Plenary Sessions

Colorado River Basin Science and Resource Management Symposium

November 18–20, 2008, Scottsdale, Arizona

Remarks prepared for delivery by
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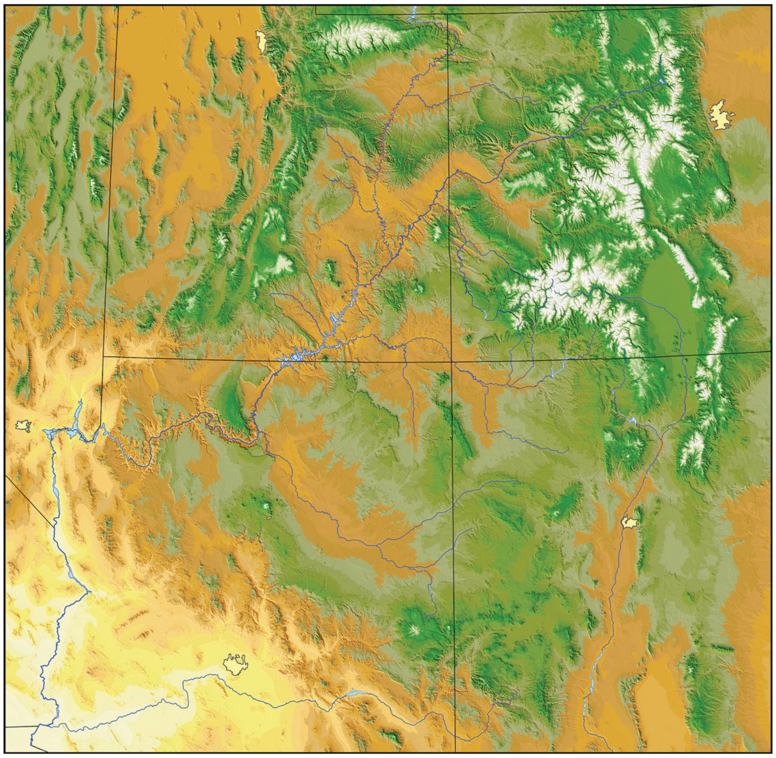
It is a pleasure and quite exciting to be here, at what is the first conference designed to share information among the various environmental programs underway here in the Colorado River Basin. I would like to commend the organizers of this conference: The goal of better coordination of scientific information across programs in the Colorado River Basin is a valuable one, though we should not minimize the difficulty and barriers to achieving better information sharing and integration.

Over the past century, there have obviously been incredible changes here in the Colorado River Basin. We have tamed the Colorado River, tapped its hydropower potential, irrigated the Southwest's vast agricultural lands, and provided water to the major urban areas of the West: Denver, Las Vegas, Phoenix and Tucson, Los Angeles and San Diego. We manage water supplies to meet our water-quantity and water-quality obligations to Mexico under the 1944 treaty and its implementing agreements. We have also protected some of the most magnificent landscapes on Earth: from the headwaters of the Colorado and Green Rivers to Mexico, the Colorado flows through and along unique landscapes, the Black Canyon, Glen and Grand Canyons, Lake Powell and Lake Mead recreation areas, and refuges.

Additionally, the ecological value of the river and its importance to Native American Tribes have gained recognition in recent decades. Today, the Colorado River Basin is intensively managed by the U.S. Department of the Interior (DOI) in partnership with Tribes, States, and many other stakeholders to meet a variety of social, cultural, and ecological demands.

This symposium is specifically aimed at promoting the exchange of information on research and management activities related to the restoration/conservation of the Colorado River. We probably could spend a bit of time discussing and debating whether these efforts are best described as environmental protection, environmental conservation, or



The Colorado River Basin stretches from its headwaters in the Rocky Mountains to the Gulf of Mexico. In the United States, four collaborative management programs—each working in a different portion of the Colorado River Basin—have developed over the past 20 years largely to respond to concerns about endangered species. Shaded relief map created by Barry Middleton, USGS Southwest Geographic Science Team, Flagstaff, Arizona.

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perhaps "environmental restoration," as is used in the title for this conference. Inherent in these various descriptions are statements about goals, values, and objectives.

We have seen different programs and initiatives in the basin—each with its own history, stakeholders, and approaches. From my perspective, gaining a better understanding of the elements that unite these programs and ensuring that accurate, timely scientific information is shared among these programs may be the single most important element that will distinguish between success and failure in coming years and decades—though I do not want to minimize the challenge of coming to agreement or consensus on what success looks like.

Over the past 20 years we have seen incremental development of environmental programs from the headwaters of the basin to the Mexican border. Obviously, many of these efforts have been driven by concerns regarding endangered species:

- Established in 1988, the Upper Colorado River Endangered Fish Recovery Program is a partnership of public and private organizations working to recover these endangered species while allowing continued and future water development.
- Established in 1992 with the signing of the cooperative agreement, the San Juan Recovery Implementation Program is designed to help recover the Colorado pikeminnow (*Ptychocheilus lucius*) and the razorback sucker (*Xyrauchen texanus*) while allowing water development to continue in the San Juan River Basin.
- The Glen Canyon Dam Adaptive Management Program was established in 1997 to assist the Department to meet the goals and objectives of the Grand Canyon Protection Act.
- And most recently in 2005, the Department formally established the Lower Colorado River Multi-Species Conservation Program, a 50-year, nearly $1 billion investment to enhance habitat along the lower Colorado River to both conserve species that are currently endangered and threatened and to help reduce the potential for further additional listings in the future.

> Our expectation is that the effectiveness of programs individually and collectively will be enhanced by the information that is provided and the relationships that emerge from this symposium.

So, we now have these programs—each working in a portion of the Colorado River Basin—and one of the fundamental questions and challenges we face is the integration and coordination of the scientific information that will help guide the course of these efforts. In spite of the commonalities among the programs, until now there has been no formal opportunity for information exchange among programs. This symposium is specifically aimed at promoting the exchange of information on research and management activities related to the restoration/conservation of the Colorado River in the United States.

Some of the most significant challenges that these programs face transcend program boundaries. A recent example of a transboundary issue is the quagga mussel (*Dreissena bugensis*) invasion; the mussel is an invasive species that was found in Lake Mead in early 2007 and has spread throughout many portions of the basin and the West. Also of grave concern is the spread of zebra mussels (*Dreissena polymorpha*). Both invasive organisms threaten native species and water-supply systems. Climate change is predicted to have a profound impact on water supplies and water quality and significantly alter ecological processes.

Restoration and recovery strategies need to anticipate and adapt to these basinwide challenges and what is working today may not work under tomorrow's climate regime and biological environment. Trying to determine whether proposed goals can be achieved in the face of predicted hydrologic changes that may come from both climate change and continued consumptive uses is a significant challenge.

These programs are also linked by goals that require recovery throughout the basin. Under the current recovery goals, achieving demographic criteria and minimizing and removing threats (in order to meet down-listing and delisting requirements) are expected to be accomplished through these various programs.

Our expectation is that the effectiveness of programs individually and collectively will be enhanced by the information that is provided and the relationships that emerge from this symposium. Perhaps future symposia will be expanded to include cross-border issues within Mexico at the Colorado River delta and will include more involvement from international partners.

The Difficulty of Coordination and Integration

Anyone who has worked on large-scale ecosystem efforts knows the challenges that come with working across agency, political, and policy boundaries. Any number of fundamental questions and complications are evident. How do the various programs gather, evaluate, and publish scientific information? How are the conflicting protocols, objectives, and procedures—and statutory missions—to be addressed among the agencies? How do we integrate the peer-review of emerging science into public processes such as National Environmental Policy Act (NEPA) studies and Endangered Species Act (ESA) consultation? How do we ensure continued participation by experts while integrating new researchers and new methods into research efforts?

I would ask each of you to think about the challenges of information sharing just within your own organization and then expand that difficulty across the areas that will be discussed over the next 3 days. Think of it: coordination within offices and within agencies is quite a challenge. Take that task and broaden the goal to achieve improved information sharing between researchers, universities, agencies, States, Tribes, and the broader members of the interested public. Quite a challenge. Then, on top of all of those inherent organizational challenges—add the destabilizing complexity of global climate change and the effects that are anticipated for this most arid part of our Nation. It is clear that we all have a stake in improved coordination and effective information sharing.

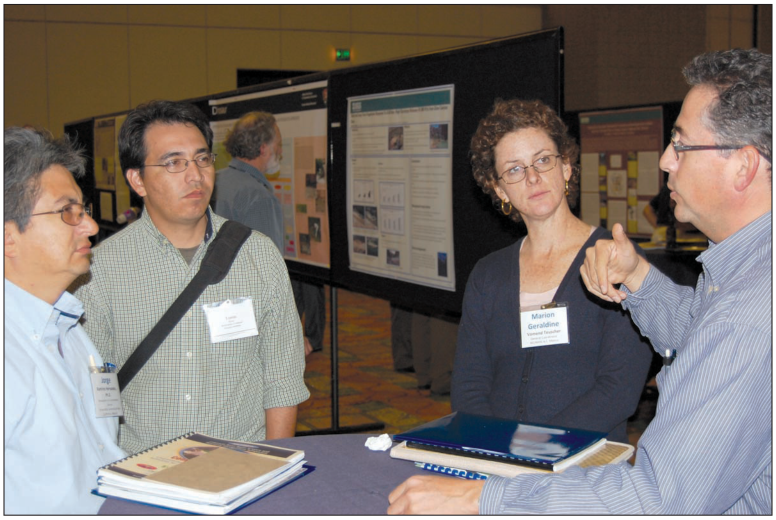
Many fields of scientific study face the same challenge of integration and coordination. In emerging areas of nanotechnology and biotechnology research, we have seen institutes formed between government agencies, universities, and private corporations to achieve better efficiencies and effective research. Some of these institutes are physical—some are virtual—but a key objective is always improved information sharing.

Here in the Colorado River Basin, we cannot simply form a Colorado River Institute and assume that the coordination we need will emerge. Instead, we will need more efforts such as this conference, continued investment in research and monitoring, and continued flexibility through adaptive management to take advantage of the scientific advances in ecosystem understanding. As we go forward, I believe that the need for independent science research from the U.S. Geological Survey (USGS) and others will remain essential. Scientific efforts need to operate separately from management actions and political influence. At the same time, we must encourage an integrative science approach to understanding and managing entire watersheds or ecosystems. Mutual respect for the scientific process—we hope—will lead to increased cooperation among diverse—at times, competing—groups of stakeholders. We have seen in a number of settings the importance of information from independent scientific research to facilitate sound policy and decisionmaking (e.g., the USGS role in polar bear research).

Outcomes of this Conference

To ensure that results of this symposium are factored into DOI management of the Colorado River Basin, I have asked the USGS to provide recommendations to me on how science and restoration efforts could be enhanced collectively through better basinwide cooperation and integration. In coming days, I will ensure that these recommendations are passed along to President-elect Obama's transition team for its consideration.

As you all are well aware, the Secretary of the Interior has a unique connection to the Colorado River—based on the unique history of the development of this basin. The Secretary has a very difficult task of balancing competing societal needs within the Colorado River Basin (a good example is water delivery, hydropower generation, and natural resource protection). In the talks that follow, the agenda will focus on how an adaptive management approach is being used to integrate science, stakeholder concerns, and water and resource management decisions, and how we can more effectively use the scientific knowledge across program lines.



Symposium participants at the Colorado River Basin Science and Resource Management Symposium, which took place November 18–20, 2008, in Scottsdale, Arizona.

Closing Observations

John Wesley Powell is certainly one of the towering figures in Colorado River Basin history. He is known as a one-armed Union veteran of the Civil War, who survived his 1869 expedition down the Green and Colorado Rivers. He later became the second Director of the USGS. Powell was known for his attempts to categorize and integrate new information—to create scientific order from new facts. Late in a life driven by scientific curiosity and exploration, he made a number of political proposals that were informed by his western explorations and Colorado River Basin experiences. One proposal—or recommendation—that he made in 1889 was to organize some of the new Western States along hydrographic basins—rather than arbitrary political lines. Powell's view was that organizing political boundaries by watersheds would allow for economic unity—and productivity—within basins. Conflict, litigation, and other costly inefficiencies would be lessened as the decisionmaking in upstream and downstream areas of a basin were integrated. Science and reason—integrated into political governance. While his advocacy on this point did not succeed, I think his observations are still quite compelling.

Efforts such as this conference—cooperative efforts to advance scientific coordination within this watershed—the Colorado River Basin—are entirely consistent with Powell's goals to advance scientific understanding and to improve societal decisionmaking. I thank you for your efforts and applaud your goal of better coordination and information sharing among the programs in the basin.

Overview of the Colorado River Basin Collaborative Management Programs

By David Campbell,[1] Scott Durst,[1] Angela T. Kantola,[2] Dennis M. Kubly,[3] Robert T. Muth,[4] John Swett,[5] and Sharon Whitmore[1]

Abstract

Today, four collaborative management programs stretch the length of the Colorado River. Each of the four programs seeks to conserve or restore species listed under the Endangered Species Act, particularly endangered fish, while continuing to meet water and hydropower demands. The Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin was initiated in 1988 and was the first Colorado River collaborative management program. The San Juan River Basin Recovery Implementation Program was established in 1992 and was followed by the Glen Canyon Dam Adaptive Management Program in 1997 and the Lower Colorado River Multi-Species Conservation Program in 2005.

All of the Colorado River collaborative programs involve multiple stakeholders, which, depending on the program, can include representatives of Federal and State resource management agencies, Colorado River Basin States, Native American Tribes, environmental groups, recreation interests, water-development proponents, and energy and power users. The programs coalesced not only because the natural systems they were dealing with were complex, as were the needs of the species they were seeking to recover, but also because no one party could resolve the challenges independently or win a lasting victory through legal or legislative action.

The four program descriptions presented here include information on program history and goals, geographic scope, participants, resources of concern, activities, and progress. The programs discussed here are at different stages of development, which is reflected in the following descriptions.

Introduction

The Colorado River provides water for more than 27 million people in the United States and more than 3.5 million acres of agricultural land (U.S. Department of the Interior, 2007). A vast system of dams and reservoirs is in place to manage the river's valuable waters; there are 22 major storage reservoirs in the Colorado River Basin and 8 major out-of-basin diversions (Pontius, 1997).

Conflict attached itself early to Colorado River water and its management. In 1922, the seven Colorado River Basin States signed the Colorado River Compact, which Congress ratified the same year, allocating the Colorado River's water resources among the seven basin States. The compact divides the river basin into two parts: the upper division (Colorado, New Mexico, Utah, and Wyoming) and the lower division (Arizona, California, and Nevada). The compact allowed for the development of water resources by the Federal government and made possible widespread irrigation. However, Arizona refused to ratify the agreement until 1944 and disputed the water allotments until the United States Supreme Court upheld the allocations in 1963.

The construction of dams in the Colorado River Basin altered the historical flow and temperature patterns of the river, which has affected the habitat and reproductive success of native fish. However, early European settlers altered the Colorado River's fish community well before the construction of mainstem dams through the introduction of nonnative fish. For more than 100 years, nonnative fish—from sports fish to escapees from aquaria—have been intentionally and unintentionally stocked in the Colorado River (Mueller and Marsh, 2002). Nonnative species are potential predators of and competitors with native species. Today, because of the range of nonnative species found in the Colorado River, nonnative fish may negatively interact with native species under virtually any temperature regime and in any habitat (Gloss and Coggins, 2005).

Four species of Colorado River fish are currently listed as endangered under the Endangered Species Act (ESA): Colorado pikeminnow (*Ptychocheilus lucius*), razorback sucker (*Xyrauchen texanus*), bonytail (*Gila elegans*), and humpback

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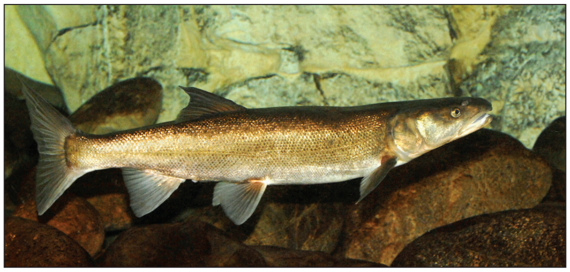
chub (*Gila cypha*). The Colorado pikeminnow and humpback chub were both added to the Federal list of endangered species in 1967, while the bonytail and razorback sucker were listed in 1980 and 1991, respectively.

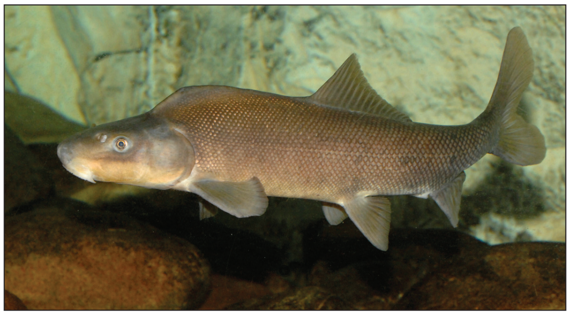
Efforts to protect declining native fish under Section 7 of the ESA resulted in entrenched conflicts. For example, in the upper Colorado River Basin, the Colorado River Water Conservation District filed suit against the U.S. Fish and Wildlife Service (Service) in the late 1970s, challenging the listing of the Colorado pikeminnow and the humpback chub. Because the Service had taken action pursuant to the ESA that would have prevented more water development along the river, the river district accused the agency of damaging property rights and hindering economic development. In 1983, water developers challenged the scientific basis for agency-proposed minimum streamflow standards.

It became clear by the early 1980s that conflicts between resource protection and resource development in the upper Colorado River Basin were unlikely to be resolved through litigation or legislative action. The parties recognized that an adversarial approach was "unlikely to result in progress toward recovery of the listed species and could lend a measure of uncertainty to future water resource development in the upper basin" (U.S. Fish and Wildlife Service, 1987, p. 1–6). As a result, the parties sought to accommodate their competing demands through discussion and negotiation under the auspices of the Upper Colorado River Basin Coordinating Committee, which was formally established in 1984 (U.S. Fish and Wildlife Service, 1987). The Coordinating Committee and its various subcommittees included the Service, Bureau of Reclamation (Reclamation), and the States of Colorado, Wyoming, and Utah, and also representatives of water users, proponents of water development, and conservation organizations.

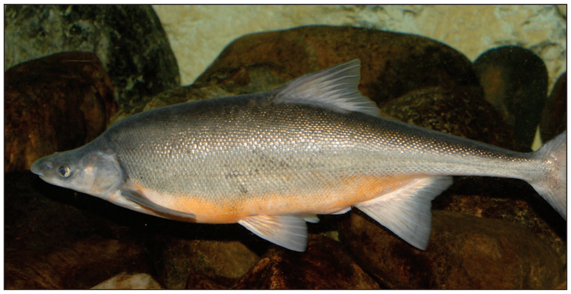
Through discussion, the members of the Coordinating Committee determined that both the biological needs of the endangered species and the hydrology of the upper basin were "exceedingly complex," requiring a systematic approach to achieve native fish conservation and continued water development in the upper basin (U.S. Fish and Wildlife Service, 1987). In the end, the group concluded that a comprehensive program was needed to implement the broad array of measures necessary to "not only preserve the listed species but to ensure their full recovery and eventual delisting" (U.S. Fish and Wildlife Service, 1987, p. 1–6). Thus, the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin (also known as the Upper Colorado River Endangered Fish Recovery Program; hereafter, UCRRP)—the first Colorado River collaborative management program—was initiated in 1988. The San Juan River Basin Recovery Implementation Program (SJRIP) was established in 1992 and was followed by the Glen Canyon Dam Adaptive Management Program (GCDAMP) in 1997



Colorado pikeminnow (*Ptychocheilus lucius*)



Razorback sucker (*Xyrauchen texanus*)



Bonytail (*Gila elegans*)

Humpback chub (*Gila cypha*)

George Andrejko, Arizona Game and Fish Department

The four collaborative management programs that focus their efforts on the Colorado River seek to restore species listed under the Endangered Species Act (ESA), particularly endangered fish. The four species of Colorado River fish currently listed as endangered under the ESA are shown above.

and the Lower Colorado River Multi-Species Conservation Program (LCR MSCP) in 2005.

The four collaborative management programs that today span the length of the Colorado River share many of the same antecedents. All four programs were created to conserve or restore species listed as endangered under the ESA, particularly endangered fish, while continuing to meet water storage, delivery, and development needs and hydropower demands. In the case of the GCDAMP, the Grand Canyon Protection Act (GCPA) gives the program's efforts a broader scope in seeking to ensure the long-term sustainability of natural, cultural, and recreation resources found downstream from Glen Canyon Dam in Glen Canyon National Recreation Area and Grand Canyon National Park. All of the programs involve multiple stakeholders which, depending on the program, can include representatives of Federal and State resource management agencies, Colorado River Basin States, Native American Tribes, environmental groups, recreation interests, water development interests, and energy and power users. The programs coalesced not only because the natural systems they were dealing with were complex, as were the needs of the species they were seeking to recover, but also because no one party could resolve the challenges independently or win a lasting victory through legal or legislative action.

Each of the four Colorado River Basin collaborative management programs is described briefly below. The four program descriptions are organized by their location, starting in the uppermost Colorado River Basin and moving downstream, and include information on program history and goals, geographic scope, participants, resources of concern, activities, and progress. Because the four programs came into existence at different times, ranging from 5 to 20 years ago, they are at different stages of development, which is reflected in the following descriptions.

Colorado River Basin Programs

Upper Colorado River Endangered Fish Recovery Program (UCRRP)

Program History

The UCRRP, also known as the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin, was formally established in January 1988 through a cooperative agreement signed by the Secretary of the Interior; the Governors of Colorado, Wyoming, and Utah; and the Administrator of the Department of Energy's Western Area Power Administration. Water users and environmental organizations signed supporting resolutions. The 1988 agreement provided for a 15-year term for the UCRRP, which was later extended to 2013 and then to 2023. The cooperative agreement grew out of a 3-year process that culminated in a 1987 framework document for the program (U.S. Fish and Wildlife Service, 1987).

Conflicts between the ESA and water development drove the need for the UCRRP. In the 1980s, the Service determined that additional depletion of water from the upper basin would constitute jeopardy to the continued existence of endangered fish. In 1983, the Service proposed minimum streamflows for all habitats occupied by endangered fish in the upper basin (pre-1960 flow levels) and required replacement of depletions on a one-for-one basis. This requirement could have stopped water development in the upper basin, put limits on the use of existing water supplies, and conflicted with existing Federal and State laws that allocate water, resulting in direct conflict among States, water users, Federal agencies, power customers, and environmental organizations.

In order to avoid a head-on collision, the parties sought to accommodate their competing demands through discussion and negotiation under the auspices of the Upper Colorado River Basin Coordinating Committee, which was formally established in 1984 (U.S. Fish and Wildlife Service, 1987). The group concluded that a comprehensive program was needed, and the UCRRP was initiated in 1988 (Wydoski and Hamill, 1991).

Program Goal

The goal of the UCRRP is to recover four endangered fish species—Colorado pikeminnow, humpback chub, bonytail, and razorback sucker—while providing for new water development to proceed in the upper Colorado River Basin.

Geographic Scope

The geographic scope of the UCRRP is the Colorado River Basin upstream from Glen Canyon Dam, excluding the San Juan River subbasin (fig. 1). The focus of the program's attention is the Colorado River and its tributaries in Colorado, Utah, and Wyoming, with the exception of the San Juan River.

Program Participants

The UCRRP is a 10-member partnership among the States of Colorado, Utah, and Wyoming; the Service; Reclamation; National Park Service; Western Area Power Administration; Colorado River Energy Distributors Association; environmental organizations; and water users.

Program Structure and Budget

The UCRRP has five principal elements: (1) habitat management through the provision of instream flows; (2) nonflow habitat development and maintenance; (3) management of nonnative species and sport fishing; (4) native fish stocking; and (5) research, data management, and monitoring. The UCRRP's Recovery Action Plan, a long-range operational plan, is consistent with the 2002 Recovery Goals (U.S. Fish and Wildlife Service, 2002a–d), contains all the actions believed necessary to recover the fish in the upper basin, and is updated annually. Using an adaptive management approach to develop and implement management actions, the UCRRP is able to continually evaluate and revise recovery actions as new information from research and monitoring becomes available and to adapt to changing factors such as the recent years of prolonged drought across the West and proliferation of nonnative fish species.

Coordination and collaboration among UCRRP stakeholders are keys to the UCRRP's success. Each partner fully participates in developing and implementing management actions that will achieve the recovery goals and lead toward delisting of the endangered fish. The UCRRP has three committee levels: a policy-level Implementation Committee; a Management Committee; and three technical committees (Biology, Water Acquisition, and Information and Education). The UCRRP's director and staff coordinate the recovery efforts and serve all of the committees.

The UCRRP's annual budget for fiscal year 2009 was $9.5 million.

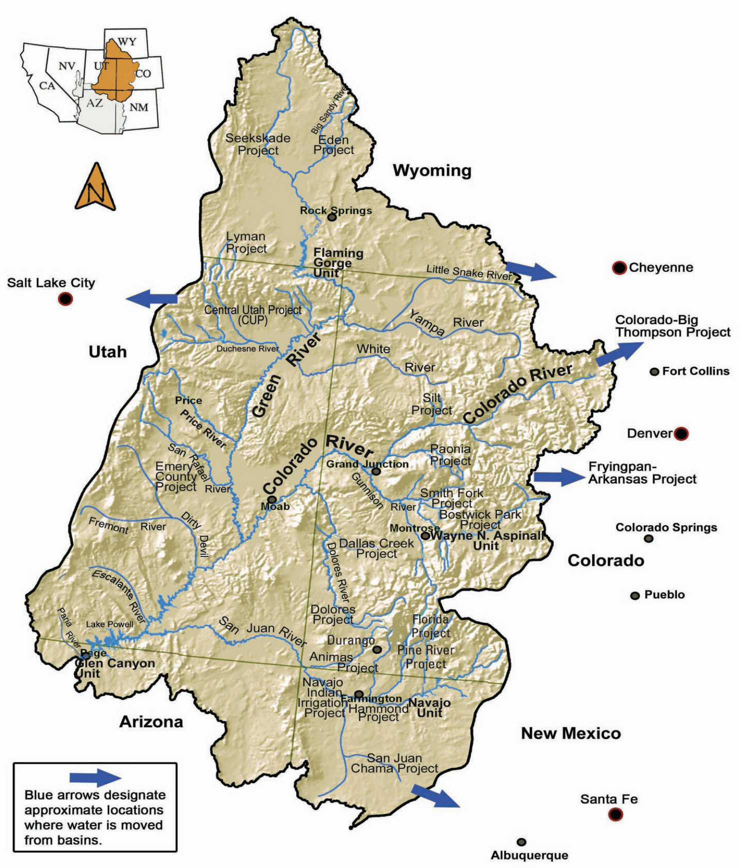


Figure 1. The area served by the Upper Colorado River Endangered Fish Recovery Program. The region includes the Colorado River Basin upstream from Glen Canyon Dam, with the exception of the San Juan River subbasin.

Program Activities

Habitat Management

Habitat management actions focus on identification and provision of instream flows necessary to achieve recovery of the endangered fish. Recovery program partners cooperatively manage water resources to benefit the endangered fish and their habitats in accordance with State water law, individual water rights, interstate compacts, and Federal authorizing legislation. Management is accomplished through a variety of means, including leases and contracts for water supplies, coordinated water releases from upstream reservoirs, participation in reservoir enlargements, efficiency improvements to irrigation systems to reduce water diversions, and re-operation of Federal dams and reservoirs. These water-management actions not only benefit the endangered fish, but also benefit recreational, municipal, and agricultural water users as well.

Operations of five principal reservoirs in Colorado are coordinated to voluntarily release water to enhance Colorado River spring peak flows and improve fish habitat without affecting those reservoirs' yields (fig. 2). Most of these reservoirs also contribute water for late-summer, base-flow augmentation. Construction of seven check structures in the Grand Valley Project Canal System in western Colorado in 2002 has reduced water diversions by 10 to 16 percent. These check structures regulate canal deliveries to meet irrigation demands and help reduce river diversions to keep more water in the river for fish.

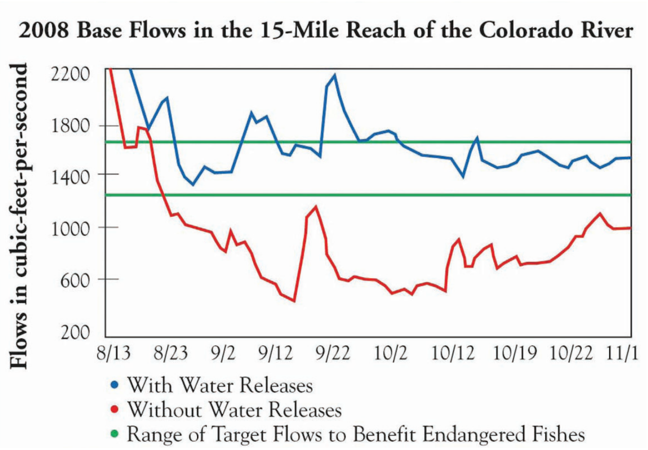


Figure 2. Additional water from upstream reservoirs in Colorado for the "15-mile reach," a segment stretching east of Grand Junction for 15 miles, of the Colorado River in 2008. Averaging 56,000 acre-feet per year since 2000, flows from reservoirs enhance late-summer and fall base flows for endangered fish. The amount of water released in 2008 was the greatest to date, totaling 114,255 acre-feet (Upper Colorado River Endangered Fish Recovery Program /San Juan River Basin Recovery Implementation Program, 2009).

The UCRRP partnered with the Colorado River Water Conservation District and other State and local agencies on a 13,000 acre-foot enlargement of Elkhead Reservoir completed in 2006. The enlarged reservoir provides up to 5,000 acre-feet of permanent water and 2,000 acre-feet of leased water for augmentation of base flows in the Yampa River and about 5,000 acre-feet of water for future growth in Moffat County, CO. The project also creates an improved recreational amenity for the residents of Routt and Moffat Counties and serves as a repository for nonnative sportfish removed from the Yampa River.

Federal reservoirs also provide water for the endangered fish. The Bureau of Reclamation operates Flaming Gorge Dam on the Green River, UT, according to a Record of Decision signed on February 16, 2006, to assist in recovery of the endangered fish (Bureau of Reclamation, 2006). The Aspinall Unit on the Gunnison River in western Colorado is made up of three Federal reservoirs—Blue Mesa, Morrow Point, and Crystal. A draft Environmental Impact Statement on re-operation of Aspinall Unit dams on the Gunnison River to assist in recovery of the endangered fish was released in February 2009 (U.S. Department of Interior, 2009), with a Record of Decision anticipated by 2010.

Habitat Development

The UCRRP restores and maintains habitat for endangered fish by constructing and operating fish passages at diversion dams, constructing and operating fish screens in diversion dam canals to keep fish from entering and becoming trapped, and acquiring and restoring flood-plain habitat to serve primarily as fish nursery areas. All habitat restoration actions are monitored by the UCRRP to evaluate their effectiveness, and management changes are implemented on the basis of evaluation results to further improve habitat conditions.

Fish passages and screens are completed and operational at the Redlands Water and Power Company, Grand Valley Irrigation Company, and Grand Valley Project diversions near Grand Junction in western Colorado, and a passage also is complete at Price-Stubb irrigation diversion. The fish passages provide endangered fish with unimpeded access to about 340 miles of designated critical habitat in the Colorado and Gunnison Rivers. At the Redlands Water and Power Company and the Grand Valley Project Canal System, the passage structures are selective in that when fish reach a holding area at the top, they are removed and sorted, and only native fish are allowed to pass through. Construction of a screen at the Tusher Wash diversion on the Green River is scheduled to begin in 2010.

Flood-plain habitats are being made accessible to all life stages of endangered fish by breaching or removing natural or manmade levees to connect the sites to the river during spring runoff. Restored river habitat also improves sources of food and shelter for other fish, plant, and animal species. The UCRRP has acquired 1,600 acres in Colorado and Utah (19 properties), of which 600 acres (four properties) have been restored. The UCRRP also has restored a total of 2,100 acres owned by the Bureau of Land Management, City of Grand Junction, Colorado Division of Wildlife, Colorado State Parks, or the Service.

Nonnative Fish and Sportfishing

Predation or competition by nonnative fish species is a serious threat to the endangered fish and poses the biggest obstacle to recovery and the greatest long-range management challenge for the UCRRP. Fourteen species or subspecies of native fish occurred historically in the upper basin. Over the past 100 years, more than 50 nonnative fish species have been introduced into the upper basin and now dominate many


Upper Colorado River Endangered Fish Recovery Program

About 2,700 acres of restored flood-plain habitat in the upper Colorado River Basin are managed for all life stages of endangered fish.

fish communities. Currently, northern pike (*Esox lucius*), smallmouth bass (*Micropterus dolomieu*), and other sunfish, including the largemouth bass (*Micropterus salmoides*), are the most problematic nonnative fish and are the principal target species for management.

Management actions of the UCRRP to reduce the abundance of nonnative fish and their impacts to endangered fish recognize the dual responsibilities of State and Federal wildlife agencies to conserve native fish species while providing sportfishing opportunities. Nonnative fish management actions include mechanically removing nonnative fish from rivers, restricting the stocking of nonnative fish, screening of off-river ponds and reservoirs to prevent escapement of fish to rivers, identifying chronic sources of nonnative fish to rivers, changing State bag and possession limits on warmwater sportfish to increase angler harvest, and monitoring the responses of nonnative and native fish to management actions. Where feasible, sportfish removed from rivers are translocated to local off-channel ponds or reservoirs to provide fishing opportunities. Research, monitoring, and adaptive management are used to identify, evaluate, and revise management strategies. Annual workshops are held to further review results of field activities and develop appropriate modifications to the nonnative fish management strategies.

Endangered Fish Propagation and Stocking

Five hatchery facilities produce bonytail and razorback sucker necessary to meet the UCRRP's annual and long-range stocking targets. Broodstocks and propagation of young are managed to maximize the genetic diversity of stocked fish to increase the likelihood that stocked fish can cope with local habitat conditions in the wild. An integrated stocking plan was finalized in 2003 to expedite reestablishment or enhancement of naturally self-sustaining populations and achieve the demographic criteria of the recovery goals (Nesler and others, 2003). Roughly 30,000 razorback suckers and 16,000 bonytails are stocked in the upper Colorado River and Green River systems each year. Survival, growth, and reproduction of stocked fish are monitored to evaluate and improve stocking strategies.

Upper Colorado River Endangered Fish Recovery Program

Some 30,000 hatchery-raised bonytail (*Gila elegans*) are stocked each year in the upper Colorado and Green River systems to reestablish and enhance naturally occurring populations of the fish.

Research, Monitoring, and Data Management

The UCRRP's early emphasis was on research to gather basic life-history information about the endangered fish and determine actions needed for recovery. Research and monitoring now generate information on reproduction, growth, and survival of endangered fish in the wild, and data management systems serve as repositories and analytical tools for that information. Data are used to evaluate and adjust management actions and recovery strategies through adaptive management. The UCRRP uses estimates of the abundance of endangered fish to monitor progress toward achieving the recovery goals.

Progress Toward Program Goals

Nonnative Fish

Over the past 10 years, progress has been made in reducing the abundance of some of the target nonnative fish species in certain rivers of the upper Colorado River Basin. However, a great deal of work remains to identify the methods and levels of management needed to minimize the threat of nonnative fish predation or competition and achieve and maintain recovery of the endangered fish (table 1).

Endangered Fish

Wild populations of Colorado pikeminnow and humpback chub occur in the upper Colorado and Green River systems. These populations have been studied since the 1960s, and population dynamics and responses to management actions have been evaluated since the early 1980s. Hatchery-produced, stocked fish form the foundation for the reestablishment of naturally self-sustaining populations of bonytail and razorback sucker in the upper Colorado and Green River systems. Significant changes in the status of the four endangered fish generally are not detected on a year-to-year basis. Closed-population, multiple mark-recapture estimators for tracking population trends are being used (where possible) in the upper Colorado and Green River systems to derive population point estimates for wild Colorado pikeminnow and humpback chub.

Recovery goals for the endangered fish identify site-specific management actions to minimize or remove threats and establish criteria for naturally self-sustaining populations. A key requirement of the population criteria is no net loss of fish over established monitoring periods. Downward trends in some wild populations of Colorado pikeminnow and humpback chub have been observed during dry weather and low river runoff conditions since 1999. Biologists hypothesize that these declines may be a result of reduced recruitment that can be largely attributed to increases in certain problematic

Table 1. The Upper Colorado River Endangered Fish Recovery Program's efforts to reduce nonnative fish abundance (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, 2009).

River	Species	History and current status
Colorado (112 miles)[a]	Smallmouth bass	• Increases in abundance first observed in 2003; removal began in 2004. • Abundance declined during 2006–2008; more removal passes added in 2007 to increase captures. • Largemouth bass are an emerging problem; catch of young fish has steadily increased since 2004.
Green (198 miles)[a]	Smallmouth bass	• Increases in abundance first observed in 2003; removal began in 2004. • Adult abundance declined over 50 percent throughout much of the Green River during 2004–2006. • Increased efforts in 2007 (continued in 2008) removed as much as 90 percent of the estimated adult population in certain high-concentration areas.
	Northern pike	• Since removal began in 2001, abundance has decreased by more than 90 percent.
Yampa (94 miles)[a]	Smallmouth bass	• Increases in abundance first observed in 2003; removal began in 2004. • Results through 2007 indicated the adult population was declining; however, substantial reproduction occurred in 2006 and 2007. • Average flows in 2008 in the Yampa, Green, and Colorado Rivers appear to have negatively affected reproduction.
	Northern pike	• Abundance steadily increased during the 1980s and 1990s; removal began in 1999. • Removal through 2007 shifted the size to smaller individuals; in 2008, the overall abundance in critical habitat was near its lowest level.

[a] River miles where work occurred in 2008.

nonnative fish and habitat changes associated with the recent drought (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, 2009). The recovery programs are actively implementing and adaptively evaluating management actions to reduce these threats and reverse the downward population trends to achieve and maintain self-sustaining populations. Meanwhile, progress is being made to reestablish specific populations through stocking.

Following are summaries of the currently available information on the status of each species related to the demographic criteria of the recovery goals for the upper Colorado River Basin.

Colorado Pikeminnow

There are two wild Colorado pikeminnow population centers, one in the upper Colorado River system and one in the Green River system, consisting of separate spawning stocks of which juveniles and adults mix. This exchange of fish sets up a population network or metapopulation, with the Green River system being the largest. Abundance of adults in the Green River system declined from 3,100 to 2,300 between 2001 and 2003 (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, 2009). Reproduction in 2006 was strong, and biologists reported a sixfold increase in the number of young-of-year (less than 1-year-old) Colorado pikeminnow captured in the Green River in the summer of 2009 compared to the average catch rate during the previous 18 years (Upper Colorado River Endangered Fish Recovery Program, 2010). Abundance of adults in the upper Colorado River system increased from about 440 in 1992 to 890 in 2005 (fig. 3) (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, 2009).

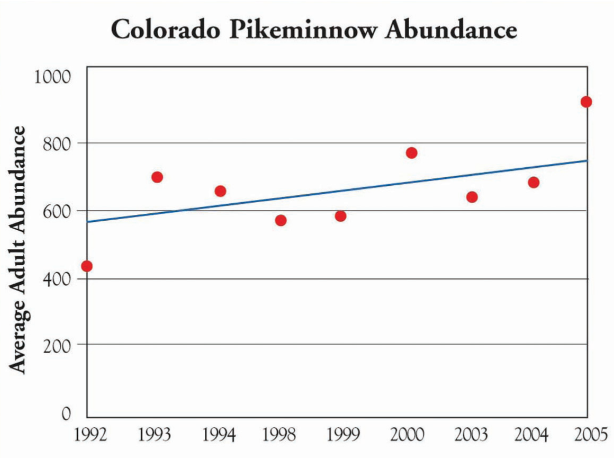


Figure 3. Estimated average abundance of adult Colorado pikeminnow in the upper Colorado River system from 1992 to 2005 (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, 2009).

Humpback Chub

Five humpback chub wild populations inhabit canyon-bound river reaches of the Colorado, Green, and Yampa Rivers. The most current estimates of abundance of these populations indicate downward trends associated with increased abundance of nonnative fish during dry weather and low river runoff conditions since 1999. About 3,000 adults occur in Black Rocks and Westwater Canyons on the Colorado River (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, 2009). Together, these populations have been identified as one core population. About 1,000 adults occur in Desolation/Gray Canyons on the Green River, and this population has been identified as a second core population. Populations in Yampa Canyon on the Yampa River and in Cataract Canyon on the Colorado River are small (as they were historically), each consisting of up to a few hundred adults.

Razorback Sucker

The razorback sucker was historically abundant in most warmwater rivers of the Colorado River Basin, but their numbers decreased dramatically beginning in the mid 1970s. Fewer than 100 wild adult razorback suckers are estimated to still occur in the Green River system, and wild populations are considered extirpated from the upper Colorado River system. Scientists recaptured 2,550 stocked razorback suckers from the Colorado, Gunnison, and Green Rivers from 2000 to 2005. Stocked razorback suckers are moving between the Colorado, Gunnison, and Green Rivers, suggesting that a network of populations (or metapopulation) similar to the Colorado pikeminnow situation may eventually be formed. Razorback suckers stocked in the Colorado and Green Rivers have been recaptured in reproductive condition, and captures of larvae in the Green, Gunnison, and Colorado Rivers demonstrate successful reproduction. Numbers of razorback sucker larvae collected from the Green River in 2007 were the highest ever recorded (fig. 4) (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, 2009). Survival of larvae through the first year is evidenced by captures of juveniles in the Green and Gunnison Rivers.

Bonytail

The bonytail is the rarest of the four endangered Colorado River fish and probably the farthest from recovery. Before stocking began, the species had essentially disappeared in the upper basin and little was known about its biology. A key aspect to bonytail recovery is research and monitoring of stocked fish to determine the life history and habitat requirements of the species and ways to modify the stocking plan to improve the survival of stocked fish. Stocking efforts have been expanded to place fish into flood-plain wetlands to enhance their growth and survival. Stocked bonytails are being recaptured in several locations and habitats throughout the Green and upper Colorado Rivers. About 200 stocked bonytails were recaptured in 2004 and 2005, all within 1 year after stocking.

Water Use and Development

The UCRRP serves as a vehicle for compliance with Section 7 of the ESA for water development and management activities by participants, including the Federal government. Under the UCRRP's "Section 7 Agreement," accomplishments of the UCRRP serve as the reasonable and prudent alternative to jeopardy and adverse modification of critical habitat from water project depletion impacts. Each year, the Service evaluates whether progress in implementing recovery actions is sufficient for the UCRRP to continue to serve as the reasonable and prudent alternative. The UCRRP is responsible for providing flows that the Service determines are essential to recovery; therefore, responsibilities to offset water project depletion impacts do not fall on individual projects or their proponents. The UCRRP provides ESA compliance for more than 1,600 water projects depleting more than 2 million acre-feet of water per year. Most of these depletions were occurring before the UCRRP's inception in 1988, with only 12 percent of this amount from new depletions.

Collaboration

The UCRRP has been effective at implementing actions designed to recover endangered fish species while working in concert with interstate water compacts and State water and wildlife laws. UCRRP participants recognize that consensus-based collaboration is better than unproductive confrontation and that they can accomplish far more working together than would ever be possible working alone. The value of the collaborative approach undertaken by the UCRRP has been recognized by Congress through bipartisan support of

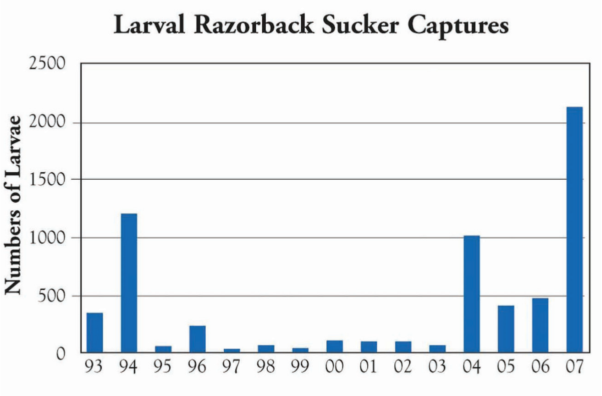


Figure 4. Captures of razorback sucker larvae for 1993 to 2007 in the middle Green River (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, 2009).

appropriations and authorizing legislation: (1) Public Law 106–392 (Oct. 30, 2000, 114 Stat. 1602) specified the Federal and non-Federal cost-sharing arrangements, (2) Public Law 107–375 (Dec. 19, 2002, 116 Stat. 3113) extended the period to complete capital construction to 2008, and (3) Public Law 109–183 (Mar. 20, 2006, 120 Stat. 290) authorized an additional $15 million for capital construction and extended the construction period to 2010.

The UCRRP is considered by many to be a national model of how to recover endangered species in the face of development conflict. Whatever success has been realized is due not to the leadership of just one or two people, but to the synergy of effort and dedication of all its participants. Much like an ecosystem, each participant plays a vital role.

A partnership approach is the only viable means to achieve recovery because each stakeholder's cooperation is needed to accomplish the many and formidable actions required to recover the endangered fish. Although drought and expanding nonnative fish populations have resulted in some recent setbacks, UCRRP partners remain optimistic that they can continue to determine and implement the necessary management actions to ultimately achieve recovery.

For more information contact:

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Upper Colorado River
Endangered Fish
Recovery Program

San Juan River Basin Recovery Implementation Program (SJRIP)

Program History

In the early 1980s, ESA compliance related to two major projects, the Animas-La Plata Project and Navajo Indian Irrigation Project, lead to the formation of the SJRIP. In the early 1990s, the Service determined that the current and cumulative adverse impacts associated with these water development projects were creating conditions that jeopardized the continued existence of Colorado pikeminnow and the razorback sucker within the San Juan River Basin. The impacts of these projects focused on water depletion but also included water-quality degradation, contamination from irrigation returns, scouring and sedimentation of the river channel, and changes to the water temperature of the river. The Service recognized that for water development to continue and for the endangered fish populations to be protected and recovered in the San Juan River Basin, a program or plan was needed for stakeholders to work cooperatively to meet both needs. To avoid jeopardy to the listed species from the Animas-La Plata Project, a reasonable and prudent alternative was agreed to in 1991; it included the development of a fish recovery program in the San Juan River Basin. A cooperative agreement established the SJRIP in 1992.

Program Goals

The specific goals of the SJRIP are to (1) conserve populations of Colorado pikeminnow and razorback sucker in the San Juan Basin consistent with the recovery goals established under the ESA and (2) proceed with water development in the San Juan Basin in compliance with Federal and State laws, interstate compacts, Supreme Court decrees, and Federal trust responsibilities to the Southern Ute Indian Tribe, Ute Mountain Ute Indian Tribe, the Jicarilla Apache Nation, and the Navajo Nation. It is anticipated that actions undertaken by the SJRIP to recover the listed species will also provide benefits to other native fish in the basin (table 2).

Geographic Scope

The geographic scope of the SJRIP is the San Juan River (fig. 5). From its origins in the San Juan Mountains of Colorado, the San Juan River flows approximately 31 miles to the New Mexico border, 190 miles westward through New Mexico to the Four Corners area, and another 136 miles through Utah to Lake Powell.

Table 2. Native fish of the San Juan River Basin (San Juan River Basin Recovery Implementation Program, 2006).

Species	Status
Bluehead sucker (*Catostomus discobolus*)	Abundant, generally distributed and typically numerous
Bonytail (*Gila elegans*)	Endangered, United States
Colorado pikeminnow (*Ptychocheilus lucius*)	Endangered, United States
Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*)	Protected, Colorado
Flannelmouth sucker (*Catostomus latipinnis*)	Abundant, generally distributed and typically numerous
Mottled sculpin (*Cottus bairdii*)	Rare, not generally distributed and never numerous
Razorback sucker (*Xyrauchen texanus*)	Endangered, United States
Roundtail chub (*Gila robusta*)	Protected, New Mexico
Speckled dace (*Rhinichtys osculus*)	Common, generally distributed but typically not numerous

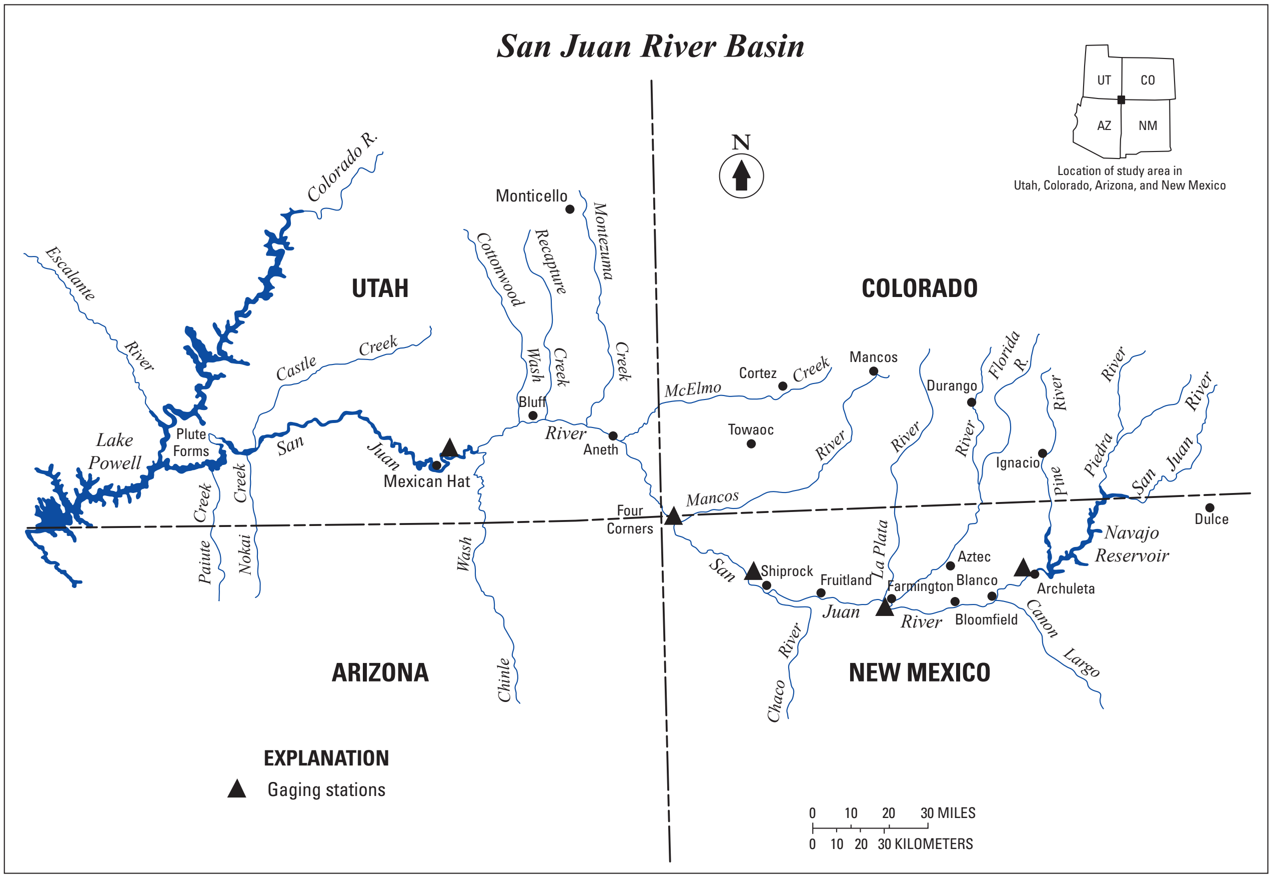

Figure 5. The San Juan River and its tributaries in Arizona, Colorado, New Mexico, and Utah.

Program Participants

- Jicarilla Apache Nation
- Navajo Nation
- Southern Ute Indian Tribe
- Ute Mountain Ute Indian Tribe
- State of Colorado
- State of New Mexico
- Bureau of Indian Affairs
- Bureau of Land Management
- Bureau of Reclamation
- U.S. Fish and Wildlife Service
- Water development interests in Colorado and New Mexico
- Conservation interests

Program Structure and Budget

The SJRIP developed a long-range plan to serve as the research, monitoring, and implementation document for recovery activities (San Juan River Basin Recovery Implementation Program, 2009). The long-range plan specifies the logical progression and priority for implementing recovery actions within the San Juan River Basin that are expected to result in recovery of the San Juan River populations of Colorado pikeminnow and razorback sucker based on the research and evaluation information provided from past studies. This plan along with other SJRIP documents provides the foundation for scheduling, budgeting, and implementing research, monitoring, and capital projects and other recovery activities.

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Genetically diverse Colorado pikeminnow (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*) produced at facilities like the Dexter National Fish Hatchery and Technology Center, which is pictured here, are used to stock the San Juan River.

Three committees—Coordination, Biology, and Hydrology—were established to carry out the SJRIP. The purpose of the Coordination Committee is to assure that the goals of the SJRIP are achieved in a timely manner. It establishes SJRIP policies, direction, procedures, and organization; approves annual work plans and budgets; and performs conflict resolution. Each participant in the SJRIP has the right to one voting representative on the Coordination Committee. Coordination Committee members appoint representatives to the Biology and Hydrology Committees.

The SJRIP's annual budget for fiscal year 2009 was $2.4 million.

Program Activities

Recovery for the Colorado pikeminnow and razorback sucker is based on the reduction or removal of threats and the improvement of the status of each species during the time it is federally listed. The recovery goals for these two endangered fish include site-specific management actions and tasks and describe objective measurable downlisting and delisting criteria (U.S. Fish and Wildlife Service, 2002b, 2002d). The recovery plans list demographic criteria that describe numbers of populations and individuals (adults and juveniles) that are required before downlisting and delisting can be considered. Recovery elements include the following areas:

Protection, Management, and Augmentation of Habitat. This element identifies important river reaches and habitats for different life stages of the endangered fish and makes appropriate habitat improvements, including providing flows in the San Juan River and passage around migration barriers to provide suitable habitat to support recovered fish populations.

Water-Quality Protection and Enhancement. This element identifies and monitors water-quality conditions and takes actions to diminish or eliminate identified water-quality problems that limit recovery.

Interactions Between Native and Nonnative Fish Species. This element identifies problematic nonnative fish species and implements actions to reduce negative interactions between the endangered fish species and nonnative fish species.

Protection of Genetic Integrity and Management and Augmentation of Populations. This element ensures that the SJRIP's augmentation protocols maintain genetically diverse fish species while producing new generations of Colorado pikeminnow and razorback sucker to stock the river system.

Monitoring and Data Management. This element evaluates the status and trends of the endangered fish species, and of other native and nonnative species, and measures progress toward achieving recovery goals.

Progress Toward Program Goals

Flow Recommendations

The Animas-La Plata Project includes several measures intended to offset or minimize negative impacts on the fish community, which are based on 7 years of research to determine the endangered fish habitat needs and to operate Navajo Dam to mimic a natural hydrograph for the life of the dam. In 1991, experimental flow releases from Navajo Dam were initiated for the recovery of the two endangered fish species in the San Juan River. Since then, the reservoir has been operated to mimic a natural hydrograph with high spring peak releases and low base-flow releases.

Based on information from the experimental flow period and the 7-year study completed in 1999, the Biology Committee developed quantitative flow recommendations for the San Juan River below the Animas River confluence (Holden, 1999). The flow recommendations consist of (1) spring snowmelt period peak-flow rates, durations, and recurrence intervals to provide for creation and maintenance of spawning and rearing habitat on the basis of flow statistics for the San Juan River at Four Corners and (2) target base flows in the San Juan River to provide low-velocity habitats for rearing during the summer, fall, and winter months as measured by a combination of gages at Farmington, Shiprock, Four Corners, and Bluff. The flow recommendations were adopted by the Coordination Committee and are being implemented by specific operations decision criteria for Navajo Dam. These operating rules provide sufficient releases of water at times, quantities, and durations necessary to meet the flow recommendations while maintaining the authorized purposes of the Navajo Unit.

Removing Barriers and Preventing Entrainment

Five diversion structures were identified in the Program Evaluation Report between river mile (RM) 180 and RM 140 that were reported to be potential barriers to fish movement, particularly upstream movement (Holden, 2000). From upstream to downstream, the identified diversions were Fruitland Diversion (RM 178.5), Public Service Company of New Mexico Weir (PNM Weir; also known as the San Juan Generating Station; RM 166.6), Arizona Public Service Company Weir (APS Weir; also known as Four Corners Generating Station; RM 163.3), Hogback Diversion (RM 158.6), and Cudei Diversion (RM 142.0). Upon further investigation, the Fruitland Diversion did not appear to be an impediment to fish passage (Stamp and others, 2005). Cudei Diversion, Hogback Diversion, and APS Weir were deemed to be passable by fish at some flows, but upstream movement was restricted by PNM Weir, especially for nonnative fish (Ryden, 2000). The Biology Committee recommended that the SJRIP work with the Bureau of Reclamation to explore alternatives that could improve fish passage at the APS Weir (U.S. Fish and Wildlife Service, 2006). In 2002, the SJRIP combined Hogback and Cudei Diversions and constructed a nonselective fish passage at the Hogback Diversion to restore access to 36 miles of critical habitat. The SJRIP completed a selective fish passage around the PNM Weir in 2003 that allows native fish to continue upstream while removing nonnative fish from the San Juan River. Fish use of the PNM passage is monitored by the Navajo Nation Department of Fish and Wildlife in monthly reports. Currently, all identified impediments to fish movement have been removed with the exception of APS Weir and Fruitland Diversion. The SJRIP continues to track fish movement up and downstream from these diversions to evaluate the number and frequency of fish that negotiate these barriers and will pursue a potential passage at APS Weir and Fruitland Diversion if it is warranted.

In addition to blocking upstream movement of adult fish, diversions may also impact endangered fish recruitment by entraining eggs and larvae. In 2004 and 2005, numerous native and nonnative fish, including more than 200 Colorado pikeminnow, were detected in irrigation canals along the San Juan River but were most numerous in the Hogback Diversion Canal (Renfro and others, 2006). The SJRIP will begin construction of a fish weir at Hogback Diversion in 2010. Methods are being implemented to ensure that endangered fish do not become entrained in these structures by shifting the timing of stocking events to occur after the active irrigation season and evaluating the need to screen the intakes to these facilities to keep fish from entering the canals (Renfro and others, 2006). The SJRIP continues to evaluate the need for fish screens or deflection weirs at other diversion and out-take structures along the San Juan River.

Nonnative Fish Removal

The introduction of nonnative species has been a major factor contributing to the extinction of many North American freshwater fish because of predation, competition, and hybridization (Miller and others, 1989). The SJRIP began limited mechanical removal of nonnative fish in 1997, and intensive removal of nonnative fish by way of raft electrofishing has occurred in the upper and lower portions of the San Juan River since 2001 and 2002, respectively (Davis and others, 2009; Elverud, 2009). Beginning in 2006, management efforts were expanded to remove nonnative fish from a greater proportion of critical habitat by including the reach from Shiprock, NM, to Mexican Hat, UT. Nonnative control efforts have focused on removing channel catfish (*Ictalurus punctatus*) and common carp (*Cyprinus carpio*) from the San Juan River. Although river-wide capture rates of channel catfish have remained relatively constant following the initiation of intensive nonnative removal efforts, catfish do appear to be responding to removal efforts and have shifted their distribution to sections of the river that have not been included in this long-term removal effort (Ryden, 2009). Capture rates of common carp have declined through time over the entire river (Davis and others, 2009; Elverud, 2009). With continued river-wide removal efforts there is hope that numbers of these


T. Ross Reeve, Bureau of Reclamation

Nonnative fish removal efforts have reduced the abundance of adult channel catfish (*Ictalurus punctatus*) in high-priority upper and lower sections of the San Juan River where catfish numbers were highest.

nonnative predators and competitors will decline. Endangered fish population response cannot yet be linked to nonnative removal efforts, but it is expected that these efforts will promote the survival of native fish as the amount of predation and competition between native and nonnative fish is reduced. However, there does not appear to be a clear response of common native sucker species to nonnative fish removal efforts (Davis and others, 2009).

Stocking and Augmentation

Of all the management actions to recover Colorado pikeminnow and razorback sucker in the San Juan River, stocking/augmentation with hatchery-produced fish has probably led to the largest population response of the endangered fish because of its direct impact on increasing endangered fish numbers. The SJRIP developed formal augmentation plans for razorback sucker and Colorado pikeminnow in 1997 and 2002, respectively (Ryden, 1997, 2003). Colorado pikeminnow are reared at Dexter National Fish Hatchery and Technology Center (Dexter) to satisfy the SJRIP's annual stocking objectives of 300,000 young-of-year and 3,000 juvenile pikeminnow. Razorback sucker reared at Uvalde National Fish Hatchery (Uvalde) are stocked in the San Juan River, and razorbacks reared at Dexter are stocked in Navajo Agricultural Products Industry (NAPI) grow-out ponds in the spring and harvested in the fall to supplement the number of fish stocked from Uvalde. The program's stocking objective for razorback sucker is 11,400 fish from Uvalde, and the 10,500 razorbacks stocked at NAPI ponds are supplemental to the 11,400 stocking target. With an expected return rate of 40 to 60 percent at NAPI ponds, an additional 4,200 to 6,300 supplemental razorback suckers are anticipated to be stocked into the river. Because both species are long-lived it will take many years to determine if these stocking activities are successful.

Coordination with Other Recovery Efforts

Activities conducted under the SJRIP are closely coordinated with the UCRRP. The programs share outreach, education, and research efforts and co-fund hatchery production efforts for razorback sucker and bonytail at Uvalde National Fish Hatchery. Coordination among recovery efforts throughout the basin could effectively reduce overlap and duplication of recovery, outreach, and research activities and improve the overall effectiveness of each program.

For more information contact:

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http://www.fws.gov/southwest/sjrip

San Juan River Basin
Recovery Implementation Program

Glen Canyon Dam Adaptive Management Program (GCDAMP)

Program History

The GCDAMP was established in 1997 as an outcome of the 1996 Record of Decision on the Operation of Glen Canyon Dam Final Environmental Impact Statement. Like many other environmental programs, the GCDAMP was the outgrowth of a long history of conflict surrounding the effects of Glen Canyon Dam operations on downstream resources in Glen Canyon National Recreation Area and Grand Canyon National Park. Glen Canyon Dam lies about 16 miles above the boundary between the upper and lower Colorado River Basin, or the “Compact Point.” This point is the boundary for water deliveries from the upper to the lower basin. So, although many of the effects of Glen Canyon Dam occur in the lower basin, the GCDAMP is treated as an upper basin program because the dam is physically located there. In this case, geopolitical boundaries and ecological boundaries do not coincide.

Controversy over the effects of dam operations motivated the Commissioner of Reclamation to initiate a science program in 1982 to examine the effects of dam operations on downstream resources. In 1989, in response to the findings of the science program, Secretary of the Interior Manual Lujan, Jr., ordered an Environmental Impact Statement (EIS) on the operation of Glen Canyon Dam and, to further protect downstream resources, in 1991 adopted interim operating criteria that restricted dam operations.

While the EIS was underway, Congress passed the 1992 Grand Canyon Protection Act (GCPA), which required the Secretary of the Interior to “operate Glen Canyon Dam…and exercise other authorities under existing law in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established, including, but not limited to natural and cultural resources and visitor use” (Sec. 1802 (a) of Public Law 102–575, Oct. 30, 1992). The act also required the Secretary to undertake this requirement “in a manner fully consistent with and subject to the [body of laws] that govern allocation, appropriation, development, and exportation of the waters of the Colorado River Basin” (Sec. 1802 (b) of Public Law 102–575, Oct. 30, 1992).

The Secretary of the Interior clearly was faced with a dilemma. Congress required operation of the dam to protect and improve park resources while fulfilling all water delivery and development purposes at a time when, admittedly, there was insufficient knowledge of how to operate the dam to achieve the required objectives. To proceed in the face of uncertainty, the Secretary decided to implement the preferred alternative outlined in the 1995 EIS, which included an adaptive management program having two major principles: (1) increased and recurrent stakeholder involvement through a Federal Advisory Committee and (2) a strong commitment to a scientific foundation for recommendations through a research and monitoring program.

Program Goals

According to the 1995 Final EIS, the “purpose of the AMP [Adaptive Management Program] would be to develop modifications to Glen Canyon Dam Operations and to exercise other authorities under existing laws as provided in the GCPA to protect, mitigate adverse impacts to, and improve the values for which the Glen Canyon National Recreation Area and Grand Canyon National Park were established” (U.S. Department of the Interior, 1995, p. 34).

Geographic Scope

The GCDAMP focuses on a study area that encompasses the Colorado River corridor from the forebay of Glen Canyon Dam to the western boundary of Grand Canyon National Park. The study area includes the approximately 15 river miles of the river from the dam to Lees Ferry within Glen Canyon National Recreation Area and the entire 277 river miles of the river below Lees Ferry and within Grand Canyon National Park. In total, the study area includes some 293 river miles of the Colorado River.

Program Participants

Tribes
Hopi Tribe
Hualapai Tribe
Navajo Nation
Pueblo of Zuni
San Juan Southern Paiute Tribe
Southern Paiute Consortium

State and Federal Cooperating Agencies
Arizona Game and Fish Department
Bureau of Indian Affairs
Bureau of Reclamation
National Park Service
U.S. Department of Energy, Western Area Power Administration
U.S. Fish and Wildlife Service

Colorado River Basin States
Arizona: Arizona Department of Water Resources
California: Colorado River Board of California
Colorado: Colorado Water Conservation Board
Nevada: Colorado Water Commission of Nevada
New Mexico: New Mexico Office of the State Engineer
Utah: Water Resources Agency
Wyoming: State Engineer’s Office

Nongovernmental Groups
Grand Canyon Trust
Grand Canyon Wildlands Council
Federation of Fly Fishers/Northern Arizona Flycasters
Grand Canyon River Guides
Colorado River Energy Distributors Association
Utah Associated Municipal Power Systems

Program Structure and Budget

The GCDAMP is facilitated by the Adaptive Management Work Group (AMWG), which is organized as a Federal advisory committee. The Secretary of the Interior appoints the group's 25 members, who include representatives from the entities identified above. The AMWG makes recommendations to the Secretary on dam operations and other actions under the Secretary's authority. Many AMWG recommendations have been for management experiments to better understand the effects of dam operations on natural resources. The GCDAMP is administered by a senior Department of the Interior official who also serves as the chair of AMWG.

The GCDAMP also includes the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center, the Technical Work Group (TWG), and independent scientific review panels. The TWG is composed of managers from the same 25-member group as the AMWG. Additional scientific expertise is provided by a standing group of science advisors and ad hoc external scientists who review proposals and provide reviews of research and monitoring protocols. Recently, the Secretary of the Interior added a Policy Group, composed of senior officials that oversee Departmental agencies, to ensure intradepartmental communication and coordination at the national level (fig. 6; Norton, 2006).

As the program's name implies, adaptive management guides the efforts of the GCDAMP. Murray and Marmorek (2004, p. 1) succinctly define adaptive management as "…a rigorous approach to environmental management designed to explicitly address and reduce uncertainty regarding the most effective on-the-ground actions for achieving management goals and objectives." The important point is that adaptive management is an iterative learning process that recognizes uncertainty and invokes science in decisionmaking. Policies are treated as experiments, and thus, they must be tested.

The GCDAMP's annual budget for fiscal year 2009 was $13.6 million.

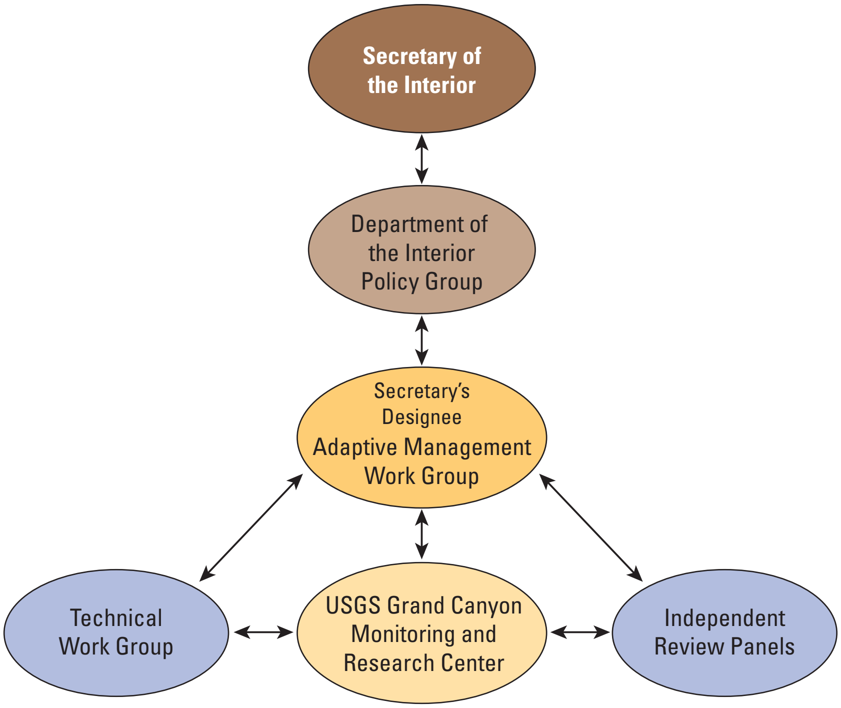

Figure 6. Structure of the Glen Canyon Dam Adaptive Management Program. The Secretary of the Interior appoints the Adaptive Management Work Group's 25 members, who include representatives from Federal and State resource management agencies, the seven Colorado River Basin States, Native American Tribes, environmental groups, recreation interests, and contractors of Federal power from Glen Canyon Dam.

Program Activities

The program undertakes three types of activities: (1) long-term monitoring, (2) research and development, and (3) flow and nonflow experimentation related to the efficacy of a range of management actions. Monitoring involves consistent, long-term repeated measurements using accepted protocols to assess status and trends of key resources, including native and nonnative fish, sediment resources such as sandbars, water quality, aquatic food production, riparian vegetation, recreation, and cultural sites. Research and development activities test specific hypotheses related to key resources and develop and test new technologies and monitoring procedures. Experimentation is used to determine how water releases from Glen Canyon Dam and other potential nonflow management actions might be used to meet resource goals. Because it is the cornerstone of adaptive management, experimentation is discussed in greater detail below.

Experimentation

The GCDAMP is best known for a series of three high-flow experiments, or water releases designed to mimic natural seasonal flooding, conducted in 1996, 2004, and 2008 (table 3). High-flow experimental releases from the dam are designed to maintain Colorado River sandbars, or beaches, by flushing tributary-derived sand from the riverbed up and onto sandbars. The high-flow experiments had multiple objectives, but two were paramount. The first purpose was to rebuild beaches used by campers and river runners, and the second was to rejuvenate and re-create attendant native fish habitats, the backwaters that formed in the lee spaces between the sandbars and the river banks. By building beaches and backwaters along the shores of the main channel, managers and scientists also sought to provide habitats that would be used by young native fish, especially in their first year of life.

Another major experiment occurred in 2000, when low summer steady flows, bordered by powerplant capacity habitat maintenance flows, were released from Glen Canyon Dam. This complex flow experiment was considered a test of concept for the seasonally adjusted steady flow reasonable and prudent alternative issued by the Service in its 1995 biological opinion.

In 2002, an environmental assessment written by Reclamation, the National Park Service, and the USGS increased the range of GCDAMP experimental actions by including

Table 3. Chronology of experiments conducted under the Glen Canyon Dam Adaptive Management Program.

Year	Dam operations	Nonflow actions
1996	Modified low fluctuating flows/beach/habitat-building flow	None
1997	Modified low fluctuating flows/habitat maintenance flow	None
1998	Modified low fluctuating flows	None
1999	Modified low fluctuating flows	None
2000	Modified low fluctuating flows/low summer steady flows/ habitat maintenance flows	None
2001	Modified low fluctuating flows	None
2002	Modified low fluctuating flows	None
2003	Modified low fluctuating flows /nonnative fish suppression flows	Nonnative fish mechanical removal/tributary translocation of endangered humpback chub
2004	Modified low fluctuating flows/beach/habitat-building flow/ nonnative fish suppression flows	Nonnative fish mechanical removal/tributary translocation of endangered humpback chub/habitat conservation for endangered Kanab ambersnail
2005	Modified low fluctuating flows/nonnative fish suppression flows	Nonnative fish mechanical removal/tributary translocation of endangered humpback chub
2006	Modified low fluctuating flows	Nonnative fish mechanical removal
2007	Modified low fluctuating flows	None
2008	Modified low fluctuating flows /beach/habitat-building flow/ Sept.-Oct. steady flows	Tributary translocation of endangered humpback chub/habitat conservation for endangered Kanab ambersnail/nearshore ecology research
2009	Modified low fluctuating flows/Sept.-Oct. steady flows	Nonnative fish removal/tributary translocation of endangered humpback chub/hatchery refuge/nearshore ecology research

T. Ross Reeve, Bureau of Reclamation

Glen Canyon Dam releases high flows of Colorado River water on the night of March 6, 2008. A high-flow experiment was undertaken to determine if water releases designed to mimic natural seasonal flooding could be used to improve a wide range of resources in Glen Canyon National Recreation Area and Grand Canyon National Park.

mechanical removal of nonnative fish in the Colorado River and translocation of endangered humpback chub to an unoccupied reach of the Little Colorado River. The transition to an experiment containing both flow and nonflow actions was important because not all threats to Colorado River resources could be addressed adequately through dam operations. The 2002 environmental assessment also contained triggers that dictated minimum tributary fine sediment inputs necessary to initiate the second experimental high flow. The environmental assessment reduced the period of the high release from 1 week to 60 hours and included increased winter daily dam release fluctuations ranging from 5,000 to 20,000 cubic feet per second as “nonnative fish suppression flows.” Because of drought and the associated low tributary sediment inputs, this high release did not occur until November 2004.

In 2008, Reclamation proposed a 5-year (2008 to 2012) experimental plan containing a high-flow experiment, steady flows during each September and October, and a diverse set of conservation measures that included nonnative fish removal in the Colorado River and its tributaries, translocation of endangered humpback chub, establishment of a hatchery refuge for the endangered fish, continued development of a comprehensive management plan and watershed plan for the endangered chub, evaluation of endangered razorback sucker habitat for potential augmentation, and monitoring of other endangered species. This combination of efforts indicates a further recognition of the likely suite of actions that may be necessary to fully evaluate dam operations and other actions under the authority of the Secretary of the Interior. Other actions considered in the interim have included the construction and operation of a temperature control device to deliver warmer water through the dam and sediment augmentation through a slurry pipeline from Navajo Canyon in Lake Powell (Randle and others, 2007) to one or more locations below Glen Canyon Dam.

Progress Toward Program Goals

In its recently published guidebook on adaptive management, the Department of the Interior identified four measures of success in carrying out adaptive management: (1) stakeholders are actively involved and committed to the process, (2) progress is made toward achieving management objectives, (3) results from monitoring and assessment are used to adjust and improve management decisions, and (4) implementation is consistent with applicable laws (Williams and others, 2007). These metrics should be common to most adaptive management programs and should therefore have widespread utility in such assessments, including that of the GCDAMP.

Stakeholder Involvement and Support

The various GCDAMP members have very different ideas about what decisions the Secretary of the Interior should make to achieve an acceptable balance in dam operations priorities. To understand how different their values and positions are, it is only necessary to realize that the dam provides water and energy to supply the needs of millions of people, but it also sits within a national recreation area and above a national park containing one of the seven natural wonders of the world, Grand Canyon. Yet early acrimony among the members has given way to orderly development of annual budgets and work plans, complete with major experiments that use the dam as a learning tool, all delivered as recommendations to the Secretary. It appears that even people with very different value systems can work cooperatively when the goal is to increase the understanding of how a contested system works.

The primary purpose of the AMWG is to advise the Secretary of the Interior on actions that will assist in achieving the balance of interests identified in the GCPA, but not to manage or make operational decisions for the Secretary. This proximity to the ultimate decisionmaker (that is, the Secretary of the Interior) is one aspect of the GCDAMP that does not occur in many adaptive management programs. It provides a high level of relevancy to the recommendations made by the committee and a clear opportunity for them to understand the extent to which their advice is heeded in decisionmaking.

Monitoring Results Used to Adjust and Improve Management Decisions

A major challenge for the Secretary of the Interior is to balance the Colorado River Storage Project purposes for Glen Canyon Dam with subsequent responsibilities for resource stewardship provided through environmental laws and the GCPA. Any serious attempt to achieve this balance depends on a program of monitoring to determine the responses of system variables to actions taken by the adaptive management program. From its earliest days, the GCDAMP has been engaged in developing and implementing research and monitoring to assess the effects of dam operation on Colorado River resources. Because of the emphasis on active adaptive management, the GCDAMP does not just monitor resources, it also purposefully perturbs the Colorado River ecosystem through experiments and measures the resource responses. Three resources—fine sediments, endangered fish (humpback chub), and hydropower—with perceived divergent objectives exemplify the issues over how the dam is operated.

Fine Sediments

Nearly all the fine sediments that were carried through Grand Canyon before the emplacement of Glen Canyon Dam are now deposited on the bottom of Lake Powell and are unavailable to build beaches in Grand Canyon. Two tributaries below the dam—Paria River and Little Colorado River—now provide much of the fine sediments to the Grand Canyon reach of the Colorado River. Scientists measure the inputs of fine sediment from these tributaries; the concentration and size distribution of the particles as they are carried downstream, deposited, and re-suspended by the Colorado River; and the amount of sediment leaving Grand Canyon to develop a sediment budget. As with the money entering and leaving a bank account, this approach provides an index of whether one is overspending the account. These data combined with topographic surveys of the beaches and bathymetric surveys of the river bottom provide a portrayal of not only whether the remaining fine sediment below the dam is being conserved, but also where it is residing in the river corridor over time.

From dam experiments and attendant monitoring, scientists have determined that the sediment conservation paradigm used to develop EIS alternatives overestimated the residence time of new fine sediment added to the river bottom by downstream tributaries under the preferred alternative operations (Rubin and others, 2002; Melis and others, 2007). This discovery has led to development of minimum tributary sediment input criteria that must be met before a high-flow experiment can be implemented (U.S. Department of the Interior, 2002). Because the river never rests and ensuing clearwater flows released from the dam gradually reclaim the sediment thrown temporarily above its normal flow lines, the principal question for sediment researchers is whether there is a sustainable flow-only dam operation alternative that will rebuild and maintain sandbar habitats over decades. This question is being addressed through a combination of monitoring the effects of research flows and using models to determine if there is enough sand (Wright and others, 2008).

Endangered Humpback Chub

The population of endangered humpback chub in Grand Canyon is estimated through mark and recapture data that are incorporated into an age-structured stock assessment model similar to those used successfully for exploited marine fish (Coggins and others, 2006). All humpback chub of a sufficient size are marked with passive integrated transponders that respond to electronic signals by registering an identifying number. Movement information and change in size and condition are recorded when these same fish are recaptured. Because many individuals of this species reside for parts of the life cycle in the Little Colorado River and Colorado River where conditions for growth, reproduction, and survival differ markedly, it is a major accomplishment to gain such insight into the ecology of this fish.

The first continuous series of annual population estimates for the endangered humpback chub population in Grand Canyon (fig. 7) has been accomplished during the GCDAMP (Coggins, 2008; Coggins and Walters, 2009). A credible series

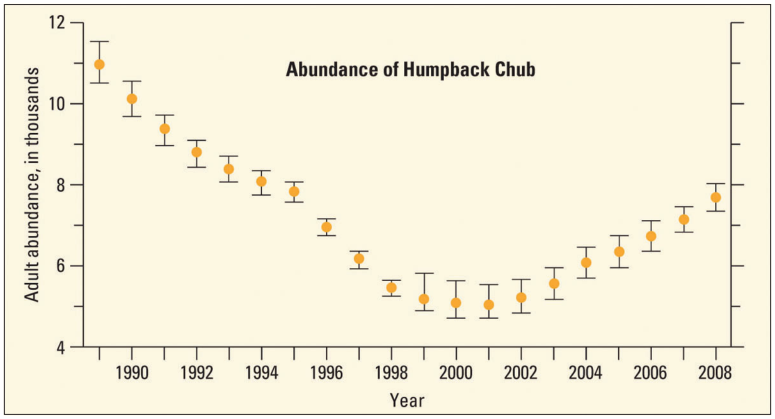

Figure 7. Estimated adult humpback chub abundance in Grand Canyon using age-structured mark recapture model and incorporating uncertainty in assignment of age (Coggins and Walters, 2009).

of estimates was not available in 1995, when the Service reached its determination of jeopardy. Model estimates showed that approximately 7,400 adults were present in the Grand Canyon population in 1995. Adult numbers subsequently fell to a low of about 5,000 in 2001, but by 2008 had rebounded to an estimated 6,000 to 10,000 adults (fig. 7) (Coggins and Walters, 2009). This turnaround, in conjunction with conservation measures for the endangered fish being undertaken by Reclamation through the GCDAMP, has convinced the Service to rescind its earlier jeopardy opinion in favor of a non-jeopardy opinion (U.S. Fish and Wildlife Service, 2008).

Hydropower

Hydropower monitoring data for the GCDAMP were largely collected and held by Reclamation and Western Area Power Administration until 2007. These data are available from the System Control and Data Acquisition system on an hourly time step and are reported daily, weekly, and monthly. The Western Area Power Administration is preparing to provide the hydropower data to the USGS Grand Canyon Monitoring and Research Center to serve through its Web site. Much of the interest in these data has been for their use in retrospective analyses of costs associated with experiments that released water and bypassed the powerplant or reduced the ability to match hydropower demand with hydropower production.

Another use of hydropower production data is to determine whether projections of the 1995 EIS preferred alternative have been borne out. The change in hydropower production under the preferred alternative in the 1995 EIS was projected to be a decrease of 442 megawatts (MW) of capacity in winter and 463 MW in summer (U.S. Department of the Interior, 1995). Economic cost increases of $15.2 to $44.2 million per year were estimated, and the financial costs to utilities were estimated at $89.1 million per year. Attribution of impacts to hydropower, including supplemental purchases, from the GCDAMP experiments is difficult and has not yet been done in a comprehensive manner, although the cost of replacement power for the recent 2008 high-flow test was estimated to be $4.1 million. It is clear from hydropower generation data that there has been a decrease in peaking generation capacity and associated revenue at Glen Canyon Dam since the 1996 Record of Decision and that costs for replacement power must be added. There are, however, a number of confounding factors, not the least of which is the loss of head from declining reservoir elevations during the recent protracted drought, which challenges this analysis (fig. 8). Efforts now underway (Tom Veselka, Argonne National Laboratory, oral commun., October 20, 2008) will soon close this gap and determine the cost to hydropower from resource protection in the adaptive management framework.

Progress Toward Achieving Resource Objectives

The 1995 EIS assessed effects of dam operations on 11 resource categories. In its 2001 strategic plan, the GCDAMP identified 11 resource goals, which are largely directed at these same resources (table 4). Nested under the 11 goals are 56 management objectives for resources or program functions. One shortcoming of most resource objectives is that although they contain metrics to be measured, they do not prescribe well-defined desired future conditions. In 2007, as part of development of a long-term experimental plan,

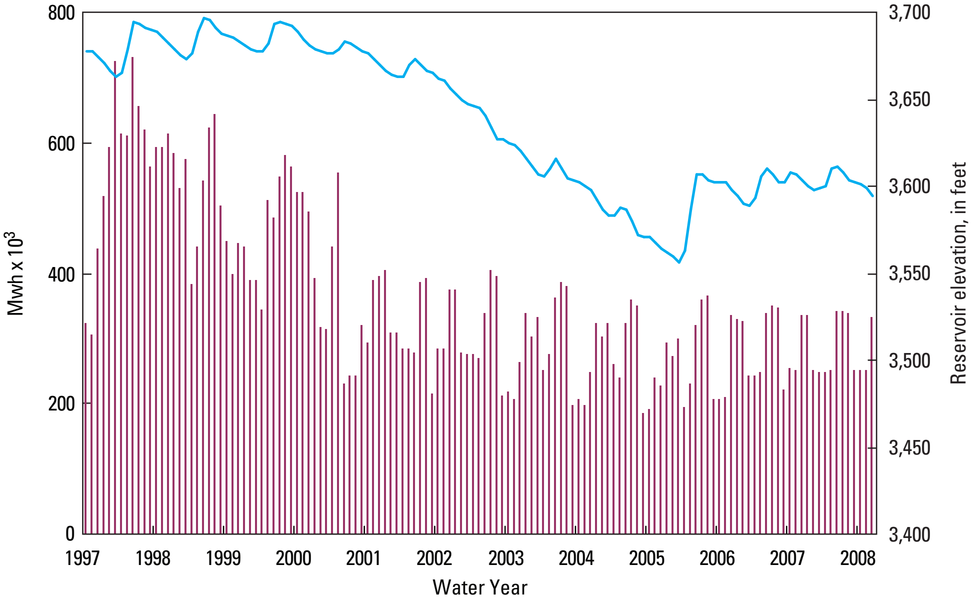

Figure 8. Monthly net generation of hydroelectric energy from Glen Canyon Dam (bars) and Lake Powell reservoir elevation (line) during the period from 1997 to 2008.

Table 4. The resource goals identified by the Glen Canyon Dam Adaptive Management Program (GCDAMP) currently being pursued and a summary of 2009 resource conditions (Glen Canyon Dam Adaptive Management Program, 2001; Hammill, 2009).

[EIS, Environmental Impact Statement]

Resource and GCDAMP goal	1995 EIS prediction	2009 summary
Natural resources		
Water quality (Goal: Establish water temperature, quality, and flow dynamics to achieve GCDAMP ecosystem goals)		
Water temperature	No effect	Since 2003, downstream water temperatures have increased in response to drought conditions.
Specific conductance (salinity)	No effect	Drought conditions, prevalent since 1999, generally result in increases in specific conductance.
Sediment (sandbars and related physical habitats) (Goal: Maintain or attain levels of sediment storage within the main channel and along shorelines)	Modest improvement	Sandbars erode during periods between high flows. Increases in total sandbar area and volume are only possible when high-flow releases follow large tributary floods that enrich sand supplies in the main channel.
Aquatic food web (Goal: Protect or improve the aquatic food base)	Potential major increase	Increases were apparent in Glen Canyon Dam tailwater reach, but the trend is unclear along downstream reaches. Unlikely that quagga mussels (*Dreissena bugensis*) will become well established in the mainstem Colorado River below Lees Ferry or its tributaries.
Native fish (humpback chub) (Goal: Maintain or attain viable populations of existing native fish)	Potential minor increase	The population of adult humpback chub (*Gila cypha*) decreased between 1989 and 2001; however, adult abundance has increased more than 50 percent since 2001.
Trout (Goal: Maintain a naturally reproducing population of rainbow trout above the Paria River)	Increased growth potential, dependent on stocking	Rainbow trout (*Oncorhynchus mykiss*) numbers have decreased in the Lees Ferry reach.
Riparian vegetation (Goal: Protect or improve the biotic riparian and spring communities)	Modest increase	Native and nonnative woody vegetation continues to expand in the river corridor. Nonnative tamarisk (*Tamarix ramosissima*) is the dominant species, making up 24 percent of vegetation.
Kanab ambersnail (Goal: Maintain or attain viable populations of Kanab ambersnail)	Some incidental take	Snail habitat increased since 1998.
Cultural resources		
Archeological sites affected (Goal: Preserve, protect, manage, and treat cultural resources)	Moderate degradation (less than 157 sites affected)	Archeological site condition continues to decline because of a combination of factors including erosion, gravity, visitor impacts, and insufficient sediment.
Traditional cultural resources affected (Goal: Preserve, protect, manage, and treat cultural resources)	Increased protection	Tribes have developed protocols for monitoring the condition of cultural resources in accordance with Tribal values.
Recreation resources		
Whitewater boating camping beaches (average area at normal peak stage) (Goal: Maintain or improve the quality of recreational experiences)	Minor increase	Areas suitable for camping have decreased on average 15 percent per year between 1998 and 2003.

GCDAMP members began to develop a list of desired future conditions. Initial objectives for two resources, humpback chub and fine sediment, put forward by two members with differing views, Western Area Power Administration and the National Park Service, were developed through the Technical Work Group and Grand Canyon Monitoring and Research Center and were submitted to the AMWG with a request for direction to proceed with additional resources. Completion of this endeavor would provide an important feedback loop for monitoring to determine the effectiveness of the GCDAMP in meeting its resource objectives and provide a better foundation for the Secretary to balance project purposes with resource protection.

One of the criticisms of adaptive management, particularly of large programs like the GCDAMP, is that they are expensive. Since the inception of the program in 1997, approximately $92 million have been expended on this effort, with the primary source of funding coming from revenue derived from the generation of hydropower. Views among GCDAMP members, and indeed the public, vary greatly on whether this expenditure will result in desired future resource conditions and an equitable balance among the differing interests. None can dispute, however, that uncertainty is being replaced with knowledge and that adaptive management is providing a more objective basis for consideration of policy change.

Implementation Consistent with Applicable Laws

Until February 2006, GCDAMP members could contend that adaptive management serves as an insulator against legal action. Major experiments were carried out with little resistance, and no lawsuits were threatened or carried out against the program. In that month, however, five environmental groups sued the Secretary of the Interior and Reclamation claiming violations of the GCPA, ESA, and National Environmental Policy Act (NEPA). An out-of-court settlement of the lawsuit, which provided for initiation of NEPA and ESA compliance activities by agreed upon dates, was reached in August 2006.

With the legal waters settled, the GCDAMP moved forward with assistance from the Grand Canyon Monitoring and Research Center in 2007 toward developing a long-term experimental plan intended to cover approximately 10 years of scientific studies beginning in 2008 (U.S. Geological Survey, 2008). Reclamation and 16 cooperating agencies prepared alternative experimental designs from which a preferred alternative in an Environmental Impact Statement would be selected. In September 2007, however, one of the environmental groups in the GCDAMP delivered a notice of intent to sue Reclamation for violations of the ESA and NEPA. A supplemental complaint later added the Service as a defendant. The threatened legal action was taken in December 2007 and is ongoing.

An important conclusion for the process of adaptive management provided by the Glen Canyon Dam example is not whether lawsuits will occur, but whether the process reduces this likelihood. What is most important to learn in the present example is that even in the face of litigation, the GCDAMP persists and is continuing to function. In March 2008, even as litigation was underway, the hollow jet tubes again were opened on Glen Canyon Dam and a third experimental high-flow test took place. Scientists busily gathered more data to be analyzed, synthesized, and integrated into reports and publications. Scientists will present their reports to technical level managers who will convey their impressions of what has been learned to their Federal Advisory Committee counterparts. The AMWG will once again meet and make its recommendations, considering scientific, legal, and policy perspectives, to the Secretary of the Interior. And no doubt the Secretary will, with the advice of his Policy Group, use those recommendations to balance the priorities for which the dam was built with those that have come about through ensuing laws. Achieving that balance will be accomplished with much greater participation and with a much firmer scientific foundation than would have been possible in the days before the GCDAMP—not perfect, perhaps, but a definite move in the potentially fruitful direction of integrating science into policymaking.

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Lower Colorado River Multi-Species Conservation Program (LCR MSCP)

Program History

The LCR MSCP is a partnership of Federal and non-Federal stakeholders, created to respond to the need to balance the use of lower Colorado River water resources and the conservation of native species and their habitats in compliance with the ESA. This program is a long-term (50-year) plan to conserve at least 26 species along the lower Colorado River from Lake Mead to the southerly international boundary with Mexico through implementation of a Habitat Conservation Plan (HCP).

Twenty-six Federal or State-listed candidate and sensitive species and their associated habitats, ranging from aquatic and wetland habitats to riparian and upland areas, are covered in the LCR MSCP. Of the 26 covered species, 6 are currently listed under the Federal ESA. The program addresses the biological needs of mammals, birds, fish, amphibians, and reptiles, as well as invertebrates and plants.

Developed between 1996 and early 2005, implementation of the LCR MSCP began in April 2005 with the signing of a Record of Decision by the Secretary of the Department of the Interior. In December 2004, a Final Environmental Impact Statement for this effort was developed (Lower Colorado River Multi-Species Conservation Program, 2004a), which included a Habitat Conservation Plan (Lower Colorado River Multi-Species Conservation Program, 2004b) and a Biological Assessment (Lower Colorado River Multi-Species Conservation Program, 2004c). The implementation activities are based on adaptive management principles, which allow program conservation measures to be adjusted over time on the basis of monitoring and research. Reclamation, in consultation and partnership with a Steering Committee made up of representatives from the 56 participating entities, is the primary implementing agency for this activity.

Program Goals and Structure

The overall goal of the LCR MSCP is to develop and implement a plan that will

- conserve habitat and work toward the recovery of threatened and endangered species, as well as reduce the likelihood of additional species being listed;
- accommodate present water diversions and power production and optimize opportunities for future water and power development to the extent consistent with the law; and
- provide the basis for incidental take authorization.

Reclamation is the lead implementing agency for the LCR MSCP. Partner involvement occurs primarily through the LCR MSCP Steering Committee, currently representing 56 entities, including water and power users, Federal land-management agencies, State wildlife agencies, and other interested parties.

The LCR MSCP provides ESA compliance for covered actions undertaken by Federal agencies under Section 7 and by non-Federal partners under Section 10 of the act. Non-Federal partners have received incidental take authorization under Section 10(a) (1) (B). The program also allows California agencies to meet their obligations under California State law for the California Endangered Species Act (CESA).

Geographic Scope

The LCR MSCP area extends over 400 miles of the lower Colorado River from Lake Mead to the international boundary with Mexico, and includes Lakes Mead, Mohave, and Havasu, as well as the historic 100-year flood plain along the mainstem of the lower Colorado River (fig. 9).

Program Participants

Steering Committee Members:
- Federal Participants:
  - Bureau of Reclamation
  - U.S. Fish and Wildlife Service
  - National Park Service
  - Bureau of Land Management
  - Bureau of Indian Affairs
  - Western Area Power Administration
- Arizona Participants:
  - Arizona Department of Water Resources
  - Arizona Electric Power Cooperative, Inc.
  - Arizona Game and Fish Department
  - Arizona Power Authority
  - Central Arizona Water Conservation District
  - Cibola Valley Irrigation and Drainage District
  - City of Bullhead City
  - City of Lake Havasu City
  - City of Mesa
  - City of Somerton
  - City of Yuma
  - Electrical District No. 3, Pinal County, Arizona
  - Golden Shores Water Conservation District
  - Mohave County Water Authority
  - Mohave Valley Irrigation and Drainage District
  - Mohave Water Conservation District
  - North Gila Valley Irrigation and Drainage District
  - Town of Fredonia
  - Town of Thatcher
  - Town of Wickenburg
  - Salt River Project Agricultural Improvement and Power District

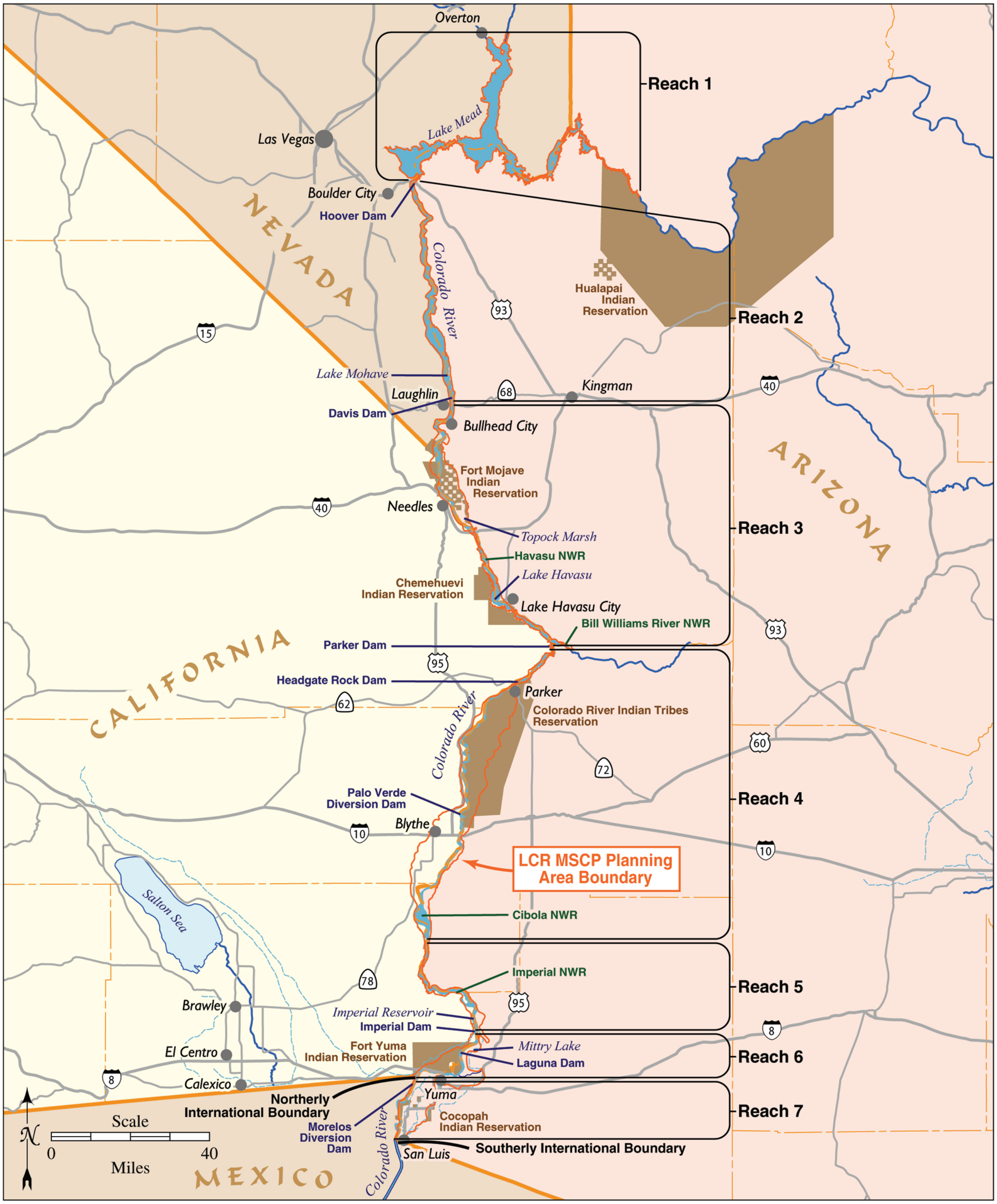

Figure 9. Lower Colorado River Multi-Species Conservation Program planning area and river reaches.

Arizona Participants (continued):
  Unit “B” Irrigation and Drainage District
  Wellton-Mohawk Irrigation and Drainage District
  Yuma County Water Users’ Association
  Yuma Irrigation District
  Yuma Mesa Irrigation and Drainage District
California Participants:
  California Department of Fish and Game
  City of Needles
  Coachella Valley Water District
  Colorado River Board of California
  Bard Water District
  Imperial Irrigation District
  Los Angeles Department of Water and Power
  Palo Verde Irrigation District
  San Diego County Water Authority
  Southern California Edison Company
  Southern California Public Power Authority
  The Metropolitan Water District of Southern California
Nevada Participants:
  Colorado River Commission of Nevada
  Nevada Department of Wildlife
  Southern Nevada Water Authority
  Colorado River Commission Power Users
  Basic Water Company
Native American Participants:
  Hualapai Tribe
  Colorado River Indian Tribes
  The Cocopah Indian Tribe
Conservation Participants:
  Ducks Unlimited
  Lower Colorado River RC&D Area, Inc.
Other interested parties:
  QuadState County Government Coalition
  Desert Wildlife Unlimited

Program Structure and Budget

The HCP outlines general and species-specific measures to conserve species and their habitats. Chief components of the plan include:

- native fish augmentation
- species research
- species and ecosystem monitoring
- conservation area development
- existing habitat protection
- adaptive management

Twenty-six species are covered under the LCR MSCP through conservation measure implementation, including 4 native fish, 12 birds, 4 mammals, 2 reptiles, 1 amphibian, 1 insect, and 2 plants. In addition, conservation measures have been established for five evaluation species, including three mammals and two amphibians. These evaluation species were not covered by the program because life-history information available during plan development was not sufficient to determine whether covered actions would affect them or to develop effective specific conservation measures.

Total LCR MSCP costs are estimated at $626 million over 50 years, in 2003 dollars indexed annually to inflation. The LCR MSCP’s annual budget for fiscal year 2009 was $15.8 million. The Department of the Interior will provide 50 percent of the program’s estimated cost, and California, Nevada, and Arizona will jointly provide the other 50 percent.

Program Activities

Program activities have two main thrusts. The native fish augmentation program is designed to increase populations of several native fish species in the Colorado River, including the razorback sucker and bonytail. Habitat is also being created for species such as the southwestern willow flycatcher (*Empidonax trailii extimus*), the yellow-billed cuckoo (*Cuccyzus americanus occidentalis*), and the Yuma clapper rail (*Rallus longirostris yumanensis*). Conservation measures require 660,000 razorback suckers and 620,000 bonytail be released in the mainstem Colorado River downstream of Davis Dam over the life of the program. The LCR MSCP will create at least 8,100 acres of new riparian, marsh, and backwater habitats.

Progress Toward Program Goals

Since 2005, approximately 107,000 razorback suckers and bonytail have been stocked into Lake Mohave and the Colorado River below Davis Dam. Research and monitoring activities are ongoing in an effort to determine the success of this program.

During the first 3 years of LCR MSCP implementation, approximately 3,300 acres and 15,000 acre-feet have been secured for potential habitat creation. Several large habitat creation projects have been initiated since 2006, including two sites near Blythe, CA. Approximately 600 acres have been established during the first 3 years of program implementation, including 450 acres of cottonwood-willow. Approximately 92 acres of marsh and backwater habitats have been constructed at Imperial National Wildlife Refuge, near Yuma, AZ, to provide habitat for fish and marsh bird species.

Future Challenges

Since the LCR MSCP is a 50-year program, with reconsultation with the Service likely at the end of the current program, adaptive management will be an important component to ensure appropriate adaptation to changes in water and power demands, water priorities, water availability, and other unexpected changes in conditions.

Conservation area development requires the mutual commitment of LCR MSCP and the landowner or land manager prior to the initiation of any habitat creation project. This commitment ensures the availability of land and water at each site through the life of the program. Since native riparian habitat being created at many sites will require active management throughout the 50 years, this commitment is essential.

Research and monitoring will continue to be important components of the LCR MSCP over the life of the program so that potential issues are identified in time to plan and implement effective management actions.

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Changing the Law-Science Paradigm for Colorado River Restoration

By Robert W. Adler[1]

Abstract

Legal mandates and scientific realities conflict when existing legal principles do not match the realities and limits of current science. Those conflicts can be addressed if scientists communicate the limits of existing scientific capabilities and if the legal system responds accordingly. One example of that phenomenon was the Federal statutory response to the limits of science in toxic tort litigation. Scientists charged with restoration of Colorado River ecosystems work within an ambiguous and limiting legal framework. Federal statutes and other legal authorities governing Colorado River management often present conflicting goals and requirements and assume that existing patterns of water and energy use are inviolate. Colorado River restoration efforts also face physical impediments because of historical development along the river, alterations in hydrology, and other factors that are difficult or impossible to reverse. One key role of scientists in the legal and policy process is to communicate those limitations clearly. Based on that information, the legal and legislative communities could alter the existing law-science paradigm governing restoration programs. A broader concept of environmental restoration would seek replacements for some of the key resources currently drawn from the river (such as water and energy) and that currently limit restoration efficacy.

Introduction

Scientists working to restore complex ecosystems express frustration when asked to give definitive answers to complex issues in the face of uncertainty, or to answer questions that cannot be answered given current knowledge or methods, or to answer questions that cannot be answered by science alone—what nuclear physicist Alvin Weinberg referred to as "trans-science" (Weinberg, 1972). In the context of minimum viable population estimates for species, conservation biologist Michael Soulé wrote: "[T]he quest for a simple bottom line is ... a question for a phantom by an untrained mind" (Soulé, 1986).

In part, other authors have suggested that this frustration reflects a "culture clash" between law and science. Sheila Jasanoff explained that "[S]cience seeks truth, while the law does justice; science is descriptive, but the law is prescriptive; science emphasizes progress, while the law emphasizes process" (Jasanoff, 1995). David Faigman wrote: "Science explores what is; the law dictates what ought to be. Science builds on experience; the law rests on it. Science welcomes innovation, creativity, and challenges to the status quo; the law cherishes the status quo" (Faigman, 1999). Lawyers often rely on enforceable legal rules and presumptions to generate stability and certainty in the face of factual uncertainty so that individuals and businesses can make decisions and invest resources with some degree of security (Adler, 2003). Scientists see the world as complex, changing, and uncertain. They test theories against the best available information, articulate hypotheses that best fit that existing knowledge, and revise those theories as better information becomes available. There is no absolute "truth" or finality.

Finality versus "Truth" in Private Litigation

The legal perspective makes sense when applied to situations in which certainty and finality are more important than the ultimate truth, and traditional common law doctrines generally have adopted that approach. A good example is a commercial transaction such as a sales contract. The contract identifies factors such as what is being sold, the price, the delivery date, and who is paying for the shipping. Even the simplest of commercial transactions, however, involve risk. The market price may change between the contract date and the transaction date, in which case one party wins and the other loses. If there is a supply shortage, the seller may not be able to deliver the goods. There may be a risk of loss or damage in transit. Parties manage those risks through educated guesses, but understand that certainty is impossible. If they

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guess wrong, “a deal is a deal.” Although the result may be harsh, business cannot proceed without the certainty provided by the law of contacts. Stability is more important than getting the “right” answer. Moreover, as between two private entities in an arm’s length transaction, society has less interest in who “wins” than in the fairness of the process.

A more disturbing example, however, might involve a toxic tort lawsuit (personal injury case arising from exposure to toxic substances). Two parents allege that their child has a terrible birth defect because of the mother’s exposure to a toxic chemical during pregnancy. The child lives with considerable pain, serious learning disabilities, and large ongoing medical and special education expenses. The relevant science is uncertain, making the case difficult to prove. There is little epidemiological evidence. Other factors may have caused or contributed to the birth defect. Toxicological evidence is debatable because of uncertainty about extrapolations from higher dose laboratory animal exposures to lower dose human exposures. Scientists might study the problem, develop one or more hypotheses, structure experiments to test those hypotheses and collect more data, and revisit the hypotheses as more knowledge and understanding are gained.

Traditional common law tort doctrines and related rules of civil litigation address the problem much differently. A “statute of limitations” requires the claim to be filed within a fixed time after the injury is discovered. The case can be dismissed for lack of diligent prosecution, meaning the plaintiff cannot wait years for additional scientific proof to be developed. The law assigns the “burden of proof” to the plaintiff in civil lawsuits, requiring them to prove their case by a “preponderance of the evidence,” meaning that it is *more likely than not* that the material facts are true (including the “fact” that the toxic exposure caused the birth defect). This standard guarantees that a large number of cases will be decided incorrectly. Scientists may not find that result surprising because, as between competing theories, the scientific process seeks the one that best explains available data and other factors with the understanding that the ultimate truth may be elusive. The key difference, however, is the legal doctrine of *res judicata* (“things adjudicated”). Once a case is decided, after a fair process and all available appeals are exhausted or waived, the matter is closed. Typically, the matter cannot be reopened *even if subsequent information suggests that the result was wrong*.

This process can lead to seemingly unfair outcomes. If the defendant loses, it may pay millions of dollars in damages for an injury caused by some other factor, or combination of factors, or bear the full costs of a harm for which it was only partially responsible. If the plaintiffs in the example above lose, the parents may not be able to afford proper medical care or remedial education. The rationale for this result is that the value of finality trumps the search for truth. Statutes of limitations allow people and businesses to move on without a perpetual shadow of liability, and resources devoted to insurance can be invested in other ways. A different standard of proof would favor one party in civil litigation, in which society cares more about a fair dispute resolution process than in the ultimate outcome.[2] *Res judicata* is often the bitterest pill for non-lawyers to swallow. Even if a new study released a year later provides much stronger evidence of causation (or lack thereof), the case cannot be reopened. The value of finality allows people to get on with their lives free of the permanent risk of uncertain liability.

Shifting the Law-Science Paradigm in the Public Law Context

The standard law-science paradigm is less helpful in describing the evolving interaction between law, science, and policy in public decisions and processes involving many more interests and the public at large. Key examples include decisions and processes about ecosystem restoration and conservation biology. In those realms, the law-science paradigm is shifting in various ways, especially as statutory approaches have supplemented or replaced common law approaches. One example, familiar to scientists involved in large-scale ecosystem restoration, is adaptive management, in which decisions are not viewed as “final” but rather as hypotheses to be tested and revised on the basis of structured iterations of management experiments, data collection, and feedback. This process has been described in similar terms by experts in science (Walters and Holling, 1990), policy (Lee, 1993), and law (Keiter, 2003).

A second example, and the main thesis here, is that where legal mandates and scientific realities present irreconcilable conflicts, which are useful in response to the search for a new law-science paradigm, just as scientists develop new paradigms to address irreconcilable conflicts between existing theories and new data. A good example is the public law (statutory) response to the toxic tort dilemma, in which it is difficult to meet traditional legal standards of causation because of uncertainty in the sciences of toxicology and epidemiology and the presence of confounding variables that may have caused or contributed to the injury. We did not abandon the law of toxic torts, and private remedies remain for plaintiffs who can meet the applicable burden of proof and other requirements. However, Congress elected to address the problem of exposure to toxic substances at a different level and from a different perspective by adopting regulatory statutes to prevent exposures to *potentially* dangerous substances rather than waiting for proof of harm. The Federal Clean Water Act prohibits the discharge of any pollutant from a point source without a permit, and without applying the

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[2] In criminal law cases, society does articulate a strong preference by imposing a much stricter standard of proof in which the government must prove its case “beyond a reasonable doubt.” This standard reflects the societal preference that it is better to let a guilty person go free than to deprive an innocent person of life or liberty.

best available treatment technology, absent any showing of harm or causation (Clean Water Act §301, 33 U.S.C. §1331). Courts ruled that Congress' regulatory approach was to target endangerment rather than demonstrated harm (Reserve Mining Co. v. Environmental Protection Agency, 514 F.2d 492, 8th Cir. 1975). Similarly, the Federal Superfund statute requires responsible parties to clean up contaminated sites or to compensate cleanup costs incurred by others based on strict liability, that is, without the need to prove causation or harm (Comprehensive Environmental Response, Compensation, and Liability Act, §107, 42 U.S.C. §9607).

This shift in the law applicable to toxic substances provided a better match between what the law requires and what science can reasonably provide. It eliminated the need to prove causation in situations where risk of harm was likely but proof of harm was elusive. It reversed the burden of proof by requiring dischargers to prove compliance with applicable treatment requirements before being allowed to discharge pollutants, rather than requiring injured parties to prove harm in order to prevent exposures from occurring. Most important for Colorado River restoration, the new approach moved upstream to tackle the root cause of the problem—exposure to toxic substances—to avoid perplexing issues of scientific proof and uncertainty that prevailed under the existing law-science paradigm.

Two key precursors helped generate this paradigm shift. The scientific community had to be honest about the limitations of current methods and understanding. This idea is fundamental to normal scientific research, in which good scientists report both the results and limitations of their research. Trials and other legal processes, however, often pit scientific experts against one another and may inhibit the willingness of each party to concede uncertainty in their respective positions. The legal community must be willing to change the legal paradigm applicable to the relevant problem, sometimes requiring a different set of societal choices and priorities. It is the *interaction* between the scientific and legal processes that is critical, however, because the wisdom of those choices turns in part on the quality of the scientific input.

Implications for Colorado River Restoration and Management

The Current Law-Science Paradigm for Colorado River Restoration

The legal regime governing Colorado River restoration is far more complex than can be summarized here. Using the Grand Canyon reach of the river as an example, however, two significant driving factors are Section 7 of the Federal Endangered Species Act (ESA) and the Grand Canyon Protection Act. Each of these statutes illustrates problems with the existing law-science paradigm governing Colorado River restoration and the manner in which science might inform a shift in that paradigm.

Section 7 of the ESA provides, in relevant part, that "… all federal agencies must take such action as is necessary to insure that actions authorized, funded, or carried out by them do not jeopardize the continued existence of" threatened or endangered species (ESA §7, 16 U.S.C. §1536). A key scientific issue suggested by this language is what level of impairment in any given circumstance constitutes "jeopardy" to the listed species. Assuming that a jeopardy determination is made, the secondary question is whether the action—in this case operation of Glen Canyon Dam—may continue based on "reasonable and prudent alternatives" sufficient to avoid jeopardy. Although the Supreme Court ruled early in the history of the ESA that Congress intended Section 7 to be interpreted strictly (Tennessee Valley Authority v. Hill, 437 U.S. 153, 1978), in practice most Section 7 decisions consider whether a balance can be struck between human economic activity supported by the Federal action and "reasonable and prudent alternatives" to mitigate the effects of the action on the listed species.

Congress sought a similar "win-win" balance in more specific legislation governing operation of Glen Canyon Dam. In the Grand Canyon Protection Act (GCPA), Congress directed the Bureau of Reclamation, guided by a multi-interest group advisory committee, to operate the dam "in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park [was] established…," and to implement the Act "in a manner fully consistent with and subject to" the Colorado River Compact and other components of the Law of the River (Grand Canyon Protection Act, Public Law 102–575, October 20, 1992, 106 Stat. 4600).

Agency officials articulate similar goals in the program documents describing the Section 7 process being used to oversee the Upper Colorado River Endangered Fish Recovery Program and for an "incidental take" permit issued for the Lower Colorado River Multi-Species Conservation Program (LCR MSCP) under Section 10 of the ESA. The upper Colorado program is designed to "recover the endangered fishes while providing for existing and new water development to proceed" (U.S. Fish and Wildlife Service, 2000). Likewise, the LCR MSCP aspires to prevent species extinction but also to "accommodate present water diversions and power production and optimize opportunities for future water and power development, to the extent consistent with the law" (Lower Colorado River Multi-Species Conservation Program, 2004). The science/policy/management dilemma this poses is whether it is really possible to meet the economic goals of water law and development and the environmental goals in the ESA and GCPA, fully and simultaneously.

Status of Existing Restoration Programs

All three major ecosystem restoration programs for the Colorado River have made significant efforts to restore species and habitats in the face of perplexing scientific and management challenges. With varying degrees of on-the-ground success, programs have been designed and implemented to control invasive species of plants and fish; replant native riparian vegetation; reconnect main channels to backwaters and flood plains; restore the level, timing, and temperature of instream flows; restock native fish and take steps to ensure their survival and reproduction; and facilitate movement of fish by installing fish passages and other structures. All are sound strategies and are either useful or essential to ecosystem recovery. However, at least to date, the programs have not succeeded in achieving the defined program goals or satisfying the applicable legal standards in the ESA and the GCPA (Gloss and others, 2005; Adler, 2007). Similar problems face other large aquatic ecosystem programs (Doyle and Drew, 2008).

One possible conclusion, especially given the adaptive management strategy adopted for all three programs, is that more time, study, and learning are necessary to modify restoration efforts until success is achieved. A more sober possibility is that the current law-science paradigm seeks impossible results under the circumstances. At least in some reaches of the Colorado River, perhaps conditions are altered to such a degree that existing restoration efforts alone, conducted within the constraints of current water law and policy, will not be sufficient to meet restoration goals. One candid scientific assessment (Mueller and Marsh, 2002) advised:

> The future is grim for native fish in the Lower Colorado River. Remnant native fish communities continue to decline, except for small refugium populations. Their fate has been sealed by the dependence on the river by 30 million water users in the United States and Mexico. *Societies' dependence on water makes native fish recovery economically and politically unlikely, and perhaps impossible*.

Several sets of anthropogenic conditions impose significant impediments to Colorado River restoration. First, human water diversions and a history of overly optimistic planning assumptions limit the amount of water available for in-stream use and restoration. The commissioners who negotiated the 1922 Colorado River Compact falsely assumed reliable average runoff in the basin sufficient to allocate at least 16.5 million acre feet (maf) of water per year, although they understood the need for significant storage capacity to buffer the impact of low water years (Meyers, 1966). Tree ring histories suggest that average flows in the basin over the past several centuries have been significantly lower than the compact assumptions (Woodhouse and others, 2006), and the hydrological impacts of climate change may reduce future runoff even further (Christensen and Lettenmaier, 2006). Development rates and patterns have been different than predicted at the time of the compact, and the upper basin States have yet to develop their full compact share. The key legal question is whether the upper basin States will get the benefit of the bargain they struck in 1922—i.e., relief from the prior appropriation doctrine of western water law—under which the lion's share of the river would have gone to more rapidly developing California (Adler, 2007). The key question for scientists is the extent to which these hydrological realities will limit the efficacy of restoration efforts.

Second, the basinwide system of dams, diversions, levees, and other physical structures built to facilitate land and water development causes hydrological and physical habitat changes that are difficult to address through minor operational modifications to that infrastructure. Those facilities alter the flow and timing of water as well as other key constituents in the aquatic environment, such as sediment, nutrients, and organic matter, and also change patterns of temperature and water-quality characteristics. One question in Grand Canyon restoration, for example, is whether sediment input below Glen Canyon Dam suffices to support long-term habitat restoration. If not, the only real solutions may be either to decommission the dam or to transport sediment stored in Lake Powell downstream.

Third, development in the river's flood plains and riparian zones, especially along the lower river, impede efforts to restore native vegetation and habitats. Existing restoration pursuant to the LCR MSCP involves labor-intensive, expensive efforts to replant relatively small areas with native plant communities, the long-term efficacy of which is inconsistent and uncertain. Even if many or all of those efforts succeed, insufficient habitat will be restored to make a real difference. Along the approximately 500 river miles below Hoover Dam, reservoirs inundate 210,000 acres of riparian habitat, approximately 300,000–350,000 riparian acres are developed, and only 23,000 acres of native vegetation remain. Against that background of losses, the LCR MSCP establishes a goal of restoring just 8,000 acres of new habitat (Lower Colorado River Multi-Species Conservation Program, 2004; Adler, 2007). Restoring natural flood regimes might be a much more successful and cost-effective strategy to restore ecosystem structure and function over a much larger area. We cannot, however, promote natural flood regimes in developed areas. The "trans-science" issue, which can be informed but not answered by the relevant science, is whether we should spend so much time and money on restoration efforts that are so constrained by existing conditions.

Implications for Colorado River Restoration

These circumstances suggest difficult choices for Colorado River restoration and management. We could accept that some places are irrevocably altered and forego restoration efforts altogether. After all, no one suggests that we try to restore the native ecosystems of Manhattan Island, and it is not prudent to use limited resources where restoration efforts are not likely to succeed. Alternatively, we could adopt more limited restoration goals. For example, in some portions of the watershed we could restore acceptable fishery habitats, but not necessarily for native species. Or, we could explore ways to undo some of the fundamental anthropogenic environmental factors that limit current restoration efforts.

All three choices would require some shift in the law-science paradigm governing Colorado River restoration analogous to the shift that occurred when Congress augmented the common law regime of torts as applied to toxic substances with preventive statutory approaches. The first two choices would require significant amendments to the ESA and other environmental laws that historically have been supported by the public and a retreat from the longstanding belief that it is possible to enjoy economic benefits from the Colorado River without sacrificing its unique ecosystems and species. The third choice—one that maintains those commitments and the integrity of our environmental statutes—would require a paradigm shift similar to the one adopted with respect to toxic pollutants. That shift would entail a significant expansion of the *concept of restoration* to include changes to some of the background conditions that constrain existing restoration efforts. The new statutory approaches to toxic pollutants addressed uncertainty in proving causation after harm occurred by shifting from *post hoc* compensation to prevention. The new approach focused on root causes rather than mitigation of effects. Likewise, broader concepts of restoration would seek to alter root causes that currently impede restoration efforts and scientific uncertainty about how to mitigate those impediments. Three brief examples are presented below, but are not intended to be exclusive.

First, we could revisit various components of the Law of the River, including the Colorado River Compact, *as a restoration strategy* (Adler, 2008). The compact was an ingenious solution to the legal and practical problems the basin States faced in 1922. Like all legal arrangements, however, it can be changed to meet current realities. For example, some have proposed that we move the location of the upper basin States' delivery obligation from Lees Ferry to Hoover Dam (Richard J. Ingebretsen, University of Utah, oral commun., 2007). This move would eliminate the need for two huge storage reservoirs simply for purposes of meeting the compact's artificial delivery obligation. Lake Powell and Lake Mead are now well below capacity, and if long-term reductions in basin runoff are likely because of climate change, this may become normal rather than “drought” conditions. If so, maintaining both reservoirs in active status significantly increases the ratio of evaporative surface area to storage volume, thus reducing water supplies for both human and environmental purposes. From a restoration perspective, taking Glen Canyon Dam out of operation would result in a far longer stretch of free-flowing river through Grand Canyon to Lake Mead.

Second, we could rethink water use and management in the basin *as a restoration strategy*. Water use in the basin is dictated largely by storage capacity and by supply and demand. Given the highly seasonal runoff pattern and the significant variability in annual runoff in the basin, storage is essential for human uses. As discussed above, however, in-stream reservoirs are major impediments to restoration. One solution to this problem would be to shift much of the basin's storage capacity from in-stream storage to a combination of off-channel reservoirs (such as the Sand Hollow Reservoir in Utah) and aquifer storage and recovery (as is being used for the Arizona Water Bank). We do not know whether there is sufficient off-stream storage capacity in the basin to eliminate the need for one or more of the major in-stream reservoirs that currently constrain restoration programs. However, we similarly did not know the potential in-stream reservoir storage capacity in the basin until we sent hydrologists and engineers to investigate in the early 20th century. Aquifer storage and recovery is one component of ongoing efforts to restore the Everglades (Comprehensive Everglades Restoration Plan, 2001). A similar effort may be appropriate here, and we could fund that effort as part of Colorado River restoration programs.

Similarly, water use in the basin depends on supply and demand. One plausible restoration strategy is to purchase water subsidies and to dedicate the saved water back to the river. If applicable science indicates that insufficient water is a limiting factor in restoration efforts, purchasing water may use limited restoration dollars more effectively than some current strategies. Similarly, direct investments in water efficiency, as have occurred in the basinwide salinity program (Bureau of Reclamation, 2005), might result in a more effective use of restoration program resources. One study estimated that over 1 maf of cost-effective water savings are possible in Arizona alone through improved irrigation (Morrison and others, 1996). On the supply side, as desalination technologies and cost-effectiveness improve (National Research Council, 2008), investment in desalination plants in California might constitute an effective restoration strategy, if Colorado River water now diverted to the west coast is dedicated back to the river for restoration.

Third, we could rethink power use and generation *as a restoration strategy*. One benefit of hydroelectric power is that it is clean and does not produce greenhouse gases (GHGs) relative to coal or other fossil fuels. However, other renewable energy sources are available in large amounts in the Southwest. For example, the total solar-generating capacity in the Southwest is estimated to be equal to seven times the current U.S. power demand (National Renewable Energy Laboratory, 2007). Arizona alone has over 2.5 million megawatts of solar-generating capacity (equal to over 1,800 Glen Canyon Dams). Moreover, investments in energy efficiency can significantly and cost-effectively reduce electric power demand in the region. If the in-stream dams that contribute to the Southwest power load also impede the efficacy of restoration programs, restoration program dollars might be spent effectively to reduce demand or to generate power from other renewable sources.

Conclusion

This analysis suggests a potential dilemma for scientists (especially those working for government agencies). Scientists need not formulate changes in law and policy, or even propose them, to facilitate shifts in the law-science paradigm governing the Colorado River (although they are certainly not precluded from doing so). Scientists involved in restoration efforts simply need to provide good, reliable, and candid information about the relative success of restoration efforts and, more importantly, key impediments to success. Available science suggests that, absent elimination of fundamental impediments to restoration, current efforts will have limited success or will fail altogether. In the face of this information, one approach is for scientists and managers simply to do what was assigned and to let someone else worry about other issues and implications. A second approach is to view the role of scientists in a broader sense as providing the information necessary to ensure sound public decisions and investments. Candid scientific assessments of both the strengths and limitations of existing restoration strategies can help legislators, senior regulatory officials, judges, and other decisionmakers to decide whether different or additional strategies are necessary or appropriate. A third approach is to do more than just provide advice and information and to advocate actively for a broader set of actions needed to ensure restoration success. The danger of the first approach is that we might continue to delude ourselves into thinking that science can achieve the impossible. The second and third approaches could facilitate the kinds of shifts in the law-science paradigm that occurred in the toxic tort example, which might facilitate more productive strategies for Colorado River restoration programs.

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A Watershed Perspective of Changes in Streamflow, Sediment Supply, and Geomorphology of the Colorado River

By John C. Schmidt[1]

Abstract

More than a century ago, John Wesley Powell urged westerners to politically organize their region by watersheds, because he believed that the need to allocate the scarce water supply was a critical decision that ought to be shared among each watershed's inhabitants. The modern Colorado River system is a modified watershed linked by a comprehensive network of dams and diversions that are regionally managed for water supply and electricity production. The river rehabilitation programs of the Colorado River and its major tributaries, however, are not managed from a watershed perspective but nevertheless have a regional context. Typically, dams have reduced the magnitude and decreased the duration of floods, increased the magnitude of base flows, and trapped incoming sediment. In response, the post-dam sediment mass balance downstream from each dam has been perturbed into sediment deficit, and these channels typically have been evacuated of sediment. In some cases, evacuation has involved large-scale bed incision, but this has not occurred in debris fan-affected segments where there is abundant coarse bed material. Elsewhere, the post-dam sediment mass balance has been perturbed into sediment surplus, and parts of the upper Colorado River, downstream parts of the Green River, and short segments of the lower river that forms the Arizona-California border have accumulated sediment. The entire network has been subject to channel narrowing that is caused by decreases in the flood regime and invasion of riparian vegetation. These perturbations cause changes in channel size and flood-plain connection that constitute changes in aquatic and riparian habitat that contribute to the endangered status of some species comprising the Colorado River's native fishery. The analysis presented here demonstrates that the magnitude and style of perturbations to different parts of the river system vary widely. Thus, different approaches are required to rehabilitate geomorphic and habitat conditions in different parts of the river network. The primary goal of this paper is to inspire a comprehensive watershed-scale geomorphic and ecological assessment of the relative challenge of rehabilitating the river network.

Introduction

Despite its modest discharge, the Colorado River is significant in terms of its utilization by human society. The Colorado River's reservoirs are larger in relation to mainstem streamflow than any other large watershed in North America (Hirsch and others, 1990), and diverted streamflow and hydroelectricity are used by more than 30 million people. Some of the dams in the watershed, such as Hoover (Stevens, 1988) and Glen Canyon (Martin, 1989), are nationally famous, as are the political debates that stopped the proposed dams at Echo Park (Harvey, 1994) and Marble Canyon (Pearson, 2002). Approximately 10 percent of the predevelopment streamflow now crosses the international border to Mexico, and most of this flow is diverted for irrigation and does not reach the Gulf of California.

The Colorado River is also significant in terms of its scenery, unique attributes of the riverine ecosystem, and the scientific studies conducted there. The Colorado Plateau portion of the watershed has the densest concentration of federally protected areas within the National Park System. Approximately 7.9 x 10^6 people visited Lake Mead National Recreation Area and its reservoir in 2008 (*http://www.nps.gov/lame/parknews/lake-mead-proves-popular-during-economic-downturn.htm*), and 4.3 x 10^6 people visited Grand Canyon National Park in 2009 (*http://www.nature.nps.gov/stats/viewReport.cfm*). The watershed's unique fishery has the highest degree of endemism of any large basin in North America (Minckley and Deacon, 1991). Many fundamental concepts in geomorphology were developed in concert with exploration of the Colorado Plateau (Powell, 1875; Gilbert, 1876, 1877; Dutton, 1880, 1881, 1882).

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Today, more than $\$4.0 \text{ x } 10^{7}$ is spent annually by four Federal-State-private collaborative programs that seek to recover endangered species or improve conditions of the native riverine ecosystem of the Colorado River or its headwater tributaries (table 1). Each of these river rehabilitation programs—the Upper Colorado River Endangered Fish Recovery Program, San Juan River Basin Recovery Implementation Program, Glen Canyon Dam Adaptive Management Program, Lower Colorado River Multi-Species Conservation Program (LCR MSCP)—is focused on a particular part of the channel network. The purpose of this paper is to provide the watershed context of these rehabilitation programs by summarizing an ever-growing body of research describing the present river ecosystem and its historical changes. A quantitative comparison of the relative perturbation of each river segment from its early 20th century condition is also presented and used to evaluate options for watershed-scale rehabilitation.

Table 1. Summary information concerning the large Colorado River rehabilitation programs.

Upper Colorado River Endangered Fish Recovery Program[a]

Established in 1988
$9.5 million/yr ($199 million; FY1989–FY2009)
Program statement: recover the Colorado pikeminnow (*Ptychocheilus lucius*), razorback sucker (*Xyrauchen texanus*), humpback chub (*Gila cypha*), and bonytail (*Gila elegans*) “while allowing continued and future water development”
Program goal: “Endangered Colorado pikeminnow, razorback suckers, bonytail and humpback chub will be considered recovered when there are self-sustaining populations of each fish species and when there is natural habitat to support them.” [specific recovery goals have been defined for each endangered species]
Program partners:
State of Colorado
State of Utah
State of Wyoming
Bureau of Reclamation
Colorado River Energy Distributors Association
Colorado Water Congress
National Park Service
The Nature Conservancy
U.S. Fish and Wildlife Service
Utah Water Users Association
Western Area Power Administration
Western Resource Advocates
Wyoming Water Development Association

San Juan River Basin Recovery Implementation Program[a]

Established in 1992
$2.4 million/yr ($43 million/yr; FY1992–FY2009)
Program statement: help recover the Colorado pikeminnow and razorback sucker while allowing water development to continue in the San Juan River Basin
Program goals:
(1) conserve populations of Colorado pikeminnow and razorback sucker in the San Juan Basin consistent with recovery goals established under the Endangered Species Act, 16 U.S.C. 1531 et seq.
(2) proceed with water development in the San Juan Basin in compliance with Federal and State laws, interstate compacts, Supreme Court decrees, and Federal trust responsibilities to the Southern Ute, Ute Mountain Ute, Jicarilla, and the Navajo Tribes.
Program partners:
State of Colorado
State of New Mexico
Jicarilla Apache Nation
Navajo Nation
Southern Ute Indian Tribe
Ute Mountain Ute Tribe
Bureau of Indian Affairs
Bureau of Land Management
Bureau of Reclamation
The Nature Conservancy
U.S. Fish and Wildlife Service
Water development interests

Table 1. Summary information concerning the large Colorado River rehabilitation programs.—Continued

Glen Canyon Dam Adaptive Management Program

Established in 1996
$13.8 x 10^6/yr (FY2008)[b]
Program goal: help the Federal government understand the relationship between dam operations and the health of the Colorado River ecosystem downstream from Glen Canyon Dam so that the Federal government can the meet its resource management obligations under the 1992 Grand Canyon Protection Act, the 1995 Glen Canyon Dam Environmental Impact Statement, and the 1996 Record of Decision
Members:

- Cooperating agencies:
  - Arizona Game and Fish Department
  - Bureau of Indian Affairs
  - Bureau of Reclamation
  - Department of Energy
  - Hopi Tribe
  - Hualapai Tribe
  - National Park Service
  - Navajo Nation
  - Pueblo of Zuni
  - San Juan Southern Paiute Tribe
  - Southern Paiute Consortium
  - U.S. Fish and Wildlife Service
- Environmental groups:
  - Grand Canyon Trust
  - Grand Canyon Wildlands Council
- Federal power purchase contractors:
  - Colorado River Energy Distributors Association
  - Utah Associated Municipal Power Systems
- Recreation interests:
  - Federation of Fly Fishers
  - Grand Canyon River Guides
- Colorado Basin States:
  - Arizona Department of Water Resources
  - Colorado Department of Water Resources
  - Colorado River Board of California
  - Colorado River Commission of Nevada
  - New Mexico Interstate Stream Commission
  - Utah Division of Water Resources
  - Wyoming

Table 1. Summary information concerning the large Colorado River rehabilitation programs.—Continued

Lower Colorado River Multi-Species Conservation Program[c]

Established in 2005

$15.8 x 10^6/yr (FY2008 actual costs; total authorized program costs are $626 x 10^6 for 50-yr period in 2003 dollars; actual costs to be adjusted for inflation)

Program goals:
- (1) protect the lower Colorado River environment while ensuring the certainty of existing water and power operations,
- (2) address the needs of threatened and endangered wildlife under the Endangered Species Act, and
- (3) reduce the likelihood of listing additional species along the lower Colorado River

Steering committee members:
- Federal participants:
  - Bureau of Reclamation
  - U.S. Fish and Wildlife Service
  - National Park Service
  - Bureau of Land Management
  - Bureau of Indian Affairs
  - Western Area Power Administration
- Arizona participants:
  - Arizona Department of Water Resources
  - Arizona Electric Power Cooperative, Inc.
  - Arizona Game and Fish Department
  - Arizona Power Authority
  - Central Arizona Water Conservation District
  - Cibola Valley Irrigation and Drainage District
  - City of Bullhead City
  - City of Lake Havasu City
  - City of Mesa
  - City of Somerton
  - City of Yuma
  - Electrical District No. 3, Pinal County, Arizona
  - Golden Shores Water Conservation District
  - Mohave County Water Authority
  - Mohave Valley Irrigation and Drainage District
  - Mohave Water Conservation District
  - North Gila Valley Irrigation and Drainage District
  - Town of Fredonia
  - Town of Thatcher
  - Town of Wickenburg
  - Salt River Project Agricultural Improvement and Power District
  - Unit "B" Irrigation and Drainage District
  - Wellton-Mohawk Irrigation and Drainage District
  - Yuma County Water Users' Association
  - Yuma Irrigation District
  - Yuma Mesa Irrigation and Drainage District
- California participants:
  - California Department of Fish and Game
  - City of Needles
  - Coachella Valley Water District
  - Colorado River Board of California
  - Bard Water District
  - Imperial Irrigation District
  - Los Angeles Department of Water and Power
  - Palo Verde Irrigation District
  - San Diego County Water Authority
  - Southern California Edison Company
  - Southern California Public Power Authority
  - The Metropolitan Water District of Southern California
- Nevada participants:
  - Colorado River Commission of Nevada
  - Nevada Department of Wildlife
  - Southern Nevada Water Authority
  - Colorado River Commission Power Users
  - Basic Water Company
- Native American participants:
  - Hualapai Tribe
  - Colorado River Indian Tribes
  - The Cocopah Indian Tribe
- Conservation participants:
  - Ducks Unlimited
  - Lower Colorado River RC&D Area, Inc.
- Other interested parties:
  - QuadState County Government Coalition
  - Desert Wildlife Unlimited

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[a] Upper Colorado River Endangered Fish Recovery Program [*http://www.fws.gov/coloradoriverrecovery/*] and San Juan River Basin Recovery Implementation Program [*http://www.fws.gov/southwest/sjrip/*] (2009).

[b] Bureau of Reclamation and U.S. Geological Survey (2008) and *http://www.gcmrc.gov/*.

[c] Lower Colorado River Multi-Species Conservation Program (2009, p. 7) and *http://www.lcrmscp.gov/*.

Hydrology and Sediment Supply Before Dams

Most of the Colorado River's streamflow enters the drainage network as snowmelt in three tributary watersheds in the middle and southern Rocky Mountains (fig. 1). The longest of these tributaries is the Green River, which has two co-equal forks, in terms of streamflow, that join at Echo Park in northwestern Colorado. The upper Green River drains the Wind River Range, Wyoming Range, and part of the Uinta Range of the middle Rocky Mountains, and the Yampa River drains part of the southern Rockies in northern Colorado. The tributary watershed with the largest unit runoff is the upper Colorado River, once called the Grand River. This watershed, including the Gunnison River that is its major tributary, drains most of the southern Rocky Mountains in central and southern Colorado. The San Juan River drains the southern part of the San Juan Mountains. These three headwater tributaries join to form the mainstem Colorado River in southeastern Utah. The only significant tributary further downstream, in terms of streamflow, is the Gila River.

Mean annual runoff in the Rocky Mountains is between 300 and 1,000 millimeters (mm) (Riggs and Wolman, 1990), and 54 percent of the total annual mainstem flow enters the network in the 15 percent of the basin comprising the exterior

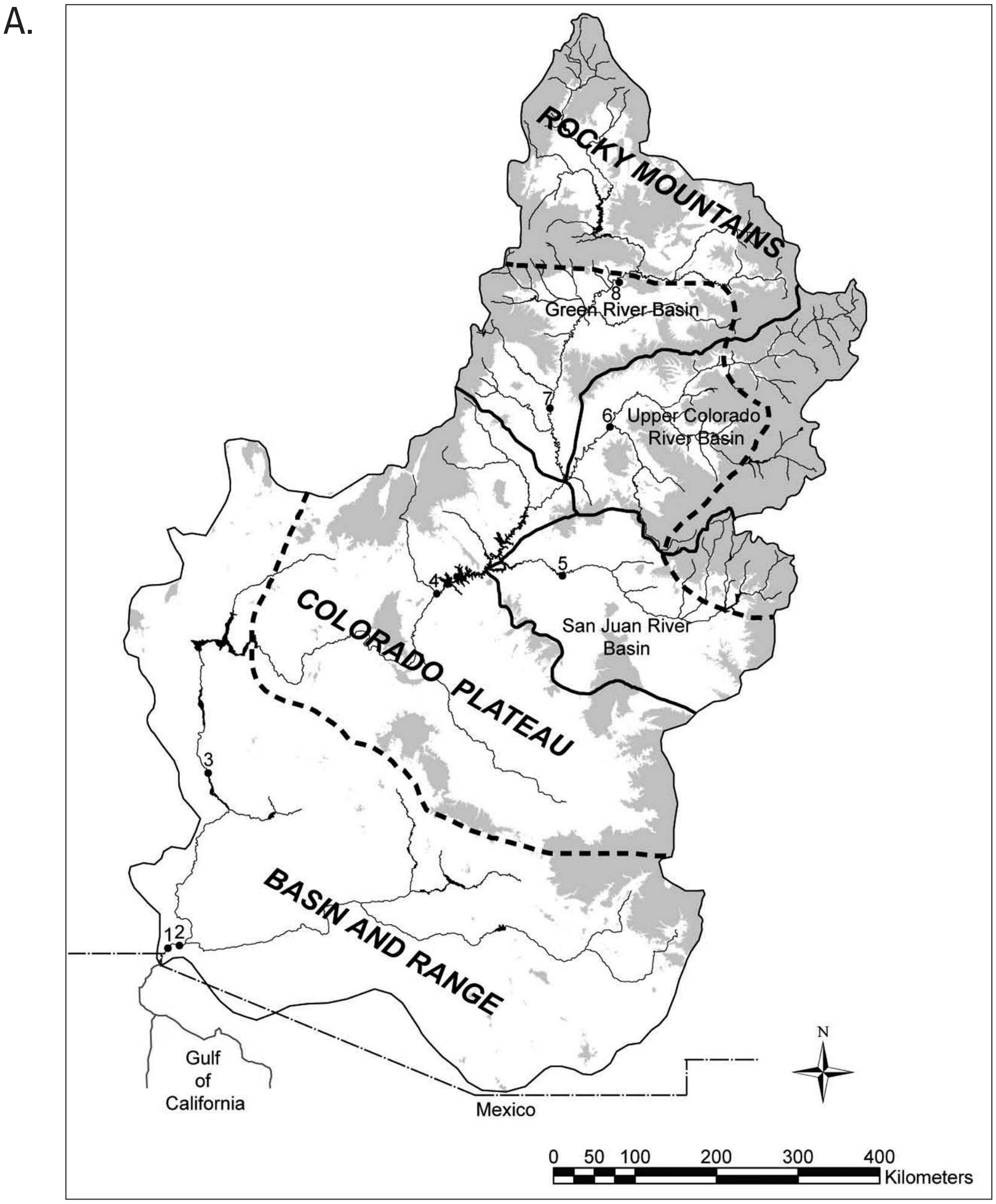


Figure 1. Colorado River Basin. (A) The three major headwater drainage basins and the three major physiographic provinces (Graf, 1987) that occur in the basin. Shaded areas are higher than 2,000 meters. Gaging stations referred to in the text are indicated by numbers: 1. Colorado River at the northern international border (NIB), 2. Colorado River at Yuma, 3. Colorado River at Topock, 4. Colorado River at Lees Ferry, 5. San Juan River near Bluff, 6. Colorado River at Cisco, 7. Green River at Green River, UT, 8. Green River at Jensen.

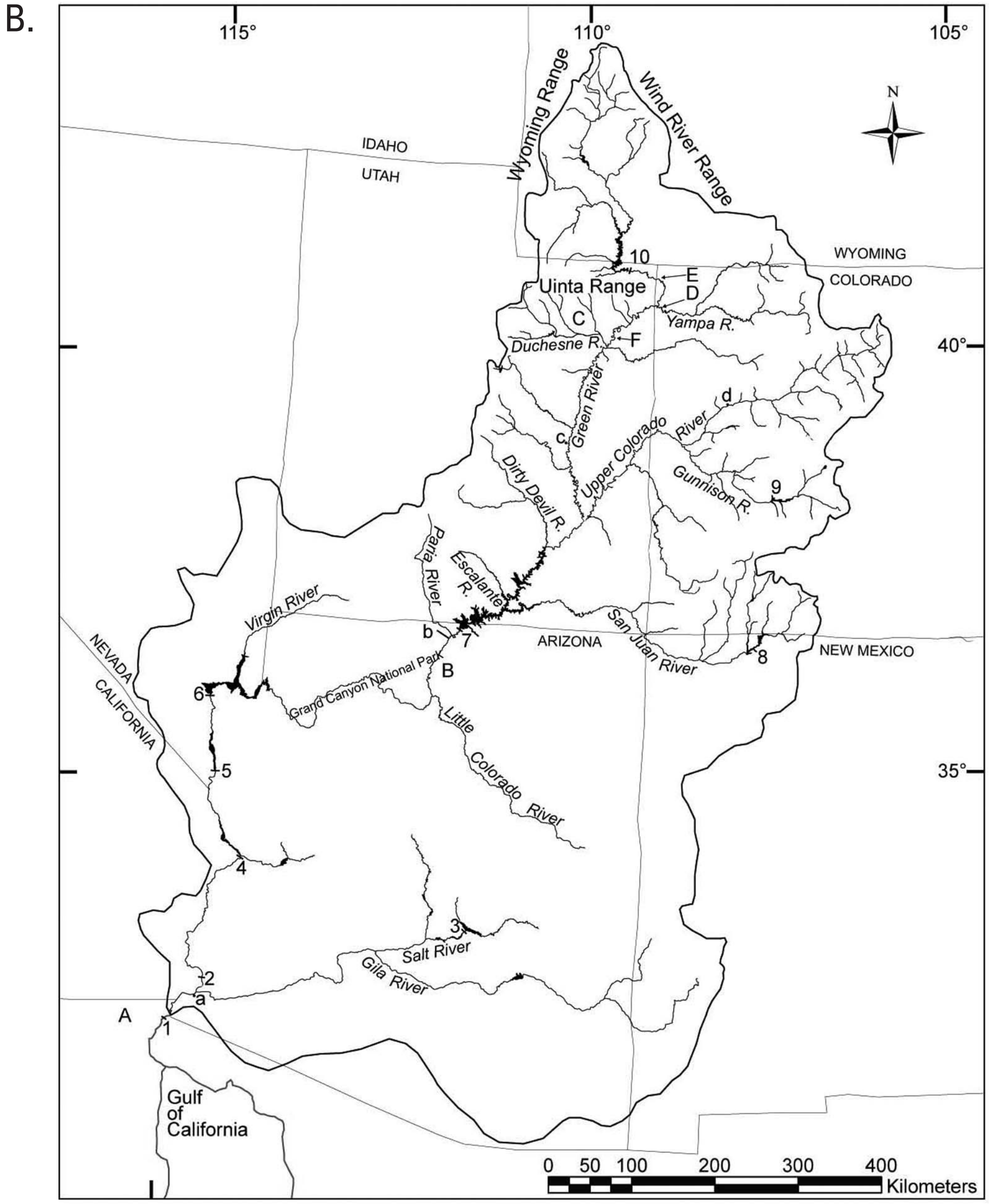


Figure 1. (continued) Colorado River Basin. (B) Locations mentioned in the text. 1. Morelos Dam, 2. Imperial Dam, 3. Theodore Roosevelt Dam, 4. Parker Dam, 5. Davis Dam, 6. Hoover Dam, 7. Glen Canyon Dam, 8. Navajo Dam, 9. Aspinall Unit, 10. Flaming Gorge Dam. A. Mexacali Valley, B. Marble Canyon, C. Uinta Basin, D. Echo Park, E. Browns Park National Wildlife Refuge, F. Ouray National Wildlife Refuge. a. Yuma, b. Lees Ferry, c. Green River, UT, d. Rulison.

watershed margin (fig. 2). The remaining 85 percent of the watershed upstream from Lees Ferry has unit runoff less than 50 mm. Before the construction of large dams, the peak flow at Lees Ferry typically occurred between late May and late June. The pre-dam, annual flood typically passed from Lees Ferry to the Gulf of California without significant change in magnitude or duration (Topping and others, 2003; Schmidt, 2007).

The Colorado River system has experienced periods of drought and times when runoff was high. The dendrohydrologic record of the Colorado River at Lees Ferry has been extended back to A.D. 762, and the mean annual runoff for the period between 1490 and 2005 is approximately $1.79 \pm 0.02 \times 10^{10}$ cubic meters (m^3) (Woodhouse and others, 2006). Pontius (1997) estimated that the long-term average annual flow entering the Colorado River's delta was 1.85×10^{10} m^3.

The Colorado River delivered about 1.0×10^8 megagrams per year (Mg/yr) of fine sediment to the Gulf of California in the beginning of the 18th century (Meade and others, 1990). Only the Mississippi River delivered more sediment from North America to the sea before extensive European settlement. The major sources of fine sediment to the

Colorado River are in the Colorado Plateau and Basin and Range Physiographic Provinces, downstream from the Rocky Mountains (fig. 3). Before construction of large dams, the average concentration of suspended fine sediment increased from the water-producing basin rim to the arid, sediment-producing central part of the watershed. Of the estimated pre-dam sediment load, approximately 27 percent came from the Green, 20 percent from the upper Colorado, and 20 percent from the San Juan River (Iorns and others, 1965). The rest came from the Dirty Devil, Escalante, Paria, Little Colorado, and Virgin Rivers, even though these streams deliver insignificant amounts of streamflow.

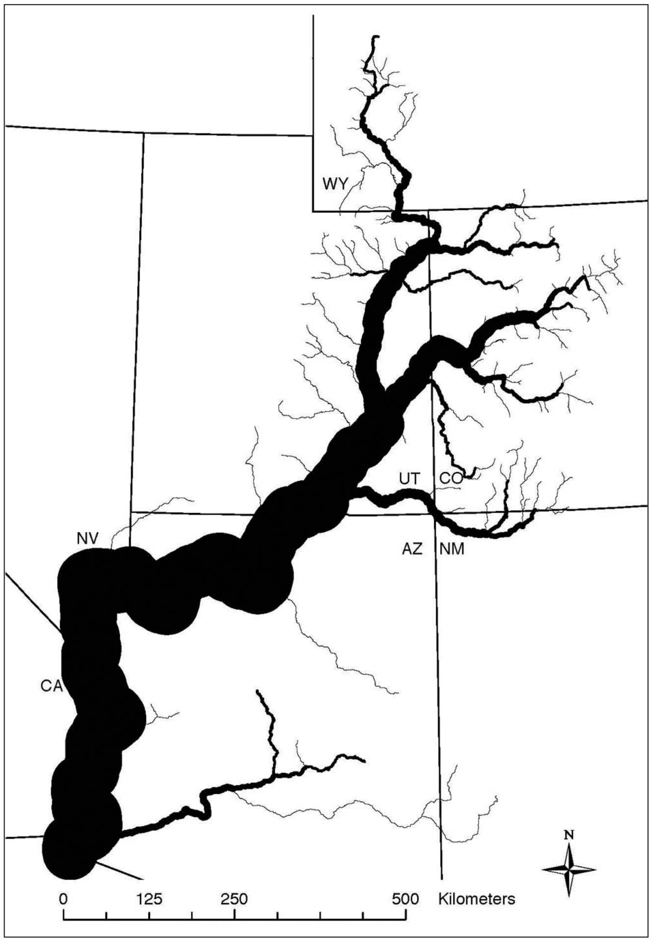


Figure 2. Relative amounts of streamflow in different segments of the pre-dam Colorado River system (reproduced from Schmidt, 2007). The majority of streamflow originated in the Rocky Mountains. The width of river segments is proportional to the widest line segment, which represents 510 cubic meters per second at the U.S.-Mexico border. Data are compiled from Iorns and others (1964) and pre-dam streamgaging records of the U.S. Geological Survey.

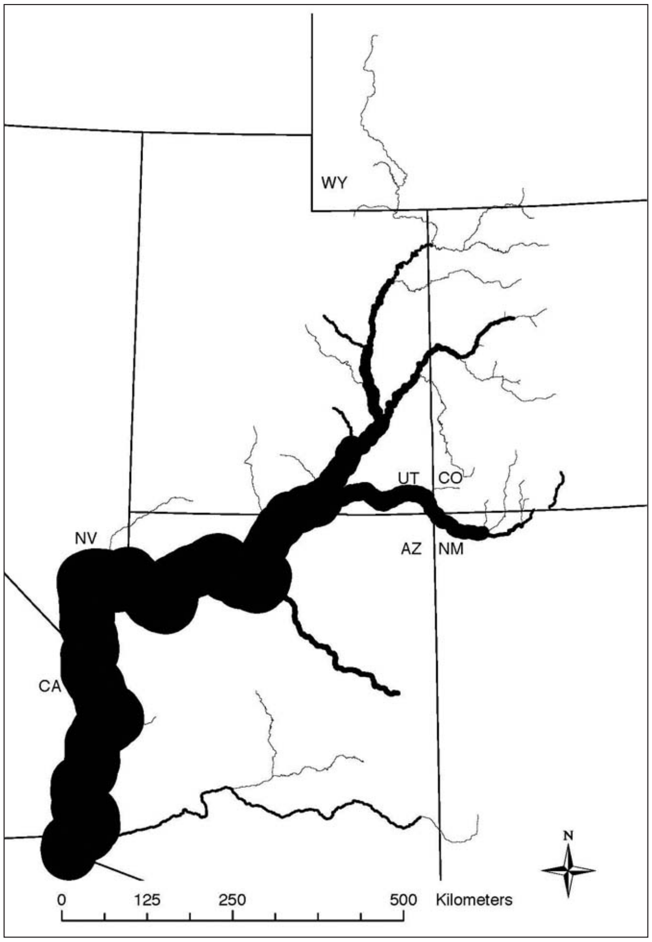


Figure 3. Relative amounts of suspended sediment in transport in the pre-dam river system (reproduced from Schmidt, 2007). These data are the estimates of Iorns and others (1965) for the period 1937–1955 and U.S. Geological Survey streamgaging stations downstream from Lees Ferry for the same period. The width of river segments is proportional to the widest line segment, which represents 1.53 x 10^7 megagrams per year at the U.S.-Mexico border.

Hydrology and Sediment Supply After Dam Construction

The first major water storage dam in the watershed was Theodore Roosevelt, completed in 1911, on the Salt River, a tributary of the Gila River. Hoover Dam, completed in 1936, was the first large dam on the mainstem, and its completion increased cumulative watershed reservoir storage to more than 4.0 x 10^{10} m^3 (fig. 4). Lake Mead is still the largest reservoir in the United States. In 1938, Parker and Imperial Dams were completed downstream from Hoover Dam (fig. 5), thereby facilitating large-scale diversions to southern California. Three additional diversion dams were completed on the lower Colorado River in 1944, 1950, and 1957, and Davis Dam was completed in 1953. Construction of large dams upstream from Lees Ferry was authorized by the Colorado River Storage Project Act of 1956, and these dams were completed in the mid-1960s. The total volume of reservoir storage is now 1.1 x 10^{11} m^3, which is nearly 7 times the long-term mean annual flow at Lees Ferry. Total basin consumptive uses are now about 1.5 x 10^{10} m^3, about 90 percent of the long-term average annual flow at Yuma. Consumptive uses upstream from Lees Ferry are about 5.0 x 10^9 m^3, or about 30 percent of the long-term annual flow at Lees Ferry. Total reservoir storage upstream from Lake Powell is 1.8 times the mean annual flow at Lees Ferry.

The transformation of the streamflow and sediment supply regimes caused by these reservoirs and by diversions has been profound (table 2). The transformation occurred earlier and the magnitude of the changes in streamflow was larger downstream from Hoover Dam, because dams there were built earlier and the total upstream reservoir storage is larger. Floods through Grand Canyon decreased greatly when Glen Canyon Dam was completed in 1963, and peak releases from the dam typically are less than 800 cubic meters per second (m^3/s) (fig. 6D). The largest dam releases have occurred when there was large snowmelt from the Rocky Mountains and when reservoir storage was full (1983, 1984, 1985, 1986), in order to create controlled floods, the purpose of which is rehabilitation of the downstream riverine ecosystem (1996, 2004, 2008), and for engineering tests or maintenance purposes (1965, 1980). Floodwaters are subsequently stored in Lake Mead. Floods on the lower Colorado River have been relatively low since 1936 when Hoover Dam was completed. Annual peak flow near Topock, AZ, downstream from Hoover and Davis Dams, typically does not exceed 900 m^3/s (fig. 6E). The largest flood released from Hoover Dam was 1,440 m^3/s in 1983, 53 percent of the pre-dam 2-year recurrence flood. Flood flows at Yuma, AZ, near where the Colorado River enters Mexico, are almost completely gone (fig. 6F).

The average hydrograph of the lower Colorado River and in Grand Canyon no longer shows a consistent, long-duration flood season, and base flows are much higher than they once

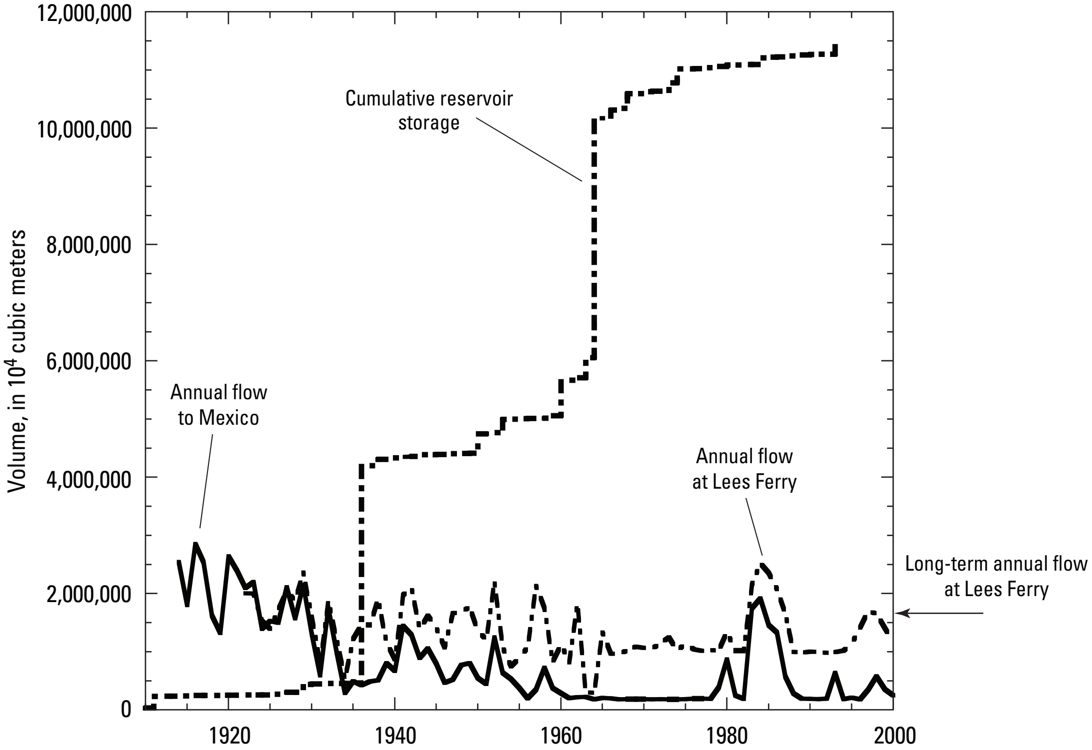


Figure 4. Cumulative reservoir storage in the entire watershed, annual flow at Lees Ferry, and annual flow crossing the international border to Mexico. The difference between annual flow at Lees Ferry and at the Mexican border is diverted to cities and towns, or is lost or stored in the regional groundwater system.

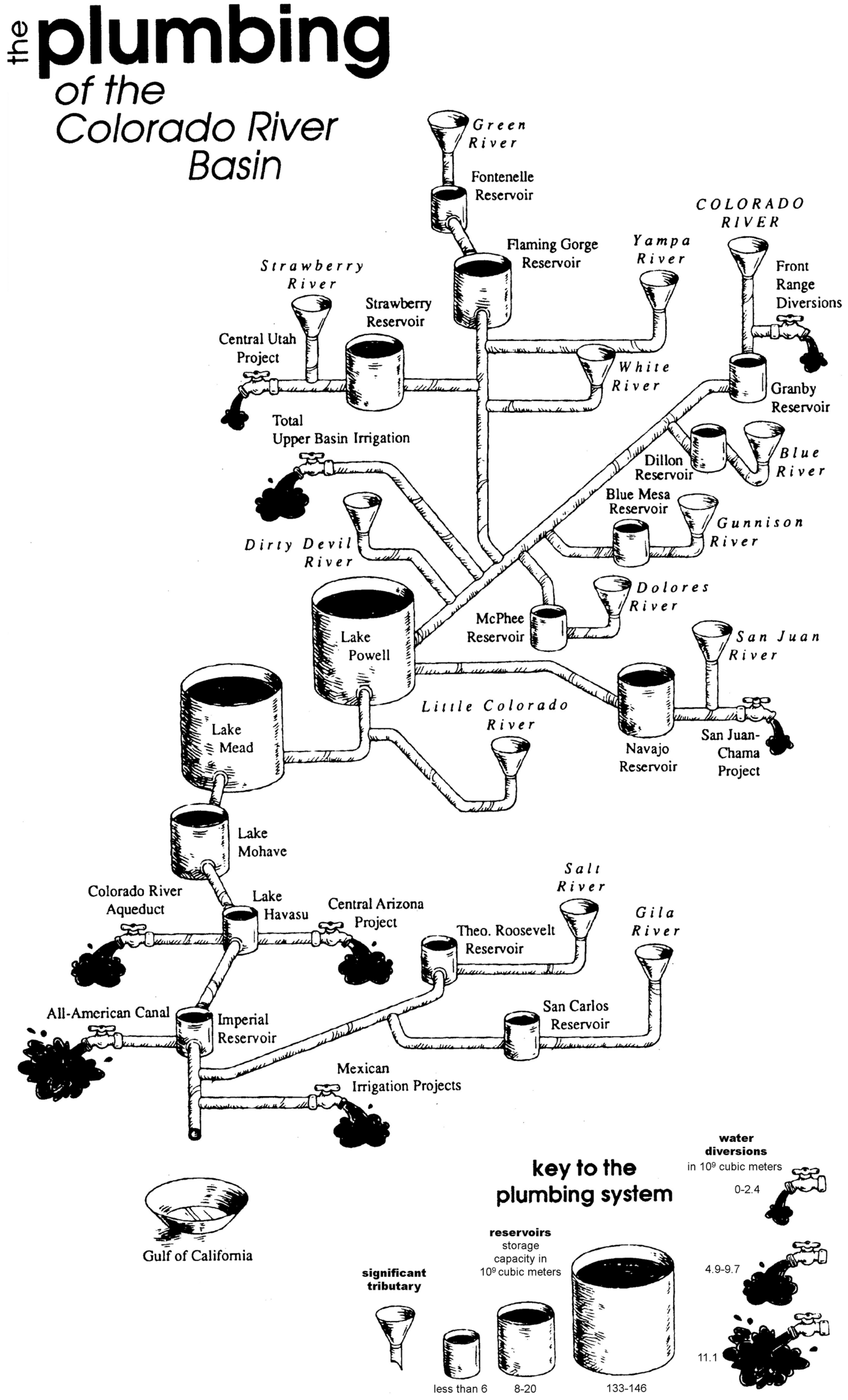


Figure 5. Distribution of reservoirs and diversions of the Colorado River system, depicted as a plumbing system. (Illustration by L. Dore and C. McKnight, reprinted with permission of High Country News.)

Table 2. Summary of changes in streamflow, sediment supply, and channel form in parts of the Colorado River system (data from Schmidt and Wilcock, 2008).

Segment number	River (Dam)	Location of upstream and downstream ends of reach, in kilometers downstream from dam	Attributes of streamflow and sediment supply				Attributes of the channel					Attributes of channel change	
			Pre-dam 2-year recurrence flood, in cubic meters per second	Post-dam 2-year recurrence flood, in cubic meters per second	Pre-dam mean annual sediment delivery, in million megagrams	Post-dam mean annual sediment delivery, in million megagrams	Pre-dam reach-average slope, in meters per meter	Post-dam reach average slope in meters per meter	Pre-dam bed material size, in meters	Post-dam bed material size, in meters	Mean flow depth at post-dam flood at nearest gage, in meters	Measured post-dam change in bed elevation, in meters	Ratio of post-dam width to pre-dam width
1	Colorado River (many dams)	0–37 [a]	725 (Cr1)	517 (Cr1)	1.6 (Cr2)	1.2 (Cr2)	NA	0.0020 (Cr3)	NA	0.058 (Cr3)	2.45	NA	0.92 (Cr2)
2	Colorado River (many dams)	67–90 [a]	725 (Cr1)	517 (Cr1)	1.6 (Cr2)	1.2 (Cr2)	NA	0.0018 (Cr3)	NA	0.058 (Cr3)	2.54	0.5 (Cr1)	0.79 (Cr4)
3	Gunnison River (Aspinall Unit)		490 (Cr1)	306 (Cr1)	1.5 (Cr4)	1.2 (Cr4)	NA	0.0012 (Cr4)	NA	0.046 (Cr4)	2.83	–0.6 (Cr1)	1.02 (Cr4)
4	Colorado River (many dams)	91–119 [a]	1,387	759	3.2	2.5 (Cr2)	NA	0.0013	NA	0.054 (Cr3)	3.01	NA	0.80 (Cr4)
5	Colorado River (many dams)	120–159 [a]	1,387	759	3.2	2.5 (Cr2)	NA	0.0010	NA	0.044 (Cr3)	3.64	0.4 (Cr1)	0.92 (Cr4)
6	Green River (Flaming Gorge)	0–18	339 (Cr5)	147 (Cr5)	0.46 (Cr6)	0.010 (Cr6)	NA	0.0021 (Cr6)	0.18 (Cr7)	0.18 (Cr7)	2.5	0 (Cr6)	0.95 (Cr6)
7	Green River (Flaming Gorge)	18–76	339 (Cr5)	147 (Cr5)	0.49 (Cr6)	0.030 (Cr6)	NA	0.00075 (Cr6)	NA	0.0010 (Cr7)	1.5	0 (Cr6)	0.81 (Cr6)
8	Green River (Flaming Gorge)	76–104	339 (Cr5)	147 (Cr5)	0.51 (Cr6)	0.052 (Cr6)	NA	0.0029 (Cr6)	0.18 (Cr7)	0.18 (Cr7)	2.0	0 (Cr5)	0.78 (Cr6)
9	Green River (Flaming Gorge)	105	626 (Cr5)	480 (Cr5)	1.6 (Cr6)	0.88 (Cr6)	NA	0.0010 (Cr5)	NA	0.025 (Cr7)	2.3	0 (Cr5)	0.90 (Cr5)
10	Green River (Flaming Gorge)	161–279	626 (Cr5)	480 (Cr5)	1.6 (Cr6)	0.88 (Cr6)	NA	0.00019 (Cr7)	NA	0.00035 (Cr8)	3.0	NA	0.96 (Cr8)
11	Duchesne River (many dams)	0–14 [b]	216 (Cr9)	102 (Cr9)	1.2 (Cr10)	0.37 (Cr10)	NA	0.0019 (Cr9)	NA	0.052 (Cr10)	1.2	0 (Cr9)	0.71 (Cr9)
12	Duchesne River (many dams)	18–27 [b]	216 (Cr9)	102 (Cr9)	1.2 (Cr10)	0.37 (Cr10)	NA	0.00023 (Cr9)	NA	0.0005 (Cr10)	1.5	0 (Cr9)	0.60 (Cr9)
13	Green River (Flaming Gorge)	465–490	740 (Cr11)	586 (Cr11)	15 (Cr12)	8.0	NA	0.00040	NA	0.032	4.0	0	0.85
14	Green River (Flaming Gorge)	475–509	740	586	15	8.0	NA	0.00020	NA	0.00050	4.0	NA	0.97
15	Colorado River (Glen Canyon)	0–25	2,400	860	57	0.24	0.00036	0.00027	0.00020	0.09	6.5	–4	NA
16	Colorado River (Glen Canyon)	25–120	2,400	860	61	3.5	0.0011	0.0011	0.26	0.26	5.4	0	NA
17	Colorado River (Glen Canyon)	170–180	2,288	820	83	13	0.0022	0.0022	0.26	0.26	6.5	0	NA
18	Colorado River (Hoover)	0–70	2,704	561	145	NA	0.00035	0.00036	0.00020	0.035	3.9	–3	NA
19	Colorado River (Hoover)	70–149	2,704	561	145	3.3	0.00035	0.00028	0.00020	0.00040	3.9	–3	NA
20	Colorado River (Hoover)	149–181	2,704	561	145	6.6	0.00035	0.00027	0.00020	0.00030	3.9	1	NA
21	Colorado River (Hoover)	181–193	2,704	561	145	4.1	0.00013	0.000063	0.00020	0.00030	3.9	0.7	NA
22	Colorado River (Parker)	0–45	2,248	421.9	145	NA	0.00026	0.000095	0.00020	0.0016	2.5	–4	NA
23	Colorado River (Parker)	45–95	2,248	421.9	145	1.3	0.00028	0.00026	0.00020	0.00070	2.5	–3	NA
24	Colorado River (Parker)	95–143	2,248	421.9	145	2.6	0.00029	0.00029	0.00020	0.0045	2.5	–1.5	NA
25	Colorado River (Parker)	143–204	2,248	421.9	145	3.3	0.00027	0.00020	0.00020	0.00045	2.5	0.8	NA

a	distance downstream from Rulison, CO
b	distance downstream from Randlett, UT
Cr1	VanSteeter and Pitlick (1998)
Cr2	Pitlick and Cress (2000)
Cr3	Pitlick and Cress (2002)
Cr4	Pitlick and others (1999)
Cr5	Grams and Schmidt (2002)
Cr6	Grams and Schmidt (2005)
Cr7	Schmidt (unpub. data)
Cr8	Lyons and others (1992)
Cr9	Gaeuman and others (2005)
Cr10	Gaeuman and others (2003)
Cr11	Allred and Schmidt (1999)
Cr12	Andrews (1986)
Cr13	Topping and others (2003)
Cr14	Grams and others (2007)
Cr15	Topping and others (2000)
Cr16	Schmidt and Graf (1990)
Cr17	Schmidt and others (2004)
Cr18	Borland and Miller (1960)
Cr19	Bureau of Reclamation (1950)
Cr20	Williams and Wolman (1984)

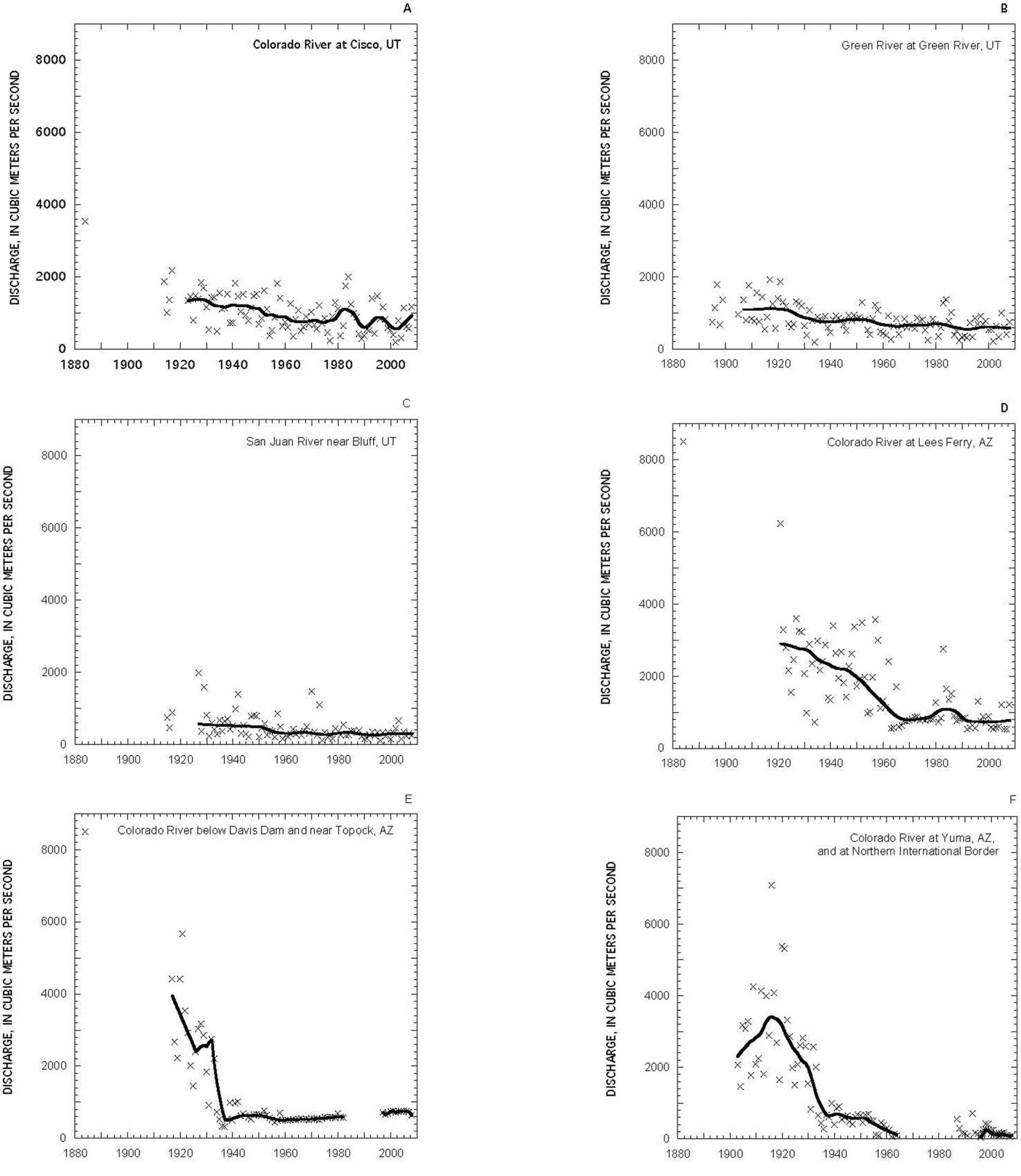


Figure 6. Annual maximum instantaneous discharge for selected streamgaging stations. The dark solid line is a running average calculated on the basis of the nearest 20 percent of the data series. Running average is calculated for the period of sequential years of record and does not include early period of occasional measurements. (A) Colorado River at Cisco, UT (gaging station 09180500). (B) Green River at Green River, UT (gaging station 09315000). (C) San Juan River near Bluff, UT (gaging station 09379500). (D) Colorado River at Lees Ferry, AZ (gaging station 09380000). (E) Combined record of Colorado River below Davis Dam (gaging station 09423000; 1997–2008) and near Topock, AZ (gaging station 09424000; 1884–1982). (F) Combined record of Colorado River at Yuma, AZ (gaging station 09521000; 1903–1964), Colorado River below Yuma Main Canal at Yuma (gaging station 09521100; 1996–2008), and Colorado River at the northern international border near Morelos Dam (gaging station 09522000; 1987–2005).

were. At Lees Ferry, AZ, streamflow is slightly higher in January and mid-summer when demand for hydroelectricity is greater than in other seasons (fig. 7D). Downstream from Hoover and Davis Dams, streamflow is greatest in spring and summer (fig. 7E). A base flow of about 30 m^3/s is released to Mexico, and no semblance of the pre-dam regime is evident (fig. 7F). This base flow is entirely diverted to the Mexicali Valley at Morelos Dam, a run-of-the-river diversion dam with no storage and a diversion capacity of 226 m^3/s. Streamflow in the 100 kilometers (km) downstream from Morelos Dam is intermittent, but some irrigation return flow and municipal effluent maintains perennial flow into the Gulf of California (Cohen and others, 2001). No flow passed Morelos Dam between the 1930s and the early 1970s. Today, in years of high basin runoff and full upstream reservoirs, releases from Hoover Dam sometimes exceed those needed for diversion and are in excess of Morelos' diversion capacity (fig. 4).

The cumulative effects of dams and transbasin diversions in the headwater tributary watersheds have decreased the magnitude of the annual snowmelt flood and increased the magnitude of base flows, but the duration of the annual snowmelt flood has not changed much. Because the large dams and major diversions in the headwater tributaries are located near the exterior rim of the basin, streamflow in the downstream parts of these same rivers reflects the cumulative effects of many reservoirs with different operating rules, different patterns of streamflow withdrawal, and inflow from unregulated tributaries. The cumulative effects of water storage and withdrawal are least on the Green River, as measured at Green River, UT, where typical floods have decreased from about 1,100 m^3/s before 1920 to about 600 m^3/s since 1990 (fig. 6B), and base flows are now typically about 100 m^3/s (fig. 7B). Similar changes in streamflow have been measured near Cisco, UT, on the upper Colorado River, where typical floods have decreased from about 1,400 m^3/s in the early 1920s to about 800 m^3/s today (fig. 6A). Base flows are now about 100 m^3/s (fig. 7A). Typical flood flows of the San Juan River near Bluff peaked at approximately 600 m^3/s in the early 1920s, but were highly variable from year to year (fig. 6C). Today's floods typically peak at about 300 m^3/s (fig. 6C), and base flows are about 30 m^3/s (fig. 7C).

The entire upstream sediment supply is now trapped in reservoirs, and none of the large dams release sediment. Essentially no sediment is delivered to the delta. Suspended sediment loads immediately downstream from each large dam are negligible. Annual sediment loads at Topock decreased from a pre-dam range between 50 x 10^6 and 400 x 10^6 Mg/yr to about 10 x 10^6 Mg/yr after completion of Hoover Dam (Williams and Wolman, 1984). Completion of Glen Canyon Dam caused a decrease of about 99.5 percent in the amount of fine sediment entering Grand Canyon (Topping and others, 2000). Downstream from Glen Canyon Dam, Schmidt (1999), Topping and others (2000), Hazel and others (2006), and Grams and others (2007) showed that there is mass balance deficit at least 170 km downstream from the dam and beyond the influence of the two largest sediment-contributing tributaries—the Paria and Little Colorado Rivers. Mass balance deficit is defined as the condition where less sediment is supplied to the reach than is the mass exported further downstream.

Unregulated tributaries that drain parts of the Colorado Plateau contribute significant amounts of sediment to the upper Colorado, Green, and San Juan Rivers. Sediment inflow from these desert watersheds significantly reduces the magnitude of post-dam sediment mass balance deficit and reduces the length of sediment deficit segments immediately downstream from the Aspinall Unit on the Gunnison River, Flaming Gorge Dam on the Green River, and Navajo Dam on the San Juan River (Schmidt and Wilcock, 2008). Annual sediment load of the upper Colorado River at Cisco, UT, decreased by about 20 percent. Grams and Schmidt (2005) computed a post-dam sediment budget for the 105 km nearest Flaming Gorge Dam and demonstrated that the uncertainties of sediment transport relations are too great to conclude that deficit conditions exist in most of this segment. Further downstream, the mean annual load at Jensen has only decreased by about 50 percent. Andrews (1986) and Allred and Schmidt (1999) showed that the Green River is accumulating sediment near Green River, UT, where the annual load has decreased by 35 to 50 percent.

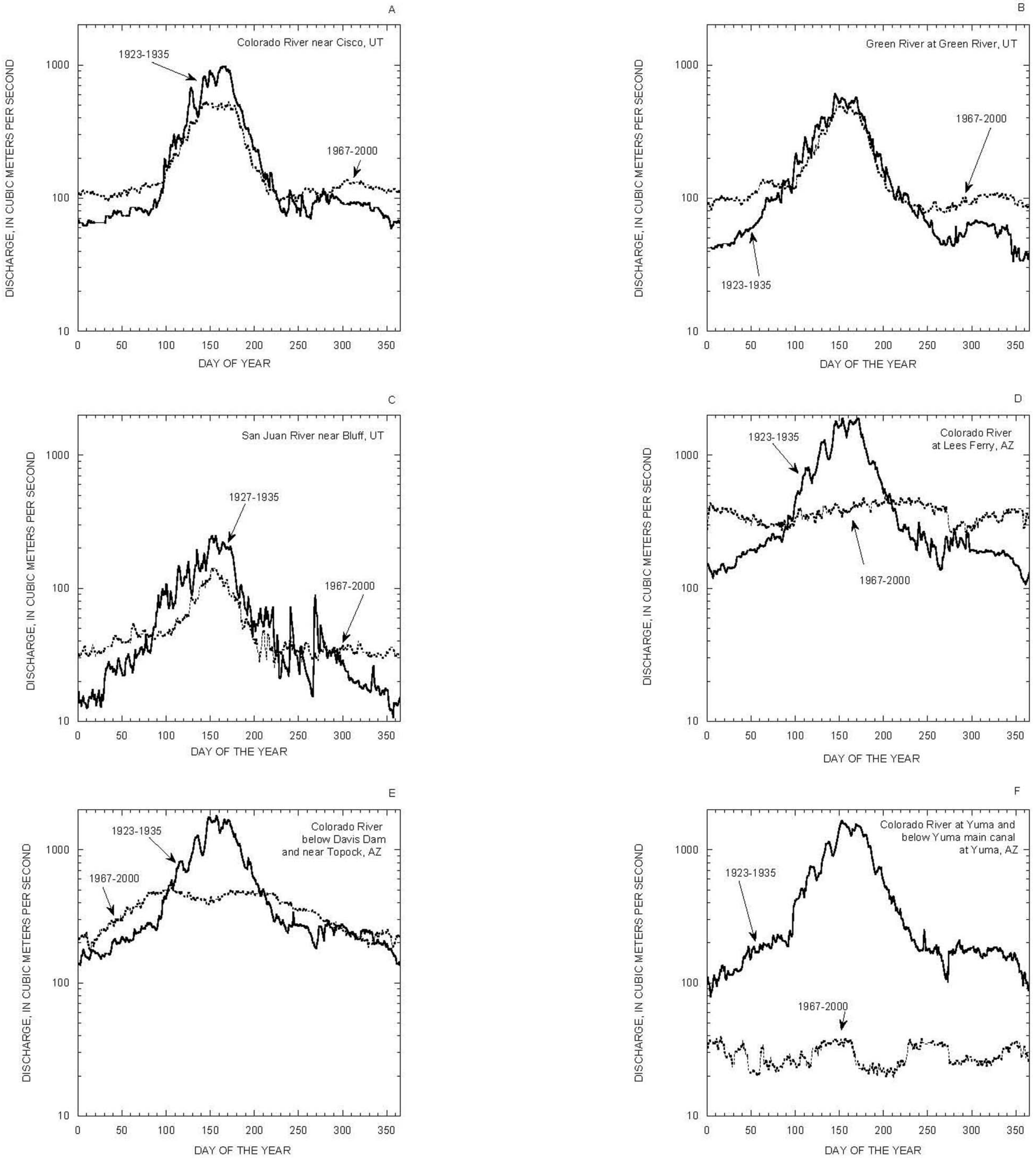


Figure 7. Median hydrographs of mean daily discharge at selected streamgaging stations in the Colorado River Basin for representative pre-dam and post-dam periods. (A) Colorado River at Cisco, UT (gaging station 09180500). (B) Green River at Green River, UT (gaging station 09315000). (C) San Juan River near Bluff, UT (gaging station 09379500). (D) Colorado River at Lees Ferry, AZ (gaging station 09380000). (E) Colorado River below Davis Dam (gaging station 09423000) and near Topock, AZ (gaging station 09424000). (F) Colorado River at Yuma, AZ, (gaging station 09521000) and Colorado River below Yuma Main Canal at Yuma (gaging station 09521100).

Channel Change

The Upper Colorado, Green, and San Juan Rivers

Most of the Green (Andrews, 1986; Lyons and others, 1992; Grams and Schmidt, 2002, 2005) and upper Colorado Rivers (VanSteeter and Pitlick, 1998) has narrowed and simplified (table 2). The Green River is between 10 and 25 percent narrower than it was at the beginning of the 20th century as measured in Browns Park (fig. 8; Grams and Schmidt, 2005), in the canyons of the eastern Uinta Mountains (Grams and Schmidt, 2002), in the Uinta Basin (Lyons and others, 1992), near Green River, UT (Allred and Schmidt, 1999), and further downstream (Graf, 1978). No evidence for bed incision is evident anywhere on the Green River, including immediately downstream from Flaming Gorge Dam (Grams and Schmidt, 2005). Narrowing has also occurred on the Duchesne River (Gaeuman and others, 2003, 2005; Schmidt and others, 2005) and on the upper Colorado River downstream from Rulison, CO (VanSteeter and Pitlick, 1998).

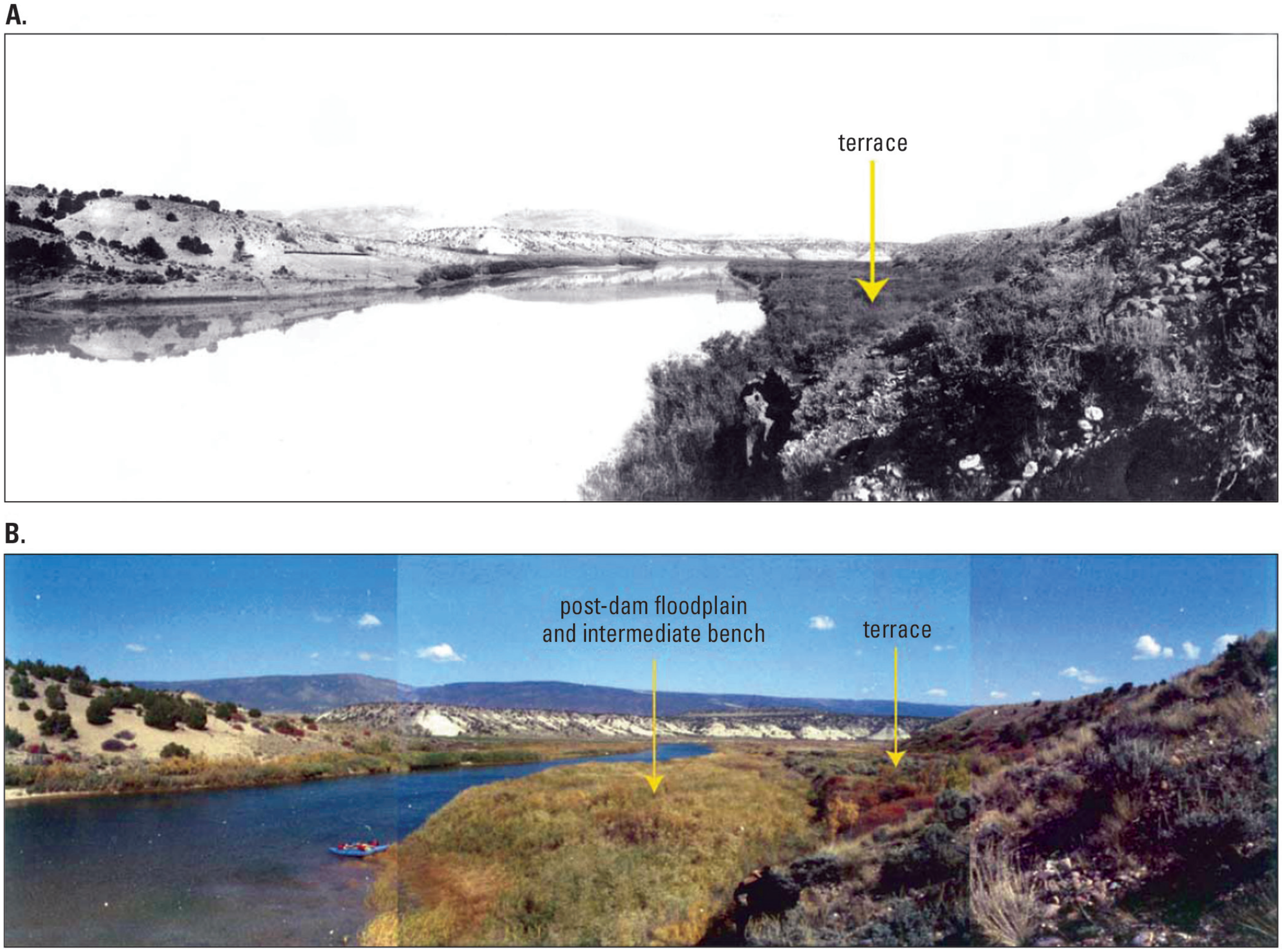


Figure 8. The Green River looking downstream from the location of the lower Bridgeport gage to the lower Bridgeport cableway. The original photograph (A) was taken October 13, 1911, by E.C. La Rue, and the repeat (B) was taken on October 7, 1999.

Glen and Grand Canyons

Large-scale bed incision downstream from Glen Canyon Dam has occurred in the 25 km between the dam and Lees Ferry that had a sand and gravel bed before dam construction. Here, pools were eroded about 6 meters (m) and riffles about 3 m (Grams and others, 2007). Water-surface elevation is now about 2.3 m lower near the dam, and the gradient has decreased about 25 percent (Grams and others, 2007). The present bed is established in what had been the underlying gravels. Today's channel is somewhat narrower and deeper than the pre-dam channel. Bed incision and reduction in flood magnitude caused abandonment of the former flood plain, and this surface is no longer inundated by typical post-dam floods (fig. 9).

Although most of the bed has been stripped of sand in Grand Canyon, there is no evidence of large-scale downward shifts in stage-to-discharge relations, because the bed profile in this debris fan-affected canyon is determined by the elevations of bouldery rapids that occur at the mouths of each steep, ephemeral tributary (Schmidt and others, 2004). Magirl and others (2005) showed that bed elevations of some bouldery rapids have increased since the 1920s. Nevertheless, fine sediment, transported in the mainstem as suspended load, has been removed from recirculation zones. The area of exposed sand in eddy bars was approximately 25 percent smaller in the 1990s than in the pre-dam era, and the thickness of sand irreversibly lost in some recirculation zones exceeds 2 m (Schmidt and others, 2004). Loss of sand from recirculation zones is because of wind deflation and fluvial erosion during post-dam base flows.

The Lower River

Completion of Hoover Dam initiated bed incision that ultimately extended approximately 150 km downstream (Stanley, 1951; Borland and Miller, 1960). Aggradation occurred in the 50 km farther downstream and extended into Lake Havasu reservoir (fig. 10). This longitudinal pattern of near-dam incision and aggradation farther downstream was repeated downstream from Parker Dam; completion of Davis Dam created a new phase of incision and shifted the aggradation reach farther downstream (Borland and Miller, 1960).

The Delta

The delta of the Colorado River once encompassed nearly 8,000 square kilometers (km^2) (Luecke and others, 1999) and was a place of tremendous biodiversity and abundance (Glenn and others, 2001). The distributary channels of the delta created a maze of shifting channels that changed course frequently. Today, the delta's extent is only about 600 km^2. The river is confined within levees for approximately 100 km downstream from Morelos Dam, and the area beyond the levees is mostly irrigated farm fields or cities. Vegetation is dominated by salt cedar (*Tamarix* spp.), but cohorts of native trees were established in the years of surplus runoff.

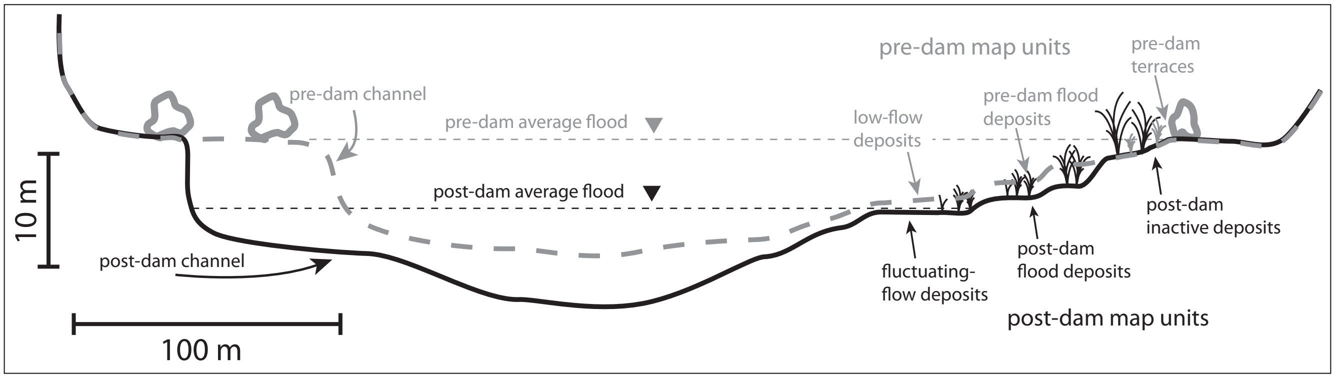
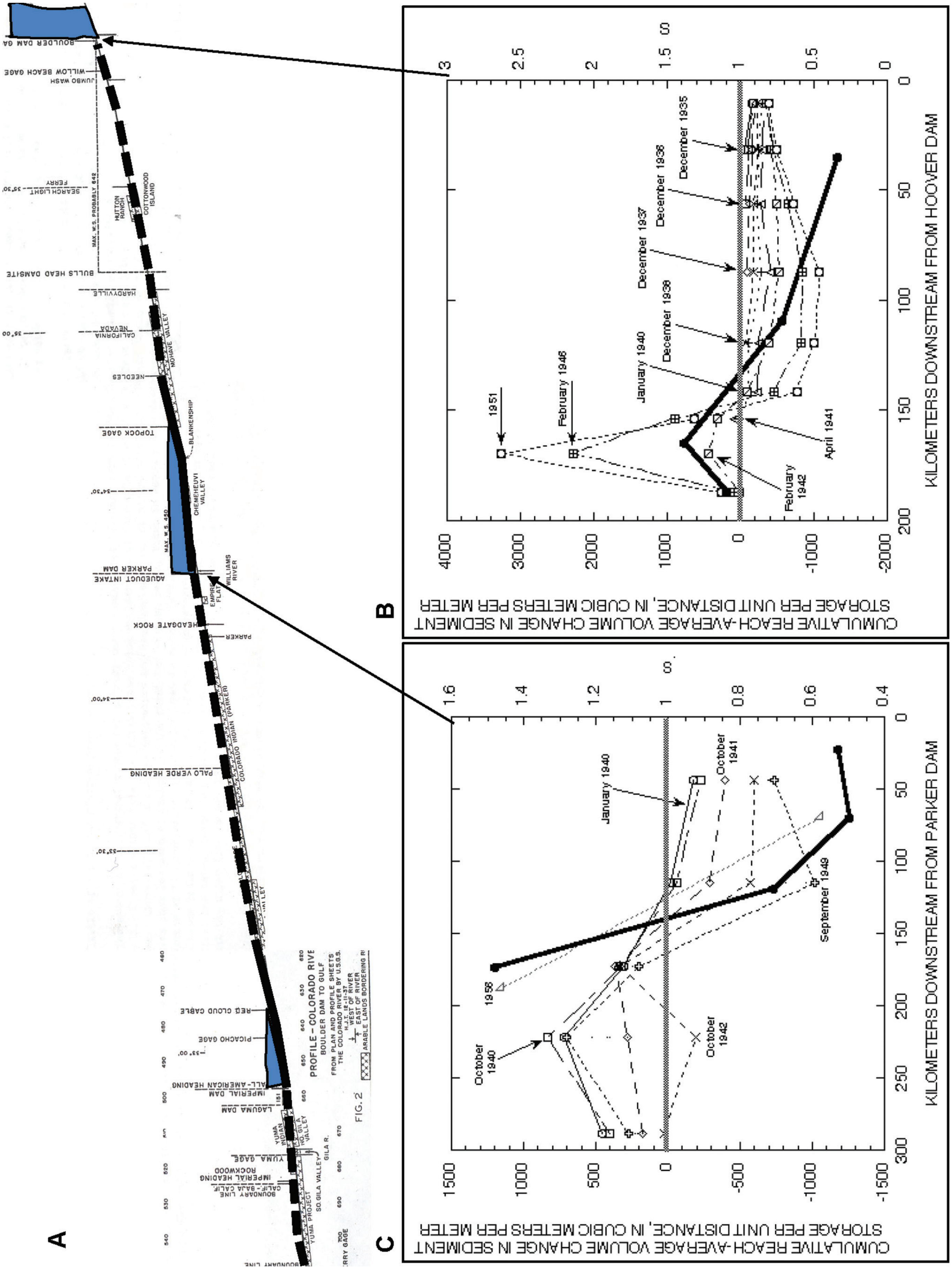


Figure 9. Cross-section changes in the Colorado River in Glen Canyon, downstream from Glen Canyon Dam. The approximate stages of the pre-dam average flood, 2,410 cubic meters per second (m^3/s), and the post-dam average flood, 890 m^3/s, are shown. The stage of the post-dam average flood now reaches elevations typical of the elevation of pre-dam, active channel bars. The combined effects of bed incision and lower typical floods have caused a transformation of the pre-dam riparian communities to upland vegetation communities. Figure adapted from Grams and others (2007).


A
B
C
PROFILE – COLORADO RIVER
BOULDER DAM TO GULF
FROM PLAN AND PROFILE SHEETS THE COLORADO RIVER BY U.S.G.S.
FIG. 2
ARABLE LANDS BORDERING RIVER
BOULDER DAM GA
WILLOW BEACH GAGE
JUMBO WASH
SEARCH LIGHT FERRY
COTTONWOOD ISLAND
HUTTON RANCH
BULLS HEAD DAMSITE
HARDYVILLE
CALIFORNIA NEVADA
MOHAVE VALLEY
NEEDLES
BLANKENSHIP
TOPOCK GAGE
CHEMEHUEVI VALLEY
PARKER DAM
AQUEDUCT INTAKE
WILLIAMS RIVER
EMPIRE FLAT
HEADGATE ROCK
PARKER
COLORADO INDIAN (PARKER)
PALO VERDE HEADING
RED CLOUD CABLE
PICACHO GAGE
ALL-AMERICAN HEADING
IMPERIAL DAM
LAGUNA DAM
YUMA INDIAN
NO. GILA VALLEY
GILA R.
YUMA GAGE
ROCKWOOD
IMPERIAL HEADING
CALIF.-BAJA CALIF. BOUNDARY LINE
SO. GILA VALLEY
YUMA PROJECT
BOUNDARY LINE
CUMULATIVE REACH-AVERAGE VOLUME CHANGE IN SEDIMENT STORAGE PER UNIT DISTANCE, IN CUBIC METERS PER METER
KILOMETERS DOWNSTREAM FROM HOOVER DAM
4000
3000
2000
1000
0
-1000
-2000
200
150
100
50
0
3
2.5
2
1.5
1
0.5
0
S
1951
February 1946
January 1940
December 1938
December 1937
December 1936
December 1935
April 1941
February 1942
KILOMETERS DOWNSTREAM FROM PARKER DAM
1500
1000
500
0
-500
-1000
-1500
300
250
200
150
100
50
0
1.6
1.4
1.2
1
0.8
0.6
0.4
January 1940
October 1941
1958
October 1940
October 1942
September 1949

Regional Comparison of the Magnitude of Perturbation of Sediment Mass Balance

Approach

Alterations of the flow regime and reduction in the sediment supply of many segments have caused imbalances between the sediment transport capacity and sediment supply, thereby causing some channels to evacuate sediment and others to accumulate sediment. The processes of sediment evacuation and accumulation in turn cause changes in aquatic and riparian ecosystems. Although sediment evacuation can manifest itself by a wide variety of changes in channel form, such as bed coarsening and pool scour, large-scale bed incision presents a particularly difficult challenge to river rehabilitation, because the frequency of flood-plain inundation is fundamentally changed (fig. 9). Another fundamental attribute of channel change that has significant impact on river rehabilitation strategies are changes in channel area and width. These changes typically scale with changes in the flood regime (Leopold and Maddock, 1953), and generally it is expected that channels get narrower if the magnitude of floods decreases. Andrews (1986) used this insight to anticipate channel narrowing on the Green River downstream from Flaming Gorge Dam. These three perturbations of geomorphic process or form—changes in sediment mass balance, large-scale changes in bed elevation, and changes in channel width—are the primary geomorphic causes of changes in aquatic and riparian habitat.

Changes in habitat are only one cause of species decline of the mainstem native fishery, and other factors include changes in streamflow temperature, fragmentation of the river network where dams block fish migration, and competition and predation from nonnative species. Nevertheless, it is instructive to evaluate the magnitude of changes in streamflow and sediment supply that drive habitat change, because changes in streamflow and sediment supply are available tools in large river rehabilitation.

Schmidt and Wilcock (2008) suggested an approach by which the relative magnitude of changes in streamflow and sediment supply in causing sediment deficit or surplus could be quantitatively compared. We summarize their work here as it pertains to the Colorado River system. Prediction of the post-dam mass balance is inspired by the widely cited proportionality of Lane (1955)

$$QsD \propto QS \qquad (1)$$

where Qs is the rate of sediment supply and D is its grain size, Q is water discharge, and S is channel slope. Henderson (1966) developed a simple approximation of this proportionality by combining equations for momentum, continuity, flow resistance, and transport rate, leading to

$$S^* = \frac{(Qs^*)^{0.5}(D^*)^{0.75}}{Q^*} \qquad (2)$$

where

$$S^* = \frac{S_{post}}{S_{pre}} \quad Qs^* = \frac{Qs_{post}}{Qs_{pre}} \quad Q^* = \frac{Q_{post}}{Q_{pre}} \quad D^* = \frac{D_{post}}{D_{pre}} \qquad (3)$$

and where the subscripts $_{pre}$ and $_{post}$ indicate conditions before and after the dam. Schmidt and Wilcock (2008) used the 2-year recurrence flood as the index value of Q, and Qs was taken as the annual sediment load.

Values of S^* indicate the potential for sediment evacuation or accumulation in response to changes in flow and sediment supply. Values of $S^* > 1$ indicate that an increase in slope is needed to transport the post-dam sediment supply with the specified flow. Thus, post-dam sediment supply is too great for the post-dam streamflow regime and pre-dam slope; sediment accumulation, therefore, is predicted. Values of $S^* < 1$ indicate that the pre-dam slope is larger than needed to transport the post-dam sediment supply with the post-dam streamflow regime, and sediment evacuation is predicted to

Figure 10. (facing page) (A) Cumulative degradation or aggradation between completion of (B) Hoover Dam in 1934 and (C) Parker Dam in 1937 and indicated time, as well as S* for the same reaches. Field data are shown in thin lines for different time periods computed from Bureau of Reclamation (1950), Stanley (1951), and Borland and Miller (1960), and the thick line is S*.

occur until such point that the initial slope is reduced. Values of S^* do not predict the time domain over which adjustment to post-dam conditions occurs, but values of S^* do predict the nature of the initial perturbation to the downstream geomorphic system caused by each dam. Thus, where bed incision does not occur because the bed material is very large, a regulated river perpetually remains in sediment deficit. In cases where bed incision occurs, however, the post-dam slope might decrease sufficiently to reduce the magnitude of the post-dam sediment deficit.

This approach, however, only provides a reconnaissance level tool with which to compare the relative magnitude of sediment deficit or surplus in a watershed. The derivation of equation 2 depends on a simplified sediment transport relation applicable to sand and fine-gravel bed streams, the assumption of a simplified channel cross section, and assumptions about the relation between the size of the sediment supply and the bed material (Schmidt and Wilcock, 2008). Nevertheless, Schmidt and Wilcock (2008) showed that there is good agreement between the locations of degradation or aggradation measured in the field and the calculated values of S^*, such as on the lower Colorado River (fig. 10). There is also good agreement between S^* and predicted deficit conditions within 100 km downstream from Glen Canyon Dam (Topping and others, 2000; Schmidt and others, 2004; Hazel and others, 2006) and for the Green River downstream from Flaming Gorge Dam (Grams and Schmidt, 2005).

Schmidt and Wilcock (2008) suggested that the potential for large-scale bed incision can be described by a Shields number, τ^*

$$\tau^* \propto \frac{h_{post} S_{pre}}{D_B} \qquad (4)$$

where h_{post} is the mean depth of post-dam floods, S_{pre} is the slope of the channel at the time of dam completion, and D_B is a characteristic bed grain size at the time of dam completion. Schmidt and Wilcock (2008) found that significant incision occurs where $\tau^* > 0.1$ and where $S^* < 1$. Insignificant incision has occurred where $\tau^* < 0.1$. The magnitude of bed incision for large values of τ^* is highly variable, because of differences in substrate, time since dam completion, and magnitude of dam releases (Williams and Wolman, 1984). Schmidt and Wilcock (2008) found no consistent trend between channel narrowing and Q^*, although extreme narrowing to less than 60 percent of the pre-dam width has been observed where $Q^* < 0.4$.

Findings

Schmidt and Wilcock (2008) summarized changes in streamflow, sediment supply, and channel form of several large rivers of the Western United States, and they calculated Q^*, Qs^*, D^*, S^*, and τ^* for 25 segments of the Colorado River drainage network (table 3). In all cases, S^* increases in the downstream direction (fig. 11). In four cases (Green River downstream from Flaming Gorge Dam, and Colorado River downstream from Glen Canyon, Hoover, and Parker Dams) where S^* was calculated near and far from the dam, the degree of sediment deficit diminishes greatly and $S^* > 1$ in some cases. No data were available with which to calculate S^* immediately downstream from dams of the upper Colorado River, and the upper Colorado River downstream from Rulison, CO, is predicted to be in sediment surplus.

Comparison of S^*, τ^*, and Q^* demonstrates that the dams and diversions of the Colorado River Basin have caused very different types and magnitudes of perturbations in different parts of the watershed (fig. 12). There are many segments where dams perturbed the sediment mass balance into deficit, but large-scale bed incision has only occurred on a subset of these segments. For example, segments 15 (S15; Glen Canyon) and 16 (S16; Marble Canyon) are in sediment deficit but only S15 has incised its bed. Sediment deficit ($S^* < 1$) exists on some segments where Q^* is small and where τ^* is relatively large, indicating that channel narrowing has occurred under conditions of sediment deficit and bed incision. Elsewhere, Q^* is small where $S^* > 1$. Thus, channel narrowing has occurred under conditions of sediment deficit and sediment surplus.

Table 3. Changes in streamflow, sediment supply, post-dam sediment mass balance, and bed incision potential for selected reaches.

Segment number	River (Dam)	Location of upstream and downstream ends of reach, in kilometers downstream from dam	Ratio of post-dam to pre-dam flood (Q*)	Ratio of post-dam to pre-dam sediment delivery (Qs*)	Ratio of post-dam to pre-dam grain size of sediment supply (D*)	Post-dam sediment mass balance (S*)	Deficit (D), Surplus (S), Indeterminate (I)	Bed incision potential (τ*)
1	Colorado River (many dams)	0–37 [a]	0.71	0.75	1	1.21	I	0.05
2	Colorado River (many dams)	67–90 [a]	0.71	0.75	1	1.21	I	0.05
3	Gunnison River (Aspinal Unit)		0.62	0.81	1	1.44	S	0.04
4	Colorado River (many dams)	91–119 [a]	0.55	0.77	1	1.61	S	0.04
5	Colorado River (many dams)	120–159 [a]	0.55	0.77	1	1.61	S	0.05
6	Green River (Flaming Gorge)	0–18	0.43	0.02	1.1	0.36	D	0.02
7	Green River (Flaming Gorge)	18–76	0.43	0.06	0.85	0.51	D	0.68
8	Green River (Flaming Gorge)	76–104	0.43	0.10	0.82	0.63	I	0.02
9	Green River (Flaming Gorge)	105	0.77	0.56	1.0	0.97	I	0.06
10	Green River (Flaming Gorge)	161–279	0.77	0.56	1.0	0.97	I	0.99
11	Duchesne River (many dams)	0–14 [b]	0.47	0.32	1	1.19	S	0.03
12	Duchesne River (many dams)	18–27 [b]	0.47	0.32	1	1.19	S	0.42
13	Green River (Flaming Gorge)	465–490	0.79	0.52	1	0.91	I	0.03
14	Green River (Flaming Gorge)	475–509	0.79	0.52	1	0.91	I	0.97
15	Colorado River (Glen Canyon)	0–25	0.36	0.00	1	0.18	D	6.99
16	Colorado River (Glen Canyon)	25–120	0.36	0.06	1	0.67	D	0.01
17	Colorado River (Glen Canyon)	170–180	0.36	0.15	1	1.08	I	0.03
18	Colorado River (Hoover)	0–70	0.21	0.01	1	0.34	D	4.18
19	Colorado River (Hoover)	70–149	0.21	0.02	1	0.72	D	4.16
20	Colorado River (Hoover)	149–181	0.21	0.05	1.5	1.39	I	4.17
21	Colorado River (Hoover)	181–193	0.21	0.03	1.5	1.10	I	1.49
22	Colorado River (Parker)	0–45	0.19	0.01	1	0.53	D	1.98
23	Colorado River (Parker)	45–95	0.19	0.01	1	0.50	D	2.11
24	Colorado River (Parker)	95–143	0.19	0.02	1	0.71	D	2.23
25	Colorado River (Parker)	143–204	0.19	0.02	2.3	1.48	I	2.02

[a] Distance downstream from Rulison, CO.

[b] Distance downstream from Randlett, UT.

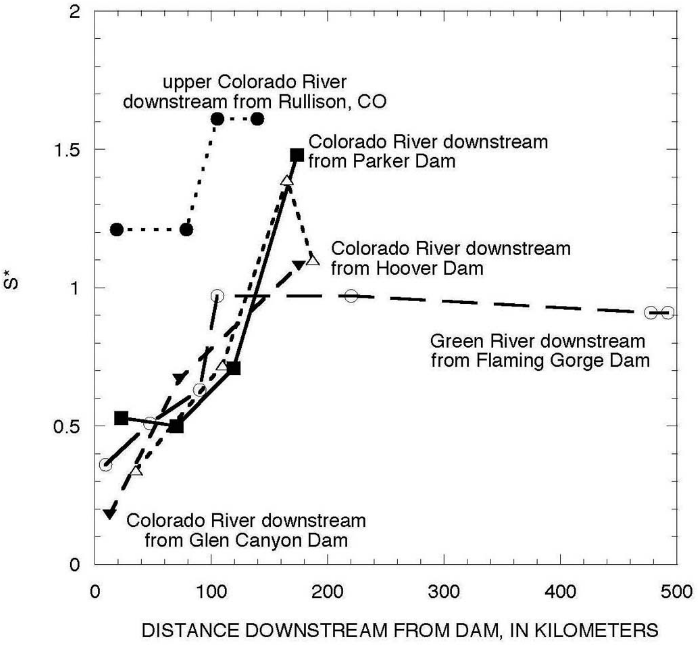


Figure 11. Downstream change in post-dam sediment mass balance (S*). Symbols and lines represent upper Colorado River downstream from Rulison, CO (solid circles and dashed line), Green River downstream from Flaming Gorge Dam (open circles and dashed line), Colorado River downstream from Glen Canyon Dam (solid, downward triangles and dashed line), Colorado River downstream from Hoover Dam (open, upward triangles and dashed line), and Parker Dam (solid square and solid line).

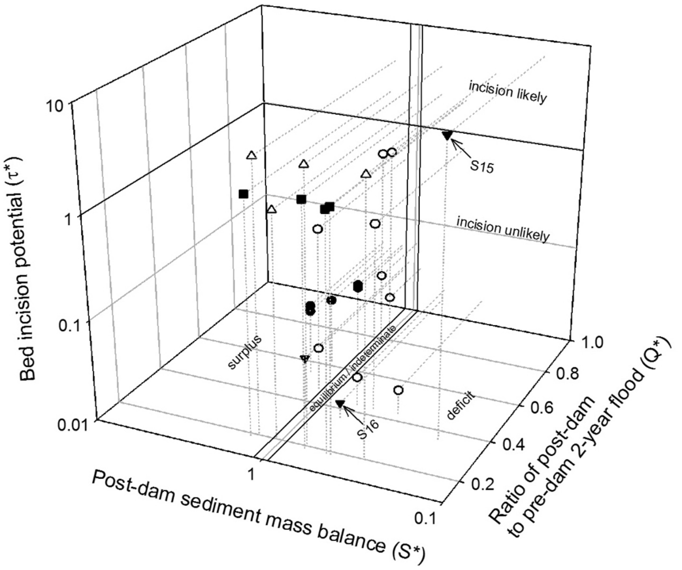


Figure 12. Post-dam sediment mass balance (S*), likelihood of bed incision (τ*), and change in flood regime (Q*) for different segments of the Colorado River system. Dams and diversions have caused a wide array of geomorphic perturbations in the drainage network and pose a range of challenges in river rehabilitation. In some cases, river segments are in severe sediment deficit, but may or may not be subject to large-scale bed incision illustrated by the difference in plotting position of S15 (Glen Canyon) and S16 (Marble Canyon).

Watershed-Scale Appraisal of the Rehabilitation Challenge

The differences in type and magnitude of perturbation illustrated in figure 12 primarily are because some dams are located in the Rocky Mountains and control streamflow but little sediment supply, but other dams are located within the Colorado Plateau and Basin and Range Provinces and control streamflow and sediment supply. Additionally, reservoirs are of different sizes and have different capacities to store flood flows; the sediment trapping efficiency of the large dams in the watershed is nearly 100 percent.

Because the network's channels have been perturbed differently, there is no one prescription concerning how to rehabilitate the entire Colorado River system, nor is it possible to generalize about how difficult rehabilitation is as a general task. Although most river segments have too little sediment for the available streamflow, other segments have too much, and the post-dam sediment mass balance defined in equation 2 provides a reconnaissance basis for assessing the effort of remediating sediment deficit or surplus. Some river segments have incised their beds, and reconnection of channels with flood plains is a significant rehabilitation challenge; elsewhere incision has not occurred. Some river segments have narrowed greatly, and elsewhere this has not occurred.

There is great diversity in river rehabilitation strategies that might be taken, even if only one of the perturbations described above is considered—post-dam sediment mass balance. Figure 13 shows that there is an infinite combination of possibilities by which sediment supply and flood regime could be changed to achieve post-dam sediment mass balance. The two end member approaches are to change only the flow regime or the sediment supply regime. These end member strategies differ in whether they also increase Q^* and thereby shift rivers back toward their early 20th century condition or further decrease Q^* and thereby shift channels toward a miniaturized condition. For example, sediment deficit conditions could be reversed by only increasing the supply of sediment, by only reducing the magnitude of floods released from the dam, or by some combination of both. The strategy of only increasing sediment supply to a river in deficit also shifts the river toward its pre-disturbance, or wild, condition. The strategy that only decreases flood flows to a river in deficit shifts the river toward miniaturized conditions and away from the natural disturbance regime of the river. Because native riverine ecosystems depend on a range of attributes of the natural flow regime (Poff and others, 1997), shifting a river into post-dam sediment balance while also shifting the flow regime toward its pre-disturbance flow and sediment supply regime is more desirable if rehabilitation of native ecosystems is the primary management goal. This is the case with all of the river rehabilitation programs listed in table 1.

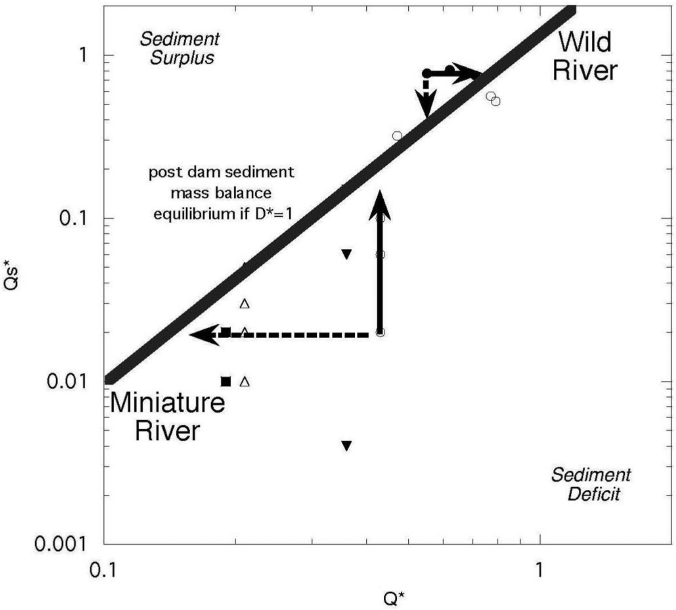


Figure 13. Stability field diagram of changes in flood flow and sediment supply that create sediment deficit or surplus. Each marker indicates a segment of the Colorado River system, and the symbols are the same as those in figures 11 and 12. Arrows indicate possible management actions for two representative segments, one in sediment deficit and one in sediment surplus. Solid arrows indicate change in sediment supply or flood regime that achieves post-dam sediment mass balance and the trajectory of which shifts the river toward pre-disturbance conditions. Dashed arrows indicate change in sediment supply or flood regime and the trajectory of which shifts the river toward further miniaturization.

Schmidt and Wilcock (2008) assessed the relative magnitude of potential rehabilitation actions that would achieve post-dam sediment mass balance and avoid further channel miniaturization by estimating the proportional increase in sediment supply or flood flows necessary to return some of the Colorado River segments to post-dam sediment equilibrium along paths indicated by solid lines as shown in figure 12 (table 4). Estimates were made by adjusting the value of Q^* or Qs^* in equation 2 such that $S^* = 1$.

These results are very imprecise but nevertheless demonstrate that there is a wide range of prescriptions for the Colorado River system if the objective were established to rehabilitate every segment into post-dam sediment mass balance. Some segments require additions of sediment while other segments require an increased flood regime. Many deficit segments require large proportional increases in sediment supply. In most cases, significant infrastructure changes would be necessary to implement these options. For example, application of equation 2 to the Colorado River in Grand Canyon indicates that augmenting the post-dam annual fine sediment supply with an additional 7.9 x 10^6 Mg/yr is necessary to eliminate deficit conditions, assuming that the post-dam flood regime is not changed. This amount of augmented sediment would only increase Qs^* to 0.13 and in no way can be considered restoration to pre-dam conditions. The required change in Qs^* is small, because the magnitude of post-dam floods has been reduced by approximately 60 percent. This amount of augmented sediment is nevertheless large in terms of engineering design. Randle and others (2007) estimated that augmentation of 4.3 x 10^6 Mg/yr to the Colorado River in Grand Canyon would cost between $220 and $430 x 10^6 in

Table 4. Proportional changes in sediment supply or magnitude of 2-year flood to achieve post-dam equilibrium sediment mass balance.

[km, kilometers]

	Ratio of post-dam to pre-dam sediment supply necessary for equilibrium mass balance conditions, assuming no change in flood regime	Proportional increase in post-dam sediment supply needed to achieve equilibrium mass balance	Ratio of post-dam to pre-dam flood conditions necessary for equilibrium mass balance conditions	Proportional change in post-dam flood flows needed to achieve equilibrium mass balance
Colorado River, 91–119 km downstream from Rulison, CO (reach 4)	0.3	–0.6	0.9	–0.4
Green River, 18–76 km downstream from Flaming Gorge Dam (reach 7)	0.24	2.9	0.2	–0.6
Colorado River, 25–120 km downstream from Glen Canyon Dam (reach 16)	0.13	1.2	0.24	–0.7
Colorado River, 70–149 km downstream from Hoover Dam (reach 19)	0.04	0.9	0.2	–0.6
Colorado River, 45–95 km downstream from Parker Dam (reach 23)	0.04	2.9	0.1	0.6

project capital costs and between \$6.6 and \$17 x 10^6 per year in annual operating costs. In comparison, the 7-day release of a controlled flood from Glen Canyon Dam in 1996 had an economic cost of \$2.5 x 10^6, which was 3.3 percent of the economic value of the hydroelectric power produced in that year (Harpman, 1999).

The Challenge of Rehabilitating the Entire River Network

Each part of the modern Colorado River system can be viewed as existing on a theoretical continuum between that segment's wild, pre-settlement channel form and fluvial processes and another condition where the channel, its streamflow, and its sediment supply are completely altered and transformed (fig. 14). Perhaps the only parts of the Colorado River watershed that are minimally impacted by humans are the small, headwater streams of federally designated wilderness and roadless areas of the Rocky Mountains and some ephemeral drainages of the Colorado Plateau. Parts of the lower Colorado River in the delta, especially downstream from Morelos Dam, may reflect the latter condition of complete alteration. The rest of the drainage network is somewhere between these end member conditions.

Although informed by river science, the decision of how far to attempt to shift present river conditions toward former wild conditions is a matter of public policy. In fact, it is a matter of public policy if such an effort should be attempted at all. A national political consensus does not exist to fully restore the Colorado River system, because such an effort would require decommissioning the large dams and diversions of the watershed and eliminating most hydropower production. Such an effort would change water and power supplies to urban centers in southern California, central and southern Arizona, southern Nevada, central New Mexico, the Colorado Front Range, Utah's Wasatch Front, and to agricultural centers such as the Imperial Valley.

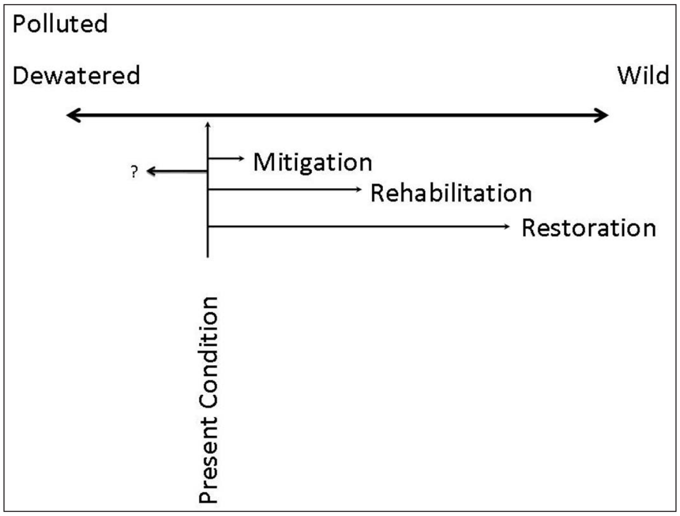


Figure 14. Each river segment in a basin exists on a continuum between its pre-disturbance wild condition and some fully transformed and degraded condition. The choice of how much to return a riverine ecosystem to its former wild condition is a matter of public policy.

Rehabilitation is a goal that improves some attributes of the native ecosystem but does not seek to fully return all aspects of channel form, flow regime, and sediment supply to pre-European conditions. This goal requires specification of which native ecosystem attributes are to be recovered and which attributes of the modern riverscape (e.g., dams, diversions) are not to be changed. A lesser goal for environmental management is mitigation, wherein specific attributes of the riverine ecosystem are targeted for improvement, but a transformed riverine ecosystem is accepted.

The adaptive management and endangered fish recovery programs upstream from Lake Mead (table 1) are rehabilitation programs, because program goals seek to recover fish populations while also assuring delivery of water supplies and hydroelectricity. Mitigation, such as is being pursued as part of the LCR MSCP, is achieved by adjusting streamflow and sediment supply as well as constructing new features of the riverine ecosystem, such as artificial wetlands. Such wetlands were constructed along the Green River in the Browns Park and Ouray National Wildlife Refuges as mitigation for lost wetlands inundated by Flaming Gorge Reservoir in the mid-1960s.

The analysis of perturbations to sediment mass balance and of the effort required to reestablish post-dam sediment mass balance demonstrates that achieving sediment mass balance equilibrium is a daunting, if not impossible, task at a watershed scale. Yet achieving sediment mass balance alone does not address issues related to reversing bed incision, reestablishing flood-plain connection, and channel narrowing. In light of the cumulative costs of rehabilitation and the impact of changing dam operations on water delivery and power supply, it is appropriate to ask, "What environmental management goals should be established for each part of the watershed?" and "Should decisions about goals be made at a segment scale by local stakeholders or at a watershed scale by national and regional interests?"

Many public policy answers to these questions are available. One answer could be to adopt the same management goal for every segment of the river network. Alternatively, each segment might have a different goal that is established by the local stakeholders. Another approach might have a different goal established for each segment based on the principle that each perturbed segment ought to be rehabilitated (1) to the same proportional extent or (2) such that the same proportional effort is expended in each segment in terms of dam reoperations or sediment augmentation. The level of effort in each rehabilitation program also might be established by the political process and reflect other priorities, such as landscape preservation, or solely focus on species populations.

Kondolf and others (2008) have asked similar questions concerning the watershed-scale approach to restoring streams of the Sacramento–San Joaquin River system in California.

Presently, there is no regional process by which the goals of each river rehabilitation program are compared, nor is there consideration of the tradeoffs between rehabilitation effort and magnitude of actual recovery. The analysis presented here indicates that the Grand Canyon segment and the lower river have been perturbed more than the tributaries of the upper basin. More money is now being spent to rehabilitate these river segments downstream from Lees Ferry (table 1), yet the task of rehabilitating the upper basin segments to sediment mass balance equilibrium is probably more tractable and less expensive.

Describing the relation between effort and recovery is one of the greatest challenges of river restoration science, and defining this relation is very difficult. However, defining even an approximation of this relation would further inform the decision of what environmental management goals to establish in each river segment. Two categories of relations can be conceived: one where there is a large degree of environmental improvement for relatively small degrees of initial investment and one where a relatively large degree of investment is required to achieve a significant degree of environmental response (fig. 15). The former category might be considered a politically “easy” path of public policy, because small financial and political compromises are needed to achieve significant environmental improvement. The latter category might be considered a politically “hard” path, because large costs are incurred for relatively small gains. It is probable that most river segments will never be fully restored; thus, those restoration programs that focus on politically “easy” problems might achieve a greater degree of ecosystem recovery.

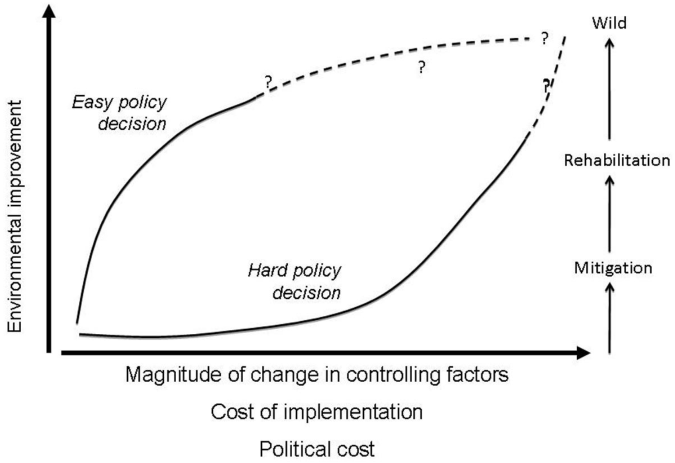


Figure 15. Conceptual graph of hypothetical relations between investment toward river rehabilitation and environmental improvement. Relations where small investments yield large returns are termed “easy” political decisions to adopt in the basin. Large investments with little return are considered “hard” political decisions.

The analysis described here has significant limitations, especially in focusing primarily on sediment mass balance as a metric to reflect a much larger range of ecosystem attributes that would have to be considered if native ecosystem restoration were to be achieved. On the other hand, native ecosystem attributes and processes track well with sediment mass balance in the Colorado River system, where the riverine ecosystems upstream from Lees Ferry generally are less perturbed than those further downstream. The need for a watershed-scale assessment identifying where the greatest return on investment can be gained has also been advocated for the Columbia River system, where Budy and Schaller (2007) showed that restoration of small headwater streams accomplishes much less for recovery of salmon populations than does removal of large dams on the lower Snake River.

Thus, the policy choices affecting the Colorado River watershed are fundamental:

> *Where should the most effort toward river rehabilitation be undertaken?*
>
> *Are there parts of the river network where a miniaturized river should be accepted?*
>
> *Are there parts of the river where even rehabilitation of parts of the native ecosystem ought to be abandoned?*

The effort undertaken to date to reverse undesirable conditions of the Colorado River system has been significant, yet the return on investment has been limited in some places. Some parts of the river network are the focus of sophisticated and comprehensive scientific river science, monitoring, and adaptive management, but other parts of the river network receive far less scientific attention. The existence of an international treaty, two interstate compacts, an integrated reservoir management program, and an integrated electricity distribution system suggests that the various river rehabilitation programs also be considered within a watershed context. Some of this work might be accomplished by a basinwide riverine science organization whose focus is the hydrologic, sediment supply, geomorphic, and ecological processes and restoration potential of the entire watershed, rather than the politically defined boundaries of each stakeholder-defined adaptive management program.

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Water Management for River Conservation: Lessons From Outside of the Colorado River Basin for Moving From Sites to Systems

By Christopher P. Konrad[1]

Abstract

Water management at individual dam sites is an important part of river conservation, but its impacts are limited without systemwide coordination of water management and broad integration of resource management across a river basin. Four concepts for basin-scale conservation are illustrated: the benefits of monitoring over large spatial scales even if conservation actions are site specific, coordination of operations of dams in a river system, integration of different types of river management actions, and the potential for conserving biological diversity in parts of the river system. Coordination of operating policies at multiple dams requires flexibility in achieving conservation and other objectives (power generation, flood control, water supply, and recreation) across a river system rather than requiring standardization at all sites. Dam reoperation for conservation is only effective when it is integrated with management of sediment, flood-plain land use, water quality, and invasive species. Basin-scale approaches offer conservation benefits well beyond site-based management in many rivers, but these approaches are complex and require specific enabling conditions. The potential benefits from a basin-scale approach to water management must be assessed relative to constraints and available resources for more coordinated and integrated management activities across the Colorado River Basin.

Introduction

Efforts to conserve freshwater ecosystems and their native species face many challenges in the Colorado River Basin. Management of water resources is central among these challenges because of the essential role of streamflow and groundwater in freshwater ecosystems. A priority for freshwater conservation efforts in the Colorado River Basin, then, is how people can use water sustainably while maintaining sufficient streamflow and groundwater to support diverse communities of native species in rivers, lakes, and springs and on flood plains.

This challenge cannot be answered provincially—by efforts only focused on limiting human impacts and improving ecological conditions locally. There are too many sites degraded by human impacts to try to address each one individually (Richter and others, 1998). Ecological processes and populations of native species depend on connectivity in river networks that cannot be replicated by restoration efforts limited to local efforts to make sites appear to function as they did historically. Instead, long-term solutions are only possible by recognizing that a river is a system that functions in a huge landscape and over the time scales of geology and evolution. Expanding the focus of conservation actions to coordinated and integrated water management across a river basin can create opportunities to eliminate site-specific constraints and align the full complement of ecological conditions needed to achieve biodiversity goals.

This paper illustrates four concepts for basin-scale conservation: the benefits of monitoring over large spatial scales even if conservation actions are site specific, coordination of operations of dams in a river system, integration of different types of river management actions, and the potential for conserving biological diversity in parts of the river system. The examples are drawn from outside of the Colorado River Basin but demonstrate general principles of basin-scale efforts that could be applied to conservation in the Colorado River Basin.

Site-Based Water Management for River Conservation

Conservation of freshwater ecosystems is a national priority as indicated by river restoration efforts in every region of the country and an active role by many Federal and State agencies, non-governmental organizations, and commercial businesses (National Research Council, 1992). Changes in how water is released from dams has been a recent focus for

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many restoration efforts (U.S. Department of the Interior, 1996; U.S. Department of the Interior, 2000; Rood and others, 2005; Alexander and others, 2006; Richter and others, 2006; Warner, 2007; King and others, 2008; Moles and Layzer, 2008; Robinson and Uehlinger, 2008). Although reoperating a dam for ecological objectives cannot address the full range of the dam's impacts (e.g., loss of longitudinal continuity in sediment transport, water-quality changes, fish migration barriers) much less the impacts of other human activities on river systems, it is a tractable immediate-term strategy for addressing one of the most pervasive changes to rivers (Vörösmarty and others, 2004; Nilsson and others, 2005). The efficacy of reoperating a dam for freshwater conservation depends on the extent to which hydrologic alteration is the principal cause of degradation and limiting factor for recovery of a river ecosystem (e.g., Bednarek and Hart, 2005).

What's Missing in Site-Based Conservation?

Despite the need for efforts to protect and improve conditions by changing operations of individual dams, a site-based approach is not adequate to address many of the challenges in conserving river ecosystems. Foremost, the outcomes from changing operations at one dam extend only for a limited distance downstream (and, potentially, not at all upstream) that may not be significant for conserving biodiversity from an ecosystem and evolutionary perspective, except for situations where a reach presents a specific ecological bottleneck (e.g., a migration barrier) or a specific ecological benefit (e.g., a refugia during extreme high or low flows). Site-specific efforts may be unable to address "far field" controls on ecological processes, including routing of sediment from hillslopes through a river network, recruitment and processing of organic material, and meta-population dynamics, including migration, interbreeding, localized extripation, and recolonization. The inadequacy of approaching conservation site by site is even more pronounced where freshwater systems are impacted by pervasive activities, such as agricultural or urban land uses that occur over large regions. Conservation efforts that are focused on dam operations, or more generally the predominant management activity at a site, lack the ability to develop solutions from coordinated management of sites in a larger system and from integrated types of different management actions for river conservation. Thus, efforts focused on changing operations of a dam may not be able to address the variety of threats to rivers or eliminate constraints on potential solutions because of the incongruence in scales.

Moving to a Basin-Scale Perspective

Recent examples are available of the real or potential benefits from moving to a basin-scale perspective on freshwater conservation. Progress can begin simply when scientists coordinate monitoring and interpret the impacts of changing dam operations (or other conservation actions) in a regional context. Coordinated operations of a system of dams can improve ecological outcomes while maintaining or expanding the services provided by those dams by focusing conservation actions (reoperation, migration, removal) on dams with environmental impacts disproportionate to their benefits to human welfare and expanding the social functions (power, water supply, flood control, recreation) from other dams in the system. Finally, integrated river basin management can create conservation opportunities by combining different types of actions, such as increased power generation at a dam that funds downstream flood-plain protection and restoration. The common principles in these examples are coordination of actions across a river system and integration of different types of actions to improve overall management of rivers and conservation of their biodiversity.

Monitoring at a Regional Scale for Interpreting Ecological Effects of Changes in Dam Operations

The Skagit River in Washington is the largest river flowing into Puget Sound and is regionally significant for salmon recovery (Puget Sound Partnership, 2007). The Skagit River has three mainstem hydropower facilities operated by Seattle City Light. Water management at these facilities was revised in 1981 to minimize redd dewatering and fry stranding. Connor and Pflug (2004) documented increases in spawner abundance for Chinook (*Oncorhynchus tshawytscha*), pink (*Oncorhynchus gorbuscha*), and chum (*Oncorhynchus keta*) salmon following implementation of higher incubation flows and a reduction in the number of peaking events and daytime ramping rates. They found that Chinook salmon spawners stabilized but did not continue to increase over time. This result, however, can be interpreted as a success because Chinook spawner abundance generally declined in other unregulated rivers in the Puget Sound Basin. In this case, researchers would not have concluded that streamflow management was effective for Chinook conservation just by looking at the Skagit River below the dams. The broader understanding of the status of Chinook across the region was critical for recognizing that flow management was at least maintaining the status of these fish in the Skagit River while it was declining elsewhere.

Upper Mississippi Long Term Resource Monitoring Program (U.S. Geological Survey (USGS) Upper Midwest Environmental Sciences Center, 2006) provides a model for coordinated regional monitoring. Authorized as part of the U.S. Army Corps of Engineers Environmental Management Program under Water Resources Development Acts of 1986 (Public Law 99–662), 1990 (Public Law 101–640), and 1998 (H.R. 3866 [105th]), the upper Mississippi monitoring program has six field stations that use common methods and shared databases. This coordination provides an opportunity for developing and evaluating more robust and consistent methods, such as the trawl nets used for fish sampling on the upper Mississippi, efficiencies in information systems that should be able to be scaled up to multiple sites, comparative analyses between sites, and a regional perspective on the status of resources.

Coordinating Water Management Across a System and Over Longer Time Scale Creates Opportunities for River Conservation

Water management that is coordinated across a system of reservoirs or other facilities can create opportunities that may not be possible when each facility is operated independently. The Bureau of Reclamation's Yakima River Basin Project in Washington provides an example of water management integrated across a river basin with multiple reservoirs. The Yakima River is used to convey water from reservoirs in the upper basin to agricultural irrigators in the lower basin from spring through early autumn. Spring-run Chinook salmon migrate into the Columbia River in the late spring and move up into the tributaries like the Yakima River during the summer. The Chinook salmon remain in the river until late summer when they spawn. Elevated river stages in August and September from releases for irrigation attract salmon to build redds along the margins of the river. These areas dry out before the salmon fry have emerged from the redds when releases from the reservoirs are reduced at the end of the irrigation season. In response, runoff during the spring and summer is stored in Rimrock reservoir on the Tieton River. Just before spawning begins, releases to the upper Yakima River are dropped, and releases from Rimrock reservoir are increased (fig. 1). Water from the Tieton River maintains supplies for agricultural users, while water levels in the Yakima River can be maintained through the salmon's incubation stage.

The "flip-flop" operation does not make the hydrographs of either river more "natural," but it is an effective solution for supplying the water needed for irrigation in the basin and for salmon incubating in the river. This water-management policy would not be possible without the system of reservoirs available for storing water, the coordinated operation by the Bureau of Reclamation, and an ability to accrue environmental benefits from the joint operations against the environmental costs across the whole system. The policy would not be possible if there were specific and equitable conservation goals for the Yakima and Tieton Rivers. Indeed, the Tieton River ecosystem does not benefit from this operation, but the ecological costs are justified currently by the sustained reproduction of salmon in the upper Yakima River.

Extending this model beyond streamflow management, the Penobscot River Restoration Project in Maine will eliminate three dams on the mainstem of the river in order to facilitate fish passage (Federal Energy Regulatory Commission, 2009). The power generation capacity lost at these dams is offset by increasing hydropower production on tributaries that have less environmental impact and provide fish passage

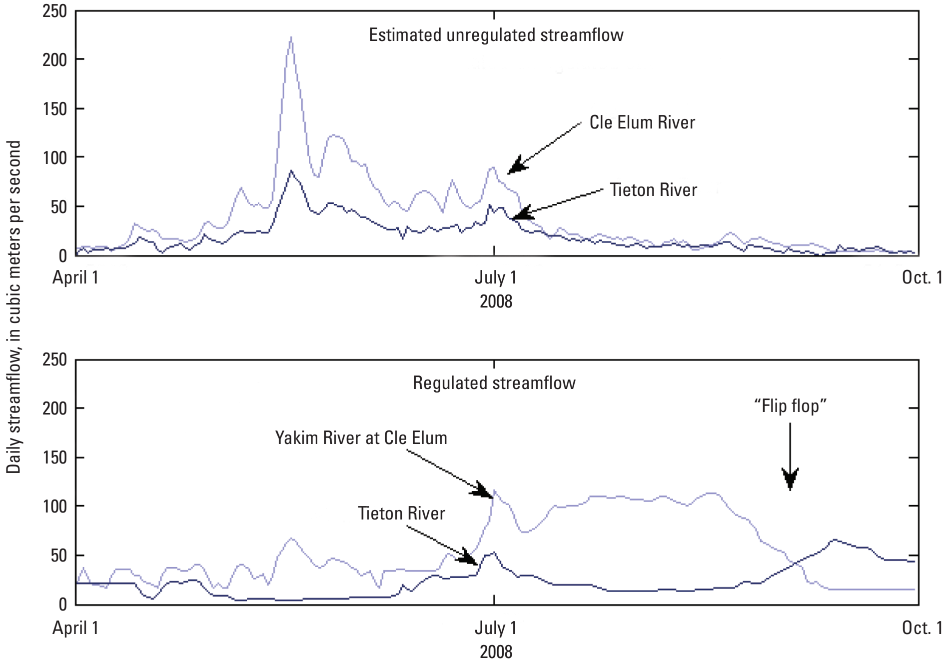

Figure 1. Hydrographs from the Yakima River Basin illustrating the "flip-flop" operation where water supplied by the upper Yakima River reservoirs is replaced by releases from Rimrock reservoir on the Tieton River so that flows in the upper Yakima can be lowered and maintained to keep salmon redds wet during incubation.

on the remaining mainstem dams. In this case as with the Yakima River, the ability to integrate management actions across multiple dams was essential for developing solutions.

The Yakima and Penobscot cases address the disconnect in scales between flow management at a single dam and broader conservation goals that extend to the status of migratory populations or ecological functions, such as routing sediment through a river network. Both involved tailoring different conservation goals for different parts of the river systems and targeting actions accordingly. A site-based approach to flow management can guarantee some minimum acceptable level of ecological condition at any point in a river system, but does not necessarily direct actions—streamflow regime needed for successful salmon reproduction in the case of the upper Yakima and eliminating key fish migration barriers in the case of the Penobscot—to the locations where they will have the greatest ecological benefits. The key to solution in both the Yakima and Penobscot Basins is the tremendous biological potential of parts of the river network that can be realized by focused management actions. For the Yakima, it is a stronghold for salmon spawning in the upper river above most of the agricultural land use in the basin that is not found in other tributaries such as the Tieton River. Similarly for the Penobscot, it is the presence of long, free-flowing river reaches without extensive human impacts above some of the dams in the system. Thus, a systemic view does not imply an inability to resolve differences in management goals for different parts of the system.

Basin-scale strategies for river conservation will only be successful if the ecological benefits accrue across the basin over time, for example, with more resilient core populations and better representation of natural ecological functions. The Truckee River, California, provides an example of coordinating management in time rather than in space for ecological objectives (Rood and others, 2005). Streamflow regulation and diversion led to a decline in flood-plain forests along the lower river in large part because Fremont cottonwood (*Populus fremontii*) seedlings could not become established after germinating. Flow prescriptions were developed, including high-flow pulses to promote Fremont cottonwood recruitment. In low water years when few trees are likely to survive, however, Rood and others (2005) recommend "water should not be directed toward population recruitment but should instead be allocated for the maintenance of riparian plants and other components of the riverine ecosystems" with a more realistic goal of getting good recruitment of riparian trees about once every 10 years. In this case and in the Savannah River, environmental flow prescriptions require the flexibility to change water management year to year, but also depend on coordination of water management over multiple years. Flow prescriptions for the Savannah River call for limits on high flows in years after successful germination of flood-plain trees to allow recruitment of the seedlings to saplings (Richter and others, 2006).

Integrating Dam Operations With Other Forms of River Management in a Basin Can Conserve River Ecosystem and Align Conservation With Human Welfare

Conservation focused on operation of a single dam cannot realize the benefits from integrating different types of actions that are necessary for protecting and restoring ecological functions in river systems. Even the constraints on reoperating a dam for conservation goals will not be surmounted without a broader focus on other actions in a basin that impact a river. Many dams serve flood control purposes and cannot be used to release large floods (by historical standards) because of downstream damage that would result, among other reasons. Conversely, low flows are elevated by dam releases for hydropower in many—though not all—rivers (Magilligan and Nislow, 2005), which downstream users depend on for assimilating wastewater discharges. Without coordination of river management for hydropower, water supply, water quality, and flood risk reduction, water managers may not be able to overcome constraints on implementing environmental flows.

Reoperating dams to create more natural flow patterns may not be effective alone without, for example, appropriate water quality of the releases, sediment for the river to carry, barrier-free fish passage, and connectivity between the river and its flood plain. Combining different types of conservation actions can have synergistic effects, as in the case of regulating the temperature of water released from a dam for environmental flows (Bednarek and Hart, 2005). Although actions aimed at reducing a specific type of human impact on river ecosystems are essential for freshwater conservation, the efficacy of these actions depends on a suite of other actions to address the full range of impacts (e.g., dam operations, diversions, wastewater and stormwater discharges, dredging, levees, flood-plain land uses, introduced species). These other impacts may be difficult to address in the context of site-based conservation that focuses on the impacts of the dominant management action at the site.

The Nature Conservancy has been working in the Yangtze River Basin to coordinate hydropower development with flood-plain management to conserve biological diversity (Harrison and others, 2007). The Jinsha Jiang (upper Yangtze River) flows from the eastern Tibetan plateau carrying runoff from the "rooftop" of the world down to the Sichuan Basin. The Jinsha Jiang has many freshwater ecosystems with significant biodiversity, including the mainstem of the river and a national native fish reserve (Heiner and others, in press). Planned hydropower development along the Jinsha Jiang (Yonghui and others, 2006) threatens these systems. The Nature Conservancy has proposed limiting dam operations for flood control, which requires seasonal drawdown of reservoirs for flood storage, and, instead, has maximized hydropower production by maintaining the "power pool" in the reservoirs at all times and increase the use of flood plains for flood control (Harrison and others, 2007). The dam releases would track inflows leading to more natural flow patterns, and the additional power revenue generated by maintaining the power pool would be used in part for flood-plain conservation.

Enabling Conditions for Basin-Scale River Conservation

Basin-scale river conservation efforts depend on four enabling conditions: multiple dams or other water-management facilities in a river system, flexibility to manage facilities for system benefits, shared conservation goals for river management, and potential to conserve or restore biodiversity. These conditions are closely related and, arguably, not separable. Nonetheless, each is worth considering to assess the viability for basin-scale river conservation in particular basins.

Coordinated management of dams or other facilities across a system is possible when these facilities are fungible to some extent: the services provided by one are interchangeable with those provided by another (e.g., because of interties in the water system or the electrical grid). Operating a group of dams for systemwide goals (e.g., generating hydropower, supplying water, or reducing flood flows) allows for management options that would not be possible when each dam must meet specific goals. Coordinated operations are facilitated when a single agency or utility operates the system for a common purpose as in the Jinsha Jiang, Penobscot River, and Yakima River. Coordinated water management can be difficult, however, even when there is only one principal water manager, such as on the Missouri River (National Research Council, 2002). Basins with multiple water managers face more daunting challenges that begin with the recognition of each other's management goals and extend to equity in achieving management goals. Water management coordinated in time depends on recognition that ecological benefits generated by an action such as a high-flow release have to be maintained in subsequent years or those benefits may be lost (Wright and others, 2008). Coordinated water-management systems can be encouraged by evaluating progress toward ecological goals cumulatively over time rather than incrementally each year and ecosystem function across a basin rather than the ecological conditions at each site.

Basin-scale conservation depends on flexibility to operate individual dams for ecosystem benefits. It may be more effective from a conservation perspective to have a high level of protection for ecological functions (e.g., runoff and streamflow, sediment transport, migration, biogeochemical cycling) from headwaters to mainstem in one part of a river network that supports resilient populations and diverse communities, rather than maintain minimal ecological functions throughout an entire basin with lower biodiversity and less resilience in the populations for critical species. Indeed, basin-scale conservation should not be assessed in terms of abundance (or presence) of species at each dam or other facility in a system, but instead requires integrated measures, such as population (or meta-population) size, total area of habitat in a basin, or ecosystem functions over the river network (sediment routing, nutrient cycling, reproduction and recruitment of juveniles to mature adults in migratory populations). Management flexibility at a site may be ill advised, however, in cases where it could negatively impact population and significantly increase the risk of extirpation or extinction.

Successful conservation at a basin scale requires integrating the range of management activities that affect rivers and flood-plain ecosystems. As with coordinated system operations, integrated river basin management can create solutions to freshwater conservation and water-management issues that would not be possible by only considering one type of management action at an individual site. The administrative challenges of integrating different types of dam operations and flood-plain management loom large in places like the upper Yangtze River, but ultimately surmounting these challenges is necessary to conserve river and flood-plain connectivity. Integrating management in a river basin depends on an alliance of stakeholders with shared ecological goals who are willing to work together rather than trying simply to comply with regulatory requirements applicable to their site.

The starting points for conservation at the scale of a river basin are potential for conserving biodiversity and options for doing so. Many of the examples presented here represent places with high biological diversity and ecosystem integrity. The Sustainable River Project started with the Green River, Kentucky, because of its significant aquatic biodiversity and endemism with 150 fish species and more than 50 mussel species (Silk and Ciruna, 2005; Moles and Layzer, 2008). The Yakima River retains three of its six native stocks of anadromous salmon and is a significant part of the mid-Columbia River evolutionarily significant units for spring-run Chinook salmon and steelhead (*Oncorhynchus mykiss*). The Yangtze River has a native fish reserve downstream from the proposed dams for the Jinsha Jiang and harbors tremendous aquatic biodiversity throughout its upper basin.

The advantages of basin-scale conservation compared to site-specific efforts depend on the availability of options for different spatial arrangements of conservation actions that could achieve conservation goals. These conservation options are analogous to management flexibility at sites: if the condition of every reach in a river network is subjected to the same environmental standards or objectives, there may be little opportunity to realize larger ecological benefits in terms of productivity or biodiversity across the basin rather than at each site. Alternatively, if there are options of achieving conservation objectives, there may be an opportunity to align conservation with other water-management objectives to promote basinwide improvement in the resiliency of species and ecosystem function.

Prospects for Freshwater Conservation at the Scale of the Colorado River Basin

Moving conservation actions to a basin scale will not be simple in the Colorado River Basin. The enabling conditions for basin-scale conservation are only pre-requisite for further action. Actions themselves will be difficult to plan, will be controversial, and may take a long time to implement. In the short term, scientists can use the results of monitoring and research in different parts of the Colorado River Basin to inform site-specific management. In this way, basin-scale conservation can begin with greater coordination of monitoring methods and sampling locations, collaboration on research questions, and shared information systems. Justification of basin-scale conservation efforts depends on the potential for improving biological strongholds that harbor native species or reestablishing streamflow and water-quality conditions that benefit biota throughout the system. It may be impractical to believe that conservation priorities emerging from a regional perspective on the river basin would be adopted locally, but it is not clear that conservation goals for the operation of single dams or other water-management facilities are a feasible and efficient route to protect ecological functions and viable populations of native species in the Colorado River system. At the very least, a broader perspective on freshwater ecosystems and river management options may be warranted at sites where neither freshwater conservation nor water management currently achieves their goals.

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In-Stream Flow Management: Past, Current, and Future Operation of Upper Colorado River Reservoirs

By Thomas Ryan[1]

Abstract

Operations of reservoirs in the upper Colorado River Basin have been modified largely because of environmental legislation. A major driving influence for reservoir reoperation has been endangered Colorado River fish. The Upper Colorado River Endangered Fish Recovery Program published flow recommendations for the Green River in 2000 and for the Colorado and Gunnison Rivers in 2003. The San Juan River Recovery Implementation Program published flow recommendations for the San Juan River in 1999. Flaming Gorge and Navajo Reservoirs are now being operated to meet authorized project purposes as part of the flow recommendations. An Environmental Impact Statement is currently underway to modify operation of the Aspinall Unit (Blue Mesa, Morrow Point, and Crystal Dams) to help achieve flow recommendations for the Gunnison River and portions of the Colorado River.

The operation of Glen Canyon Dam was modified to address environmental resource concerns with the passage of the 1992 Grand Canyon Protection Act and with the signing of the 1996 Record of Decision. The Glen Canyon Adaptive Management Program, which includes the Adaptive Management Work Group (a Federal Advisory Committee), has been in place since 1997 and makes recommendations to the Secretary of the Interior on the operation of Glen Canyon Dam for resource protection and impact mitigation below the dam. Future modifications to the operation of upper Colorado River reservoirs for environmental resources are foreseeable as new scientific information becomes available and as ecosystems and climate change.

Introduction

Reservoir operations in the upper Colorado River Basin have been modified largely because of environmental legislation. Four endangered fish species are native to the upper Colorado River Basin: (1) Colorado pikeminnow *(Ptychocheilus lucius)*, (2) humpback chub *(Gila cypha)*, (3) razorback sucker *(Xyrauchen texanus)*, and (4) bonytail *(Gila elegans)*. The Endangered Species Act of 1973 (Public Law 93–205) has resulted in significant modifications to reservoir operations in the basin, and the 1992 Grand Canyon Protection Act (title XVIII of Public Law 102–575) has required modification of operations at Glen Canyon Dam for protection of downstream environmental and cultural resources. Flow recommendations to enhance recovery of endangered fish are described for segments of the Colorado River below major upper Colorado River Basin facilities—Flaming Gorge Dam on the Green River, the Aspinall Unit (Blue Mesa, Morrow Point, and Crystal Dams) on the Gunnison River, and Navajo Dam on the San Juan River.

Flow Recommendations

The Upper Colorado River Endangered Fish Recovery Program and the San Juan River Recovery Implementation Program have conducted extensive research to track population status and trends, threats, and habitats of endangered fish. The Upper Colorado River Endangered Fish Recovery Program published flow recommendations for the Green River in 2000 (Muth and others, 2000) and flow recommendations for the Colorado and Gunnison Rivers in 2003 (McAda, 2003). The San Juan Recovery Implementation Program published flow recommendations for the San Juan River in 1999 (Holden, 1999). These flow recommendations were developed by using a synthesis of research conducted over many years to determine habitat, flow, and temperature requirements likely necessary to achieve recovery of endangered fish. These flow recommendations are for river segments below major Federal dams: (1) Flaming Gorge Dam on the Green River, (2) the Aspinall Unit on the Gunnison River, and (3) Navajo Dam on the San Juan River.

A common element in all three sets of flow recommendations is that flows more closely mimic a natural hydrograph. River regulation by Flaming Gorge, Blue Mesa, and Navajo Dams reduces spring peak flows from pre-dam levels, while elevating base flows from those observed before the closure of the dams. Water temperatures for regulated rivers are much

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cooler than that of unregulated systems. While none of the flow recommendations advocate a complete return to a natural hydrograph, a shift in flows is proposed in all three sets of flow recommendations. Consequently, the flow recommendations reflect more water being released in the spring and less being released in the base-flow period when compared to reservoir operation practices in place at the time the flow recommendations were published.

Flaming Gorge and Navajo Dams are now being operated to meet authorized project purposes and the flow recommendations. For Flaming Gorge Dam, an Environmental Impact Statement (EIS) was completed in November 2005 (Bureau of Reclamation, 2005), a Biological Opinion was completed in August 2005 (U.S. Fish and Wildlife Service, 2005), and a Record of Decision (ROD) was signed in February 2006 (Bureau of Reclamation, 2006c). For Navajo Reservoir, an EIS was completed in April 2006 (Bureau of Reclamation, 2006a), and a ROD was signed in July 2006 (Bureau of Reclamation, 2006b). An EIS is currently underway to modify the operation of the Aspinall Unit to help achieve flow recommendations for the Gunnison River and portions of the Colorado River. A draft EIS on Aspinall Unit operations was published in February 2009 (Bureau of Reclamation, 2009), and a Programmatic Biological Assessment was submitted to the U.S. Fish and Wildlife Service in January 2009 (Bureau of Reclamation, 2008).

Operations to Achieve Spring Flow Recommendations in the Green River Downstream from Flaming Gorge Dam: A Case Study

"Flow and Temperature Recommendations for Endangered Fishes in the Green River Downstream of Flaming Gorge Dam" (Green River flow recommendations) was published in 2000 by the Upper Colorado River Endangered Fish Recovery Program (Muth and others, 2000). The Green River flow recommendations divide the Green River into three reaches, delimited by tributaries. Reach 1 extends from Flaming Gorge Dam to the confluence of the Yampa River. Reach 2 extends from the Yampa River confluence to the confluence of the White River. Reach 3 extends from the White River confluence to the confluence of the Colorado River.

Reach 1 has only minor tributary inflow with flow almost completely dominated by releases from Flaming Gorge Dam. Flows in Reach 2, however, are composed of a combination of releases from Flaming Gorge and the flow of the Yampa River. Reach 2 supports Colorado pikeminnow and a riverine population of razorback suckers. Reach 2 can be viewed as a two-headwater system; almost half of the natural flow in Reach 2 originates in the Yampa River Basin. The flow of the Yampa River is largely unregulated with high spring peak flows observed in all but the driest of years. Reach 3 is important for the reproduction and recruitment of humpback chub in Desolation Canyon and Colorado pikeminnow and razorback sucker below that point. The flow recommendations for Reach 2 and Reach 3 require releases from Flaming Gorge Dam to be coordinated with flows on the Yampa River.

In the spring, high releases from Flaming Gorge Dam are implemented with the occurrence of peak and post-peak flows on the Yampa River. The magnitude and duration of these flows are tied to the hydrologic conditions (percentiles of expected runoff) in the Green and Yampa Rivers. Generally, the wetter the hydrologic conditions, the higher the spring flow and the duration of the peak flow. Specific spring peak target flows for all three reaches are described in the Green River flow recommendations. The goals of the flow recommendations are to create and maintain in-channel habitats and inundate flood-plain habitats believed to be important for recruitment of endangered fish. While achieving spring flow targets in all three reaches is important, Reach 2 generally is regarded as the most important endangered fish habitat of the three.

Flaming Gorge Dam has been operated for the past 3 years in accordance with the ROD. In 2006, the Flaming Gorge Technical Working Group (FGTWG) was established to provide annual proposals to the Bureau of Reclamation on what flow regimes would best achieve ROD objectives on the basis of current year hydrologic conditions and the conditions of the endangered fish. The FGTWG is also charged with integrating, to the extent possible, any requests concerning flow recommendations from the Upper Colorado River Endangered Fish Recovery Program into the proposal so that recovery program research and adaptive management can be facilitated. The FGTWG is represented by technical staff from the U.S. Fish and Wildlife Service, Western Area Power Administration, and Bureau of Reclamation. This group also serves as the informal consultation body for Endangered Species Act compliance as has occurred historically and as directed by the ROD. Public outreach and information exchange occur through the Flaming Gorge Working Group, a public forum which typically meets twice annually.

Since the signing of the 2006 ROD, three different operations at Flaming Gorge have been implemented to achieve spring flow targets. In 2006, based on hydrologic conditions in the Green River Basin with consideration for research requests from the recovery program, an instantaneous peak target flow of 527 cubic meters per second (m^3/s) was targeted and achieved in Reach 2 as measured at the Green River at Jensen, UT, streamgaging station. To achieve this target, bypass releases of approximately 57 m^3/s were added to powerplant capacity releases of 127 m^3/s for a total peak release of 184 m^3/s from Flaming Gorge. This flow combined with the peak flow of the Yampa River achieved the target flow of 527 m^3/s. An instantaneous peak flow of 527 m^3/s in Reach 2 is required in 50 percent of the years under the Green River flow recommendations.

In 2007, drier conditions in the Green River Basin resulted in targeting a lower instantaneous flow at Jensen, UT. An instantaneous peak target flow of 235 m^3/s or greater was targeted and achieved in Reach 2. Powerplant capacity releases from Flaming Gorge Reservoir combined with Yampa River flows resulted in the peak flow in Reach 2 in 2007 being 363 m^3/s. Additionally, a flow duration of 235 m^3/s for 7 days was achieved in Reach 2. The flow recommendations require that this flow duration target be achieved in 90 percent of the years. This flow duration was also achieved in 2006.

In 2008, the hydrologic conditions in the Green River Basin were more favorable with "average" conditions above Flaming Gorge Reservoir and "moderately wet" conditions in the Yampa River Basin. A spring operation was implemented in 2008 to achieve a flow-duration target of 527 m^3/s for 14 days. The flow recommendations require that this flow duration be achieved in 40 percent of the years. Above average spring runoff in the Yampa River combined with powerplant capacity releases from Flaming Gorge Reservoir resulted in achieving the desired flow-duration target. Bypass releases were not required at Flaming Gorge in 2008, although river simulation modeling indicates that bypass releases will be required to achieve this particular target in some years.

During all years under ROD operations to date (2006–2008), temperature objectives as specified in Muth and others (2000) have been achieved through operations of a selective withdrawal system on Flaming Gorge Dam in concert with flow-specific ambient warming rates of the river itself.

Glen Canyon Dam Operations

The operation of Glen Canyon Dam has been influenced by the Endangered Species Act and the 1992 Grand Canyon Protection Act. The Grand Canyon Protection Act required the Secretary of the Interior to prepare an EIS on the long-term operation of Glen Canyon Dam for protection of downstream environmental and cultural resources. An EIS was completed in 1995 (Bureau of Reclamation, 1995), and a ROD was signed in 1996 (U.S. Department of the Interior, 1996; see Campbell and others, this volume, for details).

From the 1960s into the early 1990s, Glen Canyon Dam was operated as a peaking power facility, with releases often varying by over 700 m^3/s within a 24-hour period. The 1996 ROD implemented the modified low fluctuating flow operational alternative. The basis for the Secretary of the Interior's decision in the 1996 ROD was "not to maximize benefits for the most resources, but rather to find an alternative dam operating plan that would permit recovery and long-term sustainability of downstream resources while limiting hydropower capability and flexibility only to the extent necessary to achieve recovery and long-term sustainability." The 1996 ROD set flow parameters concerning minimum and maximum releases from Glen Canyon Dam and limited the rate at which flows could fluctuate.

The Glen Canyon Adaptive Management Program (AMP), which includes the Adaptive Management Work Group (a Federal Advisory Committee), was created by the 1996 ROD. The AMP has been in place since 1997 and makes recommendations to the Secretary of the Interior on the operation of Glen Canyon Dam for resource protection and impact mitigation below the dam. Numerous flow and nonflow activities have been coordinated through the program including high flow, fluctuating flow, and steady flow experiments to support restoration and scientific understanding of the ecosystem in Grand Canyon.

Drought

The Colorado River experienced extreme drought conditions during the 5-year period from 2000 to 2004. While flows were above average in 2005, flows in 2006 and 2007 were below average. The natural flow during the 8-year period from 2000 to 2007 was the lowest 8 consecutive year flow in the 100-year record of the Colorado River. The Colorado River Basin may be in a multidecadal drought. Drought conditions have lowered Lake Powell with current live storage (February 2009) at 54 percent of capacity. Releases from Lake Powell in water years[2] 2001 through 2007 met the minimum objective releases of 10,150 million cubic meters. In 2008, equalization releases were made according to the "Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead" (Department of the Interior, 2007). These guidelines were adopted in December 2007. The total release from Lake Powell in water year 2009 was 11,070 million cubic meters.

Conclusions

Future modifications in the operation of upper Colorado River reservoirs for restoration are foreseeable as new scientific information becomes available, as ecosystems shift, and as the climate changes. Flow recommendations for river systems above Lake Powell were developed on the basis of the best available science. However, it remains to be seen if the desired ecological response (increased recruitment and reduced mortality of endangered fish) can be achieved. Research and monitoring may result in changes or refinements to flow recommendations to achieve the desired response.

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[2] Water year is the period from October 1 to September 30 and is defined by the year in which the period ends.

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In an Era of Changing Climate—Description of Interim Guidelines for Lake Powell and Lake Mead

By Terry Fulp,[1] Carly Jerla,[1] and Russell Callejo[1]

Abstract

Combined, all of the reservoirs on the mainstream of the Colorado River have a total storage capacity of some 60 million acre-feet, approximately four times the river's average annual recorded inflow. During 2000 to 2005, the Colorado River experienced the worst drought in approximately 100 years of recorded history, and that drought continues. Although there have been shortages in Upper Basin tributaries, deliveries in the Lower Basin (downstream from Lees Ferry, Arizona) have been made with 100 percent reliability primarily as a result of the ability to capture water systemwide during high-flow years and to deliver that water during low-flow years.

With the onset and continuation of the current drought, the Bureau of Reclamation's (Reclamation) Upper and Lower Colorado Regions initiated a National Environmental Policy Act (NEPA) process in 2005 to develop Lower Basin shortage guidelines and coordinated management strategies for the operation of Lake Powell and Lake Mead. Following an intensive period of public input and analysis from late 2005 through 2007, the Secretary of the Interior implemented the "Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations of Lake Powell and Lake Mead" (Interim Guidelines) in December of 2007. The guidelines provide a prescriptive methodology to determine the annual releases from Lake Powell and Lake Mead for an interim period (through 2026). The guidelines focus on encouraging conservation of water in the Lower Basin, considering reservoir operations at all water levels, and gaining valuable experience operating the reservoirs to improve the basis for making future operational decisions during the interim period and (or) thereafter.

In 2004, Reclamation's Lower Colorado Region initiated a research and development program, collaborating with other Federal agencies and universities, for the purpose of enabling the use of new methods for projecting possible future river flows that take into account increased hydrologic variability and potential decreases in the river's annual inflow owing to changing climate. As part of this effort and in conjunction with the development of the new Interim Guidelines, additional analyses were included in the 2007 Final Environmental Impact Statement that considered the impacts of greater hydrologic variability than have been seen in the 100-year record. Reclamation is committed to continuing this research and development program to further its ability to analyze the potential impacts of climate change and to use that information in water and power operations and planning studies to be able to adapt, as appropriate, the operation and management of the river to a changing future climate.

Introduction

The Colorado River is a critical resource in the Western United States; seven Western States and Mexico depend on the Colorado River for water supply, power production, recreation, and environmental resources. The Colorado River Basin (basin) is divided, both politically and physically, into the Upper and Lower Basins at Lees Ferry, Arizona—a result of the Colorado River Compact of 1922 (Compact). The Compact also divided the seven basin States into the Upper Division and the Lower Division States. The Upper Division States includes Colorado, New Mexico, Utah, and Wyoming. Arizona, California, and Nevada make up the Lower Division States (fig. 1).

Climate varies significantly throughout the basin. Most of the basin is arid and semiarid, and generally receives less than 10 inches of precipitation per year. In contrast, many of the mountainous areas that rim the northern portion of the basin receive, on average, over 40 inches of precipitation per year. The annual flow of the Colorado River varies considerably from year to year. As illustrated in figure 2, over the past approximately 100 years (1906 through 2008), the natural flow (estimate of streamflow that would exist without human development) at the Lees Ferry gaging station (located approximately 16 miles downstream from Glen Canyon Dam) has ranged from 5.5 million acre-feet (MAF) to 25.5 MAF, with an average of 15.0 MAF.

Recent tree-ring reconstructions provide a rich view of the magnitude and duration of the natural streamflow

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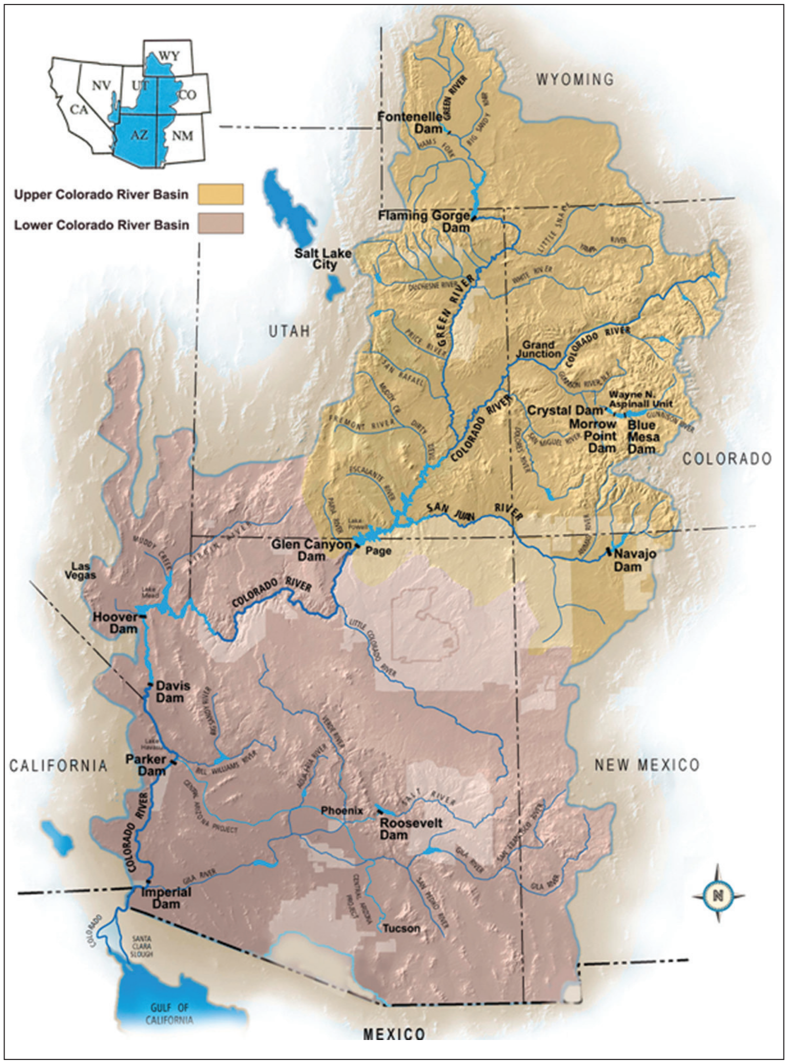
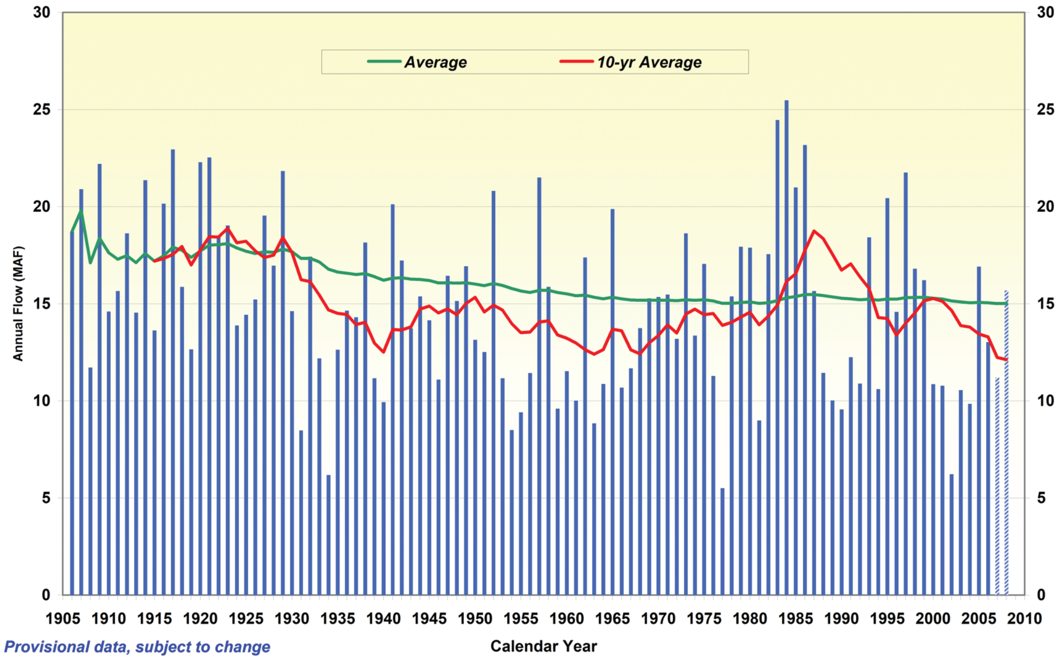


Figure 1. The Colorado River Basin.



Provisional data, subject to change
2007-2008 are estimated values

Figure 2. Natural flow of the Colorado River at Lees Ferry, AZ.

variability and indicate that the long-term average may be close to 14.7 MAF (Meko and others, 2007). As shown in figure 3, more severe droughts have occurred in the past 1,200 years, specifically during the 1100s. A severe drought, known as the Medieval Drought (1118–1179), occurred during this time. The Medieval Drought has the lowest 25-year mean of 12.6 MAF in the paleorecord and is characterized by a notable absence of high flows for a 60-year period (Meko and others, 2007).

The Secretary of the Interior (Secretary), acting through the Bureau of Reclamation (Reclamation), is vested with the responsibility to manage the mainstream waters of the Lower Basin of the Colorado River pursuant to applicable Federal law. This responsibility is carried out consistent with a body of documents referred to as the Law of the River, of which the Compact is the underpinning agreement. The Compact apportioned to the Upper Basin and Lower Basin, in perpetuity, the exclusive beneficial consumptive use of 7.5 MAF per year. The Compact also stipulated that the flow in the Colorado River at Lees Ferry not be depleted below 75 MAF for any period of 10 consecutive years. Furthermore, the Upper and Lower Basins agreed in the Compact to share in any deficiency in meeting future water commitments to Mexico, which was allocated 1.5 MAF annually in a 1944 treaty.

The Colorado River system is operated on a tight margin. Apportioned water in the basin totals 16.5 MAF, and the average natural flow of the observed record is 15.0 MAF. The Upper Basin has not fully developed and uses less than its 7.5 MAF apportionment. Consumptive use in the basin has averaged approximately 12.8 MAF over the last 10 years. The Colorado River system, which contains numerous reservoirs, provides an aggregate of approximately 60 MAF of storage, or roughly 4 years of average natural flow of the river. Lake Powell and the downstream Lake Mead provide approximately 85 percent of this storage. Although there have been shortages in Upper Basin tributaries since 2000, all of the requested deliveries were met in the Lower Basin despite having the worst 10-year drought in the last century.

Colorado River Drought: Impetus for the Interim Guidelines

During 2000 to 2005, the Colorado River experienced the worst drought in approximately 100 years of recorded history. This drought reduced Colorado River system storage, while demands for Colorado River water continued to increase. From October 1999 through the end of September 2005, combined storage in Lake Powell and Lake Mead decreased from 47.6 MAF (approximately 95 percent of capacity) to 27.2 MAF (approximately 54 percent of capacity) and was as low as 23.1 MAF (approximately 46 percent of capacity) in 2004. Although a drought of this magnitude is unprecedented in the modern history of the river, tree-ring records show that droughts of this severity have occurred in the past, and climate experts and scientists suggest that such droughts are likely to occur in the future.

In the spring of 2005, declining reservoir levels in the basin led to interstate and interbasin tensions. Specific guidelines to address the operations of Lake Powell and Lake

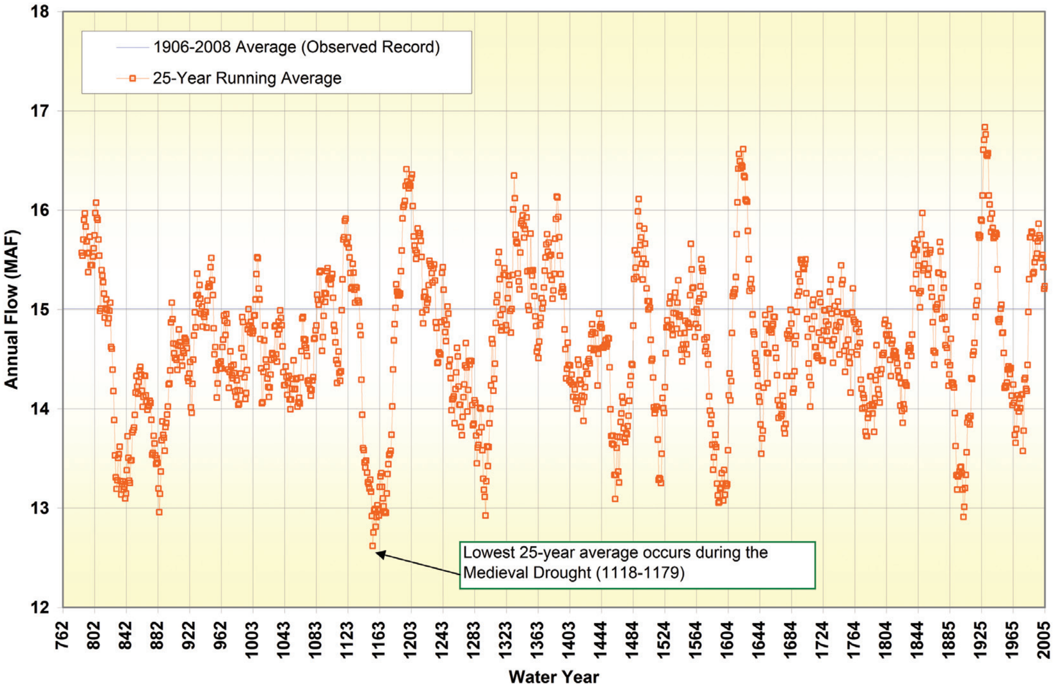


Figure 3. Paleo reconstructed flow of the Colorado River at Lees Ferry, AZ (from Meko and others, 2007).

Mead during drought and low reservoir conditions had not yet been developed, because these types of low-reservoir conditions had simply not been experienced with both reservoirs in place.[2] Storage of water and flows in the Colorado River had been sufficient so that it had not been necessary for the Secretary to reduce deliveries by determining a "shortage" on the lower Colorado River.[3] Without operational guidelines in place, water users in the Lower Basin who rely on Colorado River water were not able to identify particular reservoir conditions under which a shortage would be determined. Nor were these water users able to identify the frequency or magnitude of any potential future annual reductions in their water deliveries.

Operations between Lake Powell and Lake Mead were coordinated only at higher reservoir levels (at a Lake Powell capacity of 61 percent or higher) through an operation known as equalization. Below the equalization level, the Lake Powell release was governed by the minimum objective release of 8.23 MAF, without regard to the condition of the two reservoirs. To minimize shortages in the Lower Basin and avoid the risk of curtailments of Colorado River water use in the Upper Basin, a more coordinated approach to the operations between the reservoirs, for a full range of reservoir conditions, was needed.

These factors, along with the acknowledgment that lower reservoir conditions may occur more frequently because of changing hydrologic conditions and anticipated future demands on Colorado River water supplies, led the U.S. Department of the Interior to conclude that additional management guidelines were necessary and desirable for efficient management of the Colorado River.

The Development of the Interim Guidelines

In May 2005, the Secretary tasked the Upper and Lower Division States (basin States) to develop a consensus plan to mitigate drought in the basin. The Secretary was clear that the U.S. Department of the Interior was committed to developing guidelines with or without the States' consensus. Accordingly, the Secretary directed Reclamation to engage in a process to develop guidelines for Lower Basin shortages and the operation of Lake Powell and Lake Mead, particularly under drought and low reservoir conditions. Later that year, Reclamation announced its intent to initiate a National Environmental Policy Act (NEPA) process to develop such guidelines.

During the scoping phase of the NEPA process, three important considerations were identified: (1) the importance of encouraging conservation of water, particularly during times of drought; (2) the importance of considering reservoir operations at all operational levels, not just when reservoirs are low; and (3), the importance of establishing operational guidelines for an interim period to gain valuable operational experience to inform future management decisions. Out of these three considerations, four key operational elements emerged: (1) shortage strategy for Lake Mead and the Lower Division States, (2) coordinated operation of Lake Powell and Lake Mead, (3) mechanism for the storage and delivery of conserved system and nonsystem water in Lake Mead, and (4) modified and extended elements of existing Interim Surplus Guidelines (ISG). Each element was addressed in the broad range of reasonable alternatives analyzed in the 2007 Final Environmental Impact Statement (Final EIS; Bureau of Reclamation, 2007).

The alternatives were developed in coordination with a diverse body of stakeholders, including the basin States, a consortium of environmental nongovernmental organizations (NGOs), Native American Tribes, Federal agencies, and the general public. The basin States submitted a consensus alternative that signified a historic agreement on issues of this magnitude.

The preferred alternative, based on the basin States' alternative and the "conservation before shortage" alternative submitted by the environmental NGOs, was made up of four key elements, corresponding to those listed previously. First, the preferred alternative proposed discrete levels of shortage volumes associated with Lake Mead elevations to conserve reservoir storage and provide water users and managers in the Lower Basin with greater certainty to know when, and by how much, water deliveries will be reduced during low reservoir conditions. Second, it proposed a fully coordinated operation of Lake Powell and Lake Mead to minimize shortages in the Lower Basin and avoid risk of curtailments of use in the Upper Basin. Third, the preferred alternative proposed an Intentionally Created Surplus (ICS) mechanism to provide for the creation, accounting, and delivery of conserved system and nonsystem water, thereby promoting water conservation in the Lower Basin. Fourth, it extended the term of the ISG and modified those guidelines by eliminating the most liberal surplus conditions, thereby leaving more water in storage to reduce the severity of a future shortage should one occur.

A Record of Decision (ROD; U.S. Department of the Interior, 2007) was issued in December 2007, officially adopting the guidelines (Interim Guidelines). Prescribed operations at Lake Powell and Lake Mead under the Interim Guidelines are described in figure 4.

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[2] Lake Mead first filled in 1935; Lake Powell first filled in 1980.

[3] The Secretary annually determines the water-supply condition for the Lower Division States; a "normal" condition is determined when 7.5 MAF of water is available, a "surplus" condition is determined when more than 7.5 MAF of water is available, and a "shortage" condition is determined when less than 7.5 MAF of water is available.

Lake Powell		
Elevation (feet)	**Operation According to the Interim Guidelines**	**Live Storage (maf)[1]**
3,700	**Equalization Tier** Equalize, avoid spills or release 8.23 maf	**24.3**
3,636 - 3,666 (2008-2026)	**Upper Elevation Balancing Tier[4]** Release 8.23 maf; if Lake Mead < 1,075 feet, balance contents with a min/max release of 7.0 and 9.0 maf	**15.5 - 19.3** (2008-2026)
3,575	**Mid-Elevation Release Tier** Release 7.48 maf; if Lake Mead < 1,025 feet, release 8.23 maf	**9.5**
3,525	**Lower Elevation Balancing Tier** Balance contents with a min/max release of 7.0 and 9.5 maf	**5.9**
3,490		**4.0**
3,370		**0**

Lake Mead		
Elevation (feet)	**Operation According to the Interim Guidelines**	**Live Storage (maf)**
1,220	**Flood Control Surplus or Quantified Surplus Condition** Deliver > 7.5 maf (± ICS[2] if Quantified Surplus)	**25.9**
1,200 (approx.)[3]	**Domestic Surplus or ICS Surplus Condition** Deliver > 7.5 maf ± ICS	**22.9** (approx.)
1,145	**Normal or ICS Surplus Condition** Deliver ≥ 7.5 maf ± ICS	**15.9**
1,105		**11.9**
1,075	**Shortage Condition** Deliver 7.167[5] maf + DSS[6]	**9.4**
1,050	**Shortage Condition** Deliver 7.083[7] maf + DSS	**7.5**
1,025	**Shortage Condition** Deliver 7.0[8] maf + DSS Further measures may be undertaken[9]	**5.8**
1,000		**4.3**
895		**0**

Diagram not to scale

[1] Acronym for million acre-feet.

[2] Acronym for Intentionally Created Surplus. See the 2007 Interim Guidelines.

[3] This elevation, and the corresponding storage value, is approximate. It is determined each year by considering several factors including Lake Powell and Lake Mead storage, projected Upper Basin and Lower Basin demands, and an assumed inflow.

[4] Subject to April adjustment which may result in a release according to the Equalization Tier.

[5] Of which 2.48 maf is apportioned to Arizona, 4.4 maf to California, and 0.287 maf to Nevada.

[6] Acronym for Developed Shortage Supply. See the 2007 Interim Guidelines.

[7] Of which 2.40 maf is apportioned to Arizona, 4.4 maf to California, and 0.283 maf to Nevada.

[8] Of which 2.32 maf is apportioned to Arizona, 4.4 maf to California, and 0.280 maf to Nevada.

[9] Whenever Lake Mead is below elevation 1,025 feet, the Secretary shall consider whether hydrologic conditions together with anticipated deliveries to the Lower Division States and Mexico are likely to cause the elevation at Lake Mead to fall below 1,000 feet. Such consideration, in consultation with the Basin States, may result in the undertaking of further measures, consistent with applicable Federal law.

Figure 4. Operational diagrams for Lake Powell and Lake Mead from the Interim Guidelines.

Efforts to Address Climate Change and Variability in the Development of the Interim Guidelines

In 2004, Reclamation's Lower Colorado Region initiated a research and development program—with a collaboration with other Federal agencies and universities—for the purpose of enabling the use of new methods for projecting possible future river flows that take into account increased hydrologic variability and potential decreases in the river's annual inflow owing to a changing climate. As part of this effort and in conjunction with the development of the Final EIS, a group of leading climate experts (Climate Technical Work Group) was empanelled to assess the state of knowledge regarding climate change in the basin and to prioritize future research and development needs. The findings and recommendations of the work group were published as Appendix U to the 2007 Final Interim Guidelines EIS. Owing to the time horizon of the decision (approximately 20 years) and the lack of precise knowledge of the potential impacts of climate change on the basin, the recommendation of the Climate Technical Work Group was to include additional analyses considering the impacts of greater hydrologic variability than has been seen in the 100-year record. Following this recommendation, a quantitative sensitivity analysis using paleoclimate evidence was included as Appendix N in the 2007 Final Interim Guidelines EIS, accompanied by a qualitative discussion of the potential impacts of climate change.

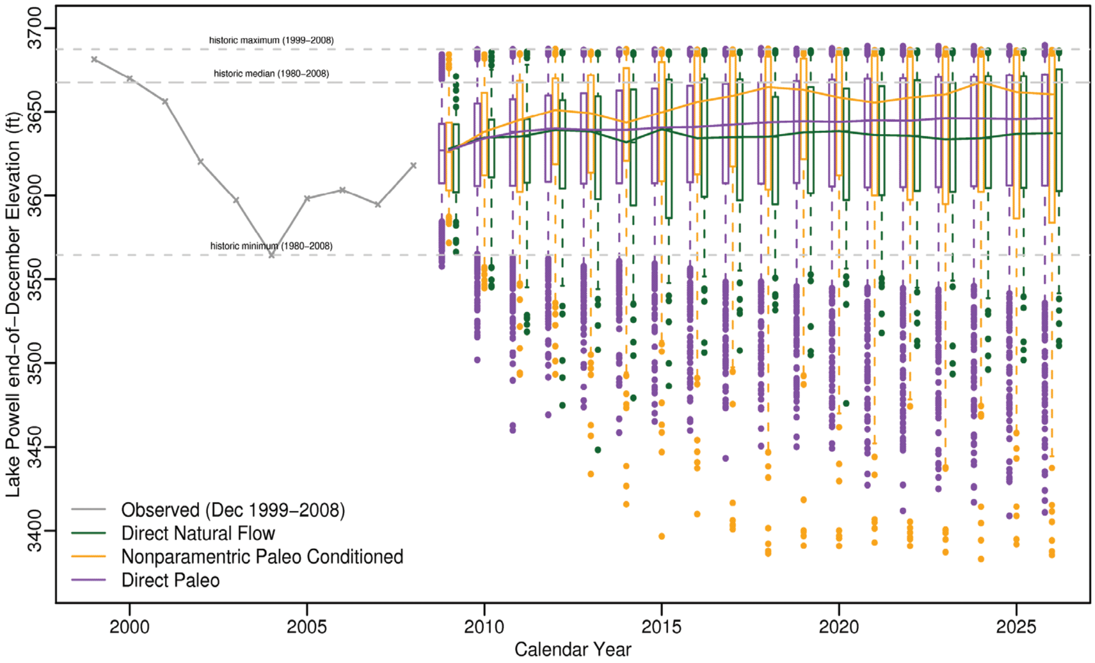
Appendix N analyzed the impacts of hydrologies outside the historical range of flows. In particular, the analysis focused on the sensitivity of hydrologic resources (e.g., reservoir storage, reservoir releases, and river flows) to alternative hydrologic scenario methodologies (e.g., derived from stochastic hydrology and tree-ring-based paleoreconstructions), particularly methodologies that generate sequences with greater hydrologic variability. Appendix N compared the “no action” alternative and the “preferred” alternative under three hydrologic scenario methodologies.

The first scenario, Direct Natural Flow, applies the Index Sequential Method (ISM) to the observed period of record (1906–2006), resulting in 101 hydrologic traces (Ouarda and others, 1997). The Direct Paleo scenario directly resamples the recent Lees Ferry reconstruction completed by Meko and others (2007) that extends back to the year 762 using the ISM, resulting in 1,244 hydrologic traces. The Nonparametric Paleo Conditioned scenario blends the hydrologic state (e.g., wet or dry) from the paleoreconstruction with the flow magnitudes from the observed record and results in 125 hydrologic traces (Prairie and others, 2007).

The results of the Interim Guidelines under these three alternative hydrologic scenarios in relation to Lake Powell elevations are shown in figure 5 for 2009 through 2026. The Nonparametric Paleo Conditioned scenario results in the highest median for all years; however, the historic median is still higher for every year during the interim period. It is evident that the alternative hydrologic scenarios increase the range of variability seen in Lake Powell elevations, particularly at lower elevations.

Adapting Colorado River Operations to a Changing Climate

The 2007 ROD implements a robust solution to the unique challenges facing Reclamation in managing the Colorado River. The Interim Guidelines, which extend through 2026, provide an opportunity to gain valuable operating experience and improve the basis for making additional future operational decisions during the interim period or thereafter. In addition, the Interim Guidelines were crafted to include operational elements that would respond if potential impacts of climate change and increased hydrologic variability are



Note: Solid lines through boxes connect the median. Bottom, middle and top of boxes represent the 25th, 50th and 75th percentiles, respectively. At whisker ends are 5th and 95th percentiles. Outliers are beyond the whiskers.

Figure 5. Projected Lake Powell elevations.

realized during the interim period. The coordinated operation element allows Lake Powell releases to be adjusted to respond to low reservoir storage conditions in either Lake Powell or Lake Mead. The shortage strategy element for Lake Mead includes a provision for additional shortages to be considered, after appropriate consultation. The Interim Guidelines also encourage efficient use and management of Colorado River water, and enhance conservation opportunities in the Lower Basin and the retention of water in Lake Mead through adoption of the ICS mechanism. Finally, the basin States have agreed to address future controversies concerning the Colorado River through consultation and negotiation before resorting to litigation. In sum, the Interim Guidelines preserve and provide Reclamation the flexibility to deal with and adapt to further challenges such as a future changing climate and persistent drought.

On December 13, 2007, Secretary of the Interior Dirk Kempthorne signed the ROD and called the Interim Guidelines the most important agreement among the seven basin States since the original 1922 Compact. The Interim Guidelines are in place through 2026 and include a provision that states, “Beginning no later than December 31, 2020, the Secretary shall initiate a formal review for purposes of evaluating the effectiveness of these Guidelines” (U.S. Department of the Interior, 2007, p. 56). Further knowledge of the impacts of a changing climate, both realized and projected, will be critical when such a review is initiated. Reclamation’s Lower Colorado Region is committed to continuing this research and development program in order to do just that. For example, it is anticipated that the necessary tools will be in place in 2010 to analyze a suite of climate change scenarios within Reclamation’s basinwide planning model (the Colorado River Simulation System, or CRSS). This and other efforts will further our ability to analyze the potential impacts of climate change and use that information in water and power operations and planning studies to be able to adapt, as appropriate, the operation and management of the river to a changing future climate.[4]

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Sustainability and River Restoration in the Colorado River Basin: A Climate Perspective

By Katharine L. Jacobs[1]

Abstract

Meeting the expanding demands of municipal water users while protecting hydropower, recreation, Tribal, agricultural, and environmental interests will become more challenging over time, particularly in the context of moving toward fuller utilization of upper Colorado River allocations. Additional stress will be placed on management systems by changes in the climate, particularly higher temperatures, which dramatically affect both water demand and water supply. Increasing demand, changing social values, and over-allocation of water supplies mean future "normal" droughts will lead to greater impacts and more water rights conflicts. Managing for sustainability involves being prepared for multiple climate-related challenges in addition to climate change—including difficulty in defining realistic management goals in light of long-term (decade-scale) "natural" variability in the context of a changing climate regime. Because water is a key "delivery mechanism" of climate change impacts, habitat managers need to be aware of expected changes in volume and seasonality of runoff and design adaptive strategies that will enhance the resilience of the habitats and species that they manage. More work is needed to better understand the impacts of climate change on groundwater supplies within specific watersheds and on the habitats that are directly or indirectly supported by groundwater. Finally, sustainability of managed ecosystems is not just about access to sufficient water, it is about access to money, information, and political support over time.

Introduction

Beyond the stresses caused by competing demands for water, multiple implications of climate variability and climate change need to be considered by habitat managers in the Colorado River Basin. Climate variability has always posed a significant challenge for habitat restoration and protection activities, but now variability occurs in the context of underlying climate change trends and the "Death of Stationarity" described by Milly and others, 2008. The "Death of Stationarity" message is that past climate conditions are no longer a good analogue for the conditions that will be experienced in the future. Although climate has never been "stationary" in the true sense of the word, anthropogenic change has added a new climate factor that is driving the system outside of its historical range. Greenhouse gases now entering the atmosphere will impact the climate system for centuries, even if humans start doing a better job of managing greenhouse gases in the short term (Solomon and others, 2009). As a result, in order to anticipate possible future conditions, managers will need to expand the range of historical, observed experience to consider a broader set of climate conditions to frame planning assumptions. For example, managers can build future scenarios based on instrumental records plus a blend of paleoclimate and (or) projected climate information, perhaps with the use of stochastic data to enrich the set of sequences that might be considered given the chosen climate context. These approaches may require new methods of integrating scientific information into decision processes in real time (Brekke and others, 2009).

In addition to needing to master the new uncertainties that come with climate change, ecosystem managers have not yet developed a full appreciation of variability beyond the seasonal-interannual (ENSO) timeframe. Sequencing of wet and dry years associated with decadal to multidecadal trends in sea surface temperature in the Atlantic and Pacific Oceans has been shown to influence both temperature and precipitation in various parts of the United States over the past centuries (Mantua and others, 1997; McCabe and others, 2007; McCabe and others, 2008; McCabe and Wolock, 2008). Some patterns in ocean conditions persist for multiple years and sometimes result in long-lasting climate trends that last a decade or longer. Strong correlations have been shown between these patterns in ocean temperature and climate conditions in some parts of the United States, particularly in the Southwest (fig. 1). At this time we have no way of predicting when the shifts in phase between wet and dry periods might occur because we do not yet have sufficient understanding of the mechanisms that cause them. The shifts can wreak havoc with water-supply planning and environmental restoration

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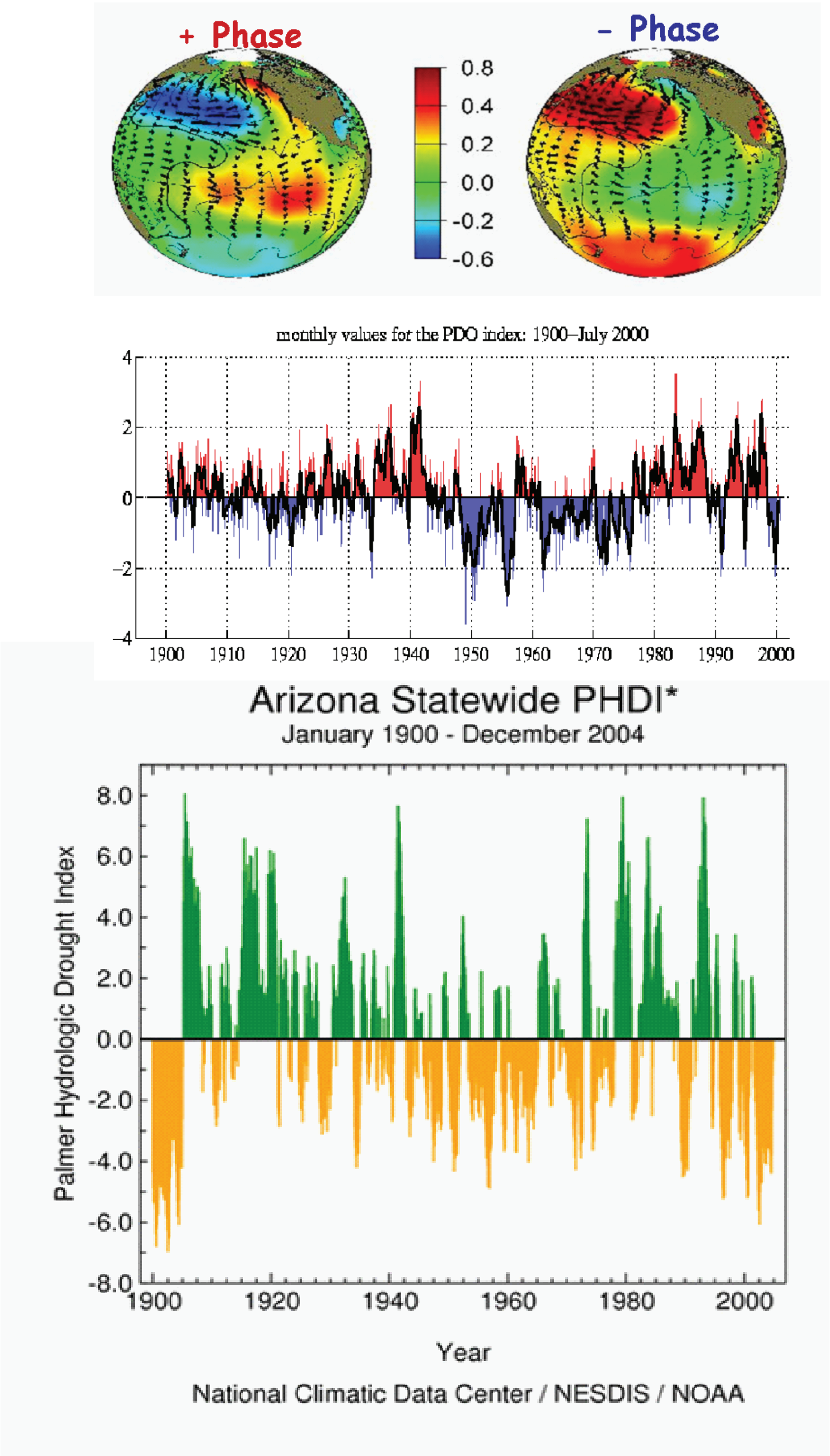


Figure 1. The Pacific Decadal Oscillation is a pattern of sea surface temperatures that is highly correlated with long-term (decadal) variability in precipitation and temperatures in parts of the United States.

efforts if they are not anticipated, and they need to be better understood in order to ensure that sufficient water supplies and (or) reservoir capacity are available even in the dryer portions of decadal cycles.

Further challenges come from the human values and regulatory requirements that control what condition managers are attempting to create through restoration efforts. If managers want to protect specific species in their current location (as is generally expected under Endangered Species Act requirements), there are different restoration challenges in the context of climate change than if it were possible/acceptable to facilitate a shift in managed areas to the north or to higher elevations. If, however, the restoration focus is to protect ecosystem functions rather than specific species, focusing on restoring the environmental conditions that protect those functions (e.g., seasonality of flows) may be the management objective, which leads to additional considerations related to the location of managed areas and access to water supplies.

Unfortunately, there is a general public perception that restoration efforts should recreate the “presettlement condition” (prior to human impacts), as if there were only one such condition. Since climate conditions have always changed, this expectation is not easy to meet. The fact that the extremes in the climate system are now moving outside of historical boundaries makes this even less reasonable. Further, the ability to create the quantity, quality, and seasonality of flows that are required for restoration supporting any specific ecosystem condition will be more difficult in light of the uncertainties associated with predicting the relevant variables into the future with enough specificity to make management decisions.

Anthropogenic climate change complicates the challenges posed by “natural” variability at various time scales. The consensus among climate experts is that across a variety of habitats, more extreme events, both floods and droughts, are likely to result (Karl and others, 2009). At this time we do not know whether climate change will modify the underlying drivers of “natural” variability (frequency of floods and droughts), but it is expected that the peaks will be exacerbated.

Incorporating Climate Information in Management Decisions

Water-management systems that are more responsive to changes in the climate system are needed. Most water rights systems allocate volumes of water based on an expectation of “normal” flows or at least flows within the historical range. New modes of management that reflect the increased understanding of the drivers of climate conditions are needed, with the potential to adjust management activities in real-time response to new types of science inputs, including probabilistic information about future conditions. The ability to respond to anticipated changes in seasonal and annual water availability, as well as changes in extremes (both floods and droughts), will be the hallmark of successful programs. It is possible that through enhanced monitoring and analysis efforts, trends can be identified much more quickly, allowing for adaptive management that incorporates a broader suite of information—from a variety of sources—including remote sensing, surface-water gages, the new National Phenology Network (which is designed to observe temporal and spatial changes in biological activity), groundwater-level monitoring, changes in species composition, etc. Combining all of these sources in real time presents significant cyberinfrastructure challenges, but an integrated understanding could also present opportunities for reducing the cost of habitat restoration and maintaining in-stream flows.

Where ecosystems are supported by groundwater, habitat managers need a better understanding of the changes in the groundwater system that may result from changes in precipitation and temperature associated with global warming. Although there is little empirical evidence, it seems likely climate change may result in a reduction in recharge in areas where temperatures are increasing, even if precipitation increases. However, these impacts are likely to be different from one groundwater basin to another because of differences in geology and recharge pathways. Changes in patterns of water demand and water supply for human uses as well as for ecosystems will emerge within tributary watersheds across the Colorado River Basin as temperatures increase and changes in precipitation patterns become more dramatic (Seager and others, 2007; Colorado Water Conservation Board, 2008). These changes in demand for groundwater also will affect the availability of groundwater to support environmental flows. Anticipating changes in the hydrologic cycle and impacts on water quality will be imperative for preservation and restoration of key environmental flow values.

Managing for Sustainability

Sustainability is a subjective concept and is particularly elusive as applied to natural ecosystems. Ecosystems have evolved in response to changes in climate and multiple other stresses for millennia, so managing specific ecosystems in specific locations as if there were a single “prehistoric” or “pre-intervention” condition is not consistent with the sustainability concept. Human interventions have already altered most hydrologic regimes. There are essentially no ecosystems that are untouched by human-induced changes, because the chemical composition of the atmosphere, atmospheric dynamics, and impacts to the climate system affect the entire globe even in places that are otherwise intact. Acknowledging that the desired management outcomes we select come from our own perceptions, experience, and values is an important step in defining sustainability for particular systems. Defining water sustainability goals requires decisions that result in a series of tradeoffs, with “winners” and “losers” associated with each intervention. For example, diversion of water from the mainstem of the Colorado River for habitat restoration in Arizona will limit the water available for ecosystems in the delta in Mexico. The Colorado River water that flows through the Central Arizona Project is viewed as a renewable and valuable water supply for Arizona, but it diverts water supplies that might otherwise have flowed into Mexico or California. Moving water from one location to another, or from one sector to another (such as agricultural to urban transfers), always results in impacts of some kind. The key to such adaptations is anticipating the impacts and mitigating them to the degree that is possible.

In this context, there is an increasing need to better understand how both climate variability and change (in combination) affect our ability to achieve habitat and species protection goals. As noted above, part of this challenge includes recognizing the impact of climate variability and climate change trends at multiple time scales on management outcomes. This approach requires continuing improvements in our understanding of the drivers of the climate system, the interactions between the climate system and ecosystems, and the development of monitoring and management systems that allow enough flexibility to experiment with using new information. Connecting science and decisionmaking in this context means building better relations that “bridge the gap” between habitat managers, researchers, climate scientists, and water managers. Such tools can include ways of visualizing trends in data, ways of explaining interrelations in complex systems, models that disclose statistical correlations between precipitation and temperature, and species viability, etc.

It is important for water and habitat managers to optimize the use of what we already know about climate change, rather than waiting for more detailed information that may or may not be more useful. There is a high probability of increases in temperature and changes in distribution and intensity of precipitation, so these changes need to be anticipated within the management system to achieve water and habitat sustainability goals. It has been established in the context of the Intergovernmental Panel on Climate Change (IPCC) that warming is “unequivocal” and that the likelihood that recent trends are significantly influenced by human activities is greater than 90 percent. The “new news” from the latest version of IPCC (Parry and others, 2007) is a strong conclusion based on 20 of 22 models that northern Mexico and the southern portions of the Southwest are expected to have less winter precipitation in addition to warmer temperatures. This widely accepted conclusion (Milly and others, 2005; Seager and others, 2007; Dettinger and Culberson, 2008) is critical to managing habitat in this region. Further, evidence exists that droughts are increasing in length and severity and that the intensity of precipitation is increasing because of the higher moisture content in the atmosphere that accompanies higher temperatures. This tendency toward more extremes—at both the high and the low end of the spectrum—will further challenge water and habitat managers.

Climate Change Impacts

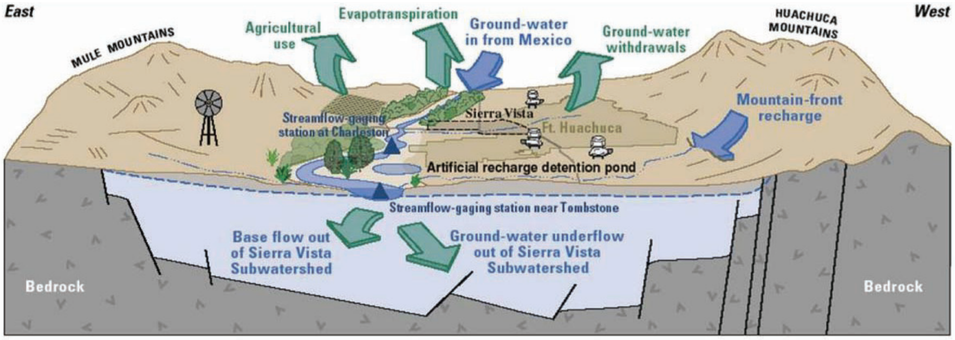
Water is a key delivery mechanism of climate change impacts—it is through the hydrologic cycle that the majority of climate change impacts can be felt. The observed changes in hydrology that are connected to climate change include changes in snowpack, seasonal patterns of runoff, increases in extreme precipitation, longer or more intense droughts, changes in water temperature and water quality, etc. (Stewart and others, 2005; Knowles and others, 2006; Karl and others, 2009). The impacts on human populations and the resources they value may be dramatically different depending on location and livelihoods. For example, ranchers who depend on rain-fed irrigation for grazing their cattle may have significantly more difficulty finding reliable forage; forest managers will face increasing risk from fire and bark beetles because of drought and more frost-free days; managers of habitat with endangered species need to be concerned that seasonal water availability could change dramatically, etc. For habitat managers, an important impact is that changes in timing of precipitation and runoff will affect environmental flow components that are critical for ecosystem health (low flows, high-flow pulses, floods).

Considerable focus has been placed on the likely reductions in flow of the Colorado River associated with climate change—the changes in temperature alone have significant impacts on both the supply side (increased evaporation from reservoirs, lower soil moisture, etc., leading to lower water availability) and the demand side (increased drought stress in plants, more water needed for irrigation, energy demand, etc.). Recent studies conducted within the National Oceanic and Atmospheric Administration (NOAA) Regional Integrated Science Assessments in the West (including researchers at NOAA, Bureau of Reclamation, Scripps, the University of Colorado, the University of Washington, and the University of Arizona) have reached a preliminary conclusion that a good estimate for reductions in supply is in the range of 15 to 25 percent by the year 2050, though this work is ongoing and no final conclusion has been reached. It is a useful exercise in any case to try to analyze the reasons why different models, methods, and datasets yield substantially different conclusions. Precipitation-runoff estimates at high elevations is an issue that is still being addressed. This is important since such a large proportion of the flow in the Colorado River is generated from snowpack at high elevations.

Although there has been a lot of focus on the Colorado River itself, little research exists on the implications for smaller tributaries, wetlands, or groundwater supplies within the watershed. Loss of snowpack—and resulting changes in seasonality of streamflow—will clearly impact these water supplies, but very few researchers have addressed the issue of groundwater implications of climate change or the implications for habitats dependent on the groundwater–surface-water interface (where surface water recharges the aquifer or groundwater aquifer outflow supports surface-water flows). It seems likely that a reduction in total streamflow will occur, and that this will result in less recharge, although in some cases major flood events have had significant impacts on aquifer storage. More research is needed in this area, because the implications of reductions in snowpack and changes in seasonality and intensity of precipitation differ for each watershed. The associated implications of climate change for water quality are understood at a conceptual level (e.g., higher temperatures reduce the oxygen level in streams), more fires will result in higher stream sediment loads, and higher runoff events can flush a load of pollutants into water bodies, but little is known at a scale that is useful for management decisions.

One way to think about the impacts of climate change within watersheds is changes in "partitioning" of precipitation—how much water is evaporated from bare soils, how much is evapotranspired by plants, how much runs off as surface flow, and how much enters the ground and recharges the groundwater supplies. This concept focuses on alternative pathways in the hydrologic cycle that can change in response to climate "drivers" like temperature. The following illustration of a cross section of the San Pedro watershed shows the fluxes in the hydrologic cycle as arrows (fig. 2). Clearly, if there is a reduction in winter snowpack, the amount of water that enters the aquifer as mountain front recharge will be reduced, which ultimately is likely to reduce the groundwater outflows that support the San Pedro River. Changes in seasonality of runoff are also critical for those who are working to protect habitat quality, because perennial flows are required for some species, and changes in the flow regime can affect multiple life-cycle components in ecosystems. There is much work to be done to enable us to understand the implications of reductions in snowpack, changes in seasonality of flows, and changes in intensity of precipitation for even one watershed, so generalizing lessons learned across the basins of the West is very challenging.

Managing for sustainability also requires a long-term perspective on how climate has varied in the past. Recently, Meko and others (2007) completed reconstructions of streamflows based on tree ring records that extend back more than 1,200 years. This reconstruction provides an opportunity to see how variability has changed over time, and also puts the climate of the past 100 years into perspective. As it turns out, the last 100 years generally was wetter than previous centuries, and the drought of the 1950s, which has always been considered to be "design drought" for the Southwest, was neither as deep or as long as droughts that occurred many centuries ago. The message that this sends to 21st century managers is that even without human-induced climate change, there have been devastating droughts that lasted for decades. The potential that the droughts of the future will be worse in a warmer world is very real, and most resource managers do not feel prepared for such droughts. Drought severity in a warmer world likely will be worse than recent historical drought experience because higher temperatures cause higher moisture stress, even if drought spells and reoccurrence patterns do



Simulated annual water budget for a ground-water-flow model — Values are in acre-feet per year

GROUND-WATER INFLOW

	Estimated range	2002 Estimates	2011 Projections
—Natural recharge	11,200–16,000	15,000	15,000
—Underflow from Mexico	3,000–3,400	3,000	3,000
—Total		18,000	18,000

GROUND-WATER OUTFLOW

	Estimated range	2002 Estimates	2011 Projections
—San Pedro base flow	3,250–6,290	3,250	3,250
—Net ground-water withdrawals		16,500	18,600
—Riparian and wetland evapotranspiration	6,230–7,700	7,700	7,700
—Ground-water underflow at Tombstone streamflow-gaging station	300–440	440	440
—Total		27,900	30,000

ANNUAL STORAGE CHANGE (no management measures)

—2002 Estimated	–9,900
—2011 Projected	–12,000

Figure 2. A cross section of the San Pedro River watershed in Arizona in the annual water budget.

not change. Evidence of this potential has been found by Breshears and others (2005) in analyzing tree mortality in the recent drought as compared to the drought of the 1950s.

A long-term perspective on climate variability is also helpful when managing for specific outcomes. Understanding trends in water-supply data when only 100 years of observed data are available can be very limiting—and in many watersheds fewer years of record are available. Depending on what years the trend line starts and ends, it is possible to come to entirely different conclusions about what is really happening to the water supply. For example, the long-term trend over the last century in flows in the Colorado River was clearly downward; however, if shorter time periods are selected for analysis, such as the period from 1955 to 1985, a very different conclusion would be reached about future water-supply availability in the region (fig. 3).

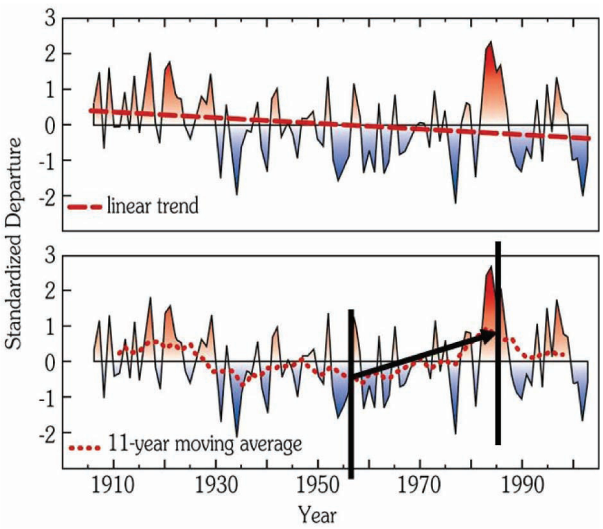


Figure 3. Long-term perspective of streamflow in the Colorado River (modified from McCabe and others, 2007).

Adaptive Management

Adaptive management is focused on monitoring the impacts of decisions that are made over time, in light of the fact that management decisions must proceed even if information is incomplete or inadequate. This management approach is essentially an ongoing experiment in optimization and a process for probing to learn more about the resource or system being managed. Thus, learning is an inherent objective of adaptive management. This is particularly appropriate in light of changing climate conditions. As we learn more, we can adapt our policies to improve management success and be more responsive to future conditions (Johnson, 1999).

Although adaptive management as a management framework is not always embraced by decisionmakers because it has a mixed record in the academic literature (Jacobs and others, 2003), it is better than managing changing systems as if there were no uncertainty. Clearly resource managers have to experiment with management options, because there are no perfect solutions available.

One approach to dealing with uncertainty is developing scenarios of a range of plausible future conditions and assessing how management objectives are affected by these alternative conditions. The careful use of scenarios can be helpful, because they can be used to assist in brainstorming potential options, evaluating the interaction between different kinds of variables, etc., before actually making decisions. The process of building scenarios is itself a learning process, because the work required to build credible baselines and trends builds understanding of the relations within complex systems. Further, the process of building scenarios can result in new knowledge networks among agency and academic scientists and researchers that can be useful resources for managers.

It is clear that we can make progress by improved monitoring of changing conditions and making better use of the data that we do collect. There is also a need to be more strategic about what is being monitored at what scale and time interval in order to identify and respond to regional and local trends and, thus, allow for better early warning systems. For example, because snowpack is a critical impact area for water resources, measuring snowpack dynamics in critical parts of the Colorado River watershed can improve our ability to project runoff conditions. There is also a need to continue to fund long-term observation stations to ensure the collection of longitudinal data, and for climate experts to engage more fully with resource managers in designing such systems.

Suggestions for enhanced monitoring while minimizing cost could include:

- Focus on critical or vulnerable systems;
- Build in operational, real-time delivery of observations;
- Provide better data access, storage, retrieval, and analysis systems;
- Provide for real-time trend analysis and visualization of data and develop "smart" monitoring systems;
- Provide feedback and evaluation of management impacts as part of each monitoring system.

Opportunities for environmental protection in the context of a changing climate include:

- Prepare for vulnerability in ecosystems by managing invasive species, protecting critical features of the natural hydrographs including low-flow standards, and providing for pulse flows that have important ecological benefits;
- Prepare for extreme events by protecting key habitat components, as preservation is always cheaper than restoration;

- Restore and maintain watersheds as an integrated strategy for managing water quality and quantity;
- Analyze effects on groundwater of drought and climate and protect groundwater recharge areas in critical habitats.

These suggestions are useful in any context—not just in the context of climate change. There are, however, multiple institutional and resource-related reasons why they are difficult to achieve.

Conclusions

Managing for water sustainability in the context of a changing climate brings multiple challenges. The demand for water supplies in many parts of the West is increasing over time because of shifts in use patterns at the same time that it appears supplies will be decreasing. This may be a zero sum game—and many decisions will have economic, political, or social consequences that overwhelm the ecological considerations. Key messages are that at a fundamental level, the past is no longer a good analogue for the future, as described in the "Death of Stationarity" article. Implications exist for water management and ecosystem management at multiple scales of time and space. Building planning scenarios of likely future outcomes to assess the impacts of a range of possible changes is one way to deal with uncertainty. A second important response is building flexibility into water management and ecosystem management systems and actively monitoring and assessing the effectiveness of management efforts. Although there are tradeoffs in flexible management systems because there is a reduction in certainty and a requirement for more professional judgment, still, decisions should be made that consider the ability of systems to remain resilient in the context of a range of future conditions. Finally, engagement between resource managers and climate experts could help frame the questions that need to be answered to incorporate both long-term climate trends and shorter scale variability into more sustainable resource management outcomes.

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Aquatic Production and Carbon Flow in the Colorado River

By Robert O. Hall, Jr.,[1] Theodore A. Kennedy,[2] Emma J. Rosi Marshall,[3] Wyatt F. Cross,[1, 4] Holly A. Wellard,[3] and Colden F. Baxter[5]

Abstract

Dams alter physical and biological processes in rivers in predictable ways, yet we have little understanding of how dams alter carbon fluxes into rivers and secondary production (elaboration of biomass through time) of animals. Production is essential to understand how the size of fish populations might be limited by the amount of available energy. We hypothesize that dams reduce inputs of transported organic matter to downstream river reaches with a subsequent increase in photosynthesis providing the energy base for the food web. We have begun measuring primary and secondary production in the Colorado River below Glen Canyon Dam. Primary production, i.e., the rate of photosynthesis, increases with declining suspended sediment concentrations and can equal rates from small, well-lit streams suggesting primary production is an important carbon source for the river food web. Aquatic invertebrates derive a large portion of their diet from algae when rates of primary productivity are high. Secondary production, i.e., the rate of invertebrate biomass accumulation, ranged from high below Glen Canyon Dam to low downstream near Diamond Creek; this variance likely is driven in part by the availability of carbon from photosynthesis. Knowledge of carbon flow within a managed tailwater like the Colorado River will assist in predicting outcomes of management decisions that alter energetics of food webs.

Introduction

The Colorado River drains a large fraction of the arid Intermountain West and is a primary water supply for users in seven States. The river holds a unique assemblage of fish species; of the 36 fish species that are native to the Colorado River system, 64 percent are found nowhere else (Carlson and Muth, 1989). The Colorado River has been extensively altered by dams to facilitate water storage and power generation. These dams alter the physical habitat and temperature regime in predictable ways (Ward and Stanford, 1983) and decrease biotic integrity, causing fish and invertebrate species to become locally extirpated. For example, the Green River in Utah below Flaming Gorge Dam lost more than 90 percent of its mayfly species following dam construction (Vinson, 2001) and now supports a productive, but nonnative, trout fishery. Four species of native fish are no longer found in the Grand Canyon reach of the Colorado River (Gloss and Coggins, 2005); one of the remaining species—humpback chub (*Gila cypha*)—is listed as endangered under the Endangered Species Act.

An important part of maintaining biological integrity at higher trophic levels is ensuring that there is a sufficient food supply to support the population. This need has been translated into policy as part of the strategic plan of the Glen Canyon Dam Adaptive Management Program, whose first goal is “Protect or improve the aquatic food base so that it will support viable populations of desired species at higher trophic levels.” But prior to managing the river for maintenance of an adequate food base it is necessary to measure carbon inputs to the ecosystem and determine how these are transferred up the food web to fish populations.

Declines in native fish populations and other undesirable changes in ecosystem function are, in part, a problem of energetics. Food limitation can be one of several aspects (e.g., predation, spawning habitat, migration) that can limit fish recruitment and production. For example, in the Colorado River tailwater of Glen Canyon Dam, artificially low water temperatures during most of the year limit rates of fish and invertebrate growth; high light penetration because of clear-water leads to increased rates of primary production; nonnative New Zealand mud snails (*Potamopyrgus antipodarum*)

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may represent a dead end for carbon flow in the food web because their thick shells protect them from fish predation; and nonnative trout, an important sportfish in the tailwater reach, may compete with and prey upon native fish in downstream reaches. Measuring organic matter flow into a river reach and through the food web in a common currency (g organic matter$\cdot$m$^{-2}\cdot$y^{-1}) provides a powerful framework for evaluating the effect of management actions on animal populations in the river. In addition, lower trophic levels will respond more quickly to changing dam operations than will slower-growing fish. The goals of this paper are to (1) describe why measurements of rates and sources of organic matter input into the river and associated production of animals can help us understand ecological function in heavily altered sections of the Colorado River, and (2) demonstrate the utility of these approaches from data we are collecting in the Grand Canyon reach of the Colorado River.

Carbon Inputs to the Base of River Food Webs

Animal production in any ecosystem, including rivers, is ultimately limited by the amount and quality of food resources entering the bottom of the food web. Physical conditions (e.g., habitat quality, temperature) certainly regulate the total animal production of an ecosystem, but the ultimate limits are set by the availability of carbon resources. Rivers with high rates of primary production or terrestrial inputs of carbon (i.e., leaf litter from streamside trees) can have higher rates of secondary productivity, assuming the physical conditions are also conducive to high production. For example, removing leaf litter inputs dramatically reduced secondary production of invertebrates in a mountain stream (Wallace and others, 1997). Secondary production of New Zealand mud snails in warm springs of the Yellowstone region are some of the highest ever measured for animal populations, but this is only possible because primary production of these springs is also extremely high (Hall and others, 2003). In turbid desert rivers, fish abundance can be higher in streams with higher rates of primary production (Fellows and others, 2009), suggesting that primary production is an ultimate control. In addition to the quantity of food resources, the quality of that food resource can also determine production. For example, adding nutrients to a heavily forested stream increased the nutritional quality, but not the quantity, of leaf litter that forms the base of the food web, thereby increasing invertebrate production (Cross and others, 2006).

We can categorize two main sources of carbon to rivers. Allochthonous carbon sources originate from outside the channel, such as leaves from streamside trees or organic matter that has been transported from a small headwater stream downstream to a large river. In contrast, autochthonous carbon is fixed by photosynthesis within the river channel by organisms such as algae or aquatic plants. Allochthonous inputs can dominate the carbon budget of many streams (Fisher and Likens, 1973) and rivers (Meyer and Edwards, 1990) and can be a dominant carbon source to consumers in food webs (Hall and others, 2000). Most streams and rivers are net heterotrophic, meaning that consumption of organic matter exceeds production of new organic matter, because allochthonous inputs allow ecosystem respiration to exceed primary production (Howarth and others, 1996; Webster and Meyer, 1997). Autochthonous production can exceed ecosystem respiration when the ecosystem is highly productive (e.g., small desert streams with warm water that receive abundant sunshine) and (or) when allochthonous inputs are minimal (e.g., spring streams that are for the most part isolated from the surrounding landscape) (Minshall, 1978). More often than not, the relative amounts of allochthonous versus autochthonous inputs vary through time; e.g., autochthonous algal production may dominate at certain times of the year when conditions promote high rates of photosynthesis (Roberts and others, 2007). For example, Roberts and others (2007) found that in a small Tennessee stream, autochthonous production dominated for roughly a 1-month period in the spring before leaf-out. Later in the spring and summer, shading by overstory trees limited algae growth, and in fall and winter leaf litter inputs supported elevated rates of ecosystem respiration, and autochthonous production was low.

Measuring the relative inputs of allochthonous versus autochthonous organic matter is an important step in a food web study because these resources represent the base of the food web, but relative differences in the quantity of these resources may not control which resource is actually providing the carbon source for animal consumers in a river. Algae, such as diatoms, are often a high-quality food source relative to more refractory allochthonous organic matter, so even a relatively small amount of primary production in a highly heterotrophic ecosystem may provide the primary energy source for food webs. In small streams, invertebrates derive their carbon from autochthonous sources at higher rates than predicted by relative differences in autochthonous and allochthonous inputs (McCutchan and Lewis, 2002). Evidence from large rivers suggests that algal production supports much of the animal secondary production, even in turbid rivers that carry large quantities of terrestrial organic matter where algal production is minimal, (Thorp and Delong, 2002). The Riverine Productivity Model (Thorp and Delong, 2002) posits that, despite large quantities of terrestrial inputs either from flood plains or from inefficient processing by upstream reaches, locally produced algal carbon should provide the base for riverine food webs. Evidence supports this model. Carbon isotope data from turbid, desert rivers show that primary production within the river channel supplies nearly all of the carbon to animals, despite high terrestrial inputs (Bunn and others, 2003). Primary production was locally high in these rivers even though they were turbid, and the combination of locally high production with high nutritional quality of algae relative to terrestrial inputs likely contributed to the importance of algae to the food web (Bunn and others, 2003). Hamilton and others (1992), also reported that in grass-dominated flood-plain lakes, animals received nearly all of their carbon from attached microalgae and not from the grass itself.

Production in the Colorado River Below Glen Canyon Dam

Primary Production and Consumption by Invertebrates

“Open-channel” methods are being used to measure primary production on the Colorado River (Odum, 1956; Hall and others, 2007). This procedure measures the change in oxygen (O_2) concentrations in the river as a surrogate for carbon because photosynthesis releases O_2 at approximately the same molar ratio as carbon fixation. Seasonally, we measure O_2 concentration throughout 2 nights and 1 day at five locations in Grand Canyon ranging from Marble Canyon to Diamond Creek. To calculate gross primary production (GPP; i.e., the rate of photosynthesis not including algal respiration), we use a model fitting procedure following Van de Bogert and others (2007), where we fit the following model to the O_2 data:

$$C_t = C_{t-1} + \frac{GPP}{z_t} \times \frac{PAR_t}{\sum PAR} + \frac{CR\Delta t}{z_t} + K(C_s - C_{t-1})\Delta t$$

C_t and C_{t-1} are O_2 concentrations across a 5-minute time step (Δt); C_s is the calculated saturation concentration of oxygen at a given temperature and barometric pressure. *K* is the rate of oxygen exchange at the air-water interface (1/d) and is calculated on the basis of measured oxygen exchange in the first 20 kilometers (km) of river (R.O. Hall and others, unpub. data, 2009); z_t is water depth (meters, m) at time *t*; PAR_t is the instantaneous amount of light hitting the river (µE m^{-2} s^{-1}) over a reach length equal to 80 percent of the O_2 travel distance; and ΣPAR is the total light summed for the day. Modeling oxygen concentrations and solving for GPP and ER (ecosystem respiration) is superior to standard calculations (Hall and others, 2007) because it allows calculating uncertainty in any one metabolism estimate. We calculated light as a function of river topography by following Yard and others (2005). The two variables that were solved for were GPP (g O_2 m^{-2} d^{-1}) and community respiration (g O_2 m^{-2} d^{-1}, CR). Because the river was consistently supersaturated with O_2, it was not possible to accurately estimate respiration using this technique, so we solved for CR, but the values were not reported. CR is not robust because it is not known what the O_2 concentration would be in the absence of biological activity. The common assumption is that streams would be at air-saturation if there were no CR and that CR lowers O_2 from this air saturation. Because the river was supersaturated, we have no reference point for which to measure respiration. GPP estimates, on the other hand, are robust because we are modeling the amplitude of the diel excursion and not the absolute concentration. We were able to measure rates of GPP despite extremely high rates of reaeration driven by rapids. Diel changes in oxygen concentrations were about 0.1 to 0.4 milligrams of oxygen per liter (mg O_2/L), which is small but easily modeled (fig. 1). We solved the model by minimizing the negative log-likelihood function between the model and the data. Because we measure invertebrate production by using g ash-free dry mass (AFDM, equivalent to organic matter), we converted these oxygen fluxes to organic matter assuming molar ratios between organic matter and O_2 = 1.

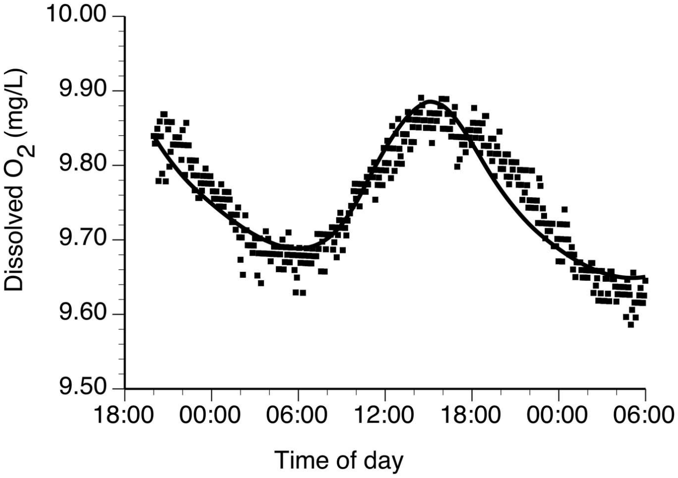

Figure 1. Example of oxygen data (points) versus model (line) for one metabolism calculation near National Canyon, AZ, from July 2008. Gross primary production was 2.6 g O_2 m^{-2} d^{-1}.

Gross primary production was strongly a function of suspended sediment concentrations (fig. 2); high sediment concentrations block light, thus reducing primary production. Because sediment concentration increases downstream, production tends to decline downstream when considering all seasons. The rates of primary production were similar to those in small streams across the United States (Mulholland and others, 2001), including those from high-light areas, which ranged from 0.2 to 24 g organic matter m^{-2} d^{-1} (Hall and Tank, 2003). Rates of primary production were greater than 10-fold higher than for water-column-based rates in tropical rivers (Lewis, 1988). The role of benthic algae in contributing to production in these tropical rivers was unknown but considered small (Lewis, 1988). Most production in the Colorado River is likely from river-bottom algae, though planktonic algae likely contribute to primary production because of a moderate amount of chlorophyll in the water column (0–2 micrograms chlorophyll *a* per liter (µg Chl *a* /L)). Because rates of GPP in the Colorado River can be as high as rates from small streams, the flux of carbon to this river from autochthonous primary production may be high enough to be important for

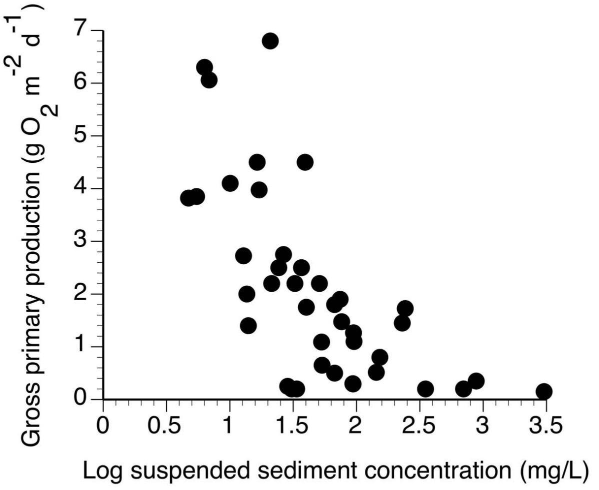

Figure 2. Daily rates of gross primary production decline as a function of $\log_{10}$ suspended sediment concentrations.

consumers, even though rates essentially are zero during times of year of low water clarity.

We also are attempting to make open-channel measurements of GPP in the Glen Canyon tailwater. However, because dam operations contribute to daily changes in O_2, in addition to the primary production of interest, open-channel measurements of GPP will require a different approach that is still being developed. Rates of GPP estimated from chambers that contained individual algae-covered rocks were very high: 15 g organic matter m^{-2} d^{-1} (Brock and others, 1999). This rate is up to 10 times higher than average rates for Grand Canyon. However, comparisons between chamber estimates and open-channel estimates must be made with caution, because high spatial heterogeneity in the distribution of river-bottom algae makes scaling rates measured on individual rocks up to the entire reach difficult. Nonetheless, these limited chamber data suggest that rates of production in the Glen Canyon reach are likely to be very high.

The rates of GPP in Grand Canyon are high enough for algae to represent a significant food resource for animal consumers. We have been measuring the diets of animals from all locations and across all seasons to calculate flows of carbon from basal resources into animal populations. These data show that algae (in this case, mostly microscopic algae known as diatoms) can constitute a large fraction of invertebrate gut contents (fig. 3); diets for the two taxa shown in figure 3 (*Simulium arcticum*, a filter-feeding blackfly, and *Gammarus lacustris*, a small crustacean) can contain up to 60 percent diatoms. Further, the proportion of diatoms consumed is positively related to the rate of primary production at the time and place the invertebrates were collected. These preliminary data suggest that below Glen Canyon Dam, primary productivity supports the growth and production of animal consumers. This finding is consistent with what is known about other desert rivers (Bunn and others, 2003) and theories of carbon flow in big-river food webs (Thorp and Delong, 2002).

Secondary Production of Invertebrates

The effect of large dams on diversity and assemblage structure of invertebrates in downstream ecosystems is well known. Many species of invertebrates have lifecycles that are cued in some way to temperature (Elliott, 1978). Because of relatively cold and constant temperatures downstream from high-head dams, many invertebrates are unable to complete their lifecycle and therefore become locally extirpated (Sweeney and Vannote, 1978). Consequently, the number of

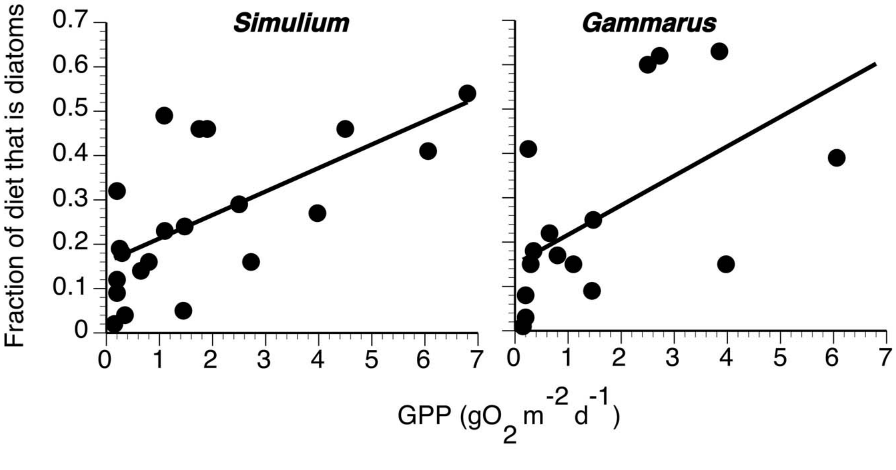

Figure 3. The fraction of invertebrate diet derived from diatoms increases with increasing rates of gross primary production (GPP). Lines are statistically significant least squares regressions, r^2 for *Simulium* = 0.41 and for *Gammarus* = 0.31.

invertebrate species often is lower below large dams than in free-flowing rivers. Before construction of Flaming Gorge Dam, the Green River contained more than 30 species of mayflies. After the closure of Flaming Gorge, the number of mayfly species declined to one common and two rare species (Vinson, 2001). Fewer data are available for the Colorado River below Glen Canyon Dam. Upstream from Lake Powell in Cataract Canyon, Haden and others (2003) found 49 invertebrate taxa of which 9 were mayflies. The Colorado River downstream from Glen Canyon Dam contains about 10 common taxa, none of which are mayflies (Stevens and others, 1997; W.F. Cross and others, unpub. data, 2009). The most common species in this reach are nonnative (i.e., *Oligochaetes*, *Gammarus lacustris*, and *Potamopyrgus antipodarum,* the New Zealand mud snail), suggesting that the Colorado River downstream from Glen Canyon Dam is best suited for stenothermic, cosmopolitan taxa.

To examine the degree to which the amount of invertebrates available for consumption by fish potentially limits the abundance of fish populations, it is necessary to estimate invertebrate production. Invertebrate production represents the amount of invertebrate biomass produced per area (square meters) per time (month, year). In other words, invertebrate production measures the flow of carbon per time through invertebrate assemblages. Although the exact procedures for determining invertebrate production are complicated, production is essentially the product of invertebrate biomass and invertebrate growth rates (Benke, 1984). Invertebrate biomass in tailwater sections immediately below dams is often high (Vinson, 2001), but it is not possible to estimate secondary production based solely on biomass because growth rates are strongly and positively related to temperature and taxonomic identity (Benke, 1984; Huryn and Wallace, 2000).

In contrast to what is known about benthic invertebrate assemblage structure, little is known about how dams alter invertebrate production. We have begun measuring assemblage-level secondary production from six sites in the Colorado River. The upstream site is in the tailwater and runs from Glen Canyon Dam to Lees Ferry. The downstream site is 240 river miles from the dam, at Diamond Creek, and four sites, more or less evenly spaced, are in between. To measure secondary production, we measure taxon-specific (a taxon is grouping of organisms, for example, mayflies) abundance and biomass monthly (Glen Canyon and Diamond Creek) or seasonally (four sites in Grand Canyon). We collect 18 to 20 samples per site each sampling period from a variety of habitats, sort, identify, and measure the length of invertebrates to the nearest 0.1 mm to estimate biomass using length-mass regressions for each taxon. We multiply these estimated biomasses by empirically measured, size-specific growth rates to calculate production as a flux (g organic matter m^{-2} y^{-1}). Secondary production is habitat weighted to reflect the fraction of different habitat types (e.g., cobble bars, cliff faces, sand, etc.) that are present within that particular reach of river. Currently we have data analyzed for 1 year at Glen Canyon and Diamond Creek.

Invertebrate secondary production was about 50 times higher at Glen Canyon than Diamond Creek (fig. 4). At Glen Canyon, production was dominated by New Zealand mud snails, scuds, and freshwater worms (subclass Oligochaeta). Annual invertebrate production in this reach is high relative to many streams and rivers and is in the upper 25 percent of values sampled from the literature (R.O. Hall, unpub. data, 2009). In contrast, annual secondary production in the Colorado River near Diamond Creek is in the bottom 10 percent of values from other streams and rivers and is in the range of “low production” values from Huryn and Wallace (2000). This difference in productivity between the two reaches is likely caused by higher primary production and more abundant hard surfaces in Glen Canyon; the sandy and unstable surfaces that are common along downstream reaches support lower invertebrate biomass and secondary production. It should be noted that the invertebrates that formally were present in this river may have had higher biomass and production in sandy sediments than those currently found.

Which of these two rates of secondary production is likely closest to that for pre-dam conditions? We do not know at this time because there are no secondary production estimates for river reaches in the Colorado River Basin, but we can examine invertebrate biomass at other sites as a first approximation. For example, average biomass on cobble habitats in the relatively unimpacted Cataract Canyon reach was 0.4 $g \cdot m^{-2}$ (Haden and others, 2003), which is comparable to our preliminary estimate of 0.55 $g \cdot m^{-2}$ for cobble habitats at Diamond Creek. For comparison, invertebrate biomass in the Glen Canyon tailwater reach is 7 $g \cdot m^{-2}$, or 17-fold higher than Haden and others’ (2003) value for Cataract Canyon. Despite

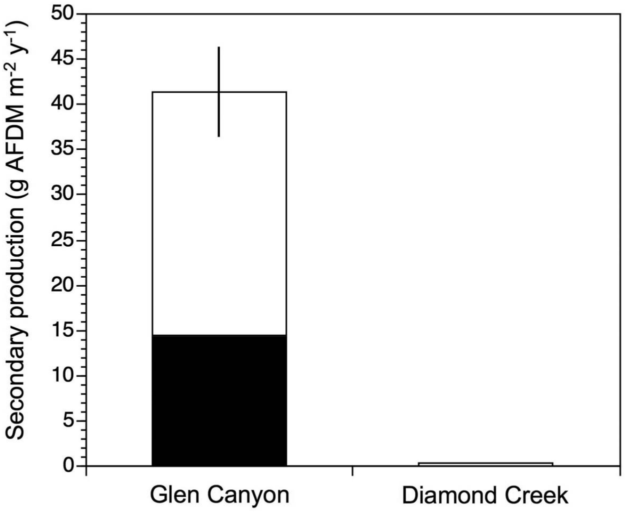

Figure 4. Secondary production in Glen Canyon reach is much higher than that for Diamond Creek reach of the Colorado River, AZ. The dark section of the bar for Glen Canyon is secondary production of New Zealand mud snails (*Potamopyrgus antipodarum*). Error bar is 95 percent bootstrapped confidence interval.

that biomass is similar between these two sites, we cannot speculate that production is the same because the thermal regime and assemblage structure are so different between the two sites that it is likely that assemblage-level biomass turnover and, therefore, secondary production will strongly differ also. Thus it may be that the high secondary production found immediately below a dam may be anomalously high relative to unregulated reaches or reaches where sediment inputs constrain primary and secondary production.

Prospectus

Despite a large body of research examining primary production (Mulholland and others, 2001; Roberts and others, 2007) and secondary production (Huryn and Wallace, 2000) in small streams, knowledge of primary and secondary production in nontidal rivers lags far behind. Measurements of phytoplankton and benthic production for many rivers using chamber approaches (e.g., Lewis, 1988; Cotner and others, 2006; Fellows and others, 2009) show that primary productivity can range from very low to high. In the Colorado River, rates of primary production essentially are unknown outside of rates for reservoirs (e.g., Gloss and others, 1980), and we are only beginning to measure rates of secondary production for animals. A limitation of our research in Grand Canyon is that we have no such data from before the construction of the dam, so we do not have a firm understanding of ecosystem function in the absence of a large dam. Currently, the only way to approximate pre-dam conditions is to perform similar measurements is parts of the Colorado River less altered by dams and other human activities, e.g., Cataract Canyon, Westwater Canyon, and the Yampa River. The huge reductions in downstream carbon transport and insect biodiversity (Vinson, 2001) and changes to habitat suggest that sections of the Colorado River less altered by dams will function much differently.

We argue that knowing rates of organic matter flow in the food web is critical for evaluating how management actions affect animal populations and ecosystem processes; evaluating the effect of management actions on resources is a critical step in the adaptive management process. For example, temperature strongly controls growth rates of invertebrates (Cross and others, in press; Huryn and Wallace, 2000). If a selective withdrawal structure is installed on Glen Canyon Dam to raise the temperature of releases, as was done for Flaming Gorge Dam, how will temperature-mediated increases to invertebrate growth rates alter secondary production and thus food availability for fish? If sediment inputs to the Colorado River increase because of sediment augmentation, how will reductions in water clarity alter riverine primary production and also secondary production of animals? Answers to these questions require detailed knowledge of food web energetics.

Acknowledgments

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An Overview of the Spread, Distribution, and Ecological Impacts of the Quagga Mussel, *Dreissena rostriformis bugensis*, with Possible Implications to the Colorado River System

By Thomas F. Nalepa[1]

Abstract

The quagga mussel (*Dreissena rostriformis bugensis*) was first found in the Great Lakes in 1989 and has since spread to all five lakes. Although its spread through the system was slower than that of the zebra mussel (*Dreissena polymorpha*), once established, it replaced zebra mussels in nearshore regions and is colonizing deep regions where zebra mussels were never found. Outside the Great Lakes Basin, quagga mussels do not appear to be increasing to any extent in the Ohio and Mississippi Rivers, even after being present in these rivers for over a decade. In contrast, numbers in the Colorado River system have continued to increase since the quagga mussel was first reported. It will likely become very abundant in all the reservoirs within the Colorado River system, but attain limited numbers in the mainstem. Ecological impacts associated with the expansion of quagga mussels in the Great Lakes have been profound. Filtering activities of mussel populations have promoted the growth of nuisance benthic algae and blooms of toxic cyanobacteria. In addition, the increase in quagga mussels has led to a major disruption of energy flow though the food web. An understanding of food webs in the Colorado River system, particularly the role of keystone species, will help define future ecological impacts of quagga mussels in this system.

Introduction

Two species of dreissenid mussels*, Dreissena rostriformis bugensis and Dreissena polymorpha* (quagga mussel and zebra mussel), are part of a group of biofouling, filter-feeding bivalves that are spreading around the world (Karatayev and others, 2007). When established in a new water body, these dreissenid species can increase rapidly and attain densities that generate far-reaching changes in physical, chemical, and biological components of the ecosystem. Many studies have documented ecological impacts of these two invading species, and broad patterns have emerged that are consistent across water bodies. Thus, to a certain extent, some ecological impacts can be predicted and prepared for. Yet other impacts have been unexpected and unique to a given taxa or habitat associated with the invaded system.

For several reasons, less is known of the specific life history, environmental tolerances, and impacts of quagga mussels compared to zebra mussels. The zebra mussel colonized North America first and quickly attained high densities, resulting in ecological changes that were widely evident and well documented (Nalepa and Schloesser, 1993). In comparison, the quagga mussel spread less rapidly, and impacts could not, at least at first, be readily discerned from the zebra mussel. Recent evidence, however, suggests that although ecological changes in the Great Lakes resulting from the proliferation of quagga mussels are functionally similar to those of the zebra mussel, the changes are more severe and pervasive in scope. As studies show, the quagga mussel spreads just as rapidly as the zebra mussels once established, is more flexible in colonizing different habitats, and attains higher densities in certain lake areas.

This paper summarizes current knowledge of the spread, life habit characteristics, and broad ecological impacts of the quagga mussel. Given the discovery of quagga mussels in the Colorado River system, such a summary may be useful when assessing ecological risks to this system. Quagga mussel characteristics and ecological impacts are presented in relation to the zebra mussel since both species have been introduced into Western States, and both frequently co-inhabit an invaded system during the early stages of the colonization process. Both dreissenid species attach to hard substrates and create clogging problems for power companies, water plants, and other raw-water users; however, it is beyond the scope of this summary to include a discussion of control options.

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Expansion Patterns and Taxonomic Definition

The quagga mussel was first reported in North America in 1989 in the eastern basin of Lake Erie. Like the zebra mussel, which was discovered several years earlier, the quagga mussel was likely introduced into North America via the discharge of ballast water from transoceanic ships. Based on genetic studies, these first North American individuals appear to have originated from the lower Dnieper River, Ukraine (Spidle and others, 1994; Therriault and others, 2005). Although given a common name, the taxonomic status of the quagga mussel was at first unclear, but was later determined to be *Dreissena bugensis* on the basis of allozyme data and morphological characters (Spidle and others, 1994). In subsequent analysis, this species was also found to be genetically similar to *D. rostriformis*, which is a brackish water species found in the Caspian Sea (Therriault and others, 2004). Given this clear separation in environmental tolerances (freshwater versus brackish water) and following rules of nomenclature, *D. bugensis* is currently considered a freshwater race of *D. rostriformis* and referred to as *Dreissena rostriformis bugensis.*

After first discovery in Lake Erie, the quagga mussel proceeded to spread into all the other Great Lakes, first into Lake Ontario, then into Lakes Michigan and Huron in 1997, and finally into Lake Superior in 2005 (Nalepa and others, 2001; Grigorovich, Kelley, and others, 2008). It was found in the Ohio and Mississippi Rivers in the mid-1990s, and in Lake Mead within the Colorado River system in 2007 (U.S. Geological Survey Web site: *http://nas.er.usgs.gov/taxgroup/mollusks/zebramussel/*). The spread of the quagga mussel within the Colorado River system has been rapid; by the end of 2008, it was reported in over 30 lakes and reservoirs in Arizona, California, Colorado, Utah, and Nevada. The likely vector by which mussels spread from the east to the far west was via the overland transport of recreational boats.

A unique aspect of quagga mussel populations in North America is the presence of two phenotypes. Although genetically similar (Claxton and others, 1998), these two phenotypes prefer vastly different habitats. In the Great Lakes, one phenotype (*D. r. bugensis* "sensu stricto-eplimnetic"; Claxton and others, 1998) is found exclusively in shallow-warm bays and basins, and the other phenotype (*D. r. bugensis* "profunda"; Dermott and Munawar, 1993) is found mostly in deep, cold offshore regions but also in some nearshore areas above the thermocline. The profunda phenotype has not been specifically reported from European waters, but some individuals from the Ukraine resemble North American specimens (A. Protosov, Institute of Hydrobiology, Ukraine, written commun., January 2009). Interestingly, North American specimens of profunda are more genetically similar to North American specimens of the epilimnetic phenotype than to specimens from the lower Dnieper River, Ukraine (Spidle and others, 1994). The dominant phenotype found in various water bodies in the Western United States, including the Colorado River system, is not clear at this time.

Although the quagga mussel has been found in large river systems in eastern Europe, it tends to reach greatest abundances in lakes and reservoirs (Mills and others, 1996; Orlova and others, 2005). This species was confined to its native range in the lower Dnieper–Bug River systems (northern Black Sea) until the late 1940s/early 1950s when a series of reservoirs were constructed on the Dnieper River system (Orlova and others, 2005). It is believed that these impoundments led to environmental changes (i.e., reduced water velocity, more stable temperatures), which better suited this species. Over the next several decades, the quagga mussel gradually expanded its range into the Volga River and Don–Manych River systems and more recently (2004–2007) into the Rhine, Danube, and Main Rivers in central Europe (Popa and Popa, 2006; Molloy and others, 2007; van der Velde and Platvoet, 2007). Overall, population growth in European rivers has been less rapid than in lakes/reservoirs, and abrupt, unexpected declines have been reported in some river systems (Zhulidov and others, 2006). Similar expansion patterns (i.e., a preference of lakes/reservoirs over rivers) are apparent in North America. For instance, while quagga mussels increased rapidly once established in Lakes Ontario and Michigan (Mills and others, 1999, Nalepa and others, 2009), a recent study in the upper Mississippi and Ohio Rivers found that quagga mussel distributions had not greatly expanded since being reported 10 years earlier, and densities remained uniformly low (Grigorovich, Angradi, and others, 2008). For the Colorado River system, these expansion patterns would indicate that the quagga mussel will increase more rapidly and attain greater abundances in the reservoirs of this system than in the river itself.

Physiological/Environmental Tolerances and Morphological Characteristics

The quagga mussel has several physiological and morphological features that allow it to proliferate in lake habitats where environmental conditions limit zebra mussels. In laboratory studies of both species, quagga mussels had a lower respiration rate under different seasonal temperatures and a higher assimilation efficiency, particularly at low food concentrations (Baldwin and others, 2002; Stoeckmann, 2003). Lower respiration and higher assimilation efficiency allow quagga mussels to better survive and grow under a wider variety of food regimes. In the Great Lakes, quagga mussels are expanding in offshore regions where food resources are naturally low and are also attaining high densities in shallow regions where food can be limiting during certain seasonal periods. These physiological traits are the likely reason why quagga mussels are displacing zebra mussels in many lake areas (Wilson and others, 2006; Nalepa and others, 2009). In addition, quagga mussels can reproduce at lower water temperatures compared to zebra mussels. Both quagga mussel phenotypes displayed gonadal development and spawned at water temperatures of 4–9 degrees Celsius (°C), whereas zebra mussels showed no reproductive activity at these low temperatures (Claxton and Mackie, 1998). Thus, quagga mussels can not only reproduce and thrive in deep, hypolimnetic regions, but can also spawn earlier in the spring than zebra mussels in shallow, epilimnetic regions.

As noted, population growth of quagga mussels in large river systems such as the Ohio and Mississippi has been slow (Grigorovich, Angradi, and others, 2008). Large rivers usually have elevated levels of suspended inorganic sediments (silt and clay), which negatively affect dreissenids in various ways. Inorganic particles foul gills and interfere with respiratory function. Also, these particles, although filtered, have no nutritional value. Mussels expend energy in expelling these particles that is better spent for growth and reproduction. Since quagga mussels are less widely distributed than zebra mussels in the Ohio and Mississippi Rivers (Grigorovich, Angradi, and others, 2008), it seems logical to assume that quagga mussels are less suited physiologically to handle suspended particulates. Yet laboratory experiments have shown that the two species respond similarly to elevated levels of suspended material; to a degree, both species were able to adapt to increased levels of turbidity (Summers and others, 1996). Regardless of some ability to adapt, both species are negatively affected by high concentrations of suspended sediments. The potential for zebra mussel growth was zero/negative at suspended sediment concentrations greater than 100 milligrams per liter (mg/L) (Madon and others, 1998). Concentrations typically found in the Ohio and Mississippi Rivers are below this level, whereas levels in the Missouri River are far above it (Summers and others, 1996). This may explain why few zebra mussels and no quagga mussels were found in the Missouri River system in a recent study (Grigorovich, Angradi, and others, 2008).

While quagga mussels thrive in deep, continuously cold environments, of relevance to their expansion in the Southwest United States is their tolerance to high summer temperatures. In several laboratory studies, quagga mussels were found to be less tolerant of elevated water temperatures compared to zebra mussels. The upper thermal tolerance limit for quagga mussels was about 30 °C, but could be as low as 25 °C because mussels could not be maintained in the laboratory at the latter temperature (Domm and others, 1993; Spidle and others, 1995). Given this, it is unlikely temperature will limit populations in the mainstem of the Colorado River system where temperatures range between 5 and 20 °C (Kennedy, 2007). In Lake Mead, mean monthly temperatures in the summer are 26–29 °C in shallow regions (<4.5 meters (m) water depth), and thus temperature-induced stress may eventually limit populations in this region. However, mean temperatures do not exceed 22 °C in deeper regions (>18 m water depth) (*http://www.missionscuba.com/lake-mead/lake-mead_average-water-temp.htm*). When considering temperature limits, other environmental factors must also be considered such that laboratory studies of upper lethal temperatures are often not good predictors of success in the natural environment. Quagga mussels exposed to unfiltered Ohio River water survived high, sublethal temperatures (>30 °C) better than zebra mussels (Thorp and others, 2002). This was attributed to the differential ability of quagga mussels to obtain and assimilate food at higher temperatures. Relevant to this issue, it is noted that quagga mussels are presently very abundant even in the shallow, warmer regions of Lake Mead (B. Moore, University of Las Vegas, oral commun., November 2008).

Besides temperature, another important environmental variable that affects quagga and zebra mussel distributions, and eventual population densities, is calcium concentration. Mussels require calcium for basic metabolic function and for shell growth. Based on field distributions, quagga mussels apparently have a slightly higher calcium requirement than zebra mussels. In the St. Lawrence River, quagga mussels were not found in waters with calcium concentrations lower than 12 mg/L, while zebra mussels were present (but not abundant) at concentrations as low as 8 mg/L (Jones and Ricciardi, 2005). Calcium concentrations in the Colorado River system are far greater than the values above, so calcium limitation is not an issue (Whittier and others, 2008). Indeed, high concentrations in this system (>80 mg/L) may favor quagga mussels over zebra mussels (Zhulidov and others, 2004). A summary of mussel tolerance limits for other environmental variables, such as dissolved oxygen, pH, and salinity, is provided in Cohen (2007).

The shell morphology of the quagga mussel differs from the zebra mussel in that it has a rounded ventral margin compared to one that is sharply defined. The lack of a flattened ventral surface does not allow the quagga mussel to attach as tightly to hard surfaces as the zebra mussel, and may prohibit it from easily colonizing habitats with strong water velocities such as found in some rivers. Unlike zebra mussels, however, quagga mussels do not necessarily need to attach to hard substrates. They can lie unattached on their longer, wider lateral side, which is an advantage in soft substrates because it prevents sinking. The profunda phenotype has an incurrent siphon that is far longer than the incurrent siphon of both the epilimnetic phenotype and the zebra mussel (fig. 1). This elongated siphon, which can be three-fourths the length of the shell, is a characteristic of bivalves adapted to inhabiting soft sediments. It allows filtration above the layer of fine inorganic particles generally found suspended at the sediment-water interface.

General Ecological Impacts

Ecological impacts of dreissenids, both quagga mussel and zebra mussel, are a function of achieved densities and characteristics of the invaded system. Where conditions are favorable and dreissenids become abundant, fundamental changes in energy and nutrient cycling occur, and all

Figure 1. Comparison of the incurrent siphon of the zebra mussel (top), quagga mussel-epilimnetic phenotype (middle), and quagga mussel-profunda phenotype (bottom). Note the longer siphon of the profunda phenotype.

components of the food web are affected. Several articles have provided excellent, detailed summaries of ecological impacts of dreissenids (Strayer and others, 1999; Vanderploeg and others, 2002), so only far-reaching changes that have strong implications to resource managers will be presented here. Dreissenids are filter feeders and hence remove phytoplankton and other particulates from the water. These filtered particles are ingested and assimilated or deposited on the bottom as feces or pseudofeces. Feces is material that is ingested but not assimilated, and pseudofeces is material that is filtered but not ingested (rejected). As a result of these filter-feeding activities, dreissenids divert food resources from other food web components, such as invertebrates inhabiting both the water (zooplankton) and bottom sediments (benthos). On average, dreissenid colonization in a given lake or river has been accompanied by a greater than 30 percent increase in water clarity, a greater than 35 percent decline in phytoplankton biomass, and a greater than 40 percent decline in zooplankton (Higgins and Vander Zanden, 2010). Impacts on benthic invertebrate communities have varied depending on feeding mode and habitat of the particular species (Ward and Ricciardi, 2007). Species able to feed on dreissenid biodeposits (i.e., feces and pseudofeces) or positively influenced by greater habitat complexity offered by mussel beds (predation refuge) have increased in abundance. On the other hand, species that filter feed or depend on fresh sedimentary inputs of phytoplankton have declined. Changes in the abundance and composition of pelagic and benthic invertebrate communities ultimately affect the fish community because fish rely on these invertebrate groups as a source of food. Fish impacts depend on habitat, diets, and population state of the particular species (Vanderploeg and others, 2002; Strayer and others, 2004; Mohr and Nalepa, 2005), but dreissenid impacts on the fish community are now becoming more apparent as quagga mussels increase and expand into new habitats.

The re-direction of energy and nutrient flow by dreissenids has been broadly termed the “nearshore shunt” (Hecky and others, 2004). In brief, dreissenids have shifted nutrient resources from pelagic to benthic zones and have focused them in nearshore relative to offshore regions. As an example, phosphorus concentrations in nearshore waters of the Great Lakes are increasing despite stable or decreased external loads (Higgins, Malkin, and others, 2008). The likely reason is that phosphorus associated with particles is being sequestered, mineralized, and excreted in soluble form by dreissenids found at high densities in nearshore areas. In addition, phosphorus associated with dreissenid feces and pseudofeces is being deposited on the bottom, enriching bottom sediments and near-bottom waters. The combination of greater light penetration resulting from increased water clarity and the greater availability of phosphorus has led to increased growth of benthic algae and macrophytes (Lowe and Pillsbury, 1995; Skubinna and others, 1995). In particular, there has been resurgence in the nuisance benthic algae *Cladophora* in the Great Lakes since dreissenids became established (Higgins, Malkin, and others, 2008). Overall, nearshore regions have become more nutrient enriched and benthic productivity has increased, whereas offshore regions have become more nutrient starved and pelagic productivity has declined.

Dreissenids have also been implicated in the resurgence of cyanobacteria blooms in some bays and basins of the Great Lakes and in some inland lakes (Vanderploeg and others, 2001; Knoll and others, 2008). Blooms were common in the Great Lakes before the mid-1970s as a result of excessive nutrient input (phosphorus), primarily from point-source loads. After nutrient abatement programs were initiated in the mid-1970s, cyanobacteria blooms were rarely observed. Blooms began to reappear just after dreissenid colonization in the early 1990s, and now extensive blooms occur almost every summer (Vanderploeg and others, 2002). Cyanobacteria are a group of phytoplankton associated with taste and odor problems in drinking water, and some species/strains produce toxins that are detrimental to human, animal, and ecosystem health. The most frequent bloomer in the Great Lakes is *Microcystis*, a taxa that produces microcystin, a hepatotoxin. During bloom events, microcystin concentrations often exceed the World Health Organization limit for drinking water of $1 \cdot \mu g\ L^{-1}$ (Dyble and others, 2008). Dreissenids promote cyanobacteria through the process of selective rejection (Vanderploeg and others, 2001). As dreissenids indiscriminately filter phytoplankton from the water, they reject toxic strains of cyanobacteria as pseudofeces because of unpalatable taste or size. The rejected cells are still viable, and when the pseudofeces is resuspended in the water during turbulent mixing events, these cells grow rapidly because of diminished nutrient competition from phytoplankton that are filtered and assimilated by the mussels. An increase in cyanobacteria has not occurred in all water bodies invaded by dreissenids (i.e., Hudson River, some Dutch lakes). Some factors influencing whether or not a bloom occurs include the fraction of water column filtered by dreissenids, relative taste/size of the particular strain of cyanobacteria, and nutrient and light regimes (Vanderploeg and others, 2001).

A Case History: Quagga Mussels in Lake Michigan

The quagga mussel was first found in northern Lake Michigan in 1997 and within 5 years had spread throughout the lake (fig. 2) (Nalepa and others, 2001, 2009). Regular monitoring of populations at 40 sites of various water depths in the south indicated that abundances at sites shallower than 50 m increased rapidly after 2002 and began to peak by 2007 (Nalepa and others, 2009). Abundances at sites deeper than 50 m did not begin to increase until 2005 and were still increasing as of 2007. The quagga population in the main basin of the lake consists entirely of the profunda phenotype. While zebra mussels were present in the lake since 1989 and ecological impacts were long evident, several important aspects of the quagga mussel expansion were relevant in effecting additional ecological changes. First, in shallow regions (<50 m) the quagga mussel population attained mean densities that were seven times greater than mean densities ever achieved by zebra mussels. Second, the quagga population is presently increasing in the deeper, offshore regions where zebra mussels were never found. The net result is that overall dreissenid biomass (wet weight; tissue and shell) in the lake has increased dramatically since the expansion of quagga mussels. Based on lakewide sampling, dreissenid biomass increased from $2.6 \cdot g\ m^{-2}$ in 1994/1995 when only zebra mussels were present to $188 \cdot g\ m^{-2}$ in 2005 when quagga mussels became dominant (Nalepa and others, 2009). Estimated lakewide biomass increased to $529 \cdot g\ m^{-2}$ in 2007, which is a 203-fold increase in just 12 years.

The proliferation of quagga mussels in Lake Michigan has led to many ecological changes that were not evident when only zebra mussels were present in the lake. Spring chlorophyll concentrations have declined fourfold, recently falling to below 1 microgram per liter (µg/L) (G. Fahnenstiel, National Oceanic and Atmospheric Administration, unpub. data, 2009). Chlorophyll is an indicator of phytoplankton biomass, and levels usually peak in the spring because of an increase in diatoms. Diatoms are a phytoplankton group rich in essential nutrients and thus are an important food source for many pelagic and benthic invertebrates. The decline in the spring diatom bloom can be linked to the filtering activities of quagga mussels. During unstratified conditions in the spring, the water column is well mixed, and bottom-dwelling mussels in deep areas (below the thermocline) have access to phytoplankton found throughout the water column. Further, because mussels occur at the sediment surface, they can filter out diatoms before this rich food settles to the bottom and is available to sediment-dwelling organisms.

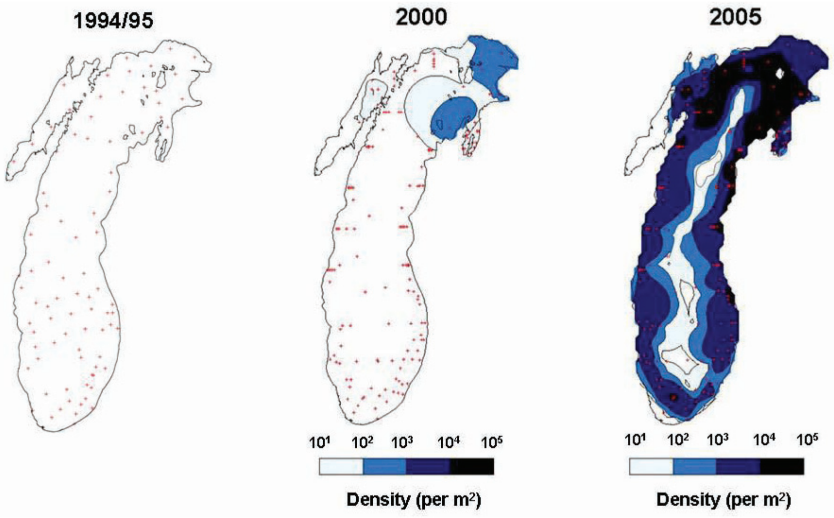

Figure 2. Mean density (number per square meter) of quagga mussels in Lake Michigan in 1994/1995, 2000, and 2005. The small red crosses are the locations of sampling sites.

Since dreissenids became established in Lake Michigan, water clarity in nearshore areas has increased twofold (Bootsma and others, 2007), and similar increases have been noted in offshore areas since quagga mussels became abundant (G. Fahnenstiel, National Oceanic and Atmospheric Administration, oral commun., 2009). Dissolved phosphorus in nearshore waters has also increased (Bootsma and others, 2007). The combination of increased light and available phosphorus has led to a proliferation of *Cladophora.* Biomass of this nuisance algae has increased nearly threefold along the rocky western shoreline between the pre-mussel period and 2006, with most of the increase occurring since quagga mussels became abundant (Bootsma and others, 2007). In late summer when temperatures increase, the *Cladophora* dies, floats to the surface, and gets washed up on shoreline beaches. The decaying algae harbors bacteria, creates a foul smell, and severely limits beach use (*http://dnr.wi.gov/org/water/greatlakes/cladophora/*).

Whereas zooplankton biomass in the lake has declined since quagga mussels became abundant (S. Pothoven and H. Vanderploeg, National Oceanic and Atmospheric Administration, unpub. data, 2009), perhaps the most dramatic change in the invertebrate component of the lower food web has been the loss of the native amphipod *Diporeia* spp. (Nalepa and others, 2009). This organism once dominated benthic biomass in Lake Michigan (>70 percent) and was a keystone species in the cycling of energy between lower and upper trophic levels. *Diporeia* lives in the top few centimeters of sediment and feeds on organic material settled from the water column, being particularly dependent upon the spring settling of diatoms as a food source. Declines in *Diporeia* were first observed in the early 1990s, just a few years after zebra mussels became established in the lake in 1989. As zebra mussels spread, declines in *Diporeia* became more extensive and by 2000 *Diporeia* had disappeared from large areas of the lake shallower than 50 m in water depth. The decline of *Diporeia* extended to lake areas greater than 50 m once quagga mussels expanded to these depths. This amphipod is high in lipids and a rich food source for fish, and studies have shown that its decline is having a negative impact on the fish community. For one, growth and condition of lake whitefish (*Coregonus clupeaformis*), an important commercial species that feeds heavily on *Diporeia*, have decreased 27 percent since the mid-1990s (Pothoven and others, 2001). Also, the abundance and energy density of many prey fish have declined where *Diporeia* was no longer present (Hondorp and others, 2005). Prey fish (alewife, *Alosa pseudoharengus*; sculpin, *Cottus* spp.; bloater, *Coregonus hoyi*; etc.) serve as prey for the larger piscivores (salmon, trout; *Oncorhynchus* spp.) within the lake. Lakewide biomass (wet weight) of prey fish declined from 91 kilotonnes in 2005 to 31 kilotonnes in 2007, which is down from 450 kilotonnes in 1989 (C. Madenjian, U.S. Geological Survey, oral commun., 2009). Most of the recent decline can be attributed to the collapse of the alewife population, which is a pelagic planktivore, but at times feeds on *Diporeia*. In contrast, lakewide biomass (wet weight) of quagga mussels was 36 kilotonnes in 2005 and estimated at 113 kilotonnes in 2007 (Nalepa and others, 2009). Thus, total biomass of the quagga mussel population in the lake is now estimated to be about 3.8 times greater than total prey fish biomass. Mussel mass represents a major energy sink and a disruption of energy flow through the food web. Some fish species are feeding on quagga mussels, but the problem with fish switching from food sources like *Diporeia* to mussels lies in the ingestion of the mussel shell, which comprises more than 80 percent of the total dry mass in quaggas. The shell offers little nutrition to the fish and represents an energetic cost to the fish in terms of handling, ingestion, retention time, and egestion. Further, there is an energetic cost to the mussel to produce the shell. Thus, energy is lost to the food web when the shell is ingested and also lost when the shell is produced.

Implications to the Colorado River System

It is difficult to predict all the relevant ecological changes that will result from the quagga mussel invasion of the Colorado River system. In the Great Lakes, some changes, such as increased water clarity, decreased phytoplankton biomass, and an increase in benthic productivity, could have been predicted from the European experience. Yet other important impacts, such as the return of cyanobacteria blooms and the loss of the native amphipod *Diporeia,* were unexpected. Ecological impacts are a function of mussel densities, and since mussels are proliferating in large reservoirs of the Colorado River system (i.e., Lake Mead; Moore and others, 2009), some changes in these reservoirs might be expected. In contrast, high levels of suspended sediment and high inorganic:organic particle ratios will limit, if not prevent, mussel expansion in the mainstem portions of the river (Kennedy, 2007). Yet even if mussels do not proliferate in the mainstem, some ecosystem changes may occur. The mainstem river is coupled to upstream reservoirs, and mussel-mediated changes in the water quality (i.e., dissolved nutrients, phytoplankton, zooplankton) of such reservoirs as Lake Powell and Lake Mead will likely impact food web structure or trophic linkages in the downstream riverine ecosystem. Concerns over increased algal blooms in the reservoirs are real, since blooms of some species have already occurred before the quagga mussel invasion (*Pyramichlamys dissecta* and *Cylindrospermopsis* r*aciborski*), and *Microcystis,* which now regularly blooms in some shallow, warm regions of the Great Lakes, is a component of phytoplankton communities in these reservoirs (St. Amand and others, 2009). Most certainly, productivity will shift from the pelagic to the benthic region, and an increase in biomass of many benthic invertebrates will likely result. Because bottom habitat drives the food web in some Colorado River reservoirs (Umek and others, 2009), this shift may benefit many bottom-feeding fish species, including some of the natives (i.e., razorback sucker, *Xyrauchen texanus*). On the other hand, the threadfin shad (*Dorosoma petenense*), a pelagic planktivore and a forage base for some sport fish, may be adversely affected much like the alewife was affected in the Great Lakes.

Currently, the quagga mussel population is expanding in the Colorado River system, but eventually the population will stabilize as abundances reach equilibrium with the surrounding environment. During this process, both acute and chronic ecological impacts will be realized as ecosystem components respond at different rates, leading to outcomes that can be both interactive and cumulative over time (Strayer and others, 2006). It may take many years, but eventually the ecosystem will reach a new, different steady state. Monitoring of key ecosystem parameters during this process is essential in understanding interactions that form the basis for a new paradigm of resource management.

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Economic Values for National Park System Resources Within the Colorado River Watershed

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Abstract

This paper provides a literature review of economic valuation studies of recreational use and other ecosystem services provided by National Park Service (NPS) resources in the Colorado River watershed. These parks are nationally important recreation and conservation resources and in 2005 had a total of about 10.5 million recreational visits to reservoir and river sites. Existing economic valuation studies can be grouped into two main areas: (1) estimates of direct recreational use values and (2) passive use values, including existence and bequest motives. With respect to recreation values, one study, now more than 20 years old was conducted for floating in Glen and Grand Canyons and for fishing in the Lees Ferry river section. No survey-based estimates of visitor by willingness to pay (WTP) have been conducted for Lake Mead, Curecanti, Dinosaur, or Canyonlands park units, which support over 80 percent of water-related visits to NPS Colorado River Basin park units. With respect to passive use values, a second study measured national values for improved conditions to Grand Canyon endangered fish and associated river ecosystems through modified flow regimes. The available economic valuation estimates for these resources are not comprehensive, do not consider Tribal perspectives, and are generally dated.

Introduction

For purposes of planning and participation in water-resource allocation decisions, the National Park Service (NPS) needs to know the economic values of the resources it manages within park units along the Colorado River system (including major tributaries). At present, the NPS does not have recent or comprehensive values to represent their current water-related activities within these Colorado River park units. The purpose of this paper is to summarize economic estimates relevant to these resources in the Colorado River Basin.

The NPS units located along the Colorado River and its tributaries (table 1) accounted for nearly 20 million recreational visits in 2005. Of these, more than 10 million visits were directly linked to water-based activities and, thus, were dependent to some extent on water levels within the Colorado River system.

Existing economic studies of NPS Colorado River park units and related economics literature can be grouped into two main areas: (1) estimates of direct recreational use values (net economic benefits as measured willingness to pay (WTP) over and above trip costs) and (2) passive use values, which include the benefits individuals derive from simply knowing that a unique natural environment or species exists even if the individual does not visit or see the resource. These are sometimes called existence and bequest values.

The impacts of water levels on recreational values occur through two influences: water levels influence the quality of the recreational trip and accordingly the WTP per trip, and water levels affect visitor participation. For example, river-sections use drops to zero at very low (impassable or quite dangerous) flow levels and to near zero in extreme floods. Participation and trip quality are generally optimized at intermediate flow levels. By contrast, use on some reservoirs increases continuously with reservoir elevations and is maximized at full pool. By identifying the relation of participation and value to water levels, it is possible to estimate the marginal value of water associated with recreational use. This typically is expressed in terms of dollars per acre-foot (af) of storage on reservoirs and dollars per cubic foot per second (ft^3/s) or per acre-foot per year on rivers.

Recreational visitation to NPS units within the Colorado River system is associated with significant economic values. These values generally are described within two distinct accounting frameworks: net economic value and regional economic impact. The first measure of value, net economic value, describes both the direct use value associated with park visitation and passive use value within the context of a benefit/cost framework. The second framework, regional economic impact analysis, describes the impact of visitor spending on a defined local or regional economic area. The focus in this paper is on net economic values.

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Table 1. National Park Service Colorado River units and associated visitation characteristics.

[NP, national park; NRA, national recreation area; NM, national monument]

Park unit	Waters	Type of water	Total 2005 visitation[a]	Colorado River water-related 2005 visitation[a]
Arches NP	Borders Colorado River	River	781,670	negligible
Black Canyon of Gunnison NP	Gunnison River	River	180,814	46
Canyonlands NP	Colorado and Green Rivers	River	393,381	11,508
Curecanti NRA	Blue Mesa, Morrow Point, and Crystal Reservoirs	Reservoir	882,768	882,768
Dinosaur NM	Green and Yampa River	River	360,584	12,802
Glen Canyon NRA	Lake Powell	Reservoir	1,863,055	1,863,055
	Colorado River	River	45,671	45,671
Grand Canyon NP	Colorado River	River	4,401,522	22,000[c]
Lake Mead NRA	Lake Mead	Reservoir	7,692,438	7,692,438
	Colorado below Hoover Dam	River		
	Lake Mojave	Reservoir		
Rocky Mountain NP	Headwaters of Colorado River	River	2,798,368	negligible

[a] Total 2005 recreational visitation from the National Park Service Public Use Statistics Office (*http://www2.nature.nps.gov/mpur/index.cfm*).

[b] The NRA units (Curecanti, Glen Canyon, and Lake Mead) are assumed to be entirely water-based recreation.

[c] Total float use of Grand Canyon has been relatively stable at 20,000 to 24,000 visits in recent years (Grand Canyon National Park Management Plan Final Environmental Impact Statement).

Direct Recreational Value Estimates

To date, the number of published estimates of the value of recreational visits to National Park System units nationwide is somewhat limited. Kaval and Loomis (2003) identified 11 studies that provided 49 activity-specific net economic value per activity day estimates. The activities included sightseeing, boating, picnicking, hiking, and wildlife viewing. Updating the Kaval and Loomis (2003) average estimates from 1996 dollars to 2005 dollars indicates an average value per day across all 49 observations of $53.88. The updated average that Kaval and Loomis report for the Southwest region national parks is $28.16.

To date, two major economic studies related to NPS-related uses in the Colorado River corridor have been conducted, both in the context of the Glen Canyon Dam studies. These studies had a fairly narrow geographic scope (just the river corridor through Glen Canyon and Grand Canyon). Both of these earlier studies focused on identifying marginal values, in the sense of measuring the change in value associated with moving from the base case or no action alternative in the environmental impact statement (EIS) planning process for Glen Canyon Dam to some specific alternative. By having these marginal values, it was possible in the EIS process to compare the tradeoffs of alternative uses, including recreation and power generation values.

The first Glen Canyon Dam economic study focused on recreational use and was undertaken by Bishop and others (1987). The second study focused on passive uses and will be discussed in a following section. The Bishop study was conducted as part of the Glen Canyon Environmental Studies efforts during 1984 and 1985. The overall goal of the Bishop study was to evaluate the impacts of alternative flow release patterns from Glen Canyon Dam on whitewater boating, day-use rafting, and fishing on the Colorado River below the dam. The authors of the 1987 study conducted a several-phase investigation in order to address their goal. First, user surveys were conducted to identify the attributes of fishing and floating trips that provided value to users. A second, more comprehensive contingent valuation (CV) survey of river users addressed potential changes in resource values associated with alternative flow release patterns. While Bishop and others (1987) found no statistically significant relation between flow levels and values associated with day-use floating below Glen Canyon Dam, they found a strong link between flows and both fishing and whitewater boating values. The study found that for whitewater rafters, relatively constant flows between 20,000 and 25,000 ft^3/s yielded the highest satisfaction and associated values. For anglers, a similarly constant flow regime in the 10,000 ft^3/s range yielded improved recreational trip values over existing flow regimes (Bishop and others, 1987). As an example of the range in values, the net economic value per trip (WTP over and above trip costs) for commercial whitewater boaters was estimated at $176 per trip ($319 in 2005 dollars) at a 5,000 ft^3/s flow level and rose to a maximum value of $602 per trip ($1,093 in 2005 dollars) at higher flows.

With respect to the significance of recreation use values in the Glen Canyon Dam operations context, the influence of flows on recreational values is primarily through the effect on the quality of the trip. There is excess demand for river recreation below Glen Canyon Dam (use is basically always at the permitted capacity in the main season). This limits the potential magnitude of changes in use values in response to changing flow regimes. By contrast, the nonuse value effects are quite large relative to the foregone power revenues for the alternatives examined and have allocative significance, as noted below.

For reservoir recreation within Colorado River Basin NPS units, Douglas and Johnson (2004) used 1997 survey responses for Lake Powell recreational visitors to estimate a travel cost model of WTP for trips to the reservoir. The authors estimated that per visit consumer surplus for Lake Powell visits ranged from $71 ($86 in 2005 dollars, based on a log-log model specification) to $159 ($174 in 2005 dollars, based on an inverse-price model specification).

Douglas and Harpman (2004) report dichotomous choice contingent valuation results for the same 1997 survey dataset as Douglas and Johnson (2004). The dichotomous choice question valued improvements in angler harvest, water quality (reduced beach closures relative to the 1991–1996 period), and archaeological site protection and restoration. The payment vehicle was the season pass. A current trip valuation question was not included. For the authors' preferred model, household benefits across the summer ranged from $396 (1997 dollars) to $1,100 per household per year. On a per visit basis, this implied a range in value of $9 to $39 per visit ($11 to $47 in 2005 dollars). It appears from the paper that this is just the incremental value of the improved trip. The value, particularly for the archaeological site scenario, may include passive use as well as recreational use value.

Martin and others (1980) estimated net economic value (NEV) per trip for anglers at Lake Mead. A zonal travel cost model was estimated for this warmwater fishery on data collected on anglers between July 1978 and June 1979. During this period, there were an estimated 1.3 million individual fishing days of use at Lake Mead, mostly targeting striped (*Morone saxatilis*) and largemouth bass (*Micropterus salmoides*). Estimated mean net benefits per individual fishing day were $45 to $61 ($126 to $174 in 2005 dollars), depending on the specification of the model. Martin and others (1980) also report angler expenditure per day with a mean value of $43 ($122 in 2005 dollars).

In 1998, visitors to two Colorado River NPS units (Glen Canyon National Recreation Area (NRA) and Grand Canyon National Park (NP)) were surveyed within the context of a study of visitor attitudes about the NPS Fee Demonstration Project. In addition to the survey questions related to the fee program, the surveys included a dichotomous choice WTP question designed to elicit per-trip NEV responses. These NEV responses were not part of the Fee Demonstration Program study objectives, and thus an analysis of the responses was not included within the study report (Duffield and others, 1999). A subsequent analysis of these responses indicates that for park visitors who said that visiting the units was the primary purpose of their trip away from home, visitors to Glen Canyon NRA have a median NEV per party trip of $109 ($157 in 2005 dollars). Visitors to Grand Canyon NP had a median NEV per party trip of $132 ($190 in 2005 dollars; table 2).

Just as there is an economic literature on in-stream flow values, there is a related literature on the effect of reservoir levels on recreation. Huszar and others (1999) developed and estimated a joint model of fish catch and recreation demand, both of which depend on water levels, to assess the losses and gains from water-level changes tied to events in the Humboldt River Basin of northern Nevada. Additionally, Eiswerth and others (2000) estimated recreation values for preventing a decline in water levels at, and even the total loss of, a large western lake that is drying up.

Table 2. Summary of literature and estimates of Colorado River National Park Service units direct recreational value estimates.

[NEV, net economic value; NPS, National Park Service; NRA, NRA, national recreation area; NP, national park; CV, contingent valuation]

Study	Description	NEV estimate	NEV estimate (2005 dollars)
Kaval and Loomis (2003)	Survey of literature – 11 studies providing 49 estimates of activity values within NPS units	\$53.88 per visitor day (2005 dollars)	\$54
Kaval and Loomis (2003)	Survey of literature – Estimates only for Southwest U.S. NPS units	\$28.16 per visitor day (2005 dollars)	\$28
Bishop and others (1987)	Study of values of Grand Canyon float boaters	\$176–\$602 per trip depending on river flow level (1985 dollars)	\$319–\$1,093
Douglas and Johnson (2004)	Travel cost study of Lake Powell recreationists	\$70.84–\$159.35 per visit consumer surplus (1997 dollars)	\$86–\$194
Martin and others (1980)	Study of Lake Mead recreation values	\$44.63–\$61.44 per angler day (1978–79 dollars)	\$126–\$174
Duffield and Neher (1999)[a]	Visitor survey of Glen Canyon NRA and Grand Canyon NP visitors. Estimates of per trip NEV based on dichotomous choice CV survey questions.	Glen Canyon NRA – \$109 per party trip Grand Canyon NP – \$132 per party trip (1988 dollars)	Glen Canyon – \$157 Grand Canyon – \$190
Douglas and Harpman (2004)	Dichotomous choice CV survey of improved trip quality scenarios (angler harvest, water quality)	\$8.63–\$38.92 per visit[b] (1997 dollars)	\$11–\$47

[a] Consumer surplus estimates were derived in an analysis subsequent to the preparation of the primary report on visitor attitudes regarding park fee increases.

[b] Not total value of current trip, but incremental values due to improvement.

Passive Value Estimates

Passive use values are an indication of the national significance of NPS resources. These values are associated with knowing that these resources are in a viable condition and with wanting future generations to also be able to enjoy this heritage.

These motives for nonuse values were first described by Weisbrod (1964) and Krutilla (1967) as existence and bequest values. Existence values can be derived from merely knowing that a given natural environment or population exists in a viable condition. For example, if there was a proposal to dam the Grand Canyon, many individuals could experience a real loss, even though they may have no expectation of ever personally visiting the river corridor through Grand Canyon. Other individuals might similarly suffer a loss if the grizzly bear were to become extinct in the Northern Rockies, even though those individuals may have no desire to directly encounter a grizzly. Bequest motives are derived from one's desire to provide for future benefit to children and others in future generations. There may be many possible motives for nonuse values, and these motives may or may not be mutually exclusive.

The methods used to estimate nonuse values are so-called stated preference methods (including contingent valuation and conjoint analysis (National Research Council, 2005)). Individuals are asked in a survey to indicate directly the value they place on nonuse services or resources. These methods are generally accepted and applied in policy analysis, as evidenced by their endorsement as a recommended method in regulatory guidelines. These include the Department of the Interior regulations for implementing the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (or CERCLA, at 43 CFR part 11) and in the U.S. Environmental Protection Agency's "Guidelines for Preparing Economic Analysis" (2000).

These methods have now been widely applied and reported in the published economics literature. When contingent valuation as a recommended approach was challenged in court (Ohio v. United States Department of Interior, 880 F.2d 432, 474 (D.C. Cir. 1989)), the court affirmed its usefulness for natural resource damage assessment. Additionally, in the context of the development of related regulations for implementation of the Oil Pollution Act of 1990 by the National Oceanic and Atmospheric Administration (NOAA), the use of contingent valuation was reviewed by a panel that included several Nobel laureates in economics. The panel endorsed the use of contingent valuation in a litigation setting, subject to the caveat that studies meet certain recommended guidelines (Arrow and others, 1993).

The National Research Council (2005, p. 6) offers the specific guidance that: "Economic valuation of changes in ecosystem services should be based on the comprehensive definition embodied in the TEV [total economic value] framework; both use and non-use values should be estimated."

Table 3 provides a summary of passive use studies relevant to water-related NPS resources, including lakes and rivers (in-stream flows and endangered fisheries). These selected studies are generally in the Southwest or intermountain West. All of the studies use stated preference methods, such as contingent valuation. Data are collected through surveys, generally of a resident population in a given geographic area. The choice of geographic area should correspond to the "market area" for the passive use service; that is to say, an area big enough to include most people expected to hold passive use values for the resource at issue. This area may be small for a county or city park of only local historical significance, but possibly national in scope for nationally significant resources such as Grand Canyon or Yellowstone.

Key characteristics of the studies summarized in table 3 include: (1) the resource service being valued, generally a change such as increased lake elevations or populations of an endangered fish, (2) the payment mechanism (e.g., increase in monthly water bill, increase in annual taxes, a one-time donation, etc.), (3) the population surveyed, and (4) the estimated values.

The previous estimates of passive use values for Colorado River park units have all been for Grand Canyon National Park resources including visibility, river flow-related habitat, and wilderness. The first such studies were focused on visibility impacts of the Navajo Generating Station and include Randall and Stoll (1983), Schulze and others (1983), and Hoehn (1991). These and other studies eventually led the U.S. Environmental Protection Agency on October 3, 1991, to issue a regulation requiring the Navajo Generating Station coal-fired powerplant to reduce sulfur emissions. In a 1990 study, the annual benefits of achieving 90-percent emission control was estimated to be between $130 and $150 million annually, compared to the estimated costs of this control of $89.6 million (1990 dollars). Deck (1997) describes both the benefit and cost studies that were the basis of this decision.

The only passive use study relating to water resources is the Welsh and others (1995) contingent valuation study undertaken as part of the Glen Canyon Dam EIS process. Harpman and others (1995) describe the importance of nonuse economic values as a policy analysis tool with specific reference to water-influenced resources in Grand Canyon.

In the Welsh and others (1995) study, contingent valuation methods were applied to estimate WTP to improve native vegetation, native fishes, game fish (such as trout), river recreation, and cultural sites in Glen Canyon NRA downstream from Glen Canyon Dam and in Grand Canyon NP (Welsh and others, 1995). This study utilized a population survey of two groups, Western U.S. households within the marketing area for Glen Canyon power and households in the entire United States. Respondents were asked questions of their WTP either increased electric power rates (Western U.S. sample) or higher taxes (national sample) to reduce flow fluctuations from Glen Canyon Dam to protect wildlife, beaches, and cultural sites. The study results (table 4) show that the "steady flow" scenario that was presented as being most beneficial to resource protection also had the highest associated values.

While the nonuse study for the Colorado River corridor in Grand Canyon NP (Welsh and others, 1995) was completed too late to be fully utilized in the 1995 EIS (U.S. Department of the Interior, 1995), the study findings did have an influence on the EIS outcome. The National Research Council panel that reviewed the Glen Canyon Environmental Studies (GCES) commented favorably on the study. Their report stated: "The GCES nonuse value studies are one of the most comprehensive efforts to date to measure nonuse values and apply the results to policy decisions. … While not completed in time to be reported in the final EIS, the nonuse value results are an important contribution of GCES and deserve full attention as decisions are made regarding dam operations" (National Research Council, 1996, p. 135).

The estimates of the Welsh and others (1995) contingent valuation study are conservative in that Welsh chose in his methodology to count only those "yes" respondents that also indicated they would "definitely yes" pay the stated amount. The use of only "definitely yes" responses has been shown in other CV validity studies to provide a valid estimate of actual WTP. Champ and others (1997) also found this result in assessing the nonuser social value of a program at Grand Canyon NP to remove compacted dirt roads on the North Rim to create a wilderness setting. A more recent study by Champ and her colleagues that is focused on riparian ecosystems (Duffield and others, 2006) also found that CV responses with a self-rated high certainty of actual contribution corresponded well with actual levels of cash donations. The application in this case was for purchases of in-stream flow rights on dewatered Montana streams, primarily to benefit riparian ecosystems, fishery species of special concern, and other wild fish.

Table 3. Empirical estimates of passive use values for water-related resources.

[WTP, willingness to pay]

Author	Survey year	Payment vehicle	Resource	Survey region	Value estimate
Lakes					
Sutherland and Walsh (1985)	1981	Annual payment into trust fund (per household)	Flathead Lake and River	Montana households	$19.99 existence $26.48 bequest
Loomis (1989)	1986–87	Monthly water bill increase (per household)	Mono Lake	California households and Mono Lake visitors	$4.12–$5.89 (households) $9.97–$12.15 (visitors)
Rivers					
Hanemann and others (1991)	1989	Annual household WTP (per household)	San Joaquin Valley	California	$181
Duffield and Patterson (1991)	1990	One-time donation to trust fund (per person)	In-stream flows in Montana trout streams	Montana resident and nonresident fishing license holders	$2.24–$4.64 (residents) $12.60–$17.36 (nonresidents)
Welsh and others (1995)	1994	Increased electric power rates or increased taxes (per household)	Colorado River riparian ecosystem	Western U.S. households and all U.S. households	$17.74–$26.91 (U.S. sample) $29.05–$38.02 (Western sample)
Brown and Duffield (1995)	1988	Annual WTP into trust fund (per household)	Bitterroot, Bighole, Clark Fork, Gallatin and Smith Rivers	Phone directory listings for major Montana cities and Spokane, WA	$6.70 (one river) $12.43 (five rivers)
Berrens and others (1996)	1995	Annual donation to trust fund for 5 years (per household)	Middle Rio Grande, Gila, Pecos, Rio Grande, and San Juan Rivers	New Mexico residents	$28.73–$89.68
Loomis (1996)	1994–95	Additional taxes for 10 years (per household)	Elwah River system	Clallam County, WA; rest of Washington; and rest of U.S. households	Clallam $59 Rest of Washington $73 Rest of United States $68
Berrens and others (1998)	1995–96	Annual payment into trust fund (per household)	Major rivers in New Mexico	New Mexico residents	$74
Berrens and others (2000)	1995–96	Annual payment into trust fund (per household)	Gila, Pecos, Rio Grande, and San Juan Rivers	New Mexico residents	$55
Duffield and others (2006)	2005	One-time donation to trust fund (per person)	Small Montana trout streams	Resident and nonresident Montana fishing license holders	$5.73 (residents) $31.07 (nonresidents)

Table 4. Welsh and others (1995) estimates of nonuse values for three Glen Canyon flow scenarios (2005 dollars).

Flow scenario	National sample		Western U.S. sample	
	Per household	Annual value (millions)	Per household	Annual value (millions)
Moderate fluctuations	$17.74	2,791	$29.05	79
Low fluctuations	$26.19	4,386	$28.25	80
Steady flow	$26.91	4,474	$38.02	107

Implications for Management

Table 5 presents a summary of the availability of existing data and estimates for the economic impacts of water flows and levels on Colorado River Basin park units. The basic finding is that existing studies are not adequate to support economic analysis, such as benefit-cost evaluation of alternative water allocations, for most units. There is a need to conduct additional economic research focused on water resource uses in the region.

Acknowledgments

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Table 5. Is sufficient information available to support benefit-cost evaluations?

[NEV, net economic value; NRA, national recreation area; NP, national park; NM, national monument; n/a, not applicable]

Park unit	Produce direct use total value estimates for water-based visitation?	Produce passive use estimates?	Estimate marginal impacts of water level on NEV?
Glen Canyon NRA			
Lake Powell	Yes	No	Yes
Colorado River (Glen-Lees)	No	No	No
Lake Mead NRA			
Lake Mead	No	No	No
Lake Mojave	No	No	No
Curecanti NRA	No	No	No
Grand Canyon NP			
Grand Canyon Float	Yes	Yes	Yes
Dinosaur NM			
Yampa and Green River	No	No	No
Canyonlands NP			
Cataract Canyon	No	No	No
Black Canyon NP	No	No	No
Arches NP and Rocky Mountain NP	n/a	n/a	n/a

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Confluence of Values: The Role of Science and Native Americans in the Glen Canyon Dam Adaptive Management Program

By Kurt E. Dongoske,[1] Loretta Jackson-Kelly,[2] and Charley Bulletts[3]

> *We don't see things as they are, we see things as we are.*
>
> —*Anaïs Nin*

Abstract

Grand Canyon and the Colorado River are important places on the landscape for many Native American Tribes. The Glen Canyon Dam Adaptive Management Program (GCDAMP) is designed to employ science as a means for gathering, analyzing, and disseminating information on the condition of resources. A Western science perspective dominates this program with recognition of Native American traditional perspectives as a valued component. Analogous to a confluence of rivers, Native American traditional perspectives were initially envisioned as enhancing the Western science approach by creating a more holistic understanding of this valued ecosystem; however, this integration has not been realized. Identified barriers to effective participation by Native American stakeholders are vast cultural differences that express themselves in complex sociocultural scenarios such as conflict resolution discourse and a lack of insight on how to incorporate Native American values into the program. Also explored is the use of "science" as a sociopolitical tool to validate authoritative roles that have had the unintended effect of further disenfranchising Native Americans through the promotion of colonialist attitudes. Solutions to these barriers are offered to advance a more effective and inclusive participation of Native American stakeholders in this program. Finally, drawing from the social sciences, a reflexive approach to the entire GCDAMP is advocated.

Introduction

Grand Canyon and the Colorado River are important places on the landscape that are central to the traditional values and histories of many Native American Tribes. During the development of the Glen Canyon Dam Environmental Impact Statement (GCDEIS), between 1991 and 1995, the Bureau of Reclamation acknowledged the importance of integrating Native American perspectives and values into the environmental analysis equation by providing five Tribes (Hopi, Hualapai, Navajo, Southern Paiute Consortium, and the Pueblo of Zuni) with cooperating agency status. The Glen Canyon Dam Adaptive Management Program (GCDAMP) was created in 1997 as a result of the Record of Decision for the GCDEIS and is designed to employ science as a means for gathering, analyzing, and disseminating information on the condition of natural and cultural resources to the appropriate managers.

A critical examination of the past 10 years of Tribal participation in the GCDAMP reveals a failure of the program to effectively integrate Native American perspectives. Our analysis and conclusions of the GCDAMP are based on direct participation as Tribal representatives. Our participation as Tribal stakeholder representatives began during the development of the Glen Canyon Dam Environmental Impact Statement and continues in the GCDAMP at the time this paper

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was written.[4] In this paper, we identify several barriers to effective participation by Native American stakeholders in the GCDAMP. Identified barriers include vast cultural differences among stakeholders that express themselves in complex sociocultural scenarios and a lack of insight by program managers and scientists on ways to affirm and respond to Tribal cultural concerns.

Also explored in this paper is the concept of Western science as it exists within the GCDAMP and how science is employed as a sociopolitical tool to validate authoritative roles within the program. The heavy reliance on Western science within the program is demonstrated to have had the unintended effect of promoting the disenfranchisement of the participating Tribes from the GCDAMP through the continuation of colonialist attitudes. Solutions to these identified barriers are proposed to advance a more effective and inclusive participation by the Native American stakeholders in this program. Finally, drawing from the social sciences, a reflexive approach to the entire GCDAMP is advocated.

Grand Canyon as Cultural Landscape

Grand Canyon and Colorado River are culturally important and represent astounding aspects of the landscape for most Americans and for individuals from across the globe. Grand Canyon has been classified as one of the seven natural wonders of the world and is also recognized as a World Heritage Site. Grand Canyon embodies a powerful and inspiring landscape that overwhelms the human senses.

In the late 1800s, Clarence Dutton (as quoted in Worster, 2001, p. 326) described Grand Canyon most appropriately when he stated that Grand Canyon is:

> More than simply two walls rising from the river, the Grand Canyon is a complex architectural wonderland some ten to twelve miles in breadth at its widest point. What nature has done here is precisely the work of an architect: chiseling, sculpting, cutting out large amphitheatres, naves, arches, and columns, leaving walls, spandrels, lintels. Hundreds of these mighty structures, miles in length, and thousands of feet in height, rear their majestic heads out of the abyss, displaying their richly-molded plinths and friezes, thrusting out their gables, wing-walls, buttresses, and pilasters, and recessed with alcoves and panels.

Nearly 100 years ago, in 1919, the beauty, diversity, and splendor of Grand Canyon and its importance as a natural and cultural jewel of the American people were formally recognized when Congress established Grand Canyon National Park. Since that time, many policies and programs have been developed to protect and preserve the diversity and unique qualities of Grand Canyon and the Colorado River ecosystem, and the GCDAMP associated with the operations of Glen Canyon Dam has become central to those efforts.

Although Grand Canyon and the Colorado River are recognized as culturally important to the greater American society, the Native American connection to this landscape existed and persevered for hundreds, if not thousands, of years before the arrival of Europeans (Schwartz, 1965; Euler and Taylor, 1966; Euler and Chandler, 1978; Schwartz and others, 1979, 1980, 1981). Native Americans relation to this vast place and their resultant knowledge of this landscape and environment are the product of a long temporal and intimate association, including having to depend upon and survive within this landscape. Given the brevity of this article, a full account of the cultural importance of Grand Canyon and the Colorado River to each of the Native American Tribes that participates in the GCDAMP is not possible. Presented below is a brief general summary of Grand Canyon's importance to participating Native Americans.

Grand Canyon and the Native American Tribes

According to multiple Tribal creation accounts, Grand Canyon is the place of origin and emergence into this the fourth world. The Colorado River, the canyons, the land, the middle of the river, and the springs, seeps, and tributaries to the river are essential to the well being, survival, and the collective and individual identities of many of the participating Tribes. As such, these Tribes are entrusted with the responsibility to care for the natural environment and the resources contained within Grand Canyon and their traditional homelands (Hualapai Tribe and Stevens, 1998; Austin and others, 2007).

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[4] The primary author began his involvement in this program in 1991 as the Hopi Tribe's representative to the cooperating agencies in the development of the Glen Canyon Dam Environmental Impact Statement (GCDEIS). He continued to represent the Hopi Tribe as their representative to the Technical Work Group and as the alternate representative to the Adaptive Management Work Group during the development and implementation of the Adaptive Management Program from 1996 to 2003. Mr. Dongoske also served as the Chair of the Technical Work Group for 5 years and is currently the Pueblo of Zuni's representative to the Technical Work Group. Ms. Jackson-Kelly represented the Hualapai Tribe during the development of the GCDEIS and has been the Hualapai Tribe's representative to the Adaptive Management Work Group since 1997. Mr. Bulletts is the Southern Paiute Consortium's representative to the Technical Work Group and the Adaptive Management Work Group, a position that he has held since 2006. Our analysis is based on direct participant observation and data acquired over an 18-year period that extends from the development of the GCDEIS to the origination and implementation of the Adaptive Management Program.

For many members of these Tribes, the Colorado River and the components of the ecosystem are regarded as living entities infused with conscious spirit. All of these elements in and around the canyons are accorded powers of observation and awareness. The Colorado River itself is regarded as an important conscious living being that has feelings and is expressive of calmness and anger. The river can offer happiness, sadness, strength, life, sustenance, and the threat of death. According to many of the Tribal beliefs, if a land and its resources are not used in an appropriate manner, the Creator will become disappointed or angry and withhold food, health, and power from humans.

Even though the current reservation lands of some of the participating Tribes are located far from Grand Canyon, these Tribes still maintain very strong ties with Grand Canyon, the Colorado River, and the Little Colorado River because of their origin and migration narratives. Traditional narratives describe the locations of shrines and sacred areas and explain why Grand Canyon is sacred. The daily prayers of many Native Americans incorporate specific locations, including sacred areas, shrines, springs, and other places of religious significance within Grand Canyon (Hart, 1995; Stoffle and others, 1995; Hualapai Tribe and Stevens, 1998). The animals, birds, rocks, sand, minerals, and water in Grand Canyon all have special meaning to the Native American people.

An Evaluation of Tribal Involvement in the Glen Canyon Dam Adaptive Management Program

Today, the Hualapai, Hopi, Navajo, and Zuni Tribes and the Southern Paiute Consortium are recognized as legitimate participants in the GCDAMP and have representatives to the Adaptive Management Work Group (AMWG) and the Technical Work Group (TWG).[5] The importance of Tribal participation in the GCDAMP was recognized by the stakeholders during the development and adoption of the GCDAMP's strategic plan. The strategic plan contains a vision and mission statement that recognizes Grand Canyon as homeland to Native American Tribes and a special place that contains properties of traditional cultural importance to Native Americans. It also acknowledges the "trust" responsibility of the Federal government to these Native American Tribes and recognizes their sovereign status and management authority.

The strategic plan also delineates 12 goals for the natural and cultural resources that are the focus of the GCDAMP. Management goal 11 addresses the preservation, protection, and management of cultural resources for the inspiration and benefit of past, present, and future generations. The recognition of past generations in this management goal is the acknowledgment by the program of the active on-going dynamic spiritual relationship contemporary Native American people have with their ancestors. Goal 11 also recognizes that the spirits of these ancestors still inhabit specific places (e.g., archaeological sites) within Grand Canyon. Accompanying management objectives 11.2 and 11.3 recognize the importance of maintaining and protecting places and resources of traditional cultural importance to Native Americans and ensuring unrestricted access to these places by Native American religious practitioners.

Management goal 12 seeks to maintain a high-quality monitoring, research, and adaptive management program that incorporates meaningful Tribal participation. Management objective 12.5 seeks to attain and maintain effective Tribal consultation through the inclusion of Tribal values and perspectives in the GCDAMP. Management objective 12.6 seeks to attain meaningful Tribal participation in management activities, research, and long-term monitoring to meet the Tribal interests to ensure that Tribal values are incorporated into the scientific activities of the GCDAMP and that Tribal interpretations are considered. Both of these management objectives are directly linked to the vision and mission statement discussed previously.

Even though the GCDAMP recognizes the importance of integrating Tribal involvement, a review of the past 10 years of research and monitoring programs indicates a rapidly declining role for the Tribes. At the inception of the GCDAMP there was significantly more Tribal involvement in research and monitoring projects than there has been during the past 5 years. For example, the Southern Paiute Consortium conducted event-specific research on dam impacts and developed a place and resource monitoring program and a corresponding educational outreach program for Paiute elders and youth (Stoffle and others, 1995; Seibert and others, 2007). The Hualapai Tribe conducted research and monitoring of places and resources between 1996 and 2003, including ethnobotanical research associated with the high-flow experiment that took place in 1996.

A sincere effort by Grand Canyon Monitoring and Research Center (GCMRC) to integrate Tribal perspectives into its terrestrial ecosystem monitoring program was put into effect between 1999 and 2002. This collaborative effort was not successful, because integration assumed that Tribal perspectives could be integrated into a framework defined and directed by the tenets of Western science. Moreover, GCMRC's inclusive intent was seriously constrained by the scientific perspective, which relies on credible, objective (i.e., numeric) data intended for model generation and a clear lack of understanding of Tribal perspectives (Austin, 2007).

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[5] The Havasupai Tribe was invited to participate in the development of the Glen Canyon Dam Environmental Impact Statement and to participate in the resultant Glen Canyon Dam Adaptive Management Program; however, they declined to actively participate on the basis of cultural and financial reasons.

Sociocultural Barriers to Effective Tribal Participation

Since GCMRC's failed attempt to integrate Tribal perspectives into the terrestrial ecosystem monitoring, there have been no further efforts at Tribal integration. The absence of a defined Tribal component in the current GCDAMP science program and a progressive decline in effective Tribal voices within the AMWG and TWG are attributable to a number of sociocultural factors. We submit several sociocultural barriers that exist within the GCDAMP that are actively limiting or marginalizing effective Tribal participation.

Cultural differences in communication present at the AMWG and TWG tables act as a barrier to effective integration. Here, Tribes are expected to communicate and act in the style of Western scientists and managers even though the Tribal representatives generally do not share the same cultural and (or) educational background of the majority of stakeholder representatives. Tribal representatives have expressed their discomfort with what they call the "bigger language of English" that dominates the TWG and AMWG meeting venues. Tribal representatives have articulated how they perceive non-Native Americans as expecting them to respond to words that are not normally employed by Tribal people. Some Tribal representatives have also expressed a feeling of condescension and intimidation associated with "bigger language of English" usage (Austin, 2007).

Strongly correlated with the discomfort associated with the use of the "bigger language of English" is the argumentative nature of many of the exchanges that take place during stakeholder meetings. Tribal representatives have expressed their discomfort with the volume and acerbity with which communication takes place and the propensity for interruptions that undermine one's ability and willingness to participate (Austin, 2007). Direct confrontation is considered impolite and inappropriate behavior within the cultural contexts of the participating Tribes and constrains the Tribal representatives' willingness to "speak up more" in meetings.

Another identified sociocultural barrier to effective Tribal participation is the uncertainty of managers on how to effectively respond to concerns and values expressed by Native American Tribal representatives. This was poignantly demonstrated when several of the Tribes expressed concern about the mechanical removal of nonnative fish at the confluence of the Colorado River and Little Colorado Rivers. These Tribes expressed their disapproval of taking of life that was associated with the planned removal and destruction of thousands of rainbow (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) as an experiment to control their predation of native fishes.

The Tribes also expressed concern about the location where this experiment was going to take place because the confluence of the Colorado and Little Colorado Rivers represents fertility and life and is considered sacred. One Tribal representative expressed his concern that the proposed mechanical removal would produce an "aura of death" over this sacred place (Leigh Kuwanwisiwma, Hopi Cultural Preservation Office, oral commun., 2002). The solution offered by managers was to provide the Hualapai Tribe with the processed trout remains to be used as fertilizer in Hualapai gardens. No solution was offered regarding the concern about the location. The conflict of cultural values expressed by the Tribe's objection to the "taking of life" associated with the implementation of this experiment was never sufficiently addressed by the program. Today, the mechanical removal is implemented regularly at the confluence of the Colorado and Little Colorado Rivers as a management action without further consideration of those expressed core Tribal concerns and values.

An additional example of sociocultural barriers underscores the deficiency of the program in effectively dealing with Tribal issues. The 2000 Protocol Evaluation Panel (PEP) of the GCDAMP cultural resources program recommended the development of a Tribal consultation plan. The panel emphasized that this plan should entail more than just improved coordination; a Tribal consultation plan would require Federal agencies and Tribes to agree to a process for communicating, coordinating, resolving differences, acknowledging roles and responsibilities, and establishing government-to-government relationships (Doelle, 2000). The development of the Tribal consultation plan began in 2001 and has been through various iterations; however, after 7 years and 14 drafts the plan has yet to be finalized or implemented. The extended delay in finalizing the Tribal consultation plan is symptomatic of the program's ineffectiveness and lack of ability to meaningfully integrate Native Americans.

Science as a Sociopolitical Tool

At the foundation of the GCDAMP is the role science plays in elucidating the integrated nature of the Colorado River ecosystem and a core belief that the Western science perspective is the only legitimate form of knowing the ecosystem. At the heart of this science program is a positivist approach to understanding the ecosystem that visualizes an unproblematically objective world presumed knowable via epistemologically transparent schemes of explanation (Whiteley, 2002). This perception of the world is rooted in the core Judeo-Christian philosophical perception of man's relationship to nature.

The GCMRC is the science provider for the GCDAMP and in that role it is ascribed an authoritative voice in ascertaining the condition of the ecosystem. The GCMRC employs science as a means for evaluating the health of the Colorado River ecosystem and the efficacy of management paradigms. The GCMRC also employs the concept of science tautologically as a rhetorical device for validating its authoritative role and justification of budgetary decisions.

As Ogden (2008) demonstrates for the Everglades, science when it becomes institutionalized can take on a life of its own and often is applied to meet the bureaucratic mandates of an agency. In the GCDAMP, resource goals have been bureaucratized into a set of scientific research and monitoring activities that structure the ways in which the ecosystem is comprehended and acted on. Within this context, Native American perspectives of the ecosystem are de-legitimized and marginalized in favor of the continued promotion and acquisition of scientific knowledge that supports the science program's philosophical underpinnings, self-interest, and authority.

All of these factors have contributed to the dominance of the Judeo-Christian perception of the world within the science program, which has had the unintended consequence of promoting antiquated colonialist attitudes toward Native Americans. These attitudes are a peculiar paradoxical blend of romanticized perception of Native Americans as the "noble savage" in the Rousseauian sense and at the same time antithetically perceiving them as a conquered people removed from the landscape as the result of a history of American Western expansionism. This explanation is offered not as an indictment of the GCDAMP, but as a possible rationale for the contradictory way in which the Tribes have been unsuccessfully included in this program.

Steps to a Holistic Integration

The dominance of science in the GCDAMP, to the exclusion of other valid forms of knowing the world, is in part the inability of the program to recogize that the fundamental differences between the dominant Anglo-American culture and Native American cultures lie not only in the acquisition of knowledge but also in the broader world views about what can be known about the world, who has the right to know it, and what is the proper place of humans in relation to nature (Austin, 2007). For an effective adaptive management program, differences in perception of and relating to the ecosystem must be more than just acknowledged. These differences must be embraced by the program with openness toward meaningful integration through validation.

This holistic integration can be accomplished through embracing Native American traditional knowledge in its complex forms composed of distinctive political and social perspectives rooted in a shared history, distinct ethical and cosmological knowledge, and a local knowledge of the ecosystem (Austin, 2007). The intimate ecological knowledge that the Tribes possess about the Colorado River ecosystem provides the authority and significance for their understanding and relating to this important place. This ecological knowledge is embedded in hundreds of years of directly relating to and living within the ecosystem, knowledge which has been passed on from generation to generation. The efficacy of the transmission and reliability of traditional knowledge has been well documented for ecology (Berkes, 1999), history (Whiteley, 2002), and ritual (Cushing, 1896; Bunzel, 1932).

Tribal knowledge about ecosystems is increasingly recognized as equivalent to scientific knowledge and is increasingly valued. As Hobson (1992, p. 2) points out:

> Often overlooked is the fact that the survival of aboriginal peoples depended on their knowledge, their special relationship with the environment, and their ways of organizing themselves and their values. Traditional knowledge was passed on from generation to the next. Today, aboriginal peoples are aware that they must integrate traditional knowledge into the institutions that serve them; it is essential to their survival as a distinct people, and it is the key to reversing the cycle of dependency which has come to distinguish aboriginal communities.

Traditional knowledge about the ecosystem is based then on empirical observations that are accumulated over generations providing an important diachronic perspective. Embodied within this perspective is an intuitive component that is based on observing natural resource patterns and relationships that are interpreted and integrated through the ethical and moral values and cosmological knowledge of the culture.

Accomplishing the holistic integration of Native American traditional knowledge into the GCDAMP necessitates a paradigm shift in the current science program toward an openness and willingness to accept traditional knowledge of the ecosystem on an equal basis as Western science generated knowledge. The past tendency of scientists and managers has been to reject Tribal traditional knowledge as anecdotal, non-quantitative, without method, and unscientific. For this perspective to change, a corresponding recognition that effective integration involves the sharing of power and decisionmaking by managers is essential.

A critical part of this paradigm change involves the acknowledgment by the science program that inherent in any interpretation of data and the resultant development of explanations about the ecosystem are developed through biased cultural lenses of managers and scientists. Cultural bias permeates the GCDAMP; it affects how resource data are interpreted, how knowledge is generated and defined, and how power for decisionmaking is ascribed and shared. Too little attention has been paid within the GCDAMP to developing effective mechanisms for bringing in and incorporating the knowledge and interests of Native peoples. For example, conspicuously absent from most discussions of Colorado River ecosystem management, especially for a place that is widely perceived to be a wilderness, are the poignant historical narratives of displacement, depopulation, and suffering that describe how this place came to be without humans and how the affected populations should be integrated into processes that are based in large part on assumptions that they or their ancestors are irrelevant to the ecosystem today (Austin and others, 2007).

A recommended first step toward effecting this paradigm shift is the development of a stronger social science component to the program administered by the GCMRC. Currently, the cultural resource program administered by the GCMRC is focused on the present condition of archaeological sites located along the Colorado River corridor and how current climatic conditions adversely impact or contribute to their preservation. In addition, the cultural program includes a recreation component that seeks to monitor and improve the recreational experience associated with non-Indian users of the Colorado River through Grand Canyon. Noticeably lacking in this cultural program is the integrated contributions that the disciplines of anthropology, sociology, psychology, and Native American studies can bring to this program. The integration of these disciplines would afford the program the tools to work toward the development of a holistic integration of Native American perspectives and values into the GCDAMP. Through the application of the tools that these disciplines can bring to the GCDAMP, a process for respectfully addressing and resolving conflicts of cultural values that arise within the program can be developed. Additionally, this process would allow for these conflicts to be addressed in a timely manner and thereby hopefully reduce feelings of disenfranchisement by a stakeholder group and the potential for litigious responses.

Confluence of Values

As noted above, the confluence of the Colorado and Little Colorado Rivers is a very important and significant place to the participating Tribes because of its literal and symbolic representation of fertility and life. The confluence is employed here as a metaphor to represent the fertility of knowledge and the beneficial outcomes that would result from the merging of diverse paradigms (i.e., scientific and traditional knowledge) for knowing the Colorado River ecosystem. Submitted for consideration is the view that this confluence is represented by three intersecting and overlapping circles of a Venn diagram (fig. 1). One circle represents the management paradigm of the GCDAMP, another circle represents the scientific paradigm about the Colorado River ecosystem, and the third circle represents the traditional paradigm of the participating Tribes regarding the Colorado River ecosystem, including their moral, ethical, and cosmological perspectives. The portions of the circles that overlap and intersect represent the successful merging of these three paradigms within the GCDAMP.

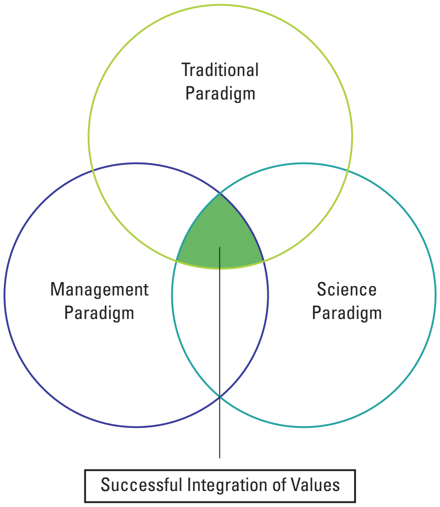

Figure 1. Confluence of values within the Glen Canyon Dam Adaptive Management Program.

This image of the confluence of values depicts a successful program of collaboration that recognizes, accepts, and seeks to integrate the diverse perspectives that scientific knowledge, Tribal traditions, and management represent. The future of working collaboratively with Native Americans within the GCDAMP rests on an honest understanding and appreciation of the diverse perspectives that have been presented above and a willingness to develop good faith communication channels between scientists, managers, and Native peoples that will only benefit the GCDAMP. When done correctly, the intersection of these competing paradigms provides an avenue for multiple views of the Colorado River ecosystem that can only enhance our understanding and appreciation of this important place.

Reflexive Approach to the GCDAMP

Finally, drawing from the social sciences, we advocate for a reflexive component of the GCDAMP. Reflexivity is an act of self-reference where examination or action “bends back on,” refers to, and affects the entity instigating the action or examination. In brief, reflexivity refers to circular relationships between cause and effect. A reflexive relationship is bidirectional; with both the cause and the effect affecting one another in a situation that renders both functions causes and effects. Reflexivity is related to the concept of feedback and positive feedback in particular.

As applied to the GCDAMP, we believe there is utility in examining the internal social dynamics of the program and the interaction among participating groups. Specifically, we believe that it is important to examine and understand the power and gender relationships that exist within the AMWG and TWG and how these affect discourses among the stakeholders and the recommendations they generate. Moreover, a reflexive analysis should examine the dynamics of cultural differences that are operant within this program, some of which have been presented above. Through the examination of these cultural differences, a clearer understanding of the role the dominant cultural bias plays within the program and how that bias impacts and directs the program’s perspective on ecosystem resources and data can be achieved. To this end, we encourage the planning and implementation of the GCDAMP effectiveness workshop, but that it should be expanded to include this reflexive component.

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The Promise and Peril of Collaboration in the Colorado River Basin

Remarks prepared for delivery by Kirk Emerson[1]

Thank you, John and Ted, for the opportunity to wrap up this morning after 2 1/2 days of packed information exchange on Colorado River science. I was invited to talk about collaboration and conflict resolution and chose a title for these remarks that should suggest that I will not be giving you a one-sided perspective on collaborative engagement; there can be a dark side to these efforts as well. However, I will suggest we can be smarter in how we do more and better collaboration in the future.

By way of background, I have lived in Tucson since 1995 when I came to the University of Arizona and started working on collaborative resource management as a political scientist. I had an earlier career in environmental planning at the county level back in Pennsylvania. My academic work soon got sidelined, however, for a good 10 years while I served as director for a Federal program called the U.S. Institute for Environmental Conflict Resolution at the Morris K. Udall Foundation in Tucson. The mission of the Institute is to assist Federal and nonfederal parties in working together to solve tough environmental and natural resource problems.[2] Sometimes that is done by mediating disputes referred by Federal court or administrative tribunals, but most often it is in helping public agencies and stakeholders reach common ground when developing policy, planning, siting, reviewing proposed actions, and managing environmental, natural resource, and public lands issues.

As a Federal program, the Institute has a national reach and works on issues all over the country from the Everglades to the coral reefs of the northwestern Hawaiian Islands. We have worked on a number of issues in the Southwest, all of which had important science components, many of which emerged from or became part of adaptive management efforts. For example, collaborative monitoring for forest management in New Mexico; recovery planning for the desert tortoise in the Southwest; sage grouse habitat conservation in the Northern and Central Plains States; Sonoran pronghorn protection on the Barry M. Goldwater bombing range; and many watershed and river basin restoration efforts involving multiple Federal, State, and Tribal actors in addition to nongovernmental stakeholders, the most ambitious of which is the recovery planning going on right now in the vast Missouri River Basin.

So I have had many opportunities to observe directly and indirectly a number of cooperative resource management efforts from the inside, but not as an insider, rather as a third party, bringing an outside perspective to the deliberations without a dog in the fight, other than to help people try to make more informed and equitable decisions together.

In the interest of full disclosure, I should note that my professional experience in the Colorado River Basin is limited, although I confess to some firsthand observation of beach improvements this spring when I spent 18 days on the river with the Grand Canyon Field Institute's annual rafting trip. This is also my first opportunity to attend a science conference about the Colorado River, and I am indeed overwhelmed with the breadth and diversity of the research being conducted.

My invitation to speak today included a charge to draw from the previous sessions and make connections for you between these presentations and the potential and challenges for collaboration as you move forward. I did my best to attend all the plenary sessions and at least sample sessions in each of the concurrent panel tracks. But my observations are certainly limited to what I was able to take in as well as what struck me as relevant to future collaborative science and management in the river basin. I will start with a few observations on what emerged for me from this symposium and then turn to a few comments about the promise and perils of collaboration, highlighting the need to:

- acknowledge just how hard it is to "do" collaboration and recognize some of the challenges that demand attention,
- pay more attention to basic principles of collaboration as well as challenge some of our long-standing assumptions, and
- refresh and adapt management programs, not just the science, over time.

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[2] Visit *http://www.ecr.gov* for more information about the U.S. Institute for Environmental Conflict Resolution.

What I have witnessed over the past few days in the sessions, along the corridors, and during meals and receptions is an amazing engagement of scholars and managers in the science of the Colorado River and its implications for management. At the same time, there are some signals of tough challenges ahead, primarily generated from outside the river basin, that will test the adaptive capacity of the physical and management systems even more.

First, as I understand it, this is the first science and resource management symposium of its kind encompassing the entire Colorado River Basin. What a feat! That alone certainly took cooperation among the basin programs and a lot of coordination. I would not underestimate the significance of this event itself. Could it have happened 10 years ago? Here is a quick thought experiment: Imagine what such a conference might have looked like in 1998 and consider the progress in your own fields of research since then. What would you have been presenting? What kinds of management questions would you have been asking? Who would you have been collaborating with on your research? How many young researchers and managers have been recruited to this work since then? Perhaps there are some of you who would be discouraged when answering these questions. But I would wager that most of you could personally attest to the progress that has been made in generating usable knowledge about the Colorado River. A substantial investment in research and resource management has been made over the past 10 years. Could it have been more? Well, of course so, that answer is always yes. But I hope you will just take a moment to acknowledge this symposium as a real-time benchmark in and of itself.

I would also observe that there has, no doubt, been an increase in collaborative science on the Colorado River over the past 10 years. I do not have the data for this myself, but it could be easily measured if it has not been already. The size and diversity of the research teams presenting over the last few days is impressive. Not just the number of scholars but the multi-institutional cooperation and support. Is this too an accomplishment of the investments made by your adaptive management programs? Have they leveraged more additional funding from multiple agencies and private sources? This is another benchmark for your collective accomplishments.

Several speakers talked about the need for better integration and coordination across the subbasin programs—to exchange information, compare findings, collaborate on data collection, etc. Perhaps this theme is a function of the novelty of this meeting, but it is impressive to me that people are talking about the need for integration, when so many other areas are competing for resources and defending turf. While I would generally agree with John Shields and Gerald Zimmerman that the diversity among the subbasins probably warrants continuing distinct programs, perhaps this interest in integration is another expression of the kind of “collaborative capital” that is being built throughout the Colorado River’s science and management community.

I would like to think so, because another theme arising from this conference is that there are significant external changes coming to the natural system that were not anticipated 10 years ago, and they will require all the collaborative capital you can muster. Chief among these challenges, of course, are invasive species and climate change. Brad Udall’s presentation on the warming trends in the Southwest and the likely reductions in rainfall and runoff was chilling, as were the data and projections on the quagga mussels by Thomas Nalepa from National Oceanic and Atmospheric Administration (NOAA).

These threats are no longer hypothetical and they will undoubtedly upset the management agreements and priorities for science that have previously been set along the Colorado River.

But such unexpected pressures, of course, are what adaptive management regimes are meant to handle, are they not? They are intended to be flexible and responsive to new discoveries, surprises, unanticipated outcomes, and changing conditions. Adaptive management is not just about trying to reduce uncertainty, it is also about sharing future risk, that is, building enough trust and transparency to allow for public experimentation and adjustment. Adaptive management is about enabling public decisionmaking that can tolerate some degree of failure in order to learn and adjust accordingly to prevent greater failure in the future.

Another recurring theme that suggests future challenges ahead was the mention of “incremental adaptation” by Kameran Onley when she referenced the National Academy of Sciences report and what I assume is a related phenomenon Kathy Jacobs brought up—“stationarity”—discussed in a recent “Science” article. While I cannot attest myself to the prevalence of incrementalism in any of the basin programs, it strikes me as a rather inevitable outcome of adaptive management approaches generally, which may not be a bad thing when you only have to effect change around the margins. But what about when bold, decisive action is demanded? Or when you have to adapt to 40 percent less annual runoff or manage the full-scale invasion of quagga mussels in Lake Powell or generate more hydropower to meet new renewable energy portfolio standards? It is likely that in the not too distant future more boldness will be required by Colorado River managers and water users. Will the gains of adaptive management inform those decisions? Will the collaborative capacity be strong enough and ready to shape those decisions?

This leads me to another emerging theme from this symposium—the call for setting priorities. We heard it from John Schmidt when he suggested we need to address the cost/benefit of certain management objectives. We heard it again during the late Tuesday afternoon discussion and again this morning with a call for more trade-off analysis; we need to prioritize the restoration and recovery goals for different river reaches for a variety of reasons, not the least of which are the financial constraints that are likely to set in when our economic crisis translates into future budget cuts at Federal and State levels. Setting priorities means, of course, setting up for difficult decisions, acknowledging there will be shared pain and few gains. This is when collaboration really gets tough. It is no longer about sharing a growing pie of research dollars or sizable funding for management options, it becomes a negotiation over minimizing losses, with fewer, not more, options to consider. We cannot have it all, as John Schmidt reminds us. There will be losers. And when there are losers, there will be conflict. Pretty grim picture, right?

So the conclusion I draw from these general observations is that more and stronger collaboration will be needed in the next 10 years, and more conflict anticipation, management, and resolution. It is not really about whether collaboration is good or bad, but rather how we can improve the way we work together. How can we optimize the effectiveness of our partnerships and our adaptive management programs? And as Dennis Kubly noted, these challenges are opportunities as well.

We are all aware of the promises "process" advocates like me make about collaboration. It reduces the risks of protracted disputes, and it helps leverage shared resources. It enables trust to emerge and social capital to be built. It creates certainty and leads to better, more informed decisions. And after all, adaptive management depends on such decisions.

What we do not acknowledge adequately is just how difficult it is to do collaboration well and the jeopardy that can occur when attempts at collaboration go south. Here are just a few of the many perils of collaboration and, by extension, adaptive management processes that I have seen over the years (perhaps you will recognize some of these from your own experiences here in Colorado River programs or elsewhere):

- All parties needed at the table are not willing to participate, yet the collaborative process moves forward nonetheless; or parties participated in bad faith or did not abide by the group norms or ground rules;
- Decisionmakers come and go, and agency commitments are not honored and as a consequence undermine the parties' confidence in the group's legitimacy or efficacy;
- Cultural differences among the parties disadvantage some and privilege others, and the norms of the process do not recognize or adapt to these differences, leading to declining participation by some groups who feel increasingly marginalized;
- Difficult personalities dominate the process and suck the energy right out of a group. Membership falls off as people prefer to avoid conflict; or
- Unresolved differences continue to fester and express themselves in renewed power struggles or end runs.

So how do we avoid all these pitfalls and make collaboration work? Let me give you two kinds of answers, with the caveat that there is no silver bullet; there is no getting around that collaboration is not for the faint of heart, particularly when you have high conflict and low trust among the stakeholders and across agencies as well.

The first answer lies in returning to first principles; that is, the best practices of conflict resolution and collaborative problem solving. In November of 2005, these were actually codified in a policy memo on environmental conflict resolution issued by the Office of Management and Budget (OMB) and the President's Council on Environmental Quality (CEQ) (Office of Management and Budget and Council on Environmental Quality, 2005). Eight principles were cited as important to ensuring the effective use of environmental conflict resolution (ECR). They apply in my view to collaborative resource management as well. I will briefly list them:

1. Informed commitment – assuring your agency or constituency is fully aware of the issues on the table, the sideboards to the discussions, and nature of the commitment and the decisionmaking authority of the group;
2. Balanced and equitable representation – of all affected and engaged interests;
3. Group autonomy – to design its own ground rules, set its own agenda;
4. Informed process – where access to all available information is assured;
5. Accountability – where participants acknowledge and work with the tension between representing their agency or organization and also hold themselves accountable to the group's shared mission and goals;
6. Openness – transparency in decisionmaking not only for the group's benefit and to build trust but for the benefit of larger public engagement and confidence in the group's legitimacy;
7. Timeliness – in decisions and actions within the regulatory management constraints; and
8. A focus on implementation – such that any proposals and recommendations are feasible and most important fundable.

These principles were gleaned from some 30 years of practitioner experience as well as negotiated by a Federal interagency working group. The policy memo, I might add, directs all Federal agencies to increase the effective use of ECR and collaborative problem solving and report annually to OMB and CEQ on their progress. A synthesis of these annual reports, now in the third year of reporting, is available as well. Hopefully this will be one of the policies the new Obama administration builds on.

The other answer to the question of how to optimize collaboration can be found in empirical research. Frankly, there is not a lot of research that directly links certain process attributes or practices to collaborative outcomes. In a recent study of 52 ECR cases, however, co-sponsored by U.S. Department of the Interior (DOI), U.S. Environmental Protection Agency (EPA), U.S. Forest Service, Federal Highway Administration (FHWA), some State partners, and the Udall Foundation with funding from Hewlett Foundation, over 500 participants responded to post-process surveys. The study found that reaching high-quality agreements and building social capital were optimized when the appropriate parties are at the table and effectively engaged; when high-quality, relevant information is accessible to all the parties; when parties have the capacity to engage; and when the facilitator or mediator employs the appropriate skills and practices. Among all those factors, effective engagement makes the strongest contribution to positive outcomes on the basis of the multilevel modeling analysis conducted in the study (Emerson and others, 2009).

This research does not speak, however, to another concern about the performance of adaptive management programs that may be relevant in particular to the Glen Canyon Dam Adaptive Management Program. That is, how to enhance or reinvigorate or remediate a longstanding collaboration. There are a growing number of older (I won't say aging) adaptive management programs started in the 1990s that face a new set of problems associated with the perils of institutionalization. Chief among these are such problems as:

- Process fatigue,
- Free riders,
- Party bail out or exercise of other options outside of the collaboration to meet their needs,
- Weakened commitment to the process or the originating mission of the group and adversarial attitudes and behaviors re-emerge,
- Once-flexible dynamics turn into formalized meetings where there is little room for real deliberation, and
- Lack of measurable progress toward improved environmental conditions discourages many involved.

These are difficult challenges. Do they invalidate adaptive management programs and their performance? The jury frankly is still out on the effectiveness of large-scale ecosystem restoration programs like those in the Everglades, the Bay Delta, the Chesapeake Bay, and the Columbia River as well as Glen Canyon Dam (Gerlak and Heikkila, 2006).

My own view is that adaptive management approaches are essential—in fact, there is no other approach at hand that can begin to deal with the complexity of these natural systems or the corresponding management challenges. With respect to retrofitting or retooling longstanding collaborative processes, I think it can be done, it is being done, and often requires assertion of new leadership, the help of outside consultation, and considerable work by the parties in assessing their individual and shared commitments.

That said, we have yet to master the adaptive management of the adaptive management program itself. And I think we have fallen victim to our own mythologizing about collaborative action and its precursors. We need to challenge some of our underlying assumptions.

For example, we talk reassuringly about the voluntary nature of these collaborations, reifying agency and self-determination. First of all, there is often some level of coercion of reluctant parties to participate, even if it is against their self-interest. But more importantly, as John Duffield will probably tell you, people respond to cues—positive and negative incentives—as we make choices. In fact, using the power of the State as an incentive to get people to the table may not be so bad. Would we have the shortage agreement on lower Colorado River Basin flows today had not the Secretary of the Interior set deadlines for the States to negotiate a plan? Acknowledging the value of external deadlines and clear consequences set by legal authority (the exertion of leadership) might be a very good thing for incentivizing joint action.

Another sacred cow of collaboration is the consensus decision rule. Unanimity can certainly be hoped for, but it is rare indeed and usually occurs only when the level of disagreement among parties is low and the stakes of the particular decision are not very high. There are many ways to set more sensitive decision rules that neither set the bar too high nor lower it to voting rules that regularly disempower minority views.

These and other assumptions about collaboration could benefit from further empirical research and theoretical challenge.

Let me conclude by underscoring what Dennis Kubly said on Tuesday about neglecting the human dimension of adaptive management. If we do not pay more attention to the psychological, the social, the cultural, the political, and the institutional dimensions of adaptive management, we risk losing the ability to translate the biophysical science we have generated into the target management options on the ground. There are now several collaborative resource management programs working in the basin consuming energy and resources, providing outputs, and interacting with the environment. The productivity of these collaborative programs may well be as important as the productivity of a given fishery or stretch of riparian habitat, as we depend on them both for the protection of ecological services. So I encourage you to reflect on, indeed, to research ways to optimize your collective productivity and explore how to adaptively manage your adaptive management programs and build more collaborative capital. Indeed, if the forecasts are correct, you will need to draw on it in the not too distant future.

Congratulations on a terrific conference. It bodes well for future progress along the Colorado River. Thank you very much, and I will be glad to take a few questions.

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