Lees Ferry do not appear to mix with the self-sustaining rainbow trout populations that occur downstream. The trout fishery is not only of recreational importance: These downstream populations have been preyed on by wintering bald eagles since 1982 (Brown and Stevens 1992).

Riparian vegetation. Glen Canyon Dam and its operations have altered the riparian ecosystem (Turner and Karpiscak 1980, Johnson 1991). Early photographs of the Grand Canyon show that channel banks inundated by flows of less than 2800 m^3/s were devoid of vegetation (Turner and Karpiscak 1980, Webb 1996). Perennial riparian vegetation existed only as a linear band above this stage on terraces and in tributary canyons (Figure 5). This vegetation consisted primarily of mesquite (*Prosopis glandulosa*), catclaw (*Acacia greggii*), Apache plume (*Fallugia paradoxa*), desert broom (*Baccharis sarathroides*), and native willows (*Salix gooddingii* and *Salix exigua*; Turner and Karpiscak 1980, Johnson 1991). Photographs first show non-native saltcedar (*Tamarix* spp.) near Lees Ferry in 1938 (Webb 1996), but saltcedar may have arrived earlier (Graf 1978). By 1962, saltcedar was well established in small, high-density stands in parts of the Grand Canyon and was also common in tributary canyons.

River-corridor vegetation now occurs in four distinct zones (Figure 5). Marshes, which were not present before the dam, occur at elevations inundated by average power-plant operations (Stevens et al. 1995). The lower riparian zone occupies formerly barren channel banks and sandbars that are inundated by discharges of 700–2800 m^3/s. The pre-dam perennial riparian vegetation now comprises the upper riparian zone, and desert vegetation occurs on high terraces and slopes that have not been inundated in more than a century (Carothers et al. 1979, Turner and Karpiscak 1980, Stevens 1989, Carothers and Brown 1991, Johnson 1991, Webb 1996). Flood control by Glen Canyon Dam has reduced upper riparian zone recruitment, productivity, and survivorship through increased drought stress (Anderson and Ruffner 1987).

The lower riparian zone, which is composed of a diverse assemblage of native and non-native plant species (e.g., *Tamarix* spp., *Salix* spp., *Baccharis* spp., *Tessaria sericea* [arrowweed]), is highly productive and well established (Johnson 1991). Soil nutrient concentrations are reduced because many post-dam deposits have less silt and clay than do pre-dam deposits. Marshes are the most productive assemblages of the lower riparian zone; they increase in area under high fluctuating flows but are scoured by flows that exceed power-plant capacity (Stevens et al. 1995). Terrestrial invertebrate and vertebrate populations, such as waterbirds, have increased in the lower riparian zone (USDI 1995, Stevens et al. 1997a). The endangered southwestern willow flycatcher and Kanab ambersnail have expanded their ranges into marshes and lower riparian-zone vegetation, respectively.

Management resources and related processes of the Colorado River in the Grand Canyon

Processes and resources that are relicts of the pre-dam river:

- Seasonally fluctuating discharge, sediment transport, turbidity
- Seasonally changing temperature
- Large, unvegetated sandbars that are emergent at low discharge
- Rapids dominated by large boulders
- Native fish assemblage, including species that are now endangered or extirpated
- Native upper riparian zone vegetation, native terrestrial species richness
- Archeological and historical sites

Processes and resources that are artifacts of the post-dam river:

- Low variability in annual discharge
- Substantial hourly variation of discharge in some years
- Low sediment transport and turbidity
- Constant low temperature
- Constricted rapids
- Blue-ribbon non-native trout fishery
- Biologically diverse marshes
- Dense lower riparian zone vegetation
- Endangered snail and bird species and other regionally significant populations occupying non-native riparian vegetation
- Hydroelectric power

The potential for river restoration

Possible Colorado River ecosystem management goals range from traditional, market-driven dam management to full restoration of the pristine river ecosystem. The identification of desired goals can lead to the selection of appropriate engineering approaches. Pursuit of a particular goal will change the status of individual resources and the direction of ecosystem development by altering ecosystem processes. Some resources and processes of the present river corridor are pre-dam relicts, others are post-dam artifacts, and a few include elements of both (See box this page). This array of resources of differing origin means that altering ecosystem processes will involve tradeoffs, because pre-dam and post-dam resources respond differently to specific engineering approaches.

From a continuum of possibilities, we identify five management approaches: traditional river management; managing the river as a naturalized ecosystem; rehabilitating it as a simulated natural ecosystem; rehabilitating it as a substantially restored ecosystem; and reestablishing a fully restored ecosystem (Table 3). Each approach alters the trajectory of this open and dynamic ecosystem, and the success of any one approach is not assured.

- Pursuit of *traditional* techniques of river management uses existing facilities to maximize power revenues and to optimize the mandated transfer of water within the basin. This approach accepts the river as a transformed ecosystem, in which the goal of river management is the efficient

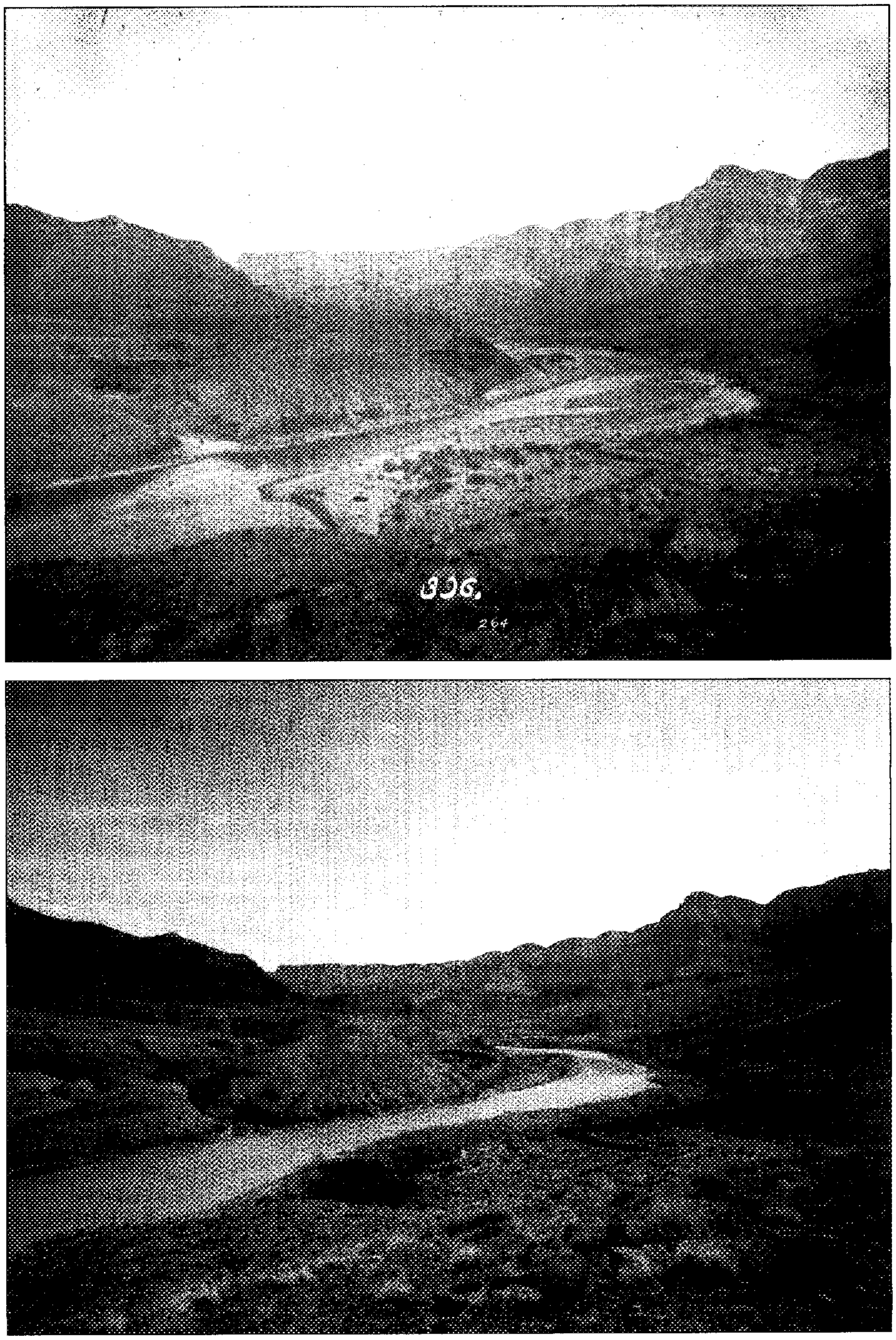

Figure 5. Upstream views of the Colorado River near Cardenas Creek (Figure 1). (top) In a photograph taken on January 23, 1890, little riparian vegetation is present along the river except for scattered mesquite and what appear to be scattered clumps of willows. A large sandbar occurs on the downstream side of the Cardenas Creek debris fan, in the left part of the center of the figure. Farther downstream, in the left part of the figure, an eddy occurs in the lee of this debris fan. Photo: Robert B. Stanton; courtesy of the National Archives. (bottom) In a photograph taken on February 26, 1993, the increase in riparian vegetation is extensive, and a smaller new sandbar is located within the former eddy. Most vegetation is saltcedar, although willow, arrowweed, and other native species have also increased. Vegetation on the new sandbar includes dry and wet riparian marsh species, and the area is a nesting habitat for endangered southwestern willow flycatchers. Photo: Steve Tharnstrom; courtesy of the US Geological Survey Desert Laboratory Collection. Photographs reprinted from Webb (1996).

performance of the utilitarian tasks of power production and water transfer; ecological integrity is a secondary value.

- Carothers and Brown (1991) argued that the appropriate direction for river management in the Grand Canyon is to preserve the present processes and elements of the river as a *naturalized ecosystem* with "a blend of the old and the new, a mixture of native and introduced organisms and natural and artificial processes." Non-native species with economic value, or that are permanently established and not a threat to the survival of native species, are managed by minor alterations of dam releases, such as restricting the range of hourly flow fluctuations and creating small floods that exceed the magnitude of average daily maximum flows. These techniques necessitate restructuring, but not eliminating, load-following power production.
- The National Research Council (NRC 1996) proposed using "operational flexibility to restore and maintain environmental conditions...that resemble as nearly as possible the original condition of the river." We term this the *simulated natural ecosystem* approach. NRC (1996) also suggested that the status of unvegetated sandbars and endangered fish habitats should be the primary measures used to evaluate the success of this approach. Operational changes under this strategy include dam releases that closely resemble the pre-dam hydrograph, including frequent floods that greatly exceed the magnitude of average daily maximum flows. Load-following power production would be substantially controlled and would vary seasonally.
- The fourth management approach, *substantial restoration of natural processes*, could be accomplished by retrofitting existing facilities or building new ones. The goal of this approach is the restoration of a large measure of pre-dam hydrologic variability, including higher sediment-transport rates and more wide ranging thermal variability. The strategy would involve constructing facilities to transfer sediment from the Colorado River delta or the San Juan River delta in Lake Powell to the Colorado River near Lees Ferry and building multilevel intake structures to allow the release of water of different temperatures when Lake Powell is thermally stratified. Constraints would be placed on power produc-

Table 3. Engineering approaches to management and the associated management goals for operation and modification of Glen Canyon Dam to manipulate conditions along the Colorado River corridor within the Grand Canyon.

Management goal	Management philosophy	Engineering approach	Results from this approach	Power production potential	Constraints on power operations	Effect on water transfers	Potential negative impacts on present recreation
Traditional river management	Maximize power production at times of maximum power price	Maximize revenues from power production	Maximum power revenues; rapid, erratic, aseasonal dam releases; flood control with occasional unplanned releases; minimal protection of ecosystem resources	Maximized	None; unlimited load-following	None	Moderate: fluctuations affect fish stranding in tailwater and campsite stability
Naturalized ecosystem	Manage existing ecosystem including desirable non-native species	Use existing structures to manage existing resources	Maximize biodiversity; maximize biological productivity; maximize recreational opportunities; constrain maximum and minimum releases	Small to moderate production	Load-following is restricted; base loading is increased	None	Low: vegetation invasion of some campsites
Simulated natural ecosystem	Simulate some pre-dam ecological processes and partially restore some pre-dam resources	Use existing structures to increase pre-dam resources	Increased endangered fish habitat; increased growth of upper riparian zone vegetation; larger sand bars; less-difficult rapids	Seasonally varying production	Load-following or base load, depending on season	Minor seasonal constraints	Low: reduced shade due to vegetation loss at some camps; potential effect on tailwater fishery
Substantially restored ecosystem	Extensive restoration of pre-dam processes and management elements	Modify structures: sediment bypass and/or thermal modification	Substantially restore pre-dam hydrology and sediment transport; restore annual range of water temperatures; restore pre-dam landscape; restore endangered fish habitat	Seasonally varying production	Load-following or base load, depending on season	Seasonal constraints	High: potentially reduce tailwater fishery; change characteristics of white-water boating in some seasons
Fully restored ecosystem	Attempt complete restoration of pre-dam processes and resources	Remove dams; remove non-native fish and vegetation	Restore pre-dam hydrology and sediment transport; only native fishes and vegetation occur	Small or no power production	Smaller power production	Eliminate flexibility in water transfers	High: eliminate tailwater fishery; change characteristics of white-water boating in some seasons

tion and on the seasonal flexibility of water transfers between the upper and lower basin.

- *Full restoration* of the river is an ambiguous management goal that has not been described precisely and may not be possible. We define this goal as restoration of all pre-dam ecosystem resources and processes by removal of flow regulation. Several different pre-dam standards might be considered as a goal. Restoration of a wide range of hydrologic variability might be accomplished by removing Glen Canyon Dam, but the full range of variability could not be restored unless all upstream dams and diversions were also removed. Even with this substantial effort, the river environment could not be returned to its 19th-century condition because many alien species, such as saltcedar, non-native fish, and non-native fish parasites, are well established and widely distributed. Only eradication of non-native species on a regional scale, which is highly controversial and infeasible at the present time, might permit full restoration. Removal of the Hoover Dam, located downstream from the Grand Canyon, might also be necessary to restore the full migration potential for wide-ranging fish species, such as the Colorado squawfish and the razorback sucker.

Attempts at full restoration by dam removal could lead to several problems. Depending on how it was managed during dam removal, sediment flushed from the drained Lake Powell might overwhelm the riverine environment of the Grand Canyon, possibly destroying some post-dam riverine resources, such as riparian marshes, and potentially threatening some pre-dam resources. Moreover, the hydroelectric power produced by Glen Canyon Dam would have to be generated elsewhere or matched by energy conservation. In addition, mandated water transfers between upper- and lower-basin states would require greater annual fluctuations in the volume of water stored in Lake Mead.

Table 4 shows the expected effects of some of the engineering techniques that could be used to implement the different management goals. Some techniques have also been analyzed by the US Department of Interior (USDI 1995). In some cases, our predictions differ from those conclusions, either because additional information has become available or because our interpretations of specific research findings differ. Assess-

Table 4. Predicted change of resources and ecosystem processes manipulated by different engineering techniques from conditions that existed in 1990.

	Engineering technique				
	Maximize revenue from power production	Use existing structures		Modify structures	
Management resources and ecosystem processes	Maximum power-plant capacity	Seasonally adjusted steady flows	Controlled floods	Sediment augmentation and floods	Thermal modification
Water					
Reservoir storage in Lakes Powell and Mead	No change	More fluctuations	Scheduled minor decrease	Scheduled minor decrease	No effect
Water quality (dissolved) in Colorado River	No change	No change	Increased flux of salts	Increased desorbed constituents	Decreased nutrient load
Monthly median streamflows	No change	More variable	More variable	More variable	No change
Flood frequency	Rare spills	Rare spills	More frequent	More frequent	No effect
Sediment					
Width of sandbars	Decrease	Increase	No change or decrease	Increase	No effect
Height of sandbars	Increase	Decrease	Increase	Increase	No effect
Probability of net long-term gain of riverbed sand	No change	Increase	No change	Increase	No effect
Frequency of flood erosion of high terraces adjacent to river	No change	Decrease	Increase	Possible decrease	No effect
River's capacity to move boulders in rapids	No change	Decrease	Increase	Increase	No effect
Benthos (macrophytes and invertebrates)	No change	Increase	Decrease	Decrease	Increase
Trophic structure					
Benthic production	Decrease	Increase, composition change	Decrease	Decrease	Increase
Woody debris decomposition	Increased wetting and drying	Decreased wetting and drying	Increased wetting and drying	Increased wetting and drying	Increased decomposition
Organic drift	No change	Decrease	Initial increase, possible later decrease	Decrease	Increase
Fishes					
Native fish	Decrease	Possible increase	Possible increase	Possible increase	Increase
Mainstem reproduction	None	None	None	None	Increase
Tributary reproduction	Restricted	Restricted	No effect	No effect	No effect
Mainstem recruitment and growth	No change	Possible increase	Possible increase	Increase	Increase
Non-native, non-sport fish	Stable or decrease	Possible increase	Stable or decrease	Stable or decrease	Increase
Interactions between native and non-native fish	No change	Possible increase	Decrease	Possible decrease	Increase
Tailwater trout fishery	No effect	No effect	No effect	Depends on input point	Increase
Tailwater reproduction and recruitment	No change	Increase	Possible decrease	Decrease if input at dam	Increase
Downstream reproduction and recruitment	No change	Increase	Unknown	Decrease	Increase
Riparian Vegetation					
Upper riparian zone	Decrease	Decrease	Decrease	Decrease	No effect
Lower riparian zone (marsh and vegetated sandbars)	No change	Increase	Decrease	Decrease	Possible no effect
Terrestrial Fauna					
Population	No change	Possible increase	Decrease	Decrease	Increase
General recruitment	Increase	Stable	Decrease	Decrease	No effect
Kanab ambersnail	No change	Increase	Decrease	Decrease	No effect
Bald eagle	No change	Possible decrease	Decrease or no effect	Decrease	Increase
Southwestern willow flycatcher	No change	No change	No change	No change	No effect
Belted kingfisher	No change	No change	No change	No change	No effect
Archaeological and historical features	No change	No change	Possible increased protection	Possible increased protection	No effect
Recreation					
Tailwater angling	No change	No change	No change	Depends on input point	Increase
Tailwater day rafting	Decreased quality	Improved quality	Decreased quality	Decreased quality	Improved quality
White-water boating					
Trip quality	No change	Increase	Possible increase	Increase and decrease	Increase
Usable camping beach area	Decrease	Decrease	Increase	Increase	No effect
Pathogenic bacteria	No change	Possible increase	Decrease	Increase	Increase
Economics	No change	Increase	No change	Possible increase	Possible increase
Power Production					
Operations	Unconstrained	Constrained	Minor constraints	Minor constraints	No effect
Wholesale and retail rates	No change	Increase	Increase	Increase	Increase
Non-use values[a]	Decrease	Decrease	Increase	Increase	Increase

[a] Wilderness character, "naturalness" of landscape.

ment of the effects of controlled flooding was also based on preliminary findings from the 1996 controlled flood in the Grand Canyon (GCMRC 1997). Predictions regarding thermal-modification impacts were based on studies of changing the thermal regime at Flaming Gorge Dam on the Green River (Holden and Crist 1981). The effects of sediment augmentation were assessed by comparing the characteristics of present river geomorphology and ecology to pre-dam conditions (Webb 1996). In our evaluation of the technique of controlled floods, we assumed no sediment augmentation, but we did assume that frequent controlled floods are part of sediment augmentation because flooding is the only mechanism to redistribute sand from the channel bed to eddies and channel margins.

No single engineering technique yields desirable responses for every ecosystem resource and process. Steady flows benefit some resources, such as the tailwater trout fishery, lower riparian-zone vegetation, and marshes, but restrictions on fluctuating flows still lead to deterioration of many resources. Disturbances caused by controlled floods are necessary to maintain some pre-dam relict resources, but controlled floods damage some post-dam artifact resources. Even during steady flow, sandbars undergo progressive erosion and the size and abundance of low-velocity nursery habitats for native fish decrease. Thus, occasional dam releases that exceed power-plant capacity are necessary to restore sandbar volume and rejuvenate nursery habitats. Floods, however, damage some post-dam artifacts, including marshes, waterbird habitat, and the endangered Kanab ambersnail population.

In some cases, modification of existing structures may permit increased flexibility in load-following hydroelectric power production. Sediment augmentation provides more frequent rejuvenation of eroded sandbars and might permit more wide-ranging, load-following dam operations. However, the increased amplitude of load-following releases would likely harm the tailwater trout fishery.

There is a large potential for error in predicting the effects of implementing a full restoration strategy. Most research in the Grand Canyon has been conducted on a transformed river, but the native endemic fish species evolved in a sediment-laden, light-limited, largely heterotrophic system. Food sources of pre-dam fish assemblages may have been linked to the decomposition of abundant woody debris, which is now much less abundant along the channel. Reconstruction of the pre-dam trophic structure in the Grand Canyon therefore represents a major scientific challenge in the development of a robust strategy for restoration.

Complex resource tradeoffs exist under the five management goals (Table 5). We believe that the choice of an appropriate management goal can be developed only through societal valuation of resources. For example, under the naturalized river strategy, biodiversity increases because disturbance intensity and biogeographic processes are reduced. By contrast, strategies that create river conditions that are more like pre-dam conditions decrease biodiversity and productivity and increase the strength of physical controls on the ecosystem. These changes are likely to be more favorable to native than non-native fishes, such as the highly valued rainbow trout.

The dichotomy between managing for relict versus artifact resources is most obvious with respect to sandbars and lower riparian-zone vegetation. The two resources are interrelated, with the management goals of maximum exposed sandbars and robust lower riparian-zone vegetation being mutually exclusive. The expansion of riparian vegetation, in-

Table 5. Expected tradeoffs in ecosystem resources under five management strategies for the Colorado River in the Grand Canyon.

Management strategy	Expected to increase or stay the same as 1990 condition	Uncertain effect	Expected to decrease from 1990 condition
Traditional river management	Non-native fishes; marsh habitat; terrestrial habitat; non-native plants; migratory species; power revenues	Biological diversity	Sandbars; rapids; aquatic habitat; native fishes; boating safety; recreational fishing
Naturalized ecosystem	Non-native plants and fishes; marsh habitat; terrestrial habitat; biological diversity; boating safety; recreational fishing	Aquatic habitat; native fishes; migratory species	Sandbars; rapids; power revenues
Simulated natural ecosystem	Sandbars; rapids; native fishes; native plants; boating safety	Aquatic habitat; non-native fishes; marsh habitat; terrestrial habitat; non-native plants; migratory species; biological diversity	Recreational fishing; power revenues
Substantially restored river	Sandbars; rapids; native fishes; native plants	Aquatic habitat; non-native fishes; terrestrial habitat; non-native plants; biological diversity; boating safety	Marsh habitat; migratory species; power revenues; recreational fishing
Fully restored river	Sandbars; rapids; native fishes; aquatic habitat; native plants	Boating safety	Non-native fishes; marsh habitat; terrestrial habitat; non-native plants; migratory species; biological diversity; recreational fishing; power revenues

cluding marshes, occurred through colonization of previously bare sandbars; consequently, restoration of barren sandbars must inevitably occur at the expense of riparian vegetation. Management complications arise because endangered Kanab ambersnails and southwestern willow flycatchers have colonized new native and non-native lower riparian-zone vegetation. If flooding is crucial to the recovery of flood-adapted species such as the humpback chub but the absence of floods is crucial to the conservation of terrestrial endangered species in new habitats, then managers face an intractable dilemma.

As if the varying impacts of the assorted management strategies on different ecosystem components do not sufficiently challenge scientists in their attempts to advise managers, their impacts on resources also change longitudinally in the Grand Canyon. These longitudinal differences occur because different reaches of the river have different geomorphic characteristics that strongly influence the depositional and erosional effects of flooding: the sediment budget changes downstream with additional tributary inputs; the population structures of native and non-native fish and riparian vegetation change downstream with changing temperature, geomorphology, sediment transport, food supply, and biogeographic influences; and some endangered species congregate at, or exhibit high fidelity to, specific sites. By necessity, some goals may apply only to specific reaches or sites.

Science and societal choice about river-corridor resources

Scientific research in the Grand Canyon demonstrates strong linkages between dam operations and the responses of individual resources of the river ecosystem. Specific engineering actions cause ecosystem changes that enhance some resources at the expense of others. Although scientists may learn to predict with increasing precision the outcome of various actions on ecosystem function, they cannot determine whether society will accept these changes. For example, riparian marshes, the most productive and biologically diverse habitat, would be eliminated if a broad range of pre-dam physical processes were restored to the river. Reduction in marsh area could reduce wintering waterfowl and southwestern willow flycatcher populations in the Grand Canyon. Is this loss of biodiversity acceptable if increased riparian habitat in the Grand Canyon offsets losses of riparian habitat elsewhere in the region? Would the loss of that biodiversity be in conflict with the legislation enabling Grand Canyon National Park, which requires management "to preserve and protect [the park] for future generations"?

Optimization strategies are often suggested as a way to balance multiobjective resource decisions, but such strategies are not appropriate for all management goals (Carothers and Brown 1991). Pursuit of an optimization strategy that seeks to identify the greatest improvement in relict *and* artifact resources while harming few of these resources is appropriate for the goal of creating a naturalized river but is inappropriate for the goal of full restoration. Optimization demands a detailed understanding of a complex ecosystem, and dam-operating plans may need to be revised repeatedly in response to changes in the relative composition of riverine resources. Although many studies have demonstrated the response trend to different dam release patterns, few provide sufficiently precise information on which to base an optimization strategy. Indeed, the monitoring and research program necessary to implement this optimization strategy may be costly and invasive to the wilderness character of the Grand Canyon.

The choice of management goals and approaches involves value-laden decisions that include economic effects and implications for other societal values (Marzolf 1991). The options facing society include protecting biodiversity; reestablishing a pre-dam landscape with lower diversity, abundance, and standing mass of biota; and establishing the sense of wildness with some relatively natural amenities. Deciding among these choices is further hindered because some altered habitats are occupied by endangered species that have expanded or shifted their range and by some non-native species that are now valued by society.

The public must choose the direction for future management of the Colorado River in the Grand Canyon. A proliferation of new scientific investigations to predict positive and negative effects of different dam operation strategies can refine ecosystem management opportunities, but values, not science, underlie the choice of a management goal for the river. The public is best served if scientists clearly communicate and refine the implications of different management scenarios. This information needs to be presented to society at large, and an informed debate on the most desirable management strategy should then proceed. Only after such a strategy is identified can scientists know where best to direct future scientific investigation, or whether such investigation is even warranted.

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