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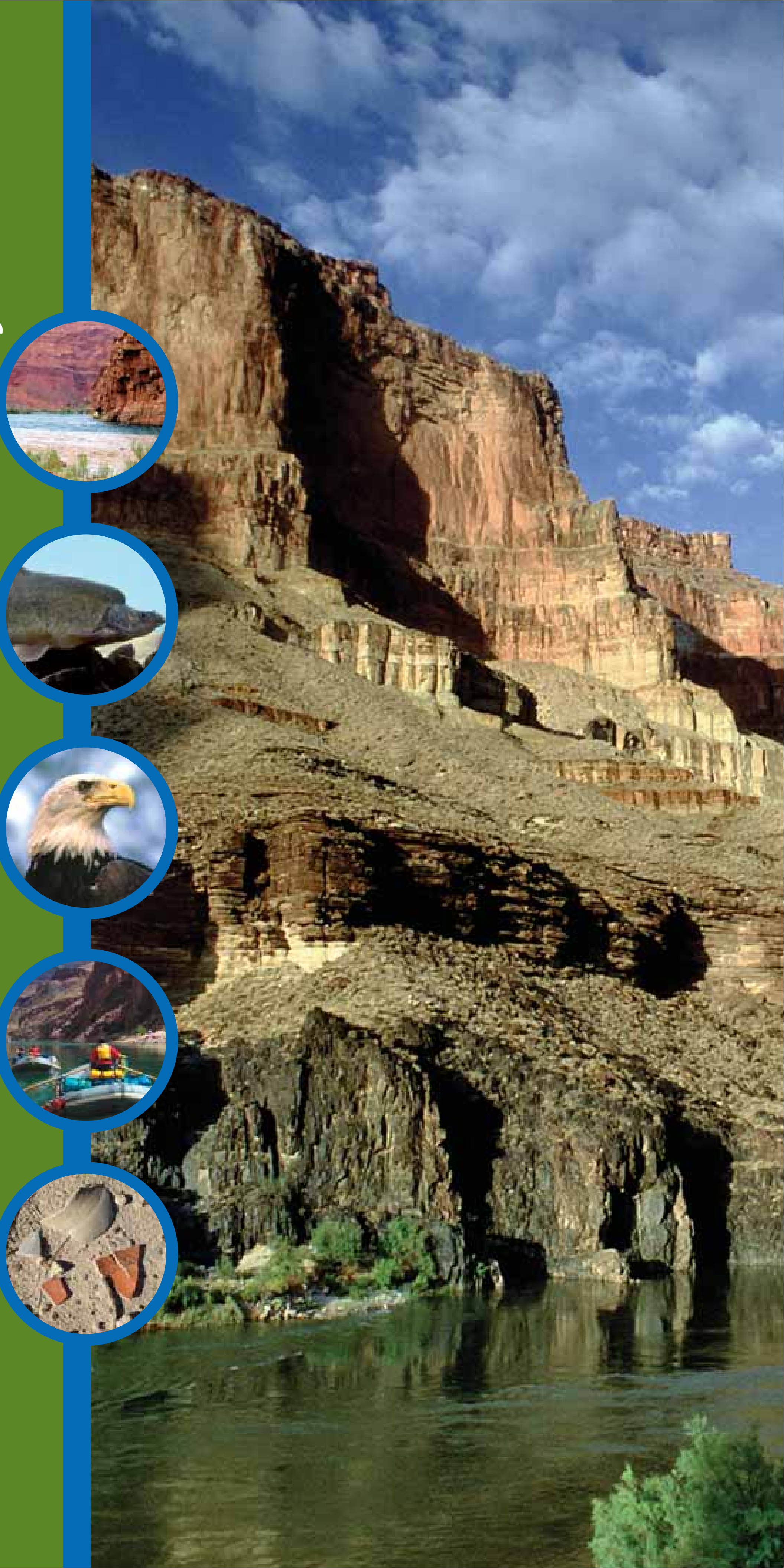
# The State of the Colorado River Ecosystem in Grand Canyon

## A Report of the Grand Canyon Monitoring and Research Center 1991-2004



USGS Circular 1282

U.S. Department of the Interior
U.S. Geological Survey

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## A Report of the Grand Canyon Monitoring and Research Center 1991-2004

Edited by Steven P. Gloss, Jeffrey E. Lovich, and Theodore S. Melis

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**U.S. Department of the Interior**
**U.S. Geological Survey**

**U.S. Department of the Interior**
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**U.S. Geological Survey**
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> This report is a scientific product of the U.S. Geological Survey. As such, it will be an important element in informing the policy dialogue for decisionmakers and stakeholders involved with or interested in operations of Glen Canyon Dam and the protection of downstream resources of Grand Canyon National Park. Like all scientific documents, however, it will be only one element of the policy dialogue. Ultimately, many other factors will also be considered by decisionmakers when they formulate official policy governing the operation of Glen Canyon Dam.

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# Foreword

As a "larger than life" Director of the U.S. Geological Survey and the first person known to have successfully rafted the Colorado River through Grand Canyon, John Wesley Powell sent out a call to raise science aloft, a call that has particular resonance for the Glen Canyon Dam Adaptive Management Program. In Grand Canyon, science offers a means of understanding and predicting the relationships between the operations of Glen Canyon Dam and downstream resources of concern. This fact was recognized by both the Grand Canyon Protection Act of 1992 and the final environmental impact statement that proposed the Adaptive Management Program. Monitoring and research were selected as the tools to allow scientists to unravel the many uncertainties that existed, and continue to exist, about downstream impacts from dam operations.

> *"Let us not gird science to our loins as the warrior buckles on his sword. Let us raise science aloft as the olive branch of peace and the emblem of hope."*
>
> —John Wesley Powell, 1882, p. 70

Significantly, science within the context of adaptive management is intended to serve management and policy. Scientists are responsible for developing relevant information, and river managers are responsible for making resource decisions by using the best information available. When scientists and managers work together, science can be the olive branch of peace and emblem of hope needed to mitigate the adverse effects of dam operations and improve the values for which Glen Canyon National Recreation Area and Grand Canyon National Park were established. These are the wishes of the American people as expressed in the Grand Canyon Protection Act of 1992.

The following chapters summarize a decade of monitoring and research activities for many key resources in the Colorado River corridor below Glen Canyon Dam. Where possible, scientists assess the effects of dam operations, particularly the modified low fluctuating flow alternative, on given resources and highlight the linkages among system features that managers identified as important.

The role that John Wesley Powell envisioned for science in 1882 reflects the highest goals of the scientists and other professionals of the U.S. Geological Survey today. In keeping with this vision, *The State of the Colorado River Ecosystem in Grand Canyon* is emblematic of the high quality science that the U.S. Geological Survey is committed to providing to its customers. Science of the type reported here, which can be used to make informed decisions, is the return on investment that American taxpayers deserve and appreciate.

P. Patrick Leahy, Ph.D.
Acting Director
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Powell, J.W., 1882, Darwin's contribution to philosophy, *in* Addresses delivered on the occasion of the Darwin memorial meeting, May 12, 1882: Washington, D.C., Biological Society of Washington, p. 60–70.

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# Overview

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## Introduction

This report is an important milestone in the effort by the Secretary of the Interior to implement the Grand Canyon Protection Act of 1992 (GCPA; title XVIII, secs. 1801–1809, of Public Law 102-575), the most recent authorizing legislation for Federal efforts to protect resources downstream from Glen Canyon Dam. The chapters that follow are intended to provide decision makers and the American public with relevant scientific information about the status and recent trends of the natural, cultural, and recreational resources of those portions of Grand Canyon National Park and Glen Canyon National Recreation Area affected by Glen Canyon Dam operations. Glen Canyon Dam is one of the last major dams that was built on the Colorado River and is located just south of the Arizona-Utah border in the lower reaches of Glen Canyon National Recreation Area, approximately 15 mi (24 km) upriver from Grand Canyon National Park (fig. 1). The information presented here is a product of the Glen Canyon Dam Adaptive Management Program (GCDAMP), a federally authorized initiative to ensure that the primary mandate of the GCPA is met through advances in information and resource management. The U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center (GCMRC) has responsibility for the scientific monitoring and research efforts for the program, including the preparation of reports such as this one.

## The Study Area

Carved from the Earth by the Colorado River, Grand Canyon is a natural wonder that is "absolutely unparalleled throughout the rest of the world," as President Theodore Roosevelt said upon seeing it for the first time in 1903 (Roosevelt, ca. 1905, p. 369). Considered one of the world's most spectacular gorges, Grand Canyon exhibits a depth of more than 6,720 ft (2,048 m) at its most extreme in Granite Gorge (Annerino, 2000). The colorful strata of the canyon's walls also reveal an invaluable record of the Earth's geologic history dating back to the 1.84-billion-yr-old rock formations found at Elves Chasm, which are the oldest rocks known in the Southwestern United States (Beus and Morales, 2003). President Woodrow Wilson signed the bill that established Grand Canyon as a national park on February 26, 1919, in recognition of its exceptional natural beauty and geologic wonders. Grand Canyon National Park is also of cultural and spiritual significance to many of the region's Native Americans and contains more than 2,600 documented prehistoric ruins, which span thousands of years and provide an important record of human adaptation to an arid environment. In addition to its geologic and cultural significance, the Grand Canyon ecosystem is home to a diverse array of plants and animals such as the humpback chub (*Gila cypha*) and the southwestern willow flycatcher (*Empidonax traillii extimus*), both of which are species that are federally listed as endangered. Because of its global significance as a natural and cultural treasure, Grand Canyon National Park was inscribed by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a World Heritage Site in 1979.

The GCPA (see timeline) directs the Secretary of the Interior to operate Glen Canyon Dam and exercise other authorities "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" (GCPA, sec. 1802(a)). As a result, the Glen Canyon Dam Adaptive Management Program, created by the 1996 Record of Decision (ROD) for the operation of Glen Canyon Dam, focuses on a study area that encompasses the Colorado River corridor from Glen Canyon Dam to the western boundary of Grand Canyon National Park. The study area includes the approximately 15 river miles (RM) of river from the dam to Lees Ferry within Glen Canyon National Recreation Area and the entire 277-RM river corridor below Lees Ferry and within Grand Canyon National Park. In total, the study area includes some 293 RM of the Colorado River (fig. 1).

## Administrative History

The Colorado River is the most important water resource in the American West, serving as the main source of drinking water for more than 25 million people (Water Education Foundation, 2001). The Colorado River has been extensively engineered to meet the demands placed upon it (see timeline). There are 22 major storage reservoirs in the Colorado River Basin and 8 major out-of-basin diversions (Pontius, 1997). The two largest storage projects—Hoover and Glen Canyon Dams—are located on either end of Grand Canyon National Park. Glen Canyon Dam is located just north of the Grand Canyon National Park boundary, where it creates Lake Powell. At full capacity, Lake Powell was designed to hold 27 million acre-feet (maf) (>33,000 million m$^3$) of water and is the key storage unit within the Colorado River Storage Project (CRSP) (U.S. Department of the Interior, 1970).

Signed into law by President Dwight D. Eisenhower in 1956, the Colorado River Storage Project Act authorized four mainstem water-storage units, including Glen Canyon Dam. Construction of Glen Canyon Dam began on September 29, 1956, and the last bucket of concrete was poured on September 13, 1963 (U.S. Department of the Interior, 1970). The regulation of the Colorado River by Glen Canyon Dam began with the closure of the dam in 1963 and when Lake Powell began filling. The CRSP reservoirs allow the upper basin States—Utah, Colorado, Wyoming, and New Mexico—to store water in wet years and release water in times of shortages, thereby enabling the upper basin to meet its obligations under the 1922 Colorado River Compact while also maximizing future water uses (Ingram and others, 1991). To repay Federal expenditures for the water-storage units and supplement the costs of related irrigation units, CRSP dams were equipped with hydroelectric generators to produce salable power. Glen Canyon Dam operates eight electric generators, which produce 78% of the total power generated by the CRSP (Hughes, 1991). In 2004, Glen Canyon Dam generated approximately 3.3 million megawatthours (MWh). The power is sold to approximately 200 wholesale customers—municipal and county utilities, rural electric cooperatives, U.S. Government installations, and other nonprofit organizations—located primarily in six States: Arizona, Colorado, Utah, Wyoming, New Mexico, and Nevada (National Research Council, 1996).

## Natural History

Before the dam, the Colorado River was a sediment-rich river that when swelled with snowmelt from the Rocky Mountains transported large quantities of sediment during spring and early summer and commonly produced flood events. Peak discharge typically reached 85,000 cubic feet per second (cfs) at 2-yr intervals and 120,000 cfs at 6-yr intervals during these seasonal flood events (Topping and others, 2003). By contrast, flows of less than 3,000 cfs were typical during late summer, fall, and winter. Prior to the dam, water temperature also

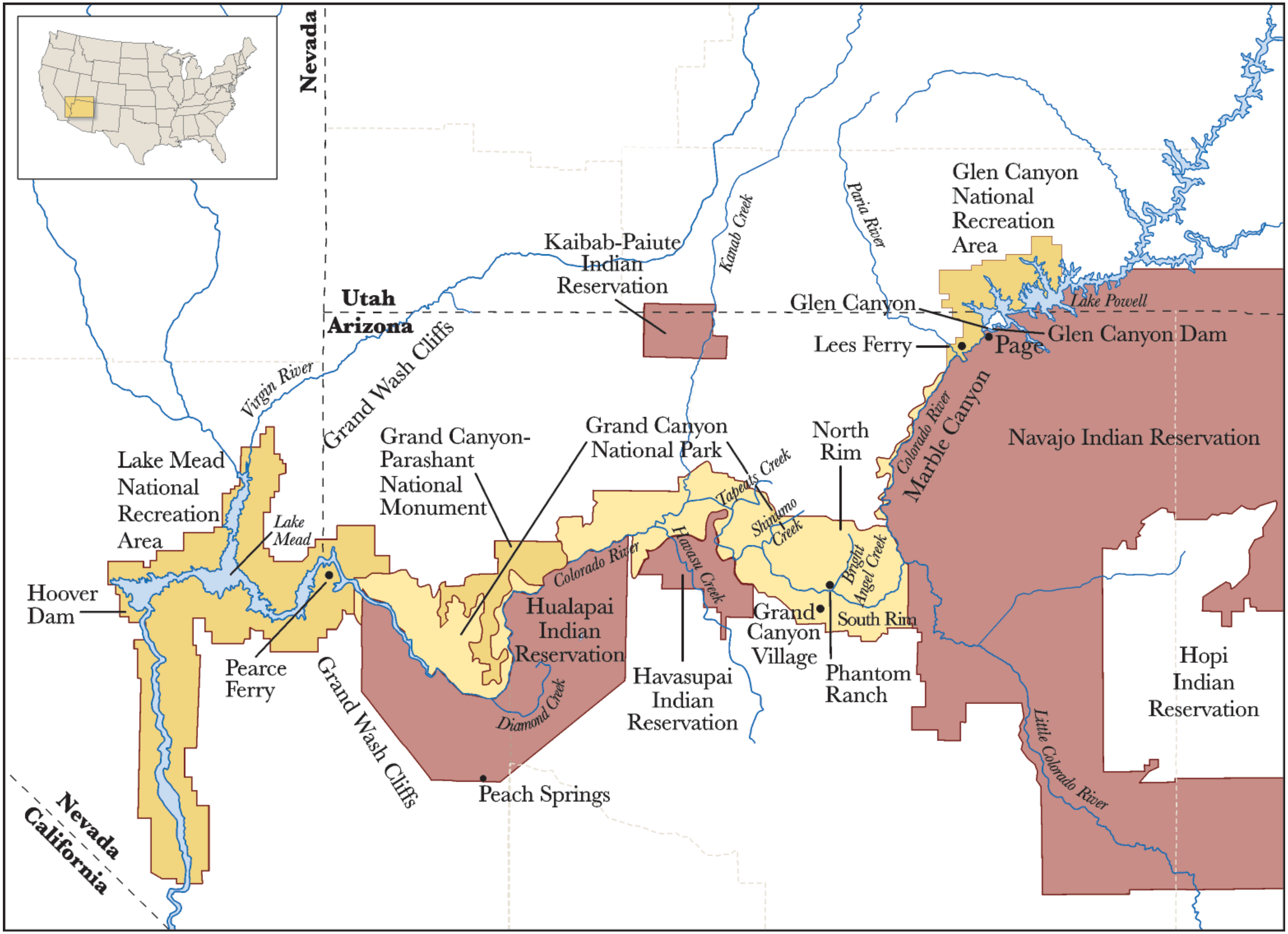


**Figure 1.** Study area.

fluctuated seasonally from 32°F to 80°F (0–29°C) (U.S. Department of the Interior, 1995).

Glen Canyon Dam has changed the seasonal flow, sediment-carrying capacity, and temperature of the Colorado River. Operation of the dam has altered the frequency of floods on the Colorado River and increased median discharge rates at Lees Ferry, whereas managing for hydroelectric power generation has introduced wide-ranging daily fluctuations (Topping and others, 2003). For example, from 1963 to 1991 (the no action period or historical operations), when the dam was managed primarily to maximize hydroelectric power revenue, it was not uncommon for daily flows to vary from 5,000 to 30,000 cfs (U.S. Department of the Interior, 1988). Release patterns of this type caused the river level below the dam to change 7–13 ft (2–4 m) per day, creating public concerns about the quality and safety of fishing and boating and about adverse impacts to natural resources (U.S. Department of the Interior, 1988). Because the sediment load of the Colorado River is deposited in Lake Powell, water released from Glen Canyon Dam is essentially clear. Furthermore, because the penstocks of the dam are well below the surface of Lake Powell, the water released from the dam is cold, with an average temperature of 46°F (8°C) (Webb and others, 1999).

The construction of Glen Canyon Dam also affected a number of aquatic and terrestrial resources downstream in lower Glen and Grand Canyons. Dam-induced changes in the Colorado River's flow, temperature, and sediment-carrying capacity are blamed for narrowing rapids, beach erosion, invasion of nonnative riparian vegetation, and losses of native fishes (Webb and others, 1999). These same changes are also associated with an increase in total species richness within Grand Canyon National Park; however, the increases are primarily for species not originally found in Grand Canyon. Some changes to the ecosystem of the Colorado River, such as the introduction of nonnative fish, were already taking place before the construction of Glen Canyon Dam (Wieringa and Morton, 1996).

It is important to note that Glen Canyon Dam was completed before the enactment of the National Environmental Policy Act of 1969 and the Endangered Species Act of 1973 (see timeline). At the time of Glen Canyon Dam's construction (1956–63), little consideration was given to how dam operations might affect the downstream environment in Grand Canyon National Park (Babbitt, 1990). Nevertheless, public values were undergoing a shift: at the same time that Congress authorized Glen Canyon Dam in 1956, authorization of Echo Park Dam on the Green River was defeated because of environmental reasons (Ingram and others, 1991).

## Federal Efforts to Protect Grand Canyon

The international prominence of Grand Canyon National Park and public concern about the impacts of Glen Canyon Dam caused the Bureau of Reclamation in 1982 to undertake a science program, Glen Canyon

**11,000 BP** Paleo-Indian peoples occupy Grand Canyon region

**1869** Major John Wesley Powell leads first recorded expedition to traverse Grand Canyon

**1893** President Benjamin Harrison creates Grand Canyon Forest Reserve

**1902** Reclamation Act creates the Bureau of Reclamation

**1908** President Theodore Roosevelt creates Grand Canyon National Monument

**1916** National Park Service Organic Act passed

Environmental Studies, to examine the effects of dam operations on downstream resources. Glen Canyon Environmental Studies, the USGS Grand Canyon Monitoring and Research Center's predecessor, issued a final report in 1988 concluding that changes in dam operations "could reduce the resource losses occurring under current operations and, in some cases, even improve the status of the resources" (U.S. Department of the Interior, 1988, p. xvi). In 1989, in response to these findings, Secretary of the Interior Manuel Lujan, Jr., ordered the Bureau of Reclamation to complete an environmental impact statement on the operation of Glen Canyon Dam. To further ensure the protection of downstream resources, Secretary Lujan adopted interim operating criteria for the dam in 1991, which restricted dam operations and remained in effect until the end of the environmental impact statement process.

Congress passed the Grand Canyon Protection Act of 1992 to provide guidance and legal support to the Secretary of the Interior in his efforts to protect Grand Canyon. In addition to directing the Secretary to operate Glen Canyon Dam to protect and improve downstream resources, the act also validated the interim operating criteria, provided a deadline for the completion of the environmental impact statement, required the creation of a long-term monitoring and research program, and allocated program costs. The act clearly stated that it was to be implemented in accordance with existing laws, treaties, and institutional agreements that govern allocation, appropriation, development, and exportation of the waters of the Colorado River Basin (GCPA, sec. 1802(b)).

The Operation of Glen Canyon Dam Final Environmental Impact Statement (hereafter EIS) was filed in March 1995, and the Record of Decision was signed by Bruce Babbitt, Secretary of the Interior, in October 1996. The Record of Decision noted that the goal "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 capacity and flexibility only to the extent necessary to achieve recovery and long-term sustainability" (U.S. Department of the Interior, 1996, p. G-11). Having established this goal, the Secretary's decision was to implement the modified low fluctuating flow (MLFF) alternative (the preferred alternative in the EIS) as described in the EIS but with minor changes in the upramp rate, maximum release rate, and the timing of beach/habitat-building flows (BHBF; see below). The document also formally established the Glen Canyon Dam Adaptive Management Program.

## Glen Canyon Dam Adaptive Management Program

The creation of an adaptive management program was a common element for all alternatives considered in the EIS, and its implementation was subsequently mandated by the Record of Decision. Adaptive management was selected to create a process whereby "the effects of dam operations on downstream resources

**1919** Grand Canyon National Park created

**1922** Colorado River Compact signed allocating the water of the Colorado River between the upper and lower basins. Upper basin States have the right to use 7.5 maf/yr only if that quantity is available after meeting delivery requirements of 7.5 maf/yr to the lower basin plus the amount required to satisfy anticipated claims by Mexico

**1921-23** U.S. Geological Survey's Birdseye Expedition surveys possible dam sites along the Colorado River

**1928** Boulder Canyon Project Act passed authorizing Hoover Dam would be assessed and the results of those assessments would form the basis of future modifications of dam operations" (U.S. Department of the Interior, 1995, p. 34). The selection of adaptive management and the focus on the effects of dam operations on downstream resources have significant implications. First, the prominence of Grand Canyon National Park elevates adaptive management and the GCDAMP to national significance. Second, the program's focus on the effects of dam operations on downstream resources constrains the range of management options and creates a relatively well-defined geographic area within which to operate.

Envisioned as a new paradigm for addressing complex environmental management problems through a dynamic interplay of ecosystem science, management, and policy, adaptive management has gained attention and has been tested in various contexts in the last several decades (National Research Council, 1999). Although concepts and methods continue to evolve, adaptive management is generally understood to be a systematic process for continually improving management practices by emphasizing learning through experimentation. Also, adaptive management incorporates collaboration among stakeholders, managers, and scientists as a means of social learning that can prevent policy gridlock. In *Downstream*, the National Research Council (1999, p. 53) noted that the key components of adaptive management include

> (1) commitment to ongoing management adjustments based, in part, upon scientific experimentation, (2) shift from "trial and error" to formal experimentation with management actions and alternatives, (3) shift from fragmented scientific investigations to integrated ecosystem science, (4) explicit attention to scientific uncertainties in ecosystem processes and effects of management alternatives, (5) formal experimental design and hypothesis testing to reduce those uncertainties and help guide management adjustments, (6) careful monitoring of ecological and social effects and of responses to management operations, (7) analysis of experimental outcomes in ways that guide future management decisions, and (8) close collaboration among stakeholders, managers, and scientists in all phases of these processes.

## The Role of Science

The Colorado River provides many benefits to society including numerous natural processes; habitat for unique organisms such as native fishes; water for humans, agriculture, and recreational purposes; and hydroelectric power generation. Science-based status and trends information is increasingly valuable as society attempts to balance the competing uses of natural resources. The need for credible scientific information that can serve as a feedback loop between management actions and the effects of those actions is of critical importance in adaptive management.

The role of science in the GCDAMP is fourfold: (1) to provide the aforementioned credible scientific information about management actions deemed appro-

**1935** Hoover Dam completed

**1944** Treaty with Mexico obligating the United States to provide 1.5 maf of Colorado River water to Mexico annually

**1946** Robert R. Miller describes humpback chub (*Gila cypha*) from specimens taken in Grand Canyon

**1948** Upper Colorado River Basin Compact signed

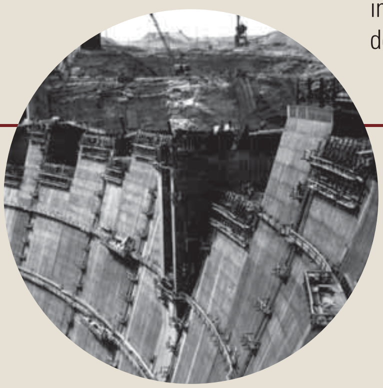
**1956** Colorado River Storage Project Act passed authorizing Glen Canyon Dam priate to implement as experiments by the stakeholders and managers, (2) to conduct and communicate peer-reviewed research relevant to management decision needs and to better understand factors governing potential responses to management actions, (3) to provide scientifically sound and defensible experimental designs for management experiments and to ensure that monitoring programs yield useful information, and (4) to structure the timing of monitoring and research results to the extent possible in a way that affords the Adaptive Management Work Group (see section on Collaboration, p. 9) and the Secretary of the Interior the best available scientific information to consider in their management decisionmaking.

Assessing the state of knowledge about the ecosystem to be managed adaptively is a key early activity of most adaptive management initiatives. This type of assessment is most effectively done by using a conceptual model that collaboratively engages scientists and stakeholders to agree on what is known about processes that operate within a given ecosystem and to examine possible interactions by using a computer model. The computer model provides a conceptual, but not necessarily predictive, capability to consider ecosystem responses to experimental management actions (see text box on p. 12–13).

## Modified Low Fluctuating Flow Alternative and Experimentation

In addition to examining the status and recent trends of key biological, cultural, and recreational resources, this report explores the effects of the implementation of the MLFF alternative, which specifies dam operations under normal conditions and includes experimental habitat maintenance flows and BHBFs when certain conditions are met. Under normal conditions, the MLFF alternative allows for dam releases to fluctuate no more than 8,000 cfs per day and generally not to exceed 25,000 cfs except during periods of high regional runoff or for experimental flows (table 1). In addition, the MLFF alternative constrains the hourly rate at which flow changes can be made, known as upramping and downramping.

Habitat maintenance flows as described in the EIS are high, steady dam releases within powerplant capacity (33,200 cfs at full reservoir elevation) for 1 to 2 weeks in March, although other months could be considered under the GCDAMP.  By contrast, BHBFs are infrequent high releases that are at least 10,000 cfs greater than allowable peak discharge but not greater than 45,000 cfs. Also, BHBF releases are timed to occur when releases in excess of powerplant capacity are required for dam safety purposes. More recently, the term “experimental high flows” has been used to describe experimental flows that exceed powerplant capacity and range from 42,000 to 45,000 cfs. Habitat maintenance flows differ from BHBFs and experimental high flows because they occur within powerplant capacity and were anticipated to occur in most years. The two types of releases, which had similar purposes of re-forming backwaters and maintaining sandbars, were not to be scheduled in the same year, and neither was to occur in a year when there



**1956-63** Glen Canyon Dam constructed

**1962** 20,000 gallons of poison applied to 500 mi of the Green River to kill native fish and establish a trout fishery, resulting in the unintentional killing of fishes as far downstream as Dinosaur National Monument

**1963** U.S. Supreme Court held in **Arizona v. California** that, as a result of the Boulder Canyon Project Act, California held an allocation of 4.4 maf, Arizona 2.8 maf, and Nevada 300,000 acre-feet of Colorado River water

**1964** Glen Canyon Dam power generation starts; National Park Service ends a 40-yr program of planting rainbow trout (**Oncorhynchus mykiss**) and brown trout (**Salmo trutta**) eggs and fingerlings in tributaries of the Colorado River within Grand Canyon

**Table 1.** Glen Canyon Dam release prescriptions under the modified low fluctuating flow alternative (cfs = cubic feet per second).

| Monthly release volume (acre-feet) | Minimum release (cfs)[1] | Maximum release (cfs) | Allowable daily fluctuation (cfs) | Upramp/ downramp (cfs/hr) |
|---|---|---|---|---|
| <600,000 | 8,000/5,000 | 25,000 | 5,000 | 4,000/1,500 |
| 600,000–800,000 | 8,000/5,000 | 25,000 | 6,000 | 4,000/1,500 |
| >800,000 | 8,000/5,000 | 25,000 | 8,000 | 4,000/1,500 |

[1] 8,000 cfs between 7 a.m. and 7 p.m. and 5,000 cfs at night; releases each weekday during the recreation season (Easter to Labor Day) would average not less than 8,000 cfs for the period from 8 a.m. to midnight.

was concern for the effects on sensitive resources such as sediment or endangered species.

On the basis of significant scientific research since 1995, some of the assumptions about how Colorado River resources would respond to ROD operations have been modified or rejected. As a result, several additional experimental flows that temporarily modified Glen Canyon Dam ROD operations have been implemented since 2000. Additional experimental flows discussed elsewhere in this report include the 2000 low summer steady flow (LSSF) test, the 2003–05 experimental fluctuating nonnative fish suppression flows, and the November 2004 experimental high flow. The LSSF test included two habitat maintenance flows (31,000 cfs for 4 d) in spring and late summer, with June through August flows held constant at 8,000 cfs. Fluctuating nonnative fish suppression releases allowed the flow of the river to fluctuate daily between 5,000 cfs and 20,000 cfs with relaxed hourly upramp and downramp rates of 5,000 and 2,500 cfs/h, respectively, from January to March. In summer and fall 2004, fine-sediment inputs from the Paria River (15 mi below the dam) reached the agreed-upon levels for triggering an experimental high flow of 41,000 cfs for 2.5 d (see chapter 1, this report).

Experimentation has largely focused on experimental flows of the type described above to achieve downstream

**1966** National Historic Preservation Act passed

**1967** Humpback chub and Colorado pikeminnow (*Ptychocheilus lucius*) federally listed as endangered

**1968** Colorado River Basin Project Act passed

**1969** National Environmental Policy Act of 1969 passed requiring Federal agencies to consider the environmental impacts of their proposed actions and reasonable alternatives to those actions

**1970** Long-range Operating Criteria developed for Glen Canyon Dam operations benefits, with a particular focus on improving fine-sediment resources and conditions for endangered native fish. Another experimental effort underway is the manual removal of nonnative fishes in order to protect native fish, particularly humpback chub (see chapter 2, this report).

## Collaboration

As for collaboration, the EIS outlined an innovative organizational structure for pursuing the GCDAMP. The program is administered by a senior Department of the Interior official (designee) and facilitated by the Adaptive Management Work Group (AMWG), which is organized as a Federal Advisory Committee. The AMWG makes recommendations to the Secretary of the Interior on how to best alter the operating criteria at Glen Canyon Dam or other management actions to protect downstream resources in order to fulfill the Department of the Interior's obligations under the GCPA (U.S. Department of the Interior, 1995). The Secretary of the Interior appoints the 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 (fig. 2). The GCDAMP also includes a monitoring and research center (USGS Grand Canyon Monitoring and Research Center), the Technical Work Group, and independent scientific review panels.

As directed thus far by the AMWG, monitoring and research on sediment dynamics, cultural resources, native and nonnative fish, and endangered species have been emphasized. Monitoring and research of these resources have resulted in better understanding of their condition and behavior.

For example, recent studies suggest that, contrary to expectations under current dam operations, sand contributed from Colorado River tributaries is rapidly exported downstream and does not remain available over multiyear timescales for restoration floods implemented between January and July, which is the current implementation schedule. Restoration floods are likely to be more effective if they are carried out in the same year that sand deliveries occur, before the new sand is lost downstream. Progress has also been made in understanding the dynamics of fish populations and the value of mechanical removal of nonnative fish for enhancing native fish populations.

## Report Organization

The chapters that follow provide status and trend data for the natural, cultural, and recreational resources of the Colorado River ecosystem in Grand Canyon. The report deals first with the aspects of the natural environment that have been most emphasized in monitoring and research—sediment and native fishes—followed by other important environmental factors including climate and drought, water quality, aquatic ecology, debris flows, birds, and shoreline ecology and its associated wildlife. The report then shifts emphasis to various human uses

**1972** Last verified record of Colorado pikeminnow caught in Grand Canyon at Havasu Creek

**1974** First lawsuit filed over Glen Canyon Dam operations by commercial raft operators contending that the disruption of normal flows was interfering with their ability to conduct river trips

**1973** Endangered Species Act of 1973 passed to protect and promote the recovery of animals and plants that are in danger of becoming extinct because of the activities of people. The act is administered by the U.S. Fish and Wildlife Service (terrestrial and freshwater species) and the National Oceanic and Atmospheric Administration–Fisheries (marine species)

**Figure 2.** Adaptive Management Work Group committee members.

## Interior Secretary's Designee

## 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 River Commission of Nevada
New Mexico: New Mexico Office of the State Engineer
Utah: Water Resources Agency
Wyoming: State Engineer's Office

## Nongovernmental Groups

### Environmental:

Grand Canyon Trust
Grand Canyon Wildlands Council

### Recreation:

Federation of Fly Fishers/Northern Arizona Flycasters
Grand Canyon River Guides

### Contractors for Federal Power from Glen Canyon Dam:

Colorado River Energy Distributors Association
Utah Associated Municipal Power Systems

**1975** Grand Canyon National Park Enlargement Act passed

**1978** U.S. Fish and Wildlife Service files jeopardy opinion on the effects of Glen Canyon Dam on endangered fishes

**1979** Grand Canyon National Park designated a UNESCO World Heritage Site; Bureau of Reclamation proposes an upgrade of Glen Canyon Dam's generators

**1980** Lake Powell reaches full pool (3,700 ft); bonytail chub (*Gila elegans*) federally listed as endangered of the ecosystem, including the economic importance of the ecosystem, hydroelectric power generation, cultural resources, and camping beaches. In each case, the information is then used to discuss the management options available to decision makers and the public based on the best scientific information available. In large measure, this report represents the first comprehensive assessment of how effectively the MLFF alternative is allowing the Secretary of the Interior to meet the resource management goals of the Grand Canyon Protection Act of 1992.

## Place Names and Units

Throughout the report, "Grand Canyon" is used broadly to refer to the Colorado River corridor between Glen Canyon Dam and the western boundary of Grand Canyon National Park, including Glen, Marble, and Grand Canyons. The study area is referred to as the "Grand Canyon ecosystem." The Colorado River is discussed in terms of four distinct sections: Lees Ferry reach, Marble Canyon, upper Grand Canyon, and lower Grand Canyon. The "Lees Ferry reach" extends from the downstream end of Glen Canyon Dam to Lees Ferry, and "Marble Canyon" extends from Lees Ferry to the mouth of the Little Colorado River. For this report, "upper Grand Canyon" refers to the river corridor that extends from the mouth of the Little Colorado River to the Grand Canyon gaging station (Topping and others, 2003), while "lower Grand Canyon" extends from the Grand Canyon gaging station to the western boundary of the park.

In this report, U.S. customary units are used for all measurements to facilitate understanding by the general reader. Metric equivalents are provided in parentheses after the U.S. customary units for all measurements except for river flow, the standard measure of which is cubic feet per second, and river mile, which is used to describe distances along the Colorado River in Grand Canyon (Stevens, 1990). The use of the river mile has a historical precedent and provides a reproducible method for describing location: Lees Ferry is the starting point, as

**1982** Glen Canyon Environmental Studies created to study effects of Glen Canyon Dam operations

**1983** Glen Canyon Dam releases more than 92,000 cfs to stop Lake Powell from overtopping Glen Canyon Dam

**1984** One of the last razorback suckers (*Xyrauchen texanus*) seen in Grand Canyon is caught and released at Bass Rapids

**1987** National Research Council completes review of Glen Canyon Environmental Studies, publishing *River and Dam Management: a Review of the Bureau of Reclamation's Glen Canyon Environmental Studies*

# The Role of Conceptual Modeling in Support of Adaptive Management in Grand Canyon

One challenge following completion of the 1995 Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) was to identify and implement monitoring efforts that would produce scientific data suitable for evaluating the new operating policy at Glen Canyon Dam. At that time, there was also a sense among managers and scientists that additional, comprehensive syntheses of available data needed to be undertaken with respect to major resource categories, such as sediment and fisheries. In addition, the need for development of a conceptual model for the Colorado River ecosystem, consistent with the adaptive environmental assessment and management process (now popularly called "adaptive management"), was also identified by the USGS Grand Canyon Monitoring and Research Center (GCMRC) and its cooperators. This modeling effort began in 1998 and was continued concurrently with the establishment of the stakeholder-based, Federal Advisory Committee—the Adaptive Management Work Group—and the development of the group's strategic goals for the Colorado River ecosystem (1998–2002). Key objectives for the conceptual modeling exercise were to (1) conduct an exhaustive knowledge assessment of the various elements of the ecosystem on the basis of existing data and hypotheses posed in the EIS and within the context of workshops that supported stakeholder and scientist interactions; (2) identify, through this process of modeling and simulation, key areas where data or knowledge did not exist and therefore were impediments to developing realistic simulations (by using historical data as a means of verification); and (3) identify future research directives (both experimental or otherwise) that would effectively fill knowledge gaps in the program related to management needs.

Development of the physical elements of the conceptual model (the Grand Canyon Model or GCM) proceeded relatively quickly, mostly because there were abundant data in some key areas (hydrology, sediment, and river flow) and an operational model for the Colorado River Basin (RiverWare™) had already been developed by the Bureau of Reclamation. Other critical areas of the model development, however, were limited by the paucity of available data related to biology and sociocultural resource areas (Walters and others, 2000). By 2000, it became clearer that

**1988** Glen Canyon Environmental Studies issues ***Glen Canyon Environmental Studies Final Report***, completing Phase I and starting Phase II, which would be accelerated to support environmental impact statement process

**1989** Secretary of the Interior Lujan orders an environmental impact statement on dam operations, and National Research Council sponsors symposium that reviews existing knowledge on Colorado River ecosystem

**1990-91** Research flows used to evaluate a variety of discharge patterns

**1991** Interim operating criteria for Glen Canyon Dam implemented; razorback sucker and Kanab ambersnail (*Oxyloma haydeni* ssp. *kanabensis*) federally listed as endangered certain critical modules of the model could not even reliably predict the general direction of ecosystem response, such as response of native fishes to warmer water conditions through implementation of a proposed temperature control device. While water could be routed through the ecosystem with confidence, there was considerably less confidence about the longer term relationship of flows to fine-sediment flux and beaches on the basis of remaining downstream sand supplies alone. Although the inability of the GCM to accurately simulate higher level trophic (e.g., fishes) responses in critical areas was cause for concern among managers, the goal of systematically identifying gaps in data and knowledge so that future research (including experimentation) and monitoring could be designed and implemented to fill the gaps was an acknowledged objective of the modeling effort.

In a sense, the largest contribution made by the conceptual modeling project was the identification of various experimental flow and nonflow treatments that would need to be tested (presumably, within some longer term design) to provide managers with scientifically based options for most effectively meeting the proposed management goals. Experimentation has long been identified as a sign of "active" adaptive management and has been shown to be an efficient means of resolving the uncertainty associated with various alternative management policies (Walters and Holling, 1990). Simultaneously, the modeling project helped identify additional monitoring data that would be required to more fully evaluate the influence of the modified low fluctuating flow policy on downstream resources of concern. Although evaluation of all the resources outlined in the EIS has not been possible because of program funding limitations, the GCM identified the general linkages between the varied resources as related to dam operation. The experimental designs proposed and implemented in the Glen Canyon Dam Adaptive Management Program have been a direct and logical outcome of conceptual modeling activities. Though still not complete, to date, the experimental results have greatly advanced ecosystem understanding. Ultimately, the knowledge gained through these scientific activities in the Colorado River ecosystem should lead to improved management options for Glen Canyon Dam that will benefit society.

**1992** Grand Canyon Protection Act of 1992 passed

**1994** Programmatic Agreement on Cultural Resources signed between the State of Arizona, Department of the Interior agencies, and six tribes over protection of cultural resources in the river corridor below Glen Canyon Dam; U.S. Fish and Wildlife Service designates critical habitat for four species of endangered Colorado River fish and completes Biological Opinion outlining reasonable and prudent alternatives that must be evaluated for dam operation

**1995** Operation of Glen Canyon Dam Final Environmental Impact Statement completed; Transition Work Group and Grand Canyon Monitoring and Research Center begin formulating strategic plan; southwestern willow flycatcher (*Empidonax traillii extimus*) federally listed as endangered; Department of the Interior constitutes the Grand Canyon Monitoring and Research Center and locates it in Flagstaff, Arizona

RM 0, with mileage measured for both upstream and downstream directions.

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**1996** Experimental controlled flood of 45,000 cfs conducted at Glen Canyon Dam; Record of Decision for the operation of Glen Canyon Dam signed by Secretary of the Interior Bruce Babbitt

**1997** Interior Secretary Bruce Babbitt signed a Notice of Establishment of the Adaptive Management Work Group, a Federal Advisory Committee with first meeting of the group in September; first test of the concept of the habitat maintenance flows conducted in November

**2000** Test of low summer steady flows for the possible benefit of endangered species of fish, second and third tests of the habitat maintenance flows concept conducted in spring and summer

**2001** Draft strategic plan for the Glen Canyon Dam Adaptive Management Program developed by program members

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**2002** U.S. Fish and Wildlife Service announces recovery goals for endangered fishes of the Colorado River Basin; Adaptive Management Work Group recommends implementation of the first 2 yr of an experimental design proposed by the Grand Canyon Monitoring and Research Center

**2003-05** Fluctuating nonnative fish suppression releases from January through March implemented and continued through 2005

**2003** Experiment begun to remove nonnative fish from the Colorado River in Grand Canyon

**2004** Drought conditions cause water level at Lake Powell to drop to lowest level since the dam began filling; triggering thresholds based on sand inputs from the Paria River and lesser Marble Canyon tributaries met; and high flow experiment initiated on Sunday, Nov. 21

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# Chapter 1

# Influence of Glen Canyon Dam Operations on Downstream Sand Resources of the Colorado River in Grand Canyon

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## Introduction

The closure of Glen Canyon Dam and the beginning of flow regulation of the Colorado River through Grand Canyon in 1963 all but eliminated the mainstem sand supply to Grand Canyon and substantially altered the seasonal pattern of flows in the Colorado River. Dam-induced changes in both sand supply and flow have altered the sedimentary processes that create and maintain sandbars and related habitats, resulting in smaller and coarser grained deposits throughout the ecosystem.

From the perspective of river management, the ecological implications associated with such changes are not well understood and are the focus of ongoing integrated science studies. The effects of Glen Canyon Dam operations on fine-sediment resources (i.e., sand and finer material), particularly the erosion and restoration of sandbars, are of interest because sandbars are a fundamental element of the Colorado River's geomorphic framework and the landscape of Grand Canyon (see Webb, 1996; Webb and others, 2002). Sandbars are also of interest in terms of the essential role fine-sediment resources play in other ecosystem processes (U.S. Department of the Interior, 1995). For example, emergent sandbars create terrestrial habitats for riparian vegetation and associated fauna. Similarly, sandbars create areas of stagnant or low-velocity flow that may be used as rearing habitat by the endangered humpback chub (*Gila cypha*) and other native fish. Recreational river runners and other backcountry visitors frequently use sandbars as campsites. Finally, abundant sand and silt deposits near and above the elevation of typical predam floods contain archeological resources and protect those resources from weathering and erosion.

Conservation of Grand Canyon's fine-sediment resources is a primary environmental goal of the Glen Canyon Dam Adaptive Management Program. Despite this fact, the dam's hydroelectric powerplant operation under the Record of Decision (U.S. Department of the Interior, 1996) continues to erode the limited fine-sediment deposits that exist downstream. Changes in the abundance, distribution, size, and composition of sandbars began to occur under the no action period (historical operations) of dam operation from 1963 through 1991. Sandbar erosion continued despite changes in the operation of the dam that resulted from the implementation of the interim operating criteria in 1991 and the modified low fluctuating flow (MLFF) alternative in

1996. The MLFF was the preferred alternative identified in the 1995 Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) and was selected in the Record of Decision (U.S. Department of the Interior, 1996).

The U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center and its cooperators have conducted extensive monitoring and research on fine-sediment transport and sandbar evolution in Grand Canyon. This chapter presents a summary of the results of studies since the 1970s, as well as conclusions derived from recent syntheses of streamflow, sediment transport, and geomorphic data from 1921 to 2004, including recent sediment budgets. The effects of the MLFF operating alternative at Glen Canyon Dam (1996–2004) on fine-sediment transport and sandbars are examined in the context of these historical data. Finally, options identified by sediment scientists for testing alternative operations aimed at more effective conservation of fine-sediment resources are discussed.

# Background

## Predam Sediment-transport Processes

As described by Rubin and others (2002), sandbars below Glen Canyon Dam in Marble and Grand Canyons are maintained by fine sediment that is transported by the Colorado River through the ecosystem. As sand is carried through these bedrock canyons by the river, some of it is deposited along channel margins and along shorelines within hundreds of eddies, thus building sandbars. The eddy areas, which are typically located immediately downstream from channel constrictions created by tributary debris fans, are susceptible to fine-sediment deposition because the flow tends to recirculate and be of lower velocity than the flow in the main channel. Using historical sediment-transport records from the Lees Ferry (RM 0) and Grand Canyon (RM 87) gages, Laursen and others (1976) and later Topping and others (2000b) identified that before closure of Glen Canyon Dam, sand would accumulate in the Colorado River channel during late summer, fall, and winter. Annual accumulation of sand in the channel during predam years apparently resulted from large sediment inputs from tributaries that occurred during periods of seasonal low flows in the main channel of the Colorado River. Following these periods of sand enrichment in the main channel, spring snowmelt floods would erode the accumulated sand from the channel and transport it out of the canyon, along the way depositing some of the sand in the low-energy eddy areas and thus leading to the building of the high-elevation sandbars. Following the spring replenishment of sandbars, some of this sand would in turn be redistributed to even higher elevations by winds (Topping and others, 2000b). On an annual basis, the inputs of sand to the system would approximately balance the export, maintaining equilibrium in background sand storage in the eddies.

## Effects of Lake Powell on Sand Transport

Before the closure of Glen Canyon Dam in 1963, approximately 25 million tons (23 million Mg) of sand passed the Lees Ferry stream gage annually. With the addition of 1.7 million tons (1.5 million Mg) of sand from the Paria River, which joins the Colorado River just downstream from Lees Ferry, the total predam annual sand supply to Marble Canyon reached about 27 million tons (24 million Mg). At the end of Marble Canyon, the Little Colorado River joins the Colorado River and contributed, on average, about 1.9 million tons (1.7 million Mg) to the annual sand supply. Thus, the total predam sand supply to Grand Canyon, from the Colorado River upstream from Lees Ferry and with the Paria and Little Colorado Rivers combined, was approximately 29 million tons (26 million Mg).

Today, because Lake Powell traps all of the sediment upstream from Glen Canyon Dam, the Paria River is the primary source of sand to Marble Canyon, supplying approximately 6% of predam sand levels. In the case of Grand Canyon, Glen Canyon Dam has reduced its sand supply to primarily the contributions of the Paria and Little Colorado Rivers. Other lesser tributaries also contribute a small amount of sand to Grand Canyon, with an estimated cumulative supply that is approximately 10% to 20% of the mean annual load provided by the Paria River. Taken together, the contributions of sand from various sources provide Grand Canyon with approximately 16% of its predam sand levels. The findings presented here are drawn from Topping and others (2000b) and Webb and others (2000); readers interested in more details on the predam and postdam sediment budgets for Marble and Grand Canyons should consult these reports.

## Effects of Dam Operations on Flow Frequency and Duration

Changes in the flow regime of the Colorado River since construction of Glen Canyon Dam have also been dramatic in terms of seasonal variability, as well as in terms of daily fluctuations that occur because of "peaking" hydroelectric power generation. Dam operations have altered seasonal variability by eliminating long-duration flood flows that occurred during the spring snowmelt and short-duration flood flows that occurred during the late summer and early fall thunderstorm season, as well as the very low flows that occurred during summer, fall, and winter. With regard to the highest flows, dam operations have reduced the 2-yr recurrence interval flood (i.e., the flood that occurs every other year on average) from 85,000 cubic feet per second (cfs) during the predam period to 31,500 cfs during the postdam period. In the predam era, discharge exceeded 9,000 cfs only 44.3% of the time, while in the postdam era this percentage has gradually increased by decade, from 52.7% in the 1960s to 82.6% in the 1990s. This decrease in the duration of low flows has important implications for sediment transport because Topping and others (2000b) showed that flows less than about 9,000 cfs result in accumulation of tributary sand inputs in the Marble Canyon and Grand Canyon reaches of the river, whereas flows above this generally lead to transport of new sand inputs through these reaches or erosion of sand from these reaches.

Dam operations have introduced large daily variations in discharge to generate hydroelectric power that tracks daily peaks in demand throughout the Western United States. Also, because peak energy demand varies seasonally in the West, with peak demand occurring in midsummer and winter, the month-to-month flow pattern related to dam operation is substantially different from natural, predam, seasonal patterns. Highest discharges in the river now occur during the two seasons when predam discharge had typically been the lowest, midsummer and winter. Furthermore, daily patterns of flow in the river have been altered by dam operations. For example, during the predam period the median daily range in discharge was only 524 cfs, whereas in the postdam era the median daily range increased to 8,580 cfs, a value greater than the predam median discharge. Before dam operation, the daily range in discharge exceeded 10,000 cfs only about 1% of all days; postdam, the daily discharge range exceeded 10,000 cfs on 43% of all days.

Initially, operation of the dam's powerplant was characterized mostly by unconstrained daily fluctuations that were designed to optimize electrical generation around peak daily demand, which had patterns that also varied on a monthly timescale related to seasonal changes in energy demand. From 1963 through 1991, these operations typically caused the Colorado River's discharge to fluctuate on a daily basis from less than 5,000 cfs to near powerplant capacity of about 31,000 cfs. These so-called "no action" daily operations (because they were considered the no action alternative in the EIS) were first altered in 1990 to facilitate experimental release patterns implemented through July 1991 as part of field investigations associated with the EIS on dam operations. The experimental flows of 1990–91 were then followed by "interim operating criteria" from August 1991 until October 1996, when Secretary of the Interior Bruce Babbitt implemented current Record of Decision dam operations. Implementation of the interim operating criteria in 1991, as well as the MLFF in 1996, constrained the change in discharge over any 24-h period to 5,000; 6,000; or 8,000 cfs, depending on the monthly volume-release schedule specified in the annual operating plan for the Colorado River Storage Project. The flow history of the Colorado River into Grand Canyon as measured at the Lees Ferry gaging station is shown in figure 1. These flow data illustrate a transformation of the Colorado River from a fluvial ecosystem with significant seasonal variability in the predam era to a postdam river ecosystem with little seasonal variability and substantial daily fluctuations.

Another important aspect of the MLFF operation is the schedule of monthly release volumes in relation to the seasonality of sediment inputs. Because of energy demand and hydropower economics, monthly release volumes are highest during months with high demand, including those in late summer. Historically, however, the late summer months were characterized by low mainstem flows and the highest tributary inputs, leading to sediment accumulation during the predam era. Postdam, high summer releases coincide with tributary inputs, leading to rapid export instead of accumulation. Therefore, not only has the sand supply been drastically reduced through the impoundment of Lake Powell, but the seasonal timing of low and high flows has also been both highly compressed and significantly shifted to later periods of the year that coincide with tributary sand inputs. The information in this section was taken from Topping and others (2003); readers with further interest in the Colorado River's hydrology, both before and after the dam was closed, should consult this report.

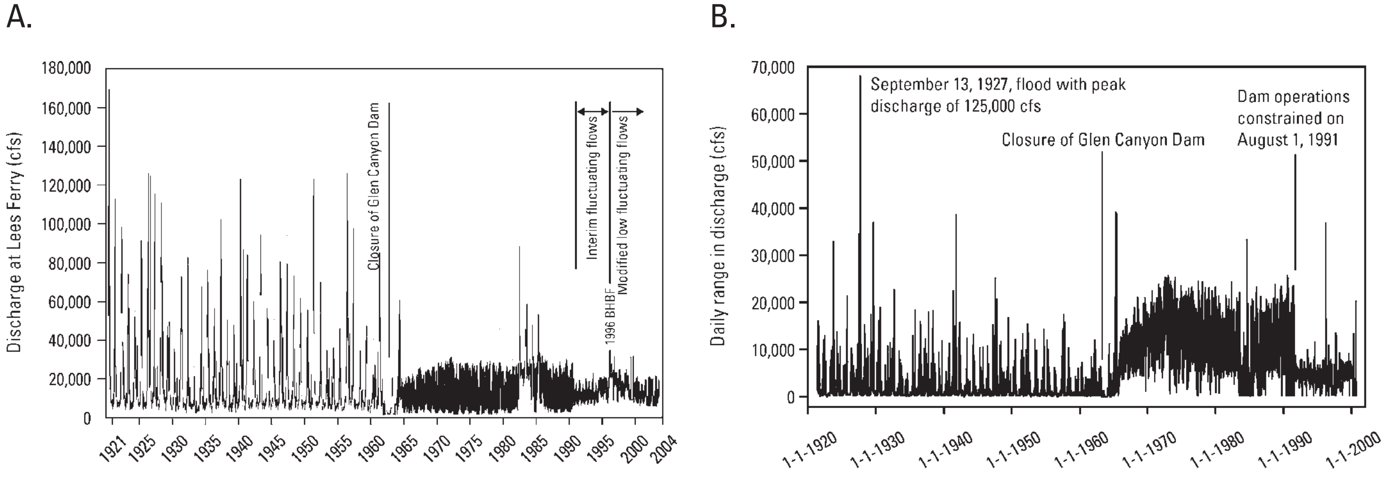


**Figure 1.** Instantaneous discharge (A) and daily range in discharge (B) in cubic feet per second of the Colorado River at Lees Ferry (RM 0) between 1921 and 2004 (modified from Topping and others, 2003). Before construction of Glen Canyon Dam, the annual peak flow routinely exceeded 100,000 cfs. Dam operations during the period from 1963 through 1990 were characterized by daily fluctuations from typically less than 5,000 cfs to near powerplant capacity, or about 31,000 cfs, and included the record wet period of the mid-1980s, which resulted in the use of the spillways in 1983 for emergency releases exceeding about 90,000 cfs. Interim operating criteria, which constrained daily release fluctuations, began in 1991 and were followed by the modified low fluctuating flow operating alternative that was implemented as part of the Secretary of the Interior's Record of Decision (ROD) in 1996 (BHBF = beach/habitat-building flow).

# Status and Trends of Fine Sediment Below Glen Canyon Dam

Changes in sand supply and flow regime downstream from a dam affect the geomorphology of the downstream channel. When a dam traps sand and releases clear water, this clear water is often termed "hungry" because it still has the capacity to transport an amount of sand and gravel proportional to the flow and will erode the downstream channel and banks in order to satisfy its appetite with respect to sediment transport. On the basis of resurveys of historical cross-sections upstream from Lees Ferry, approximately 20 million tons (18 million Mg) of material—gravel and fine sediment, including sand—have been eroded from the first 15 mi (24 km) of the Colorado River downstream from the dam, an area referred to in this report as the Lees Ferry reach (Grams and others, 2004). The amount of material removed is equivalent to a 6 to 10 ft (2–3 m) drop in channel elevation averaged over the entire reach. Most of this sediment was removed by daily, high-release dam operations designed to scour the channel of the Colorado River below the powerplant during April–June 1965 (fig. 1). Daily suspended-sediment measurements made by the USGS at the Lees Ferry and Grand Canyon gaging stations indicated that these high flows in 1965 eroded 4.4 million tons (4.0 million Mg) of fine sediment (mostly sand) from the Lees Ferry reach and 18 million tons (16 million Mg) of fine sediment (mostly sand) from Marble and upper Grand Canyons. Channel scour was anticipated below the dam during its design and was later needed to optimize energy generation within the operating range of the hydroelectric powerplant (Grams and others, 2004). Typical dam releases today do not result in much erosion from the Lees Ferry reach, and as a result very little fine sediment is transported downstream to Marble and upper Grand Canyons.

Despite the fact that its contributing drainage area is approximately 18 times smaller than that of the Little Colorado River, the single largest sand supplier to the reaches below Glen Canyon from 1990 through 2004 was the Paria River. Farther downstream in Marble and upper Grand Canyons, the fate of fine-sediment deposits is dependent upon the long-term balance between inputs to the system (i.e., tributary supply) and exports from the system (i.e., mainstem sediment-transport rates). Although sand inputs have been greatly reduced by the closure and operation of Glen Canyon Dam, the annual mainstem transport—and thus export—has also most likely been reduced because of the elimination of the highest flood flows. As a result, two possibilities exist for the postdam fine-sediment balance downstream from the Paria River. First, if the supply from the Paria River and other lesser Marble Canyon tributaries exceeds the postdam transport rate on an annual basis, then new sand inputs would accumulate in the channel and in low-elevation portions of eddies over multiple years. Such accumulated sand supplies would then be available at any time for redistribution to higher elevation sandbars through release of periodic controlled floods (i.e., beach/habitat-building flows in the EIS; hereafter BHBF) from Glen Canyon Dam. This scenario was the conclusion reached by Howard and Dolan (1981), Andrews (1990, 1991), Smillie and others (1993), and the EIS study team (U.S. Department of the Interior, 1995) for the MLFF alternative, leading to its implementation in 1996. Howard and Dolan (1981) reached their conclusion by using an estimate for the sand contribution from the lesser tributaries that is now regarded to be about a factor of four too high (Topping and others, 2000b; Webb and others, 2000). Andrews (1990, 1991) and Smillie and others (1993) reached their conclusions by using stable sand-transport relationships, also called "rating curves." A stable sand-transport rating curve exists where there is a unique value for sand concentration for any given flow. This approach invokes the assumption that the upstream sand supply is in equilibrium with transport capacity. The methods and data used to reach the conclusion in the EIS are discussed further in the following section.

Alternatively, if the annual mainstem transport rate (export) exceeds tributary supply (input), then systematic long-term erosion of fine sediment from the channel would be expected. In fact, this second scenario was originally predicted by Dolan and others (1974) and Laursen and others (1976) on the basis of their early sediment-transport studies related to effects of Glen Canyon Dam on downstream resources. In order for high-flow releases to be effective at restoring and maintaining sandbars under this second scenario, controlled floods would need to be strategically timed to coincide with or immediately follow tributary sand inputs. These early studies predated the concept of using controlled floods to restore eroded sandbars; hence, their estimates of sand transport in the postdam era could only result in net export of new sand inputs and continued erosion of existing sandbars of predam origin. More recent evidence presented in the following section further supports the conclusion that this second scenario prevails under the current reoperating strategy and that this situation is leading to systematic, long-term erosion of fine sediment from the channel bed and eddies of Marble and Grand Canyons. On the basis of existing data, it is still uncertain whether or not strategically timed managed floods can restore and maintain eroded sandbars by using only the limited and infrequent tributary-derived sand that enters the river below the dam.

## Recent Findings

### The Paradigm of Sand Transport and Storage Used in the 1995 Environmental Impact Statement

The EIS concluded that sand would accumulate over multiyear timescales in the channel of the Colorado River in Marble and upper Grand Canyons during MLFF powerplant releases in all but the highest release years (U.S. Department of the Interior, 1995). The basis for this conclusion was the assumption that the relationship between the water discharge and sand transport in the Colorado River did not change substantially over time. This assumption was used because sediment-transport data collected in the postdam Colorado River were sparse.

Prior to the early 1970s, suspended-sediment concentration was measured on a daily basis at the three USGS gaging stations that are critical to constructing a sand budget for Marble and Grand Canyons: the Paria River at Lees Ferry, the Little Colorado River at Cameron, and the Colorado River near Grand Canyon. The sediment sampling program at the Colorado River near Grand Canyon gaging station began in October 1925; the daily sediment sampling programs at the Paria and Little Colorado Rivers began in October 1947. The Little Colorado River sediment record was discontinued on September 30, 1970; the Colorado River sediment record at the Grand Canyon gaging station was discontinued on September 30, 1972; and the Paria River sediment record was discontinued on September 30, 1976. Thus, the only postdam period of overlap between these stations that could be used to construct a sand budget was the period from closure of the dam in March 1963 through September 30, 1970. Furthermore, no postdam sand-transport data were collected within Marble Canyon during this early period.

To fill this data gap, the USGS began a program of quasi-daily sediment sampling on the major tributaries to the Colorado River (that is, the Paria River, the Little Colorado River, and Kanab Creek) and at five locations on the mainstem Colorado River in Marble and Grand Canyons (Garrett and others, 1993). On the tributaries, this program extended from July through December 1983. On the mainstem, this program included the periods from July through December 1983 and October 1985 through January 1986. All suspended-sediment samples collected under this program were analyzed for grain size to allow use in constructing sand budgets.

The sand budget for the Colorado River in Marble and Grand Canyons used in the EIS was constructed by Randle and Pemberton (1987) and Pemberton (1987). For tributary sand input, they constructed stable sand-rating curves by using all of the historical and 1983 data from the Paria River, the Little Colorado River, and Kanab Creek. They also included an estimate for the sand supply from the lesser tributaries. Pemberton (1987) developed stable sand-transport rating curves at the five mainstem locations based on the USGS 1983–86 data, and the EIS states, "The sand transport equations of Randle and Pemberton (1987) and Pemberton (1987) were used for these computations" (U.S. Department of the Interior, 1995, p. 95) in reference to the sediment budget presented in figure III-15 of the EIS (and reproduced here as fig. 2). Therefore, the EIS sediment budget was based on the assumption of stable sand-transport rating curves. Results of recent studies presented in the following section suggest that this assumption is incorrect for the Colorado River below Glen Canyon Dam.

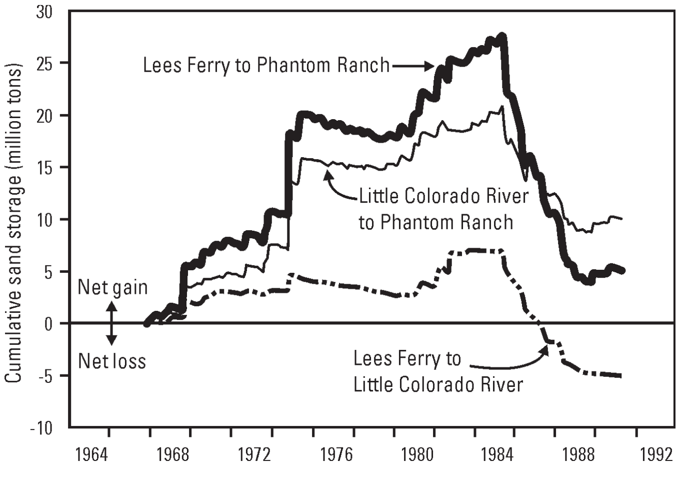


**Figure 2.** Reproduction of figure III-15 from the final environmental impact statement (EIS) (U.S. Department of the Interior, 1995), which shows the sand budget as computed by Randle and Pemberton (1987). Recent studies refute the conclusion of the EIS that sand accumulates on the bed of the Colorado River over multiple years under normal dam operations. (Phantom Ranch is the location of the Grand Canyon gage.)

## Studies Since 1996 That Refute the Environmental Impact Statement Findings

Research and monitoring conducted during and after the 1996 BHBF experiment, also known as the 1996 controlled flood, have led to several findings that refute the EIS predictions for sand conservation and suggest that the implementation of this strategy has not led to sustainable restoration and maintenance of sandbars in either Marble or Grand Canyon. Instead, the canyons' sandbars continue to erode (figs. 3–6). The primary results of several of these studies are briefly summarized below:

- Rubin and others (1998) and Topping and others (1999) showed that the sand supply during the 1996 BHBF was not as great as was assumed before the experiment and that the sand on the bed of the river and in suspension coarsened dramatically as the upstream supply of sand decreased over time during this flood. This process led to flood deposits that coarsened vertically upward (i.e., inversely graded deposits).

- Topping and others (2000a) demonstrated that the grain size of sand on the bed of the Colorado River can change by over a factor of four as functions of tributary resupply of finer sand and higher dam releases that winnow the bed and that this factor-of-four change in bed-sand grain size corresponds to a change of two orders of magnitude in the concentration of sand in suspension (for the same discharge of water). Identification of this dynamic process precludes the use of stable sand-transport relationships in the Colorado River, thus invalidating the approach used to construct the sand budget in the EIS. Topping and others (2000a) also showed that Randle and Pemberton (1987) incorrectly predicted sand accumulation in the Colorado River because the data they used to verify their modeled stable sand-export relationships were from periods in the mid-1980s, when sand in the river was anomalously coarse and sand-transport rates were anomalously low following prolonged releases above powerplant capacity between 1983 and 1986.

- Rubin and Topping (2001) showed that sand transport in the postdam Colorado River in Grand Canyon is regulated by both the discharge of water and the grain size of the sand available for transport in suspension. This information also

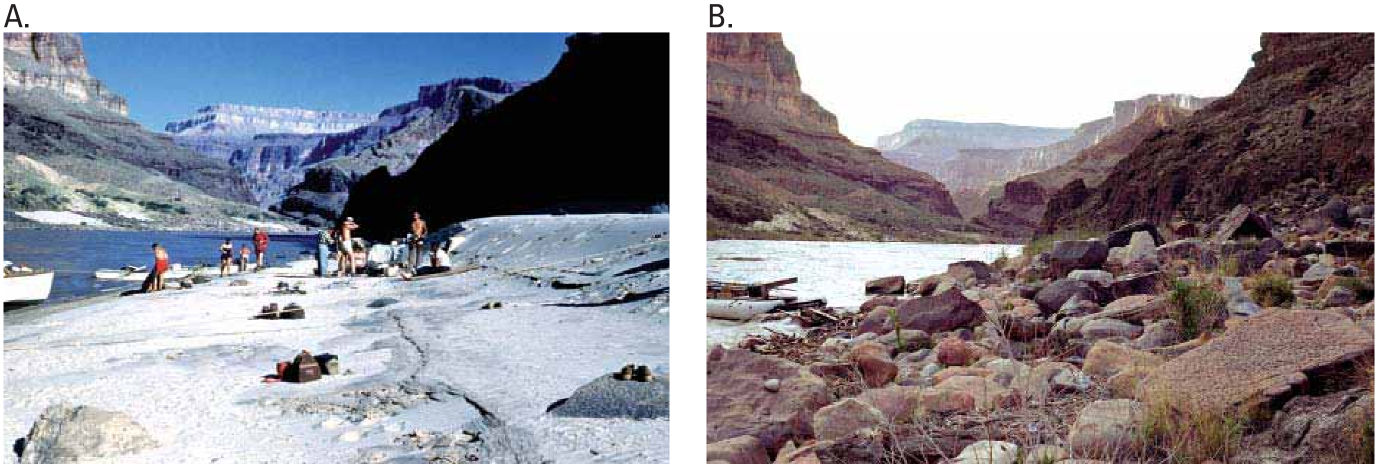
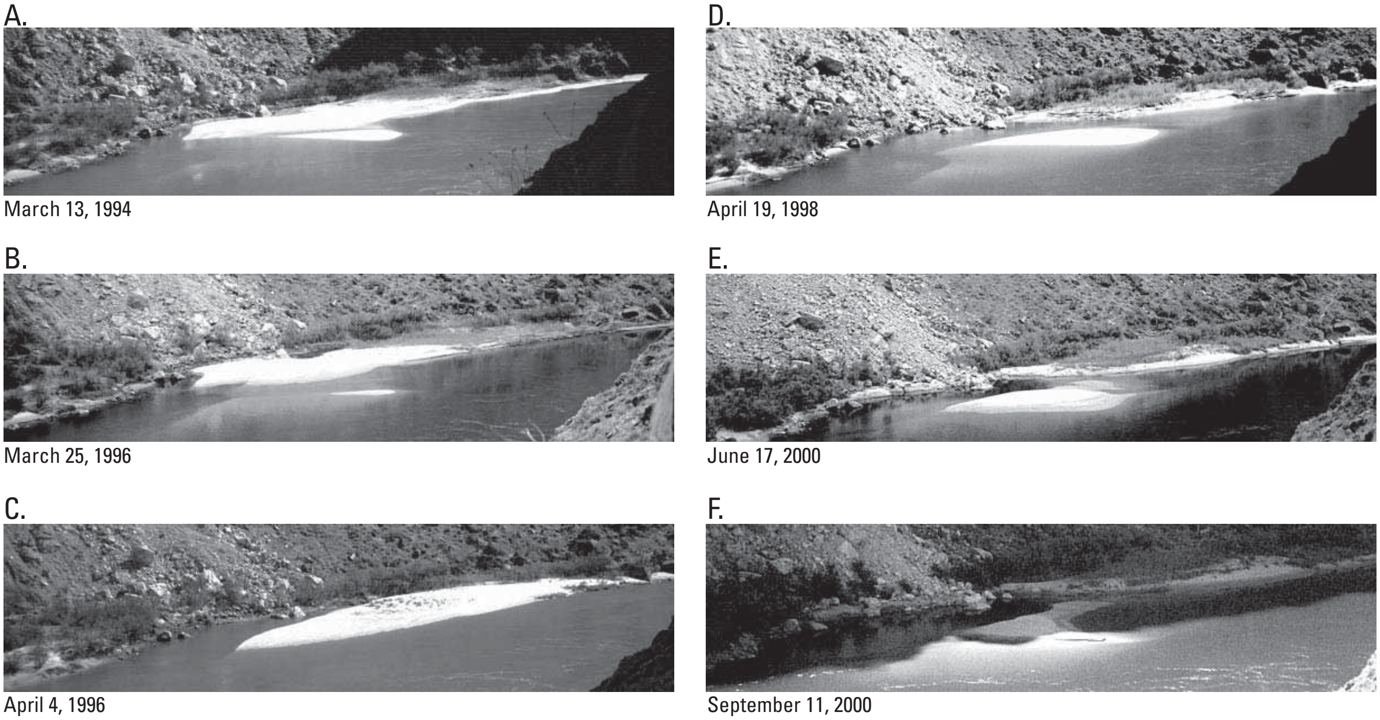


**Figure 3.** Repeat photographs of Tapeats Creek at the Colorado River, Grand Canyon (RM 133.8, right shore). A. (July 1952) This view downstream from below the mouth of Tapeats Creek shows a large sandbar with few rocks or boulders exposed. This sandbar was frequently used for layovers during river trips in the 1950s (Kent Frost, courtesy of the photographer). B. (March 27, 2003) Large rocks and boulders are now exposed because of severe beach erosion. New sand was deposited here during the 1996 beach/habitat-building flow but was quickly removed. This camp is no longer used, which creates a problem for river runners who want to visit Tapeats Creek (J. Janssen, stake 2676, courtesy of the Desert Laboratory Collection of Repeat Photography). (Figure after Webb and others, 2002.)



March 13, 1994

April 19, 1998

March 25, 1996

June 17, 2000

April 4, 1996

September 11, 2000

**Figure 4.** Time series of repeat photographs of sandbars along the left shore of the Colorado River near RM 44.5 (Eminence Break) illustrating deposition on the sandbar during the 1996 beach/habitat-building flow (March 26–April 2; high flow occurred between photographs B and C) and subsequent erosion since April 1996. Images provided by Northern Arizona University, Department of Geology in cooperation with the U.S. Geological Survey.

contradicts the approach of the EIS, where it was assumed that sand transport was regulated only by the discharge of water.

- Topping and others (2000b) showed through their analysis of the 1965–70 daily sediment-transport data collected by USGS that, under normal powerplant flows, newly input tributary sand is exported past the Grand Canyon gaging station within several months. Their analysis of predam data indicated that, prior to closure of Glen Canyon Dam, sand would accumulate in Marble and upper Grand Canyons only during the 9 mo of the year when discharges were typically lower than about 9,000 cfs.
- Measurements of the channel bed indicate that tributary sand, which is typically much finer than the sand on the bed of the Colorado River, accumulates on the bed for only a short time before being eroded and transported out of the canyon under normal MLFF dam operations (Topping and others, 2000a).
- Since August 1999, detailed suspended-sediment transport measurements have been collected at the Paria and Little Colorado Rivers to document inputs and at the USGS gaging stations above the mouth of the Little Colorado River and near Grand Canyon to document export. Initially, these quasi-daily measurements were made by using only conventional USGS methodologies to obtain cross-sectionally integrated samples of suspended-sediment concentration and grain size (methods described in Edwards and Glysson, 1999). Because substantial and rapid (within a day) changes that are due to tributary inputs can occur in suspended-sediment concentration and grain size, emerging technologies for continuous monitoring of suspended-sediment concentration and grain size were tested and implemented beginning in 2001. These technologies include acoustic backscatter and laser-diffraction methods and are described in detail in Melis and others (2004) and Topping and others (2004). The detailed sediment-transport measurements allow for the ability to construct sediment budgets based on continuous data instead of on rating curves, a very important distinction from the EIS approach of using a limited data set. These data show that the overall mass balance of sand (input minus export) continues to be negative (fig. 7), as originally predicted by Laursen and

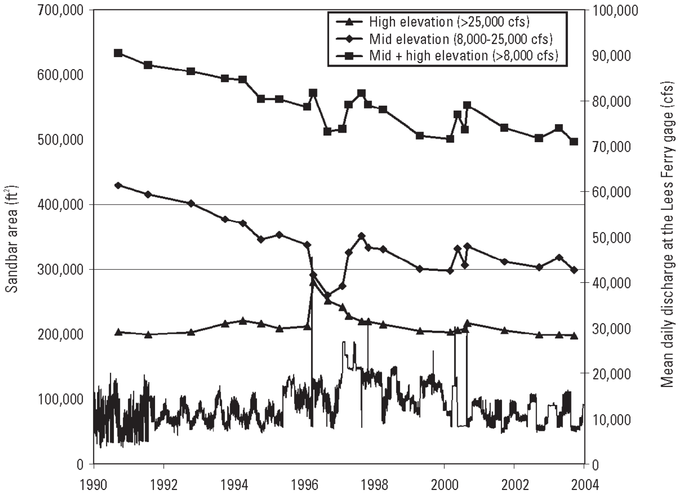


**Figure 6.** Changes in sandbar size (total surface area) are shown for 14 long-term sandbar study sites between the Lees Ferry and Grand Canyon gages (RM 0 to RM 87). Area of bars exposed above water discharges of 8,000 cfs decreased by 22% from 1991 to 2004. The 1996 beach/habitat-building flow resulted in a net transfer of sand from mid elevations to high elevations (modified from Rubin and others, 2002).

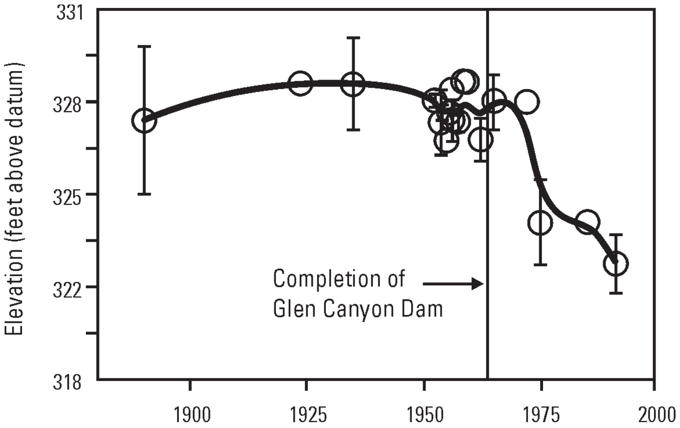


**Figure 5.** A decrease in elevation of the sandbar surface is seen at Jackass Creek camp located along the left shore of the Colorado River, 23 mi (37 km) downstream of Glen Canyon Dam. Elevations were determined by examining oblique and aerial photographs of the site and by field survey of the elevation and the former sand surface at its contact with large talus blocks. This graph shows the elevations near one prominent talus block that was inundated by predam mean annual floods, but since the dam was completed, the talus block has been inundated infrequently (modified from Rubin and others, 2002).

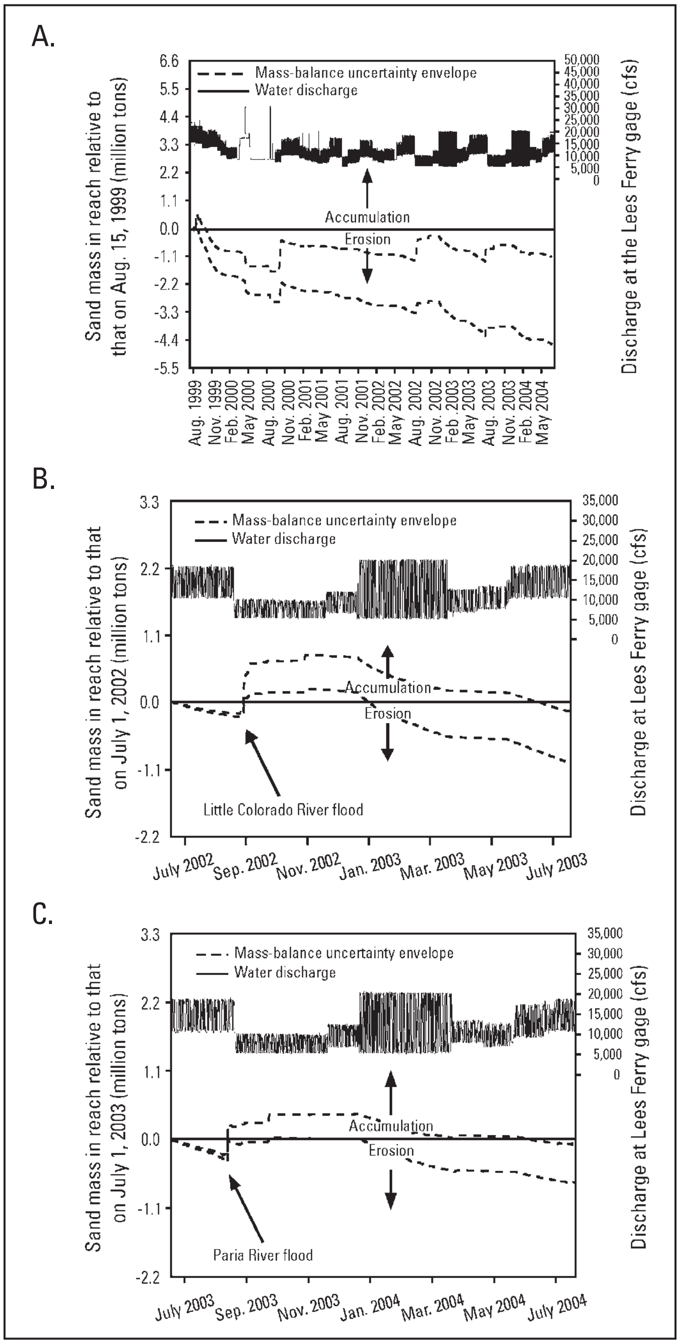


**Figure 7.** Mass balance of sand between Lees Ferry and Grand Canyon gages from August 1999 through July 2004 (A) and separately for sediment years (July–June) 2003 (B) and 2004 (C). Mass balance is computed by subtracting measured, mainstem suspended-sand export (10% uncertainty) from estimated and measured sand inputs from the Paria River (20% uncertainty) and Little Colorado River (30% uncertainty), as well as from estimated inputs from numerous lesser tributaries (50% uncertainty). The measurements illustrate the rapid export of tributary inputs by high dam releases and the continued overall loss of sand from Grand Canyon under the modified low fluctuating flow (MLFF) alternative, even during the drought-hydrology, minimum-volume release years of 2003 and 2004 (modified and updated from Rubin and others, 2002).

others (1976). Most significantly, the sand mass balance remained negative during water years 2000 through 2004, despite 5 consecutive years in which minimal release volumes (8.23 million acre-feet (10,148 million m$^3$)) from Lake Powell occurred during prolonged drought in the upper Colorado River Basin. These measurements and calculations of sand transport also show that tributary inputs are typically transported downstream and out of the canyon within a few months under typical Record of Decision operations (Rubin and others, 2002).

- Repeat topographic mapping of sandbars (Hazel and others, 1999) showed that the 1996 BHBF did increase the surface area of high-elevation sandbars, but more than half of the sand deposited at higher elevations was taken from the lower portions of the sandbars (Schmidt, 1999) rather than being derived from tributary sand supplies accumulated on the channel bed, as originally hypothesized in the 1995 EIS.
- Repeated surveys of channel cross-sections (Flynn and Hornewer, 2003) revealed erosion at 55 of the 57 locations between 1991 and 1999, even though daily operations were constrained during the time series of repeat measurements.
- Schmidt and others (2004) conducted geomorphic mapping from air photos and land surveys for the predam and postdam periods. They estimated the loss of sand to be about 25% of the area typically exposed at base flow in predam photographs, but estimates range from 0% to 55% depending on study reach and method of analysis. Their studies further suggested that loss of the sandbar area continued at a relatively steady rate between 1983 and 2002, despite constraints on daily operations imposed after 1991.

## Importance of Continuous Long-term Sediment-transport Data

Because of a lack of continuous data on sediment inputs and export that would have allowed for a sediment budget based on measured data, the EIS study team used stable sand-transport rating curves. Stable rating curves assume that for any given flow there is a single value for the corresponding sand concentration and, therefore, a predictable sand-transport rate related to flows released from Glen Canyon Dam. The recent studies reported above, however, have demonstrated that in the postdam Colorado River the relationship between flow and sand transport is not stable but instead shifts quickly and substantially relative to the grain size of sand on the bed of the river (which is controlled by tributary inputs and mainstem flows). Rubin and Topping (2001) and Rubin and others (2002) showed that the grain size of the sand in the regulated Colorado River ecosystem depends greatly on the recent history of tributary activity. For example, during low tributary flow periods the only source of sand to the mainstem Colorado River is that on the channel bed and in eddies, and that sand tends to be much coarser than tributary-delivered sand because of the winnowing of the finer sizes. When tributaries are flooding and delivering large quantities of fine sand (fig. 8), however, the supply is no longer limited to the coarser channel bed sand, resulting in much higher mainstem sand concentrations and, hence, greatly increased suspended-sediment export for any given flow released from the dam.

Because sand transport cannot be predicted based on discharge alone, sediment budgets for the Colorado River in Grand Canyon can only be constructed based on measurements of sand transport at a frequency great enough to capture changes in concentration and grain size resulting from tributary inputs. Fundamentally, the conclusions drawn by the EIS team, which are not supported by the more recent data, resulted from a lack of continuous data in the postdam era; that is, if daily records had been continued beyond 1972 and into the EIS period, then the fine-sediment budget would have been constructed based on these data rather than on stable rating curves. Recent sediment budgets suggest that under this scenario the conclusions of the EIS would have been different and possibly would have led to a different strategy for operation of Glen Canyon Dam in 1996. Though it is somewhat costly to collect long-term, high-frequency sediment-transport records, in this case it may have prevented 13 yr of dam operations that have continued to erode sandbars from Grand Canyon.

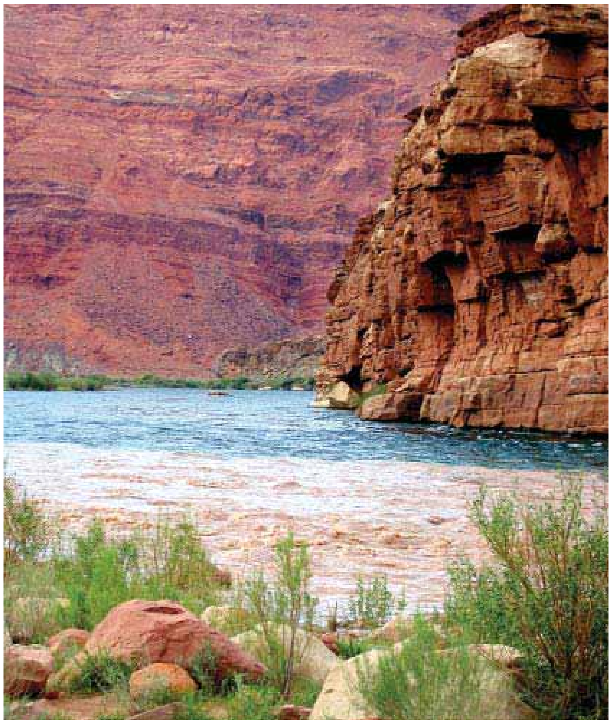


**Figure 8.** Looking upstream into Glen Canyon from the Paria River confluence with the main channel Colorado River during a Paria River flood. Tributary inputs of sand, such as the one pictured, now encounter clear Colorado River water because Lake Powell traps incoming fine sediment. The Paria River is the primary source of sand to Marble Canyon but is only about 6% of the predam sand supply (photograph by Scott A. Wright, U.S. Geological Survey).

# Current Experimental Plan for Fine Sediment

Because recent research has shown that sand does not accumulate on the river bed in Marble and Grand Canyons under normal Record of Decision dam operations, scientists have recently proposed two possible field tests of dam operating options that might more effectively conserve limited, downstream sand resources. One approach is to implement floods immediately following large tributary inputs that commonly occur in late summer and early fall. A second approach is to follow tributary sand-input events with low flows, in order to limit export and retain most of the sand input, until flooding can be implemented. This approach would require a change in the pattern of monthly release volumes and associated dam operations because July and August releases of recent drought years still resulted in half of the sand introduced by a tributary flood being exported within days or weeks (Rubin and others, 2002).

In September 2002, the U.S. Department of the Interior (2002) approved implementation of the second approach described above. Under this plan, changes in dam operations and restoration floods are linked to triggering thresholds based on sand inputs from the Paria River and lesser Marble Canyon tributaries and retention of sand in Marble and Grand Canyons. For example, the “autumn sediment input” scenario described in the 2002 environmental assessment (EA) (U.S. Department of the Interior, 2002) defined a sequence of events related to sand inputs and retention that would trigger a 2-d, 42,000–45,000-cfs experimental high flow in the following January (fig. 9). Significant sand inputs to Marble Canyon that exceeded the triggering threshold for an experimental high flow occurred during September–November 2004. Instead of constraining operations through December (a winter, peak-demand month) in order to retain sand in Marble Canyon as laid out in the 2002 EA, a supplemental EA was prepared that allowed for a hybrid of the first and second approaches to be tested and evaluated. Approval of the supplemental EA paved the way for the experimental high flow that began on Sunday, November 21, 2004, when the Bureau of Reclamation opened the bypass tubes of Glen Canyon Dam for 90 h. The peak high flows ran for 2.5 d (60 h) at about 41,000 cfs. Scientists will evaluate data collected during and after the high-flow event to determine whether or not this strategy succeeded in enlarging existing beaches and sandbars.

Other dam operation scenarios may be more effective at retaining tributary inputs, such as Record of Decision operations modified such that equal volumes of water are released from the dam each month. Alternatively, a scenario of seasonally adjusted steady flows, which was an alternative in the EIS process, may be effective. Because of the severely reduced sand supply, however, even during periods of minimum release requirements of 8.23 million acre-feet (10,148 million m$^3$) per year the possibility exists that no operational scenario will result in management objectives being achieved for restoring sandbars, simply because of the volume of water that must be released on an annual basis. If so, other, more effective alternatives for restoring and maintaining sandbars and related habitats may need to be evaluated.

Sediment augmentation, one possible alternative, was eliminated during the development of the EIS, partly because of the belief that sandbars could be restored and maintained by constraining the hourly ramping rates and range of daily dam operations and partly because of concerns about contamination of sediment upstream in Lake Powell (Graf, 1985). Addition of sediment—continuously, seasonally, or perhaps only during floods—may offer greater powerplant operating flexibility and therefore may cost less than further restrictions on annual dam operations. To this end, the feasibility of mechanically transporting fine sediment around Glen Canyon Dam and introducing it into the Colorado River below the dam is currently being investigated.

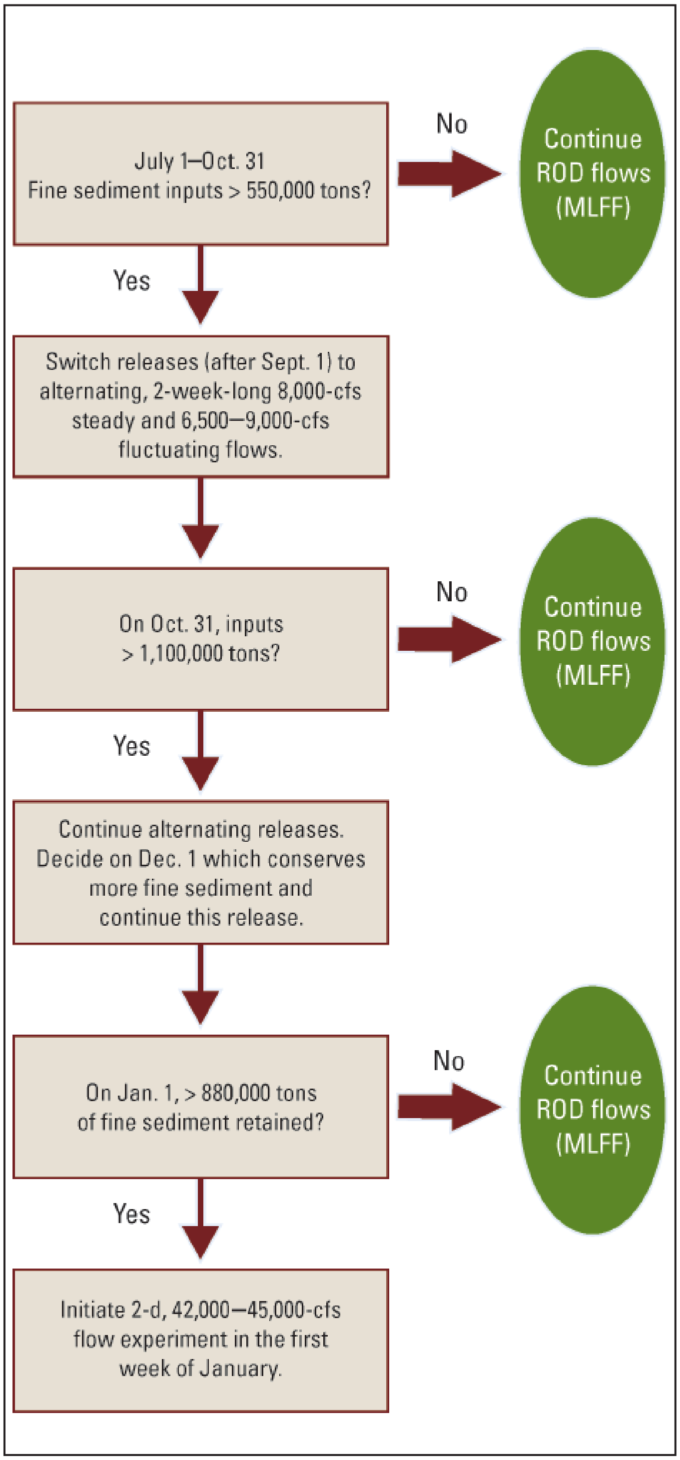


**Figure 9.** Sequence of events established in the autumn sediment input scenario in an environmental assessment by U.S. Department of the Interior (2002) related to fine-sediment inputs and retention to trigger a 2-d, 42,000–45,000-cfs experimental high flow in January. If fine-sediment inputs do not reach specified levels, then modified low fluctuating flow (MLFF) operations, as specified in the Record of Decision (ROD) (U.S. Department of the Interior, 1996), are continued.

## Discussion and Future Research Needs

Extensive research and monitoring of fine-sediment transport and sandbars since the completion of the EIS have resulted in a better understanding of the geomorphology of the Colorado River in Marble and Grand Canyons and of the effects of the operations of Glen Canyon Dam on the river's downstream resources. Probably the single most important finding of this research and monitoring is that postdam mainstem sand transport exceeds the postdam supply of sand from tributaries on a seasonal to annual basis, such that the postdam river is in an annual fine-sediment deficit (i.e., export exceeds input). This sediment deficit has resulted in a consistent downstream pattern of erosion of channel and sandbar deposits from Marble and Grand Canyons despite restrictions on daily powerplant fluctuations required by the implementation of the MLFF alternative.

The finding of an annual sediment deficit directly contradicts the critical EIS assumption that sand will accumulate on the bed of the Colorado River over multiple years under the MLFF operating alternative (and minimum annual volume releases) and has important implications for the potential success of managing tributary sediment inputs. It is also worth noting that the EIS conclusion resulted fundamentally from a lack of long-term records for tributary sand supply and mainstem sand-transport rates, illustrating the importance of long-term data sets in river management. A continuous sediment budget for the Colorado River in Grand Canyon since construction of Glen Canyon Dam, based on high-frequency measurements, likely would have resulted in a different EIS conclusion about fine-sediment dynamics below the dam, one that may have prevented the continued erosion of sandbars between 1991 and 2004.

A second important finding of recent research and monitoring efforts is that during the 1996 BHBF the primary source of sand for building high-elevation sandbars was the low-elevation portion of the sandbars instead of the channel bed as hypothesized in the EIS. This scenario of building high-elevation sandbars at the expense of the low-elevation portions was repeated during the powerplant capacity flow in September 2000 (Hazel and others, in press). This process of sandbar building is supported by the finding of an absence of multiyear accumulation on the channel bed: sand cannot be transported from the bed to high-elevation sandbars because there is typically little sand available on the channel bed.

Neither of these two findings supports the EIS hypotheses, but they have led scientists and managers to reassess the management strategy for sand resources within Grand Canyon. An emerging paradigm is the need to strategically time high-flow releases in order to take advantage of sporadic tributary sediment inputs, a scenario that requires greater flexibility in the annual operating plan for the dam with respect to both hydroelectric power generation and economic cost. Only immediately after these inputs is significant sand available on the channel bed for transfer to high-elevation sandbars through high-flow releases. Alternatively, dam releases may be constrained following inputs for a period of time until a high flow can be released from the dam; however, during extended periods of above-average upper Colorado River Basin hydrology and high storage in Lake Powell, constraining daily operations may not be possible (see fig. 1, 1995 through 1998). In the absence of high-flow releases strategically timed to redistribute tributary inputs to high-elevation sandbars, the inputs are exported from Grand Canyon in a period of weeks or months under normal dam operations, leading to continued long-term erosion of sandbars.

In November 2004, this paradigm of strategically timed, high-flow releases was tested for the first time on the Colorado River. Scientists are in the process of evaluating the results of this experiment. The findings will be critical for the long-term management of fine-sediment resources and sandbars in Grand Canyon. If a management approach of strategically timed, high-flow releases, triggered by tributary inputs, is to be followed, then further research will be required to define the appropriate triggering criteria and to develop high-flow hydrographs (peaks and durations) that may optimize deposition of tributary sand inputs within eddies while minimizing export during controlled flood peaks.

If strategically timed, high-flow releases are deemed inadequate for meeting the management objectives for Grand Canyon sandbars, then alternative approaches must be considered, such as further restraints on daily powerplant operations, changes in monthly volume release patterns, or sediment augmentation.

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Jeff Sorensen, Arizona Game and Fish Department

First page photograph credit: Jeff Sorensen, Arizona Game and Fish Department

# Chapter 2

# Fishes of Grand Canyon

Steven P. Gloss

Lewis G. Coggins

## Introduction

Fishes of the Colorado River vary from coldwater trout species found in the river's mountainous headwaters to uniquely adapted desert river species found at lower elevations. Within the study area, the Colorado River corridor between Glen Canyon Dam and the western boundary of Grand Canyon National Park (hereafter Grand Canyon), the Colorado River was a seasonally warm and turbid river characterized by large seasonal variations in flow before it was altered by the closure of Glen Canyon Dam in 1963 (Topping and others, 2003). Although water temperatures fluctuated between 32°F (0°C) during winter to a high approaching 86°F (30°C) during late summer, several warmwater native fish species successfully inhabited this stretch of the river (Cole and Kubly, 1976). Because of the harsh environment created by dramatic seasonal fluctuations in the river's predam flow and temperature, only 8 of the 32 species of native fish historically found in the Colorado River were common in the Grand Canyon reach of the river. Other native fishes within the study area were restricted to small tributary streams or occurred only in transient or seasonal numbers. Of the eight fish species that were originally common to the study area, only four species are known to persist today.

The number of species that made up the original fish community of the Colorado River was altered well before the construction of mainstem dams because of the introduction of nonnative fishes by early European settlers. Nonnative fishes, from sport fishes to escapees from aquaria, have been intentionally and inadvertently stocked in the Colorado River for more than 100 yr (Mueller and Marsh, 2002). Today, nonnative fishes originating in many parts of the world are found in the Colorado River. Table 1 contains a list of the native and nonnative fishes of the Colorado River in Grand Canyon.

This chapter examines the status, trends, and recent condition of Grand Canyon fishes, focusing particular attention on the endangered humpback chub (*Gila cypha*) because of its prominence within the Glen Canyon Dam Adaptive Management Program (see Overview, this report). The chapter begins with a discussion of the conditions that led to the development of the Grand Canyon's unique native fish populations and then moves on to the reasons for their decline. The effects of the modified low fluctuating flow (MLFF) alternative on fish

**Table 1.** Historical and present relative abundance of fish species in the Colorado River from Glen Canyon to Separation Canyon. P = present, abundance unknown; A = abundant; C = common; LC = locally common; R = rare; and - = not encountered.

[Modified from Valdez and Ryel, 1995. Species that are federally listed as endangered are indicated by an asterisk (*). Species that are endemic to the lower basin of the Colorado River but occurred almost exclusively in smaller streams or rivers tributary to the mainstem Colorado River are indicated by a plus sign (+)]

| Species | Pre-1850 | 1958–59 | 1970–73 | 1984–86 | 1990–93 |
|---|---|---|---|---|---|
| **Family: Clupeidae, shads (introduced)** | | | | | |
| Threadfin shad | - | - | R | - | C |
| **Family: Cyprinidae, minnows** | | | | | |
| Native | | | | | |
| *Humpback chub | P | - | R | R | LC |
| *Bonytail chub | P | - | - | - | - |
| Roundtail chub | P | R | - | - | - |
| *Colorado pikeminnow | P | R | - | - | - |
| Speckled dace | P | A | A | A | C |
| Virgin spinedace+ | P | - | R | - | - |
| Woundfin+ | P | - | - | - | - |
| Introduced | | | | | |
| Red shiner | - | - | R | - | A |
| Common carp | - | C | A | A | A |
| Utah chub | - | R | - | R | - |
| Golden shiner | - | - | R | R | R |
| Fathead minnow | - | A | C | A | LC |
| **Family: Catostomidae, suckers (all native)** | | | | | |
| Bluehead sucker | P | C | C | C | C |
| Flannelmouth sucker | P | C | C | C | C |
| *Razorback sucker | P | R | - | R | - |
| **Family: Ictaluridae, bullhead catfishes (all introduced)** | | | | | |
| Black bullhead | - | C | - | R | R |
| Yellow bullhead | - | - | - | R | - |
| Channel catfish | - | A | C | R | LC |
| **Family: Salmonidae, salmon and trout (all introduced)** | | | | | |
| Cutthroat trout | - | - | - | R | - |
| Coho salmon | - | - | R | - | - |
| Rainbow trout | - | - | C | A | A |
| Brown trout | - | - | - | C | C |
| Brook trout | - | - | - | C | R |
| **Family: Cyprinodontidae, killifishes (introduced)** | | | | | |
| Plains killifish | - | R | C | R | LC |
| **Family: Poeciliidae, livebearers (introduced)** | | | | | |
| Mosquitofish | - | R | R | - | LC |
| **Family: Percichthyidae, temperate basses (introduced)** | | | | | |
| Striped bass | - | - | - | R | R |
| **Family: Centrarchidae, sunfishes (all introduced)** | | | | | |
| Green sunfish | - | C | R | R | R |
| Bluegill | - | R | R | - | R |
| Largemouth bass | - | R | R | R | R |
| Black crappie | - | - | - | - | R |
| **Family: Percidae, perch (all introduced)** | | | | | |
| Yellow perch | - | R | - | - | - |
| Walleye | - | - | - | - | R |
| **Total number of species** | **10** | **17** | **18** | **20** | **22** |

populations are also examined. The chapter concludes with a discussion of possible management options to slow or reverse the decline of humpback chub numbers.

## Background

The Colorado River was one of the last areas of the continental United States to be explored by Europeans; it was first traversed during the expedition headed by John Wesley Powell in 1869. For this reason, it is not surprising that scientific descriptions of many of the organisms in the Colorado River corridor, especially the fishes, did not begin until the 1930s and 1940s; earlier expeditions collected and described fishes generally rather than specifically. Emery and Ellsworth Kolb, explorers and photographers of the Colorado River in the early 1900s, reported that fishes were very abundant (Kolb and Kolb, 1914). The humpback chub was the last of the native fishes in Grand Canyon to be described in 1946 by Robert R. Miller from specimens taken from the Colorado River in Grand Canyon (Miller, 1946).

Scientific description of the native fishes of Grand Canyon showed that these species were unique in at least two ways. Most noticeably, several of the species share unusual body shapes, including large adult body size, small depressed skulls, large predorsal humps or keels, and small eyes, which presumably developed as adaptations to life in a large, turbid, and seasonably variable riverine environment. These features are perhaps best observed in the razorback sucker (*Xyrauchen texanus*) and the humpback chub (see accompanying text box, p. 51).

A second, and perhaps more important, measure of the uniqueness of Grand Canyon native fishes is that most of these species are not found elsewhere in the world. Organisms that are native to a certain location and do not occur anywhere else are called endemic species. Of the eight native species common to the Grand Canyon, six are species endemic to the Colorado River Basin. As early as 1895, scientists recognized the special nature of Colorado River fishes and the high rates of endemism (Minckley, 1991). Later research did not alter this conclusion, and despite a relatively low number of species compared to other drainages in the United States, the Colorado River Basin has a recognized endemism at the species level of approximately 75% and supports the most distinctive ichthyofauna in North America (Minckley, 1991).

Before European settlement, the native fishes found in the Grand Canyon portion of the Colorado River were exclusively minnows and suckers. The biggest of these fish was the Colorado pikeminnow (*Ptychocheilus lucius*), which is also the largest of all native minnow (cyprinid) species in North America and was found only in the Colorado River Basin (fig. 1). Called a white salmon by early settlers, the Colorado pikeminnow reached up to 6 ft (2 m) in length and had a weight of up to 80 lb (36 kg) (Mueller and Marsh, 2002).

Today, three of the eight native fish species have been eliminated from the Colorado River in Glen and Grand Canyons (roundtail chub (*Gila robusta*), bonytail chub (*Gila elegans*), and Colorado pikeminnow), and two are federally listed as endangered (humpback chub and razorback sucker) under the Endangered Species Act. Although listed as an endangered species with designated critical habitat in Grand Canyon, the razorback sucker has rarely been collected (Minckley, 1991; Valdez and Carothers, 1998) and is widely thought to no longer be found in Grand Canyon. The status of the flannelmouth sucker (*Catostomus latipinnis*) is common, and the species persists in the study area and throughout much of the upper Colorado River Basin. The remaining two fish (bluehead sucker (*Catostomus discobolus*) and speckled dace (*Rhinichthys osculus*)) are relatively common. Brief descriptions of the life histories of all the Grand Canyon native fishes can be found in Minckley (1991); this chapter provides text boxes (see p. 50) with summary information for the four native fishes that continue to inhabit Grand

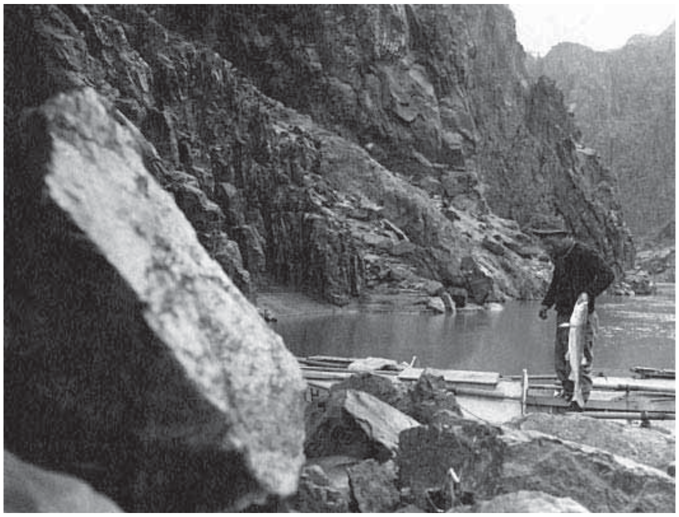

**Figure 1.** Historical photograph (date unknown) of someone identified as James Fagen holding a large Colorado pikeminnow in lower Granite Gorge (courtesy of the Kolb Collection, Cline Library, Northern Arizona University, NAU.PH.568.5737).

Canyon, as well as for the two most common nonnative species, rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*).

# Decline of Native Fish

## Introductions of Nonnative Fishes

There are a number of reasons for the decline of native fishes, including the potential effects of nonnative fish species. Nonnative fish have been found in the Colorado River since the 1800s (Minckley, 1991). These species are potential predators of and competitors with native fish and include common carp (*Cyprinus carpio*), fathead minnow (*Pimephales promelas*), plains killifish (*Fundulus zebrinus*), rainbow trout, brown trout, red shiner (*Cyprinella lutrensis*), and channel catfish (*Ictalurus punctatus*). Nonnative species may share rearing habitats used by native fish, habitats which include complex shorelines, tributaries, backwater areas, and eddies. The presence of warmwater, coolwater, and coldwater nonnative fish species in the Colorado River is an issue of considerable importance (U.S. Department of the Interior, 1995) because there are now nonnative fishes that may negatively interact with native fishes under virtually any temperature regime and in any habitat of the river.

Today, the Colorado River has nearly twice as many nonnative species (60) as native species (32); in the Grand Canyon reach of the river the situation is even more extreme, where the ratio of native to nonnative species is more than 4 to 1 (Valdez and Carothers, 1998). The introduction of nonnative species to the Colorado River, both intentionally and unintentionally, was well underway before 1900. As such, the ratio of nonnative to native fishes was high in Grand Canyon before the construction of Glen Canyon Dam. For example, the National Park Service introduced both brown trout and rainbow trout to tributaries like Bright Angel Creek in the 1920s to provide sport fishing opportunities (Valdez and Carothers, 1998). Because of the continuous nature of the river and its tributaries before dam building, species introduced almost anywhere in the basin had the potential to find their way to the Grand Canyon portion of the river, and many did. Before Glen Canyon Dam, the Grand Canyon reach was dominated by a single introduced species, the channel catfish (Valdez and Carothers, 1998). Following construction of the dam in 1963, Federal and State agencies again introduced rainbow trout below Glen Canyon Dam to establish and maintain a sport fishery in the 15-RM reach between the dam and Lees Ferry. This stocking continued for more than 30 yr, until the mid-1990s. Numerous other species of nonnative fishes were also introduced into Lake Powell and Lake Mead to create or enhance recreational fishing (Mueller and Marsh, 2002).

The effects of nonnative fish on native species, including predation and competition, are important considerations when evaluating any management action intended to benefit native fishes. These considerations are particularly important given the proximity of Lake Powell and Lake Mead, reservoirs with diverse nonnative fish populations, to Grand Canyon. Any management action intended to improve habitat conditions for native warmwater fishes also runs the risk of providing additional habitat that is suitable for nonnative predators and competitors. Nonnative fish predators currently in the Grand Canyon reach of the Colorado River include striped bass (*Morone saxatilis*), channel catfish, largemouth bass (*Micropterus salmoides*), green sunfish (*Lepomis cyanellus*), brown trout, and rainbow trout. Currently, nonnative coldwater species (trout) are abundant, while the nonnative warmwater species exist in relatively low numbers.

## Glen Canyon Dam Effects

The predam success of nonnative species was, in part, due to the fact that the river was generally what fishery biologists term a “warmwater habitat.” The annual temperature cycle of the Colorado River through Grand Canyon was similar to temperate lakes and streams at lower elevations, where temperatures ranged from cold or cool in winter to warm in summer. Native species require warmer temperatures to spawn and reproduce successfully. This seasonal pattern also allowed many of the introduced species to complete their life cycle. One of the major impacts of Glen Canyon Dam on the Colorado River was the change in water temperature to a relatively cold, steady temperature that favored coldwater species like trout over native fishes and introduced, warmwater species. While most of the warmwater species can survive in these colder waters, they cannot reproduce and do not grow well, having been adapted to at least seasonally warmer temperatures.

Other possible effects of dam operations on the riverine environment that may affect fishes include increased water clarity, altered flow patterns, and reduced sediment. All species that are native to Grand Canyon evolved in highly turbid environments, so the clear water released from the dam may favor nonnative predators like trout, which are adapted to hunting in clear water (Valdez and Ryel, 1995). Similarly, the postdam river hydrology is different from the predam river with respect to daily flow variation, flood frequency, and seasonal pattern and magnitude of maximum and minimum flows (Topping and others, 2003). These alterations in flow patterns potentially affect the spawning cues, habitat use, and distribution of native fish, as well as the suitability of mainstem Colorado River rearing habitat, in ways that are largely unknown and potentially complex (Korman and others, 2004). Finally, as Glen Canyon Dam blocks the majority of sediment transported by the Colorado River to the upstream portions of Lake Powell, the nearshore physical habitat available to native fish is fundamentally different from the predam river (Goeking and others, 2003; also see chapter 1, this report). Except for temperature, the other potential effects of the dam that are mentioned here are based on inferences about what is known regarding fishes from other river systems. Little direct scientific evidence from the Colorado River itself exists regarding these effects, and there remains considerable uncertainty regarding the potential effects of management actions associated with these factors (Walters and others, 2000).

### Other Factors

New fish parasites in the system, changes in tributary hydrology, and alterations in the food base that support fish populations are additional environmental factors that may be affecting native and nonnative fish species in Grand Canyon. Asian tapeworm (*Bothriocephalus acheilognathi*), a parasitic cestode, is a prominent example of a recently introduced parasite. Introduced into the United States in the 1970s with imported grass carp (*Ctenopharyngodon idella*) from China, the Asian tapeworm was discovered in 1990 in the Little Colorado River, which is an important spawning area for humpback chub (Choudhury and others, 2004). The tapeworm can cause mortality, but most often it is responsible for reduced growth and poor condition of infected fish. This parasite is currently restricted to the Little Colorado River because cold mainstem temperatures preclude completion of its life cycle. The Little Colorado River is also an example of a tributary system in which upstream water use and development have changed the amount and timing of flows reaching the Colorado River. Such changes could affect fishes in the Little Colorado River and throughout Grand Canyon, especially below the tributary.

## Status and Trends

Until the 1990s, there were few attempts to monitor the status and trends of fishes in Grand Canyon. Information before the mid- to late-1980s was anecdotal and was provided by explorers, river runners, and occasional scientific expeditions. As a result, few data are available for the first 20 yr after Glen Canyon Dam was closed. Early fish collection efforts were reviewed by Valdez and Carothers (1998), and where appropriate these earlier data are used in comparison to current data for fishes in Grand Canyon.

Efforts to estimate population size or relative abundance of fishes in Grand Canyon began under Glen Canyon Environmental Studies Phase II when private consulting firms, university researchers, the U.S. Fish and Wildlife Service (USFWS), and the Arizona Game and Fish Department conducted surveys and undertook population estimates in the mainstem Colorado River and in the Little Colorado River. Beginning in 1997, these efforts became the responsibility of the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center, which has worked cooperatively on monitoring activities with the U.S. Fish and Wildlife Service, the Arizona Game and Fish Department, and consulting firms (SWCA Environmental Consultants, Inc., and Ecometric Research). For the purposes of monitoring, the study area is divided into three segments: the Lees Ferry reach (15 RM of Colorado River corridor from Glen Canyon Dam to Lees Ferry); the mainstem Colorado River (downstream of Lees Ferry, RM 0, and the Paria River to RM 226 at the confluence of Diamond Creek); and the Little Colorado River (the 8.7 mi (14 km) of the tributary upstream from the mainstem). The status and trends of fish found in each of these reaches will be discussed separately. Humpback chub are discussed in a separate section.

## Lees Ferry

The Lees Ferry reach of the river is managed primarily as a rainbow trout sport fishery. The Lees Ferry reach is known as a tailwater trout fishery because it occurs downstream from a large dam where deepwater discharges afford cooler water temperatures that allow coldwater species like trout to survive. In fact, trout not only survived in the Lees Ferry reach following their initial stocking in 1964 but also flourished in the new habitat created by Glen Canyon Dam. The Lees Ferry rainbow trout fishery gained a reputation by the mid-1970s as a world class, blue ribbon fishery famous for its scenic grandeur and large, trophy-sized trout. Monitoring in this reach is primarily done through electrofishing and surveys of anglers by the Arizona Game and Fish Department in cooperation with the USGS Grand Canyon Monitoring and Research Center. The fishery was initiated with stocking efforts and was maintained primarily by stocking until the late 1990s.[1] Since closure of Glen Canyon Dam in 1963, however, this fishery has experienced variable success rates by anglers, and the trout populations have changed in response to stocking, dam releases, and food availability (McKinney and others, 1999, 2001).

Recently, more stable river flows, which are the result of the interim flows in 1991 and subsequent implementation of the MLFF alternative in 1996, have encouraged natural reproduction and made stocking unnecessary. Stable flows and increased natural reproduction resulted in an expanding number of fish (fig. 2), but the larger number of fish was offset by smaller average size and decreasing condition (plumpness) of the fish (fig. 3). Because the overall carrying capacity of the river remains relatively constant, the Lees Ferry reach is able to produce a smaller number of large fish or a greater number of small fish, a principle that is known as conservation of biomass. As early as 1996, the Arizona Game and Fish Department recognized the declining size of trout in this fishery and recommended changes in angling regulations to increase the size of fish; however, anglers appeared unwilling to accept lower catch rates of larger fish (Niccum and others, 1998). Average fish condition continued to decline for several more years but finally rebounded in 2002 (fig. 3).

As part of the Glen Canyon Dam Adaptive Management Program, fluctuating nonnative fish suppression flows were initiated beginning in 2003 and continued through 2005 in an effort to reduce the number of trout and increase their average size. The experimental flow treatment involved increased diurnal flow fluctuations of 5,000 to 20,000 cubic feet per second (cfs) from January through March of each year. Overall, these fluctuating flows were intended to disrupt spawning activity, to reduce egg survival, and to disadvantage young-of-year (YOY) trout that did survive. Early indications suggest that these experimental flows have had only minimal effects on the recruitment dynamics of rainbow trout. The total egg deposition loss because of Glen Canyon Dam operations in 2003 ranged from 30% to 40% in the Lees Ferry reach, with about half of this mortality being a direct consequence of the enhanced fluctuating flows in January through March (Korman and others, 2005); however, electrofishing catch rates began to increase in 2003 (fig. 2). There also appears to be a corresponding increase in angler use associated with

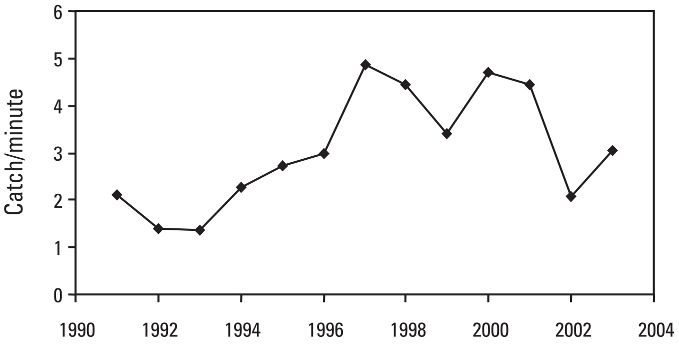

**Figure 2.** The average number of rainbow trout caught by using electrofishing at several fixed sampling locations in the Lees Ferry reach of the Colorado River from 1991 to 2003. Increasing catch-per-unit effort is thought to be indicative of an increasing number of fish in the population (Arizona Game and Fish Department and U.S. Geological Survey, unpub. data, 2005).

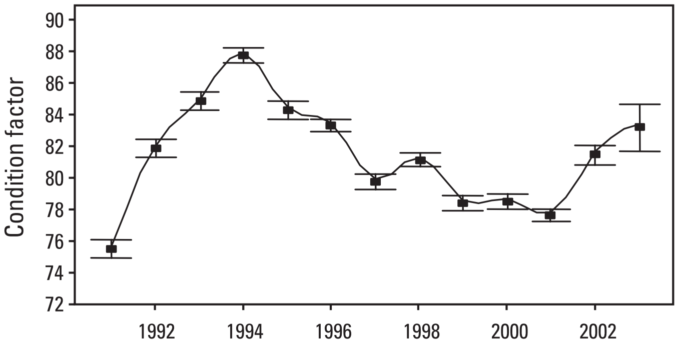

**Figure 3.** Condition factor, or relative weight, of Lees Ferry trout from 1991 to 2003. Condition factor expresses the length-to-weight relationship and is an attribute that reflects the health of individual fish as well as affects angler satisfaction. Relative weight declined with the increase in fish density in the late 1990s but increased in 2002–03. Present condition seems acceptable to anglers (Arizona Game and Fish Department and U.S. Geological Survey, unpub. data, 2005).

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[1] Stocking of fingerling rainbow trout was reduced in the mid-1990s to about 20,000 fish per year and ended completely in 1999 when it was apparent that natural reproduction under the modified low fluctuating flow alternative was producing more than enough recruitment to sustain the fishery (William R. Persons, Arizona Game and Fish Department, oral commun., 2005).

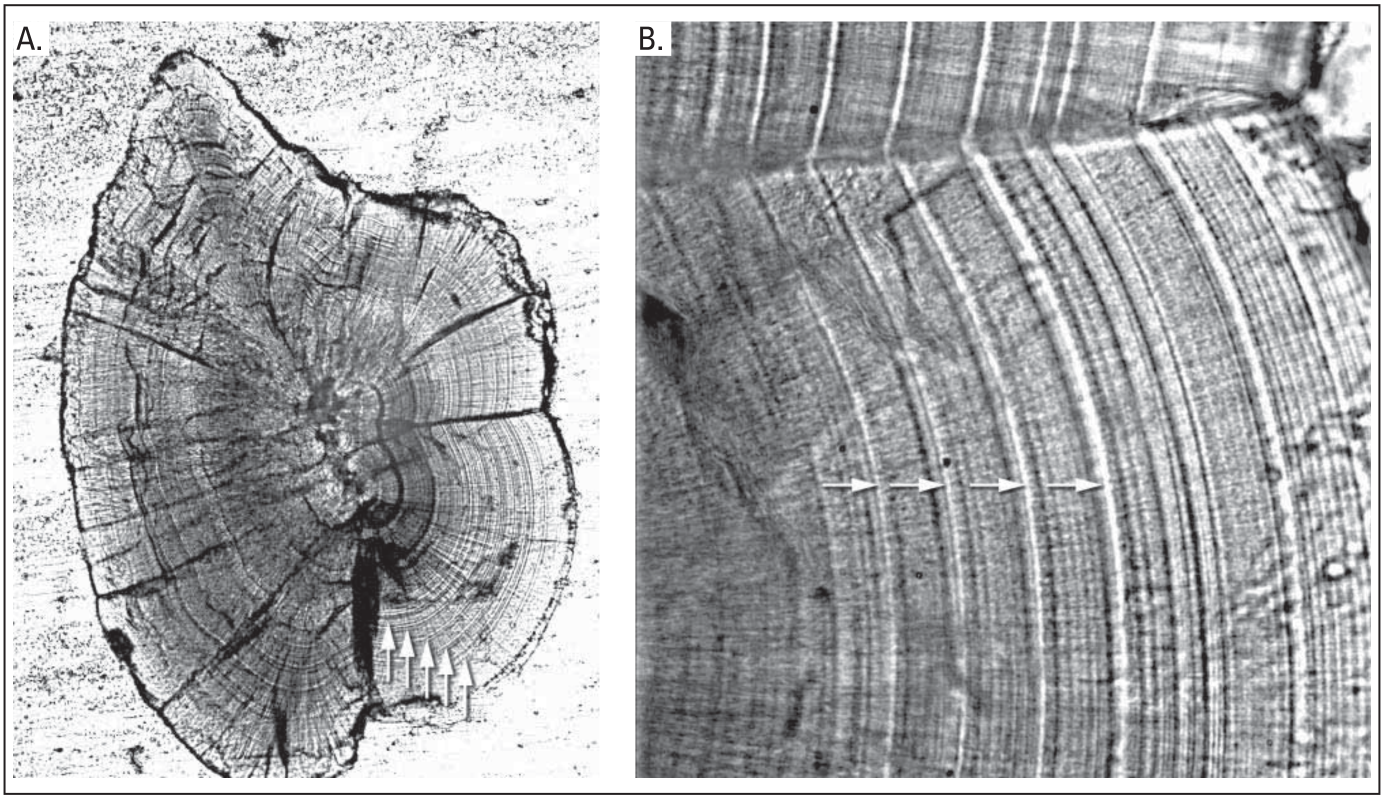


**Figure 4.** Photomicrograph of an otolith cross-section of young-of-year rainbow trout sampled from Glen Canyon in April 2003. Otoliths are minute boney structures found in the inner ear that show daily growth patterns in many fishes. The image shows the weekly striping pattern (identified by white arrows and shown at magnifications of 16x (A) and 400x (B)) caused by increased growth during lower peak Sunday flows (8,000 cfs) during April 2003 when normal weekday operations ranged from 7,000–13,000 cfs on a 24-h cycle (photographs courtesy of Steven Campana, Bedford Institute of Oceanography, Canada).

the increased electrofishing catch rate and the implementation of fluctuating flows (see chapter 9, this report).

Otoliths (minute boney structures found in the inner ear) of young rainbow trout (fig. 4) were examined in 2003 and 2004 to infer growth rate patterns during the late spring and summer months following the end of fluctuating nonnative fish suppression flows. Microscopic examination of these bony structures allows researchers to determine daily growth patterns. Results of these examinations suggest that YOY rainbow trout experienced more growth on Sundays than on other days of the week in 2003; however, otoliths collected in 2004 do not display increased growth on Sundays. Korman and others (2005) hypothesized that this difference was related to less severe flow fluctuations on Sundays during 2003 as compared to 2004.

## Mainstem Colorado River

Management objectives of the Glen Canyon Dam Adaptive Management Program call for managing the mainstem Colorado River and its tributaries below the Paria River for the benefit of native fishes (GCDAMP, 2001, http://www.usbr.gov/uc/rm/amp/amwg/mtgs/02jan17/Attach_06.pdf, accessed July 14, 2005). Fish monitoring in the mainstem Colorado River is primarily conducted by electrofishing or with trammel nets, hoop nets, and beach seines. Each of these methods is “selective,” or has higher efficiency for particular species or fish sizes. For instance, electrofishing is very effective in catching rainbow and brown trout and common carp but is inefficient in capturing adult humpback chub. Alternatively, trammel and hoop nets are more efficient than electrofishing in capturing humpback chub. These differences in sampling gear efficiency, coupled with differences in abundance, influence the ability of the monitoring program to detect differences in abundance over time and space.

The current monitoring program, which uses electrofishing for rainbow trout, brown trout, and common carp, is able to show trends in the abundance of these species over time and space (fig. 5 a, b, c). The abundance of rainbow trout declines as a function of distance

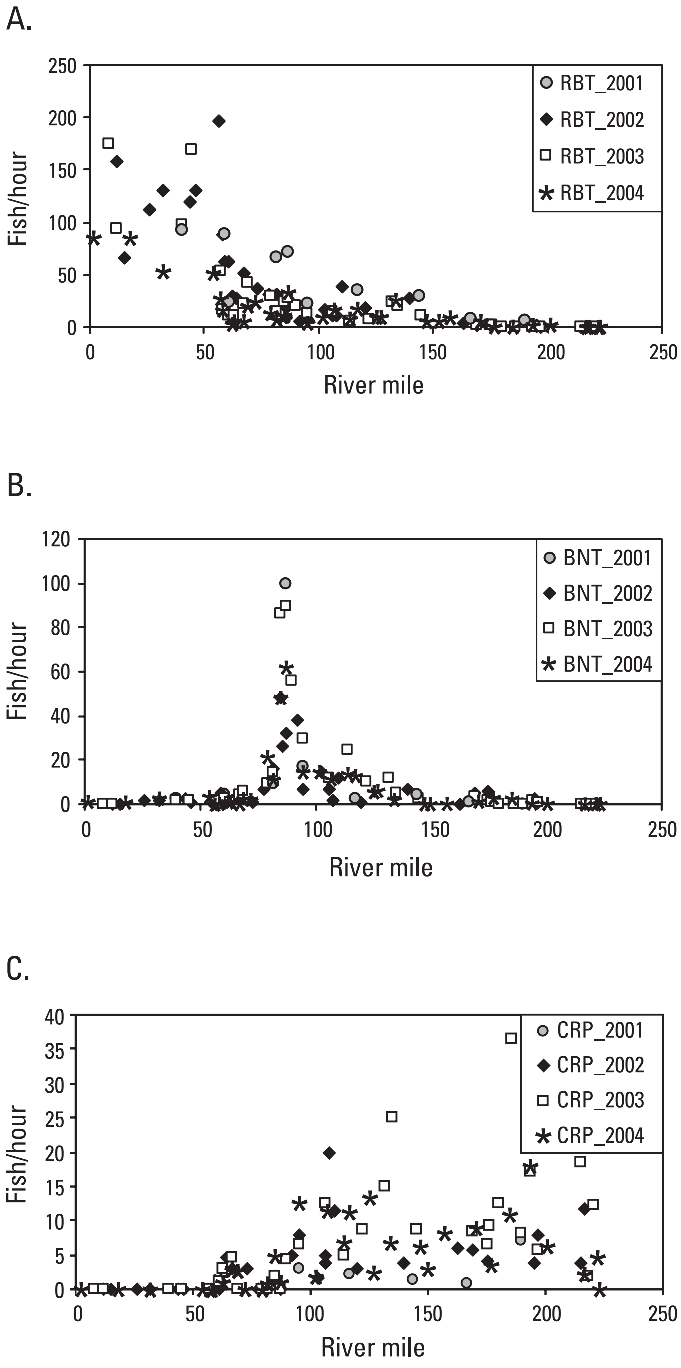


**Figure 5.** Relative abundance (mean catch-per-unit efforts, or fish/hour) of rainbow trout (A), brown trout (B), and common carp (C) as indicated by electrofishing catch rates from Lees Ferry (RM 0) to Diamond Creek (RM 226) (Arizona Game and Fish Department and U.S. Geological Survey, unpub. data, 2005). Note inverse abundance of coldwater trout to warmwater carp as distance from Lees Ferry and Diamond Creek increases. Increase in brown trout abundance in the middle of Grand Canyon is thought to be caused by spawning, which occurs in Bright Angel Creek, a tributary at RM 88. The National Park Service is trying to reduce spawning in Bright Angel Creek.

downstream of Glen Canyon Dam, but common carp increase downstream. Brown trout abundance is centered near RM 88 and declines with distance upstream or downstream of this location. This pattern is explained most readily by the occurrence of several tributaries in this reach that are suitable for spawning by this species.

Monitoring efforts in the mainstem Colorado River for both native and nonnative species have generally resulted in an adequate description of species distribution. In general, humpback chub distribution is centered near the Little Colorado River where successful spawning and rearing is known to occur (Douglas and Marsh, 1996; Gorman and Stone, 1999). Also, humpback chub occur in several other smaller aggregations throughout the river corridor (see below). Flannelmouth sucker, bluehead sucker, and speckled dace abundance typically increases with distance downstream of the Little Colorado River and is generally high near major tributary confluences (e.g., Little Colorado River, Paria River, Kanab Creek, and Bright Angel Creek) (Gorman and Coggins, 2000; Johnstone and others, 2003; Johnstone and Lauretta, 2004). Warmwater nonnative species such as channel catfish and striped bass increase in abundance with distance from Glen Canyon Dam, particularly below RM 160. Small-bodied, nonnative fish such as fathead minnow, red shiner, and plains killifish are found almost exclusively downstream of the Little Colorado River confluence, and all evidence suggests that this tributary is the dominant source of these fishes in the Colorado River ecosystem (Johnstone and others, 2003; Johnstone and Lauretta, 2004).

Although the current monitoring program is sufficient to describe these general patterns in distribution of native and certain nonnative fishes, it cannot provide a specific measure of trends in relative abundance. Despite sampling efforts that are randomly distributed over the 226 mi (364 km) of river from Lees Ferry to Diamond Creek, the monitoring program is unable to measure with any certainty the spatial or temporal trends in the relative abundance of native or nonnative fishes in the mainstem Colorado River. An exception is the abundance and distribution of rainbow trout, brown trout, common carp, and the Little Colorado River population of humpback chub previously discussed. Low abundance of these fishes coupled with the very poor sampling efficiency of current sampling gear make measuring trends in relative abundance difficult. Typically, monitoring efforts include over 600 trammel net sets each year and between 100 and 200 seining sites. Several examples of the low and highly variable catch rate experienced with trammel nets are illustrated for select species and sites in figure 6.

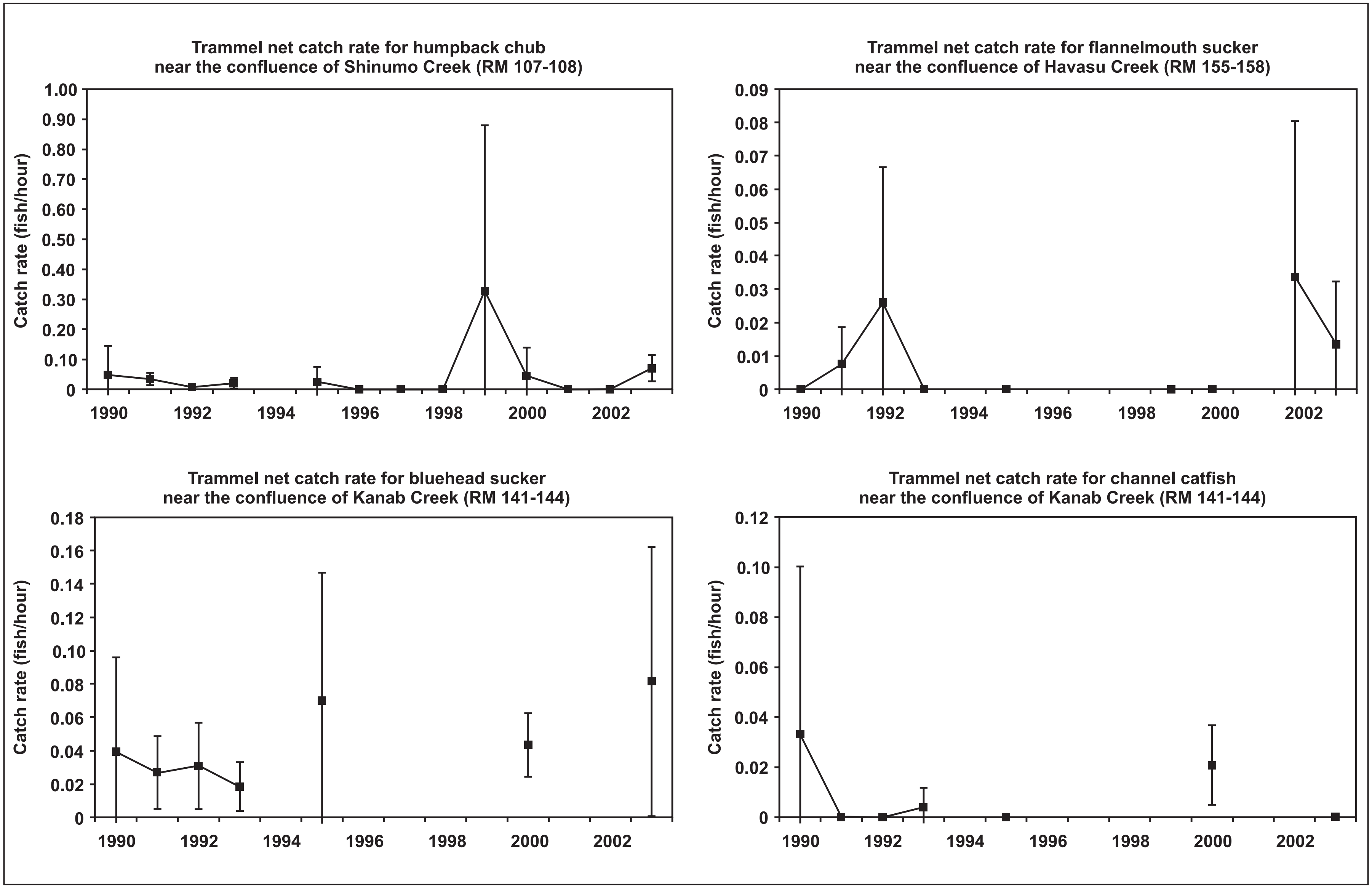


**Figure 6.** Trends in the relative abundance (trammel net catch rate, fish/hour) of selected species near the confluences of several tributaries where native fishes, particularly the suckers, attempt to reproduce. These figures illustrate the inability of the current monitoring program to detect all but extremely large changes in the relative abundance of key native and nonnative species in most areas of the Colorado River. Error bars depict 95% confidence intervals for mean catch rate. Note that catch rate estimates with overlapping confidence intervals are statistically insignificant and represent years of no statistically apparent difference in relative abundance (U.S. Geological Survey, unpub. data, 2005).

The presence of many nonnative fish in the system has created a substantial management challenge. It is known that some of these nonnative species, particularly brown trout, prey upon native fishes (Valdez and Carothers, 1998). Furthermore, nonnative species may compete for habitat and food with native species in ways that are difficult to document. Monitoring the relative abundance of nonnative fish in this part of the river provides some insight into the potential severity of the problem. Both coldwater nonnative species such as trout and warmwater fishes such as carp inhabit the river. Coldwater species dominate the upstream reaches of Grand Canyon, whereas warmwater species are more prominent further downstream because the temperature of the river water gradually increases after leaving the dam.

## Little Colorado River

The Little Colorado River, which flows into the Colorado River at RM 61, represents perhaps the best remaining native fish habitat in Grand Canyon under the current temperature and flow management regimes in the Colorado River. Because native fish are abundant and the sampling gear is efficient in the Little Colorado River, relative abundance of native fish and some nonnative fish can be well determined in this tributary. Two kinds of fish sampling are conducted in the Little Colorado River: spring and fall hoop netting aimed primarily at collecting humpback chub to estimate population size and hoop netting conducted in April and May at fixed sites in the lower 0.75 mi (1,200 m) of the river. The humpback chub data are discussed separately below. Despite the presence of several nonnative fishes in the Little Colorado River, the catch in hoop nets suggests that native fish (>80%) dominate the fish community in most years (fig. 7). The data from the lower 0.75 mi (1,200 m) sampling depict trend information for the relative abundance of three native species: humpback chub (fig. 8), bluehead sucker (fig. 9), and flannelmouth sucker (fig. 10). These data represent the best time series regarding status and trends of flannelmouth and bluehead suckers in the Little Colorado River.

## Humpback Chub

The life history and ecology of humpback chub in Grand Canyon have been intensively studied (Suttkus and Clemmer, 1979; Carothers and Minckley, 1981; Kaeding and Zimmerman, 1983; Maddux and others, 1987; Gorman, 1994; Valdez and Ryel, 1995; Valdez and Carothers, 1998). The humpback chub population in Grand Canyon is centered near the confluence of the Colorado and Little Colorado Rivers (Kaeding and Zimmerman, 1983; Douglas and Marsh, 1996; Gorman and Stone, 1999). Valdez and Ryel (1995) defined the humpback chub distribution as occurring in nine aggregations throughout Glen and Grand Canyons. Only the aggregation near the confluence of the Little Colorado and Colorado Rivers (hereafter referred to as the LCR population) is known to successfully reproduce. The other eight aggregations are much smaller in abundance, averaging from a few dozen to a few hundred fish. Most likely these eight aggregations are not supported from local reproduction but primarily from the emigration of juveniles and limited numbers of subadult and adult fish from the LCR population (Valdez and Ryel, 1995). Additionally, because of abiotic and biotic changes in the Colorado River following the construction of Glen Canyon Dam, the LCR population relies on the Little Colorado River as the primary spawning and juvenile-rearing habitat (Gorman and Stone, 1999).

### Reproduction and Early Life History

Adult fish in the LCR population initially stage for spawning runs in large eddies near the confluence of the Little Colorado River in February and March and make spawning runs into the tributary that average 17 d from March through May. As the Little Colorado River's spring flows decrease and the water warms and clears, reproduction increases and larval fish appear (Valdez and Ryel, 1995). Spawning has not been observed, primarily because of the turbid water, but ripe males have been seen gathering in areas of complex habitat structure (boulders and travertine masses near gravel deposits); it is thought that ripe females move to these areas to spawn (Gorman and Stone, 1999). After spawning, some adult chub return to specific locations in the mainstem, while others remain in the Little Colorado River for unknown periods of time.

Humpback chub require warm water to reproduce successfully. Perennially cold mainstem water temperatures are thought to be the reason for unsuccessful mainstem reproduction. The minimum water temperature for successful reproduction is 61ºF (16ºC) (Hamman, 1982; Marsh, 1985), which is well above the summer mainstem temperatures commonly observed of 50°F–54ºF (10°C–12ºC). Mortality of larval and postlarval humpback chub emerging from the warm waters of the Little Colorado River has been attributed to thermal shock and their enhanced susceptibility to predation caused by the more protracted debilitating effects of cold water on swim-

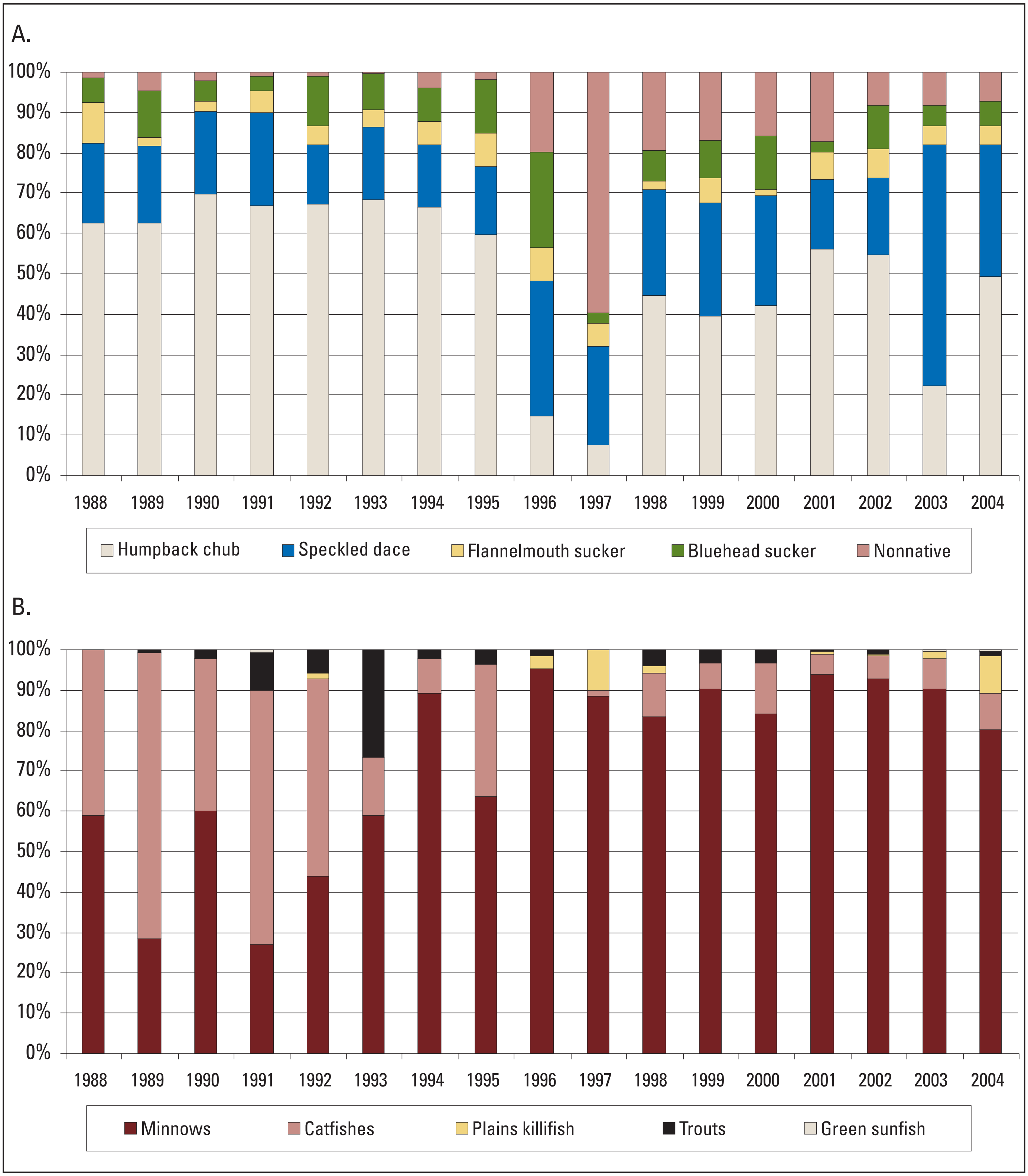


**Figure 7.** Observed species composition of all fish captured in hoop nets in the Little Colorado River, 1988–2004 (U.S. Fish and Wildlife Service, Arizona Game and Fish Department, Arizona State University, and U.S. Geological Survey, unpub. data, 2005). The top panel (A) includes species composition of the four native species and a pooled nonnative category. The bottom panel (B) displays the annual species composition of the nonnative catch. Dominant species of minnows include fathead minnow, red shiner, and common carp. Dominant species of catfishes include channel catfish and black and yellow bullheads.

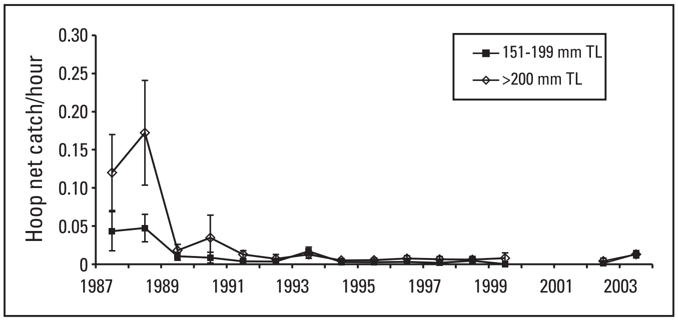


**Figure 8.** Humpback chub catch-per-unit effort (fish/hour) with 95% confidence intervals in the lower 0.75 mi (1,200 m) of the Little Colorado River using hoop nets, 1987–2003 (no sampling conducted 2000–01). Solid squares are for fish between 5.9 and 7.8 inches (151–199 mm) total length (TL) and open diamonds are for fish more than 7.9 inches (200 mm) total length (modified from Coggins and others, in press).

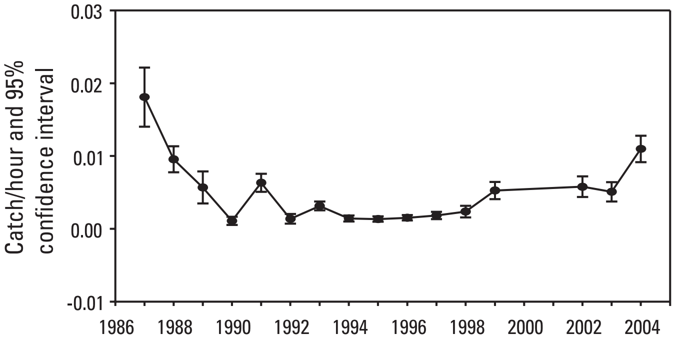


**Figure 9.** Hoop net catch (fish/hour) of adult bluehead sucker more than 7.5 inches (190 mm) in total length in the lower 0.75 mi (1,200 m) of the Little Colorado River (Arizona Game and Fish Department and U.S. Geological Survey, unpub. data, 2005).

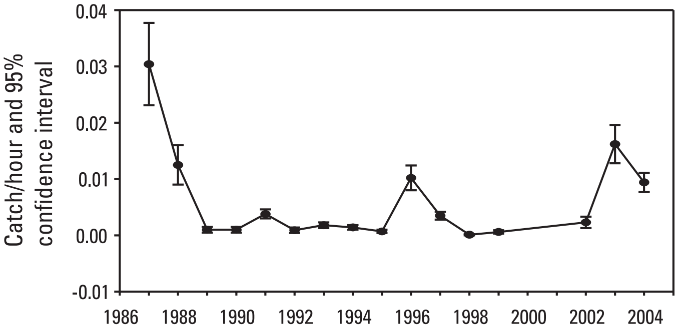


**Figure 10.** Hoop net catch (fish/hour) of adult flannelmouth sucker more than 13.8 inches (350 mm) in total length in the lower 0.75 mi (1,200 m) of the Little Colorado River, 1987–2004 (Arizona Game and Fish Department and U.S. Geological Survey, unpub. data, 2005).

ming ability and growth (Lupher and Clarkson, 1994; Clarkson and Childs, 2000; Robinson and Childs, 2001; Ward and others, 2002).

A key issue associated with humpback chub is lack of recruitment to the adult population because of the low survivorship of young fish (Valdez and Ryel, 1995). Young humpback chub remain in the Little Colorado River or drift and swim into the mainstem (Robinson and others, 1998). The lack of recruitment and documented predation indicate that mortality is extremely high in the mainstem (Lupher and Clarkson, 1994; Valdez and Ryel, 1995; Marsh and Douglas, 1997; Clarkson and Childs, 2000; Robinson and Childs, 2001). During summer, the young humpback chub that survive in the mainstem occupy low-velocity, talus, and vegetated shoreline habitats, including backwaters; however, low survivorship over the year virtually eliminates the YOY humpback chub in the mainstem. As a result, few if any humpback chub spawned during the previous year are present in the mainstem in March. Those YOY humpback chub that do survive, and ultimately recruit to the adult population, are fish that remain resident in the Little Colorado River during their early life history.

Limited breeding of humpback chub occurs among other subpopulations in the Colorado River. Valdez and Ryel (1995) documented limited spawning success at a warm underwater spring near RM 30, known locally as 30-Mile Spring, in upper Marble Canyon. YOY humpback chub in the size range of 0.4–1.2 inches (10–30 mm) have been sporadically collected at considerable distances below the Little Colorado River, usually beginning in June (Kubly, 1990; Arizona Game and Fish Department, 1996; Brouder and others, 1997). Some limited reproduction may occur in other smaller tributaries. Young humpback chub have been collected in or near Bright Angel Creek, Shinumo Creek, Kanab Creek, and Havasu Creek, but spawning success has not been well documented (Maddux and others, 1987; Kubly, 1990; Arizona Game and Fish Department, 1996; Brouder and others, 1997). These limited observations of spawning success among subpopulations outside of the Little Colorado have not been shown to lead to successful recruitment, likely because of the factors mentioned above.

## Food Habits and Diseases

Dietary analyses reveal humpback chub to be opportunistic feeders, selectively feeding on algae, aquatic and terrestrial invertebrates, and small fish (Kaeding and Zimmerman, 1983; Kubly, 1990; Valdez and Ryel, 1995; Stone, 2004). Humpback chub diet changes over the course of the year in response to food availability and turbidity-related decreases in benthic-standing biomass over distance downstream from Glen Canyon Dam (Blinn and others, 1992). Nonnative scuds (*Gammarus lacustris*) and simuliid (black fly) larvae occasionally make up a large proportion of humpback chub diet. *Gammarus lacustris* selectively feeds on epiphytes (i.e., diatoms) associated with *Cladophora glomerata*, the dominant algae species in the upper reaches where clear water conditions often prevail. Chironomid (midge fly) larvae are also important in all areas of the river. As the river becomes more turbid downstream, simuliids become the dominant food source (see chapter 5, this report).

Kaeding and Zimmerman (1983) identified 13 species of bacteria, 6 protozoans, and 1 fungus from humpback chub in Grand Canyon. The role of these organisms in the life history of humpback chub is not known. In 1990, the Asian tapeworm was first identified from humpback chub in the Little Colorado River (Clarkson and others, 1997; Choudhury and others, 2004). This cestode is particularly worrisome because it infects humpback chub at a high rate and has been reported to be pathogenic and potentially fatal in a variety of other fish (Hoffman and Schubert, 1984; Hoffnagle and others, 2000).

## Population Dynamics

Very large numbers of humpback chub, as well as of flannelmouth sucker and bluehead sucker, have been tagged in Grand Canyon since 1989. As a result, today most of the older humpback chub have been tagged. Previous analyses of the recapture data of tagged fish indicate that there is likely strong age-dependence in survival rates and that recruitment of humpback chub has likely declined considerably since the early 1990s (Coggins and others, in press). The USGS Grand Canyon Monitoring and Research Center uses an analysis method for the mark and recapture data that reinforces these results and allows recovery of information about likely recruitment changes that date back to the early 1980s. The mark and recapture data are analyzed by assigning each marked fish an age at first capture based on its size at that time and then performing mark-recapture analysis on the resulting age-structured data on first captures and later recaptures (Coggins and others, in press). Results of this open population mark-recapture model, known as age-structured mark recapture (ASMR), show decreases in the recruitment of young humpback chub into the adult population and as a consequence an overall decline in numbers of adult humpback chub (figs. 11 and 12).

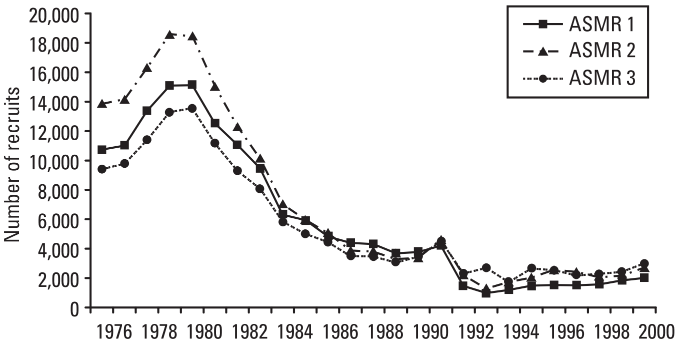


**Figure 11.** Age-2 humpback chub recruitment estimated by using the three formulations of the annual age-structured mark recapture (ASMR) model (from Coggins and others, in press).

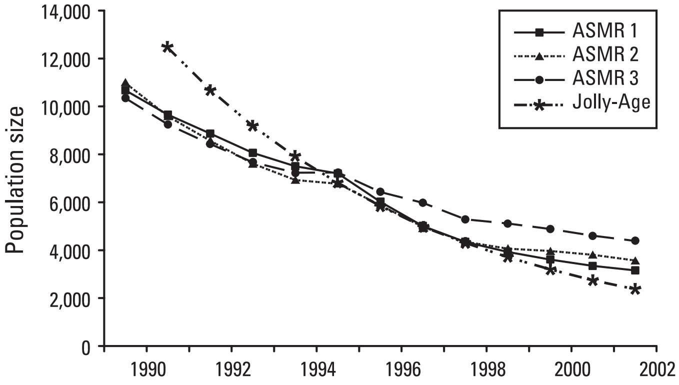


**Figure 12.** Adult (age-4+) humpback chub population estimates for 1989–2001 made by using the age-structured Jolly-Seber model and the three formulations of the annual age-structured mark recapture (ASMR) model (from Coggins and others, in press).

Overall, about 15%–20% of the adult humpback chub are dying each year. If this mortality rate and the dramatically reduced recruitment rate of young chub experienced since the early 1990s remain unchanged, there will be a decline in the adult population of humpback chub from the present 3,000–5,000 fish to a level of 1,500–2,000 adult fish over the next 10–15 yr.

## Cause and Effect Relationships

The Glen Canyon Dam Adaptive Management Program has a goal of maintaining a self-sustaining population of humpback chub in Grand Canyon (GCDAMP, 2001, http://www.usbr.gov/uc/rm/amp/amwg/mtgs/02jan17/Attach_06.pdf, accessed July 14, 2005); however, this goal is qualitative and has no defined target population abundance levels. The U.S. Fish and Wildlife Service, which has jurisdiction over the humpback chub as a federally endangered species, promulgated recovery goals based on the known distribution of the species (U.S. Fish and Wildlife Service, 2002). These goals recognize the Grand Canyon population of humpback chub as the only potentially viable population in the lower Colorado River Basin and include it, along with at least one population from the upper Colorado River Basin, as having to attain certain population numbers before the species can be considered for downlisting or delisting under the Endangered Species Act. Briefly, these goals require that a viable population be attained and maintained for a period of at least 5 yr, with a minimum of 2,100 sexually mature individuals in each population. Furthermore, the recruitment of new individuals into the population must meet or exceed the adult mortality rate, thereby providing a stable or increasing adult abundance trend. In the case of the Grand Canyon population, sexually mature fish are assumed to be 4 yr old or older.

Of paramount importance in conserving the population of the federally endangered humpback chub is determining the factors contributing to population decline and implementing management actions designed to minimize or eliminate the effect of those factors. Not all of the factors that may be responsible for the recruitment decline of humpback chub beginning in the early 1990s are clear, but a list of likely factors that could be acting either singly or in combination include (1) Colorado River and Little Colorado River hydrology (discharge and temperature), (2) infestation of juvenile humpback chub by Asian tapeworm, (3) predation by or competition with warmwater native cyprinids and catostomids and nonnative cyprinids and ictalurids within the Little Colorado River, and (4) predation by or competition with coldwater nonnative salmonids within the Colorado River.

The body of evidence available to evaluate specific questions varies among these postulated factors. For instance, beginning in 1990 the operation of Glen Canyon Dam was changed through the implementation of research flows (a series of discharges and data collection programs conducted from June 1990 through July 1991) and the interim operating criteria. This hydrology, and the subsequent MLFF alternative that continues to present, can generally be characterized as having less severe daily flow fluctuations than the previous 28 yr of the no action period when the dam was managed primarily to maximize hydroelectric power revenue. This major change in Colorado River hydrology correlates closely to the decline in humpback chub recruitment. Also, it is possible that the decline in humpback chub recruitment in the early 1990s was caused by the nearly continuous flooding in the Little Colorado River that occurred during the summer of 1992, particularly during the early summer when larval humpback chub emerge (Robinson and others, 1998). It is also possible that the high infestation rate of juvenile humpback chub by the Asian tapeworm is a factor. Humpback chub infected with Asian tapeworm were first found in 1990, and infestation rates in 2001 exceeded 90% (Choudhury and others, 2004). Finally, predation and competition by nonnative fishes either in the Little Colorado River or in the Colorado River may be driving the humpback chub recruitment trend. Although robust relative abundance data do not exist for common carp and channel catfish within the Little Colorado River, there was a large increase in the abundance of nonnative salmonids in the Colorado River documented near the confluence of the Little Colorado River (RM 56.6–68.3) (Gorman and Coggins, 2000).

## Recent Management Actions Undertaken or Proposed

While it is difficult to determine the factor most responsible for the humpback chub recruitment decline, a likely primary factor is negative interactions (predation and competition) with nonnative fish. Interaction with nonnative fish is implicated in the decline and extinction of native fishes throughout the Colorado River Basin. In response to the need to address this factor, a program of selective removal of nonnative fishes (known as mechanical removal) was implemented in 2003 near the confluence of the Little Colorado River and in other tributaries (work in Bright Angel Creek and other tributaries has been undertaken by the National Park Service). To complement these efforts, the work group also approved initiation of a multiobjective study to evaluate the potential effect of rainbow trout and brown trout predation on humpback chub recruitment and the efficacy of mechanical removal of nonnative fishes from the Colorado River near the confluence of the Little Colorado River.

In early 2003, a major effort was begun by the Glen Canyon Dam Adaptive Management Program to remove nonnative fish from the area of the river near the confluence of the Little Colorado River (RM 61), which is considered important habitat for native fish, especially humpback chub. A total of 16,045 rainbow trout and many other nonnative fish (fig. 13a) were removed from this river reach during 2003–04. While native fish contributed only approximately 5% of the overall catch in January 2003, native fish contributed greater than 35%

in September 2004, generally reflecting a reduction in nonnative fish abundance. Also, the overall abundance of rainbow trout has been reduced by more than 60% in this river reach (fig. 13b). Whether this reduction in nonnative fish density will benefit native fish is unknown at this time.

Moreover, an experimental program to move YOY humpback chub upstream of an impassable barrier (where few nonnative fish live) in the Little Colorado River was initiated and has shown some early signs of success (Stone and Sponholtz, 2005). Future introductions of humpback chub into other Grand Canyon tributary streams may help augment the population in Grand Canyon. Additional management options include potential hatchery rearing of humpback chub as a refugium population or for stocking in the river.

Other management options include the installation of a multilevel water intake structure(s) for Glen Canyon Dam to warm the water in Grand Canyon. The Bureau of Reclamation has developed preliminary plans and is scoping out the possible installation of a temperature control device, which would provide flexibility to release warmer water into the river. Warmer water could create more favorable habitat conditions for native fishes in general; however, its operation could also improve habitat conditions for nonnative, warmwater species and degrade habitat quality for trout inhabiting the Lees Ferry reach. Obviously the operation of such a device, if built, will need to be carefully considered and implemented experimentally.

## Discussion and Future Research Needs

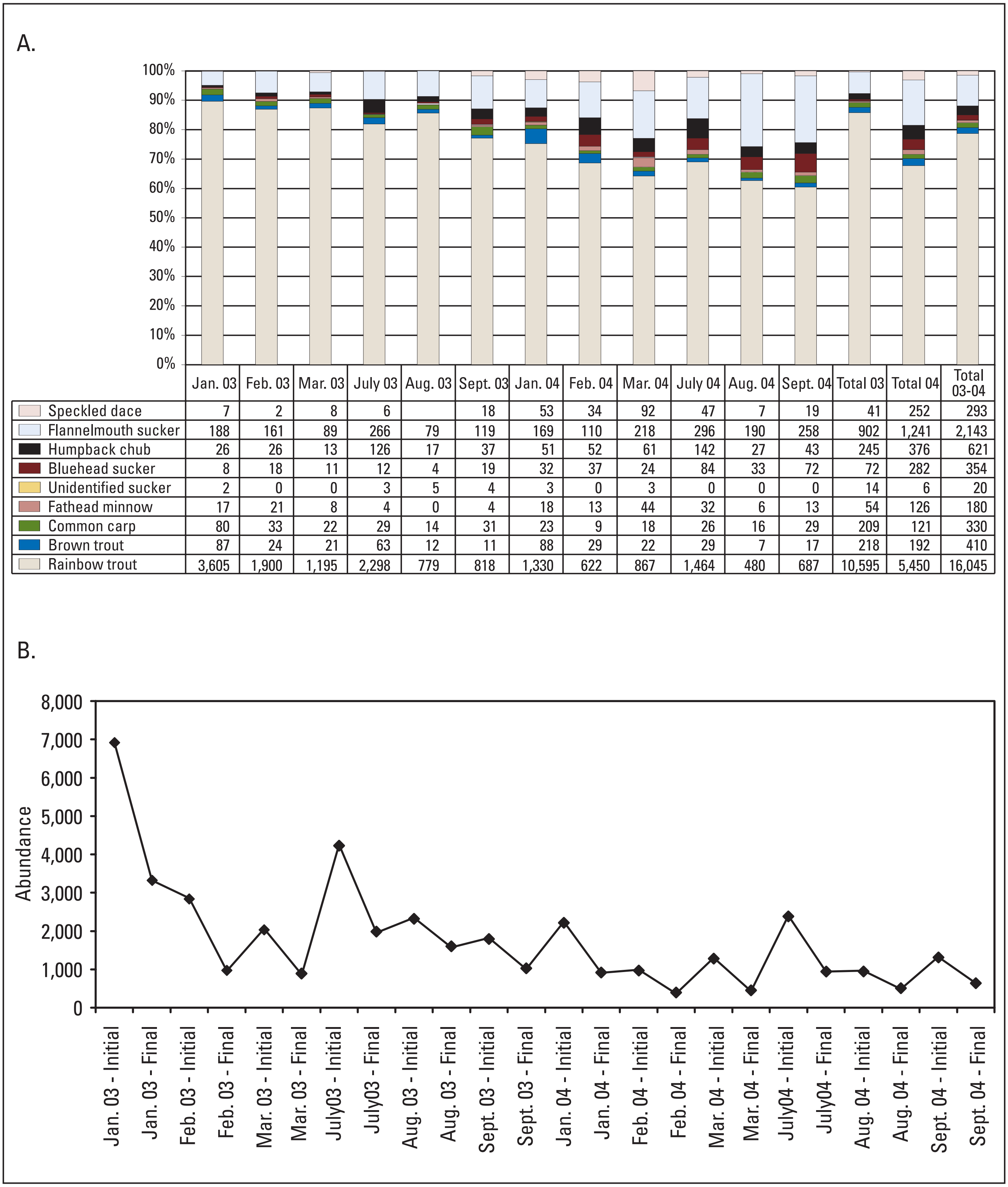
The salient findings of the research and monitoring programs undertaken by the Glen Canyon Dam Adaptive Management Program regarding fishes are twofold. First, there has been a dramatic and continuing decline in the number of adult humpback chub in the Grand Canyon ecosystem since at least the late 1980s. This decrease in adult fish is due to a steady decline in the recruitment of young fish into the population beginning in the early 1980s, with an additional reduction in the early 1990s. This decline in recruitment results in a dwindling population of adults as older age fish die off and are not replaced. It is currently estimated that if recruitment remains stable at this level, the adult population of humpback chub in the Grand Canyon ecosystem will stabilize at approximately 1,500–2,000 fish over the next decade or so. The current population decline combined with the low recruitment in this population relative to adult mortality indicates that this population will attain neither positive trends nor sufficient numbers of fish to meet USFWS recovery goals in the foreseeable future.

The second major result regarding fishes is the proliferation of rainbow trout in both the Lees Ferry reach and downstream as far as RM 75. Numbers of brown trout have also increased dramatically in the area around Bright Angel Creek and upstream to above the Little Colorado River confluence. Both of these species are known to prey on native fishes, and their substantial increase in abundance near the principal remaining native-fish habitat in Grand Canyon remains a concern. It has yet to be determined whether the experimental management action to reduce the numbers of nonnative fish in the area around the Little Colorado River confluence has resulted in any increase in survival and recruitment of the federally endangered humpback chub.

### Dam Operations

It is not possible to say conclusively that the decline in humpback chub recruitment that began to occur in the early 1990s is because of the implementation of the MLFF regime; however, the flow regime has not reversed the decline in recruitment and adult abundance either. Approximately 15%–20% of the adult humpback chub population is dying each year. These fish are most likely being replaced, albeit at a lower rate, predominately by young humpback chub that have spent the first 3 to 4 yr of their lives in the Little Colorado River. In other words, the MLFF alternative had either a negative effect or no effect at all, but it has not had a measurable beneficial effect on humpback chub.

The MLFF alternative has not improved conditions for other native fishes as indicated by their stable or declining numbers. Different daily, seasonal, or annual changes in river flows could be considered on an experimental basis. Such flow options could include reduced daily fluctuations and equalized monthly volumes to provide a more stable environment for young native fishes. There is a good chance that juvenile humpback chub dispersing into the mainstem in summer and fall would be able to grow, survive, and return to the Little Colorado River for extended rearing if they were to encounter (1) reduced predation and competition by nonnative trout (trout would have to be removed by mechanical removal treatments) and (2) relatively warm refuges in nearshore locations (these locations could be created by steady flow conditions in late summer and fall). The low summer



| | Jan. 03 | Feb. 03 | Mar. 03 | July 03 | Aug. 03 | Sept. 03 | Jan. 04 | Feb. 04 | Mar. 04 | July 04 | Aug. 04 | Sept. 04 | Total 03 | Total 04 | Total 03-04 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Speckled dace | 7 | 2 | 8 | 6 | | 18 | 53 | 34 | 92 | 47 | 7 | 19 | 41 | 252 | 293 |
| Flannelmouth sucker | 188 | 161 | 89 | 266 | 79 | 119 | 169 | 110 | 218 | 296 | 190 | 258 | 902 | 1,241 | 2,143 |
| Humpback chub | 26 | 26 | 13 | 126 | 17 | 37 | 51 | 52 | 61 | 142 | 27 | 43 | 245 | 376 | 621 |
| Bluehead sucker | 8 | 18 | 11 | 12 | 4 | 19 | 32 | 37 | 24 | 84 | 33 | 72 | 72 | 282 | 354 |
| Unidentified sucker | 2 | 0 | 0 | 3 | 5 | 4 | 3 | 0 | 3 | 0 | 0 | 0 | 14 | 6 | 20 |
| Fathead minnow | 17 | 21 | 8 | 4 | 0 | 4 | 18 | 13 | 44 | 32 | 6 | 13 | 54 | 126 | 180 |
| Common carp | 80 | 33 | 22 | 29 | 14 | 31 | 23 | 9 | 18 | 26 | 16 | 29 | 209 | 121 | 330 |
| Brown trout | 87 | 24 | 21 | 63 | 12 | 11 | 88 | 29 | 22 | 29 | 7 | 17 | 218 | 192 | 410 |
| Rainbow trout | 3,605 | 1,900 | 1,195 | 2,298 | 779 | 818 | 1,330 | 622 | 867 | 1,464 | 480 | 687 | 10,595 | 5,450 | 16,045 |

**Figure 13.** A. Total catch and percent contribution by species and month during mechanical removal efforts in the Little Colorado River removal reach, 2003–04. B. Estimated abundance of rainbow trout in the Little Colorado River removal reach before and after each mechanical removal effort, 2003–04 (U.S. Geological Survey, unpub. data, 2005).

steady flow (LSSF) experiment demonstrated that such lateral warming of backwater areas can be quite dramatic. A summer-fall steady flow experiment would need to maintain conditions for backwater warming from the time of the first summer high flow that disperses juveniles into the mainstem until around November 1, when the equilibrium temperature in standing backwaters decreases (because of nighttime cooling) to about the same as the mainstem temperature.

Three additional flow possibilities for Glen Canyon Dam could be made based on recommendations from the 2003 YOY rainbow trout surveys and analyses of otoliths: (1) fluctuating flows targeting YOY rainbow trout could be implemented from April through July to coincide with the timing of hatch, (2) summer steady flows could likely improve the growth of YOY rainbow trout, and (3) sudden reductions in the minimum daily flow could have the potential to strand or displace many YOY rainbow trout in the Lees Ferry reach. The latter recommendation was based on an almost complete absence of fry from low-angle shorelines after the reduction in the minimum flow from 10,000 cfs to 5,000 cfs in early September 2003 and a similar but less dramatic reduction in September 2004 (Korman and others, 2005). An event-based approach—in which flows are increased to approximately 20,000 cfs for 2 d, followed by a reduction to 5,000 cfs for 1 d, and implemented on a monthly basis from May through September—would almost certainly be much more effective at reducing recruitment in the Lees Ferry reach than the January–March fluctuating nonnative fish suppression flows implemented beginning in 2003. Steady flows could be conducted between events to increase water temperatures for native fish downstream and would not have beneficial effects for YOY rainbow trout, as their densities would be controlled through the temporary reductions in minimum flow.

Researchers have been unable to identify or implement an effective mainstem monitoring program for native fishes or most nonnative species (the exceptions are rainbow trout, brown trout, and carp). Because of this situation, the USGS Grand Canyon Monitoring and Research Center has called for a research initiative to investigate the utility of alternative sampling methods such as acoustic devices that may assist in providing better measures of relative abundance and change detection.

The most important research task associated with humpback chub conservation is determining the factors controlling the recruitment dynamics of this species. These factors can only be determined through an appropriately designed experiment that addresses the multiple important biotic and abiotic factors likely influencing humpback chub. As stated by Korman and others (2004, p. 395–396) in summary of an intensive modeling effort aimed at characterizing changes in nearshore humpback chub habitat with changes in Glen Canyon Dam operation,

> The interaction between habitat and ecosystem processes like competition and predation remain highly uncertain. Ultimately, questions regarding the effects of dam operations on juvenile humpback chub must be addressed by monitoring the response of critical population parameters to flow manipulations conducted within a sound experimental design.

# Profiles of Selected Fish Species Found in the Grand Canyon Ecosystem

Information compiled by Jeffrey E. Lovich

## Speckled dace (native)

Randall D. Babb, Arizona Game and Fish Department

Size–

rarely exceeds 3 inches (7.6 cm).

Distribution–

extensively distributed throughout Western United States.

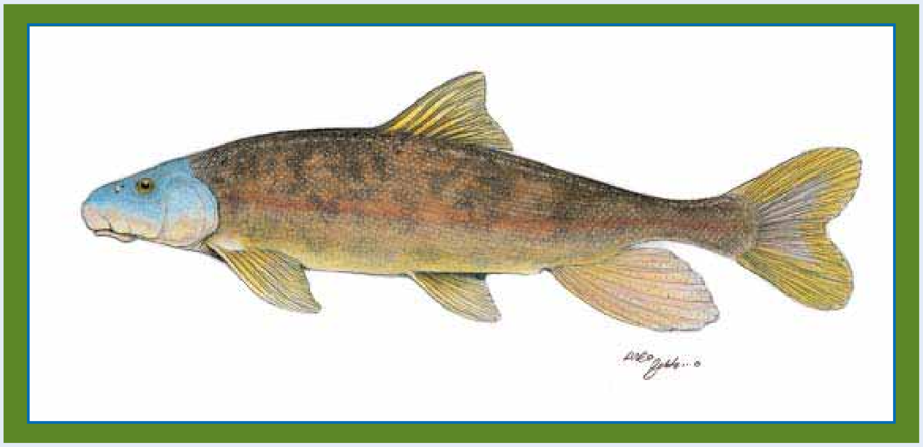
Status–

abundant in some areas and widely distributed. This species is represented by several subspecies.

Natural history–

The speckled dace (*Rhinichthys osculus*) is the only native dace in Arizona, although the genus is widely distributed elsewhere. Dace are widely distributed in the Colorado River, with many inhabiting backwaters in western Grand Canyon. Diet includes algae, insect larvae, small crustaceans, and small snails. Spawning occurs in spring and late summer. Large schools of dace congregate over gravel bottoms to spawn. Populations appear to be stable in Grand Canyon.

## Bluehead sucker (native)



Randall D. Babb, Arizona Game and Fish Department

Size–

maximum of about 20 inches (51 cm).

Distribution–

found in fast-flowing river systems in Arizona, Colorado, New Mexico, Utah, and Wyoming.

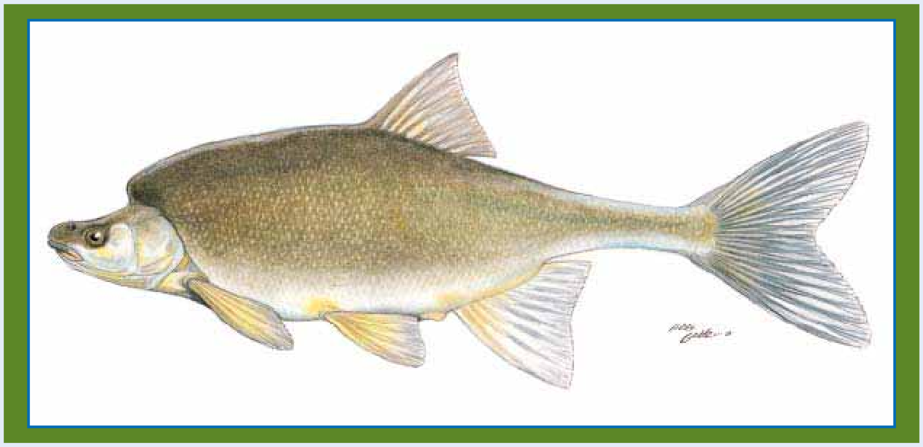
### Status–

not uncommon in some areas.

### Natural history–

This species (*Catostomus discobolus*) occurs in the Colorado River upstream from Lake Mead. Diet includes algae, diatoms, insects, amphipods, and organic debris that it scrapes from rocks with specialized cartilage lips. In Grand Canyon, spawning occurs over gravel, sand, and cobbles in April and May, when water temperatures exceed 61°F (16°C). Young inhabit backwaters in Grand Canyon. Bluehead suckers are known to hybridize with other sucker species. Populations appear to be stable in Grand Canyon. Individuals can live for more than 20 yr.

## Humpback chub (native)



Randall D. Babb, Arizona Game and Fish Department

### Size–

maximum of about 20 inches (51 cm).

### Distribution–

found only in the Colorado River system.

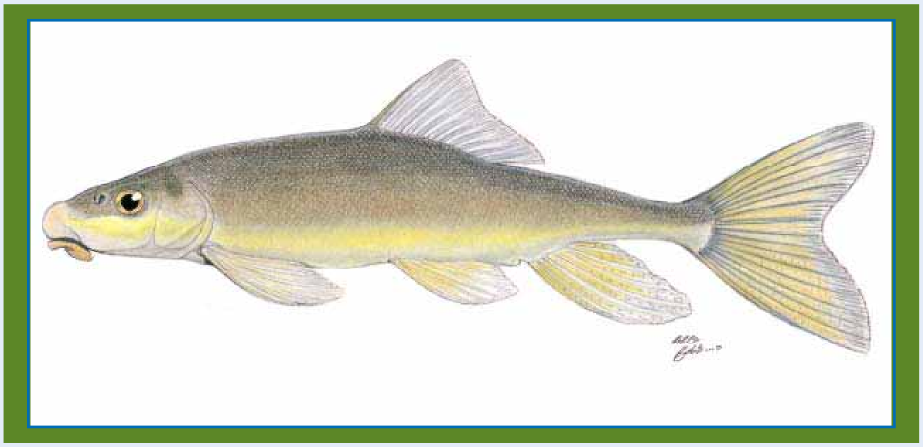
### Status–

federally endangered.

### Natural history–

The humpback chub (*Gila cypha*) formerly ranged downstream to the area now occupied by Lake Mohave, but it is now confined to several aggregations in Grand Canyon and isolated populations in various deep canyon stretches of the Colorado River and its major tributaries above Lake Powell. Most humpback chub in Grand Canyon are found in the vicinity of the Little Colorado River (LCR) and its confluence with the mainstem. Humpback chubs are omnivorous, and their diet includes a diversity of aquatic and terrestrial invertebrates, small fish, algae, and other plant material. In Grand Canyon the diet of the nonnative rainbow trout is almost identical, setting the stage for possible resource competition between the species. Spawning occurs in spring in the LCR, and young enter the mainstem during floods associated with storm events, most commonly in spring and late summer/fall. Aggregations of humpback chub, well upstream and downstream of the LCR population, may result from (1) emigration of juveniles, subadults, or adults from the LCR; (2) survival of relict fish from before the dam; or (3) mainstem spawning. The latter has not been documented in the postdam era, so additional research is needed to resolve this issue. The estimated adult population in Grand Canyon has declined sharply from about 10,000 a decade ago to about 3,000–5,000 today.

## Flannelmouth sucker (native)



Randall D. Babb, Arizona Game and Fish Department

Size–

can exceed about 20 inches (51 cm).

Distribution–

Colorado River Basin in Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming. Extirpated from the Gila River Basin of Arizona.

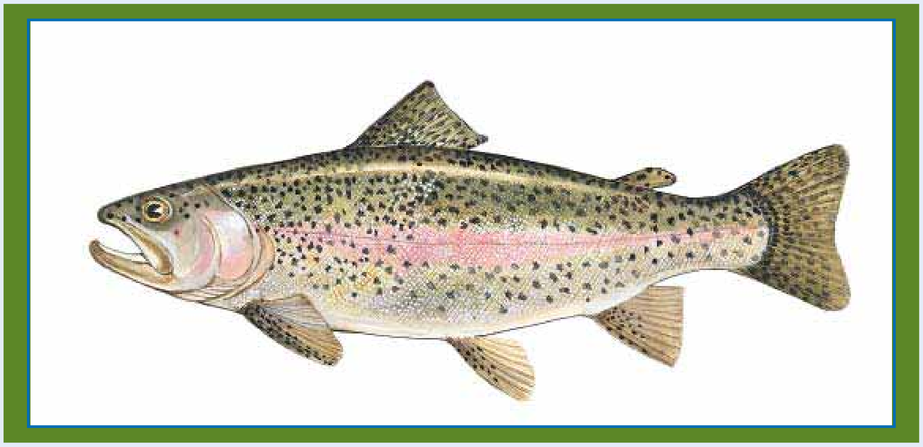
Status–

not uncommon in some areas.

Natural history–

This species (*Catostomus latipinnis*) occurs in the Colorado River upstream from Lake Mead. Flannelmouth suckers below Lake Mead exist because of the success of reintroduction from the Paria River in the mid-1970s. Diet varies with age class and size but includes algae, insects, plankton, ostracod, crustaceans, plant materials, and detritus. This species likely makes spawning runs in most of the major tributaries in Grand Canyon before returning to the mainstem. Spawning occurs from March to July, when water temperatures are between 43°F and 68°F (6°C and 20°C). Spawning occurs in shallow water over sand and gravel bottoms. Females lay from 4,000 to 40,000 eggs. Juveniles are frequently captured in the mainstem from lower Marble Canyon downstream to Lake Mead. Juveniles are also frequently captured in the Little Colorado River and other tributaries downstream. Known to hybridize with the razorback sucker, a species that is presumed to be gone from the Grand Canyon region. Populations appear to be stable in Grand Canyon.

## Rainbow trout (nonnative)



Randall D. Babb, Arizona Game and Fish Department

Size–

up to 47 inches (120 cm). Arizona State record was 32.25 inches (81.9 cm).

Distribution–

extensively distributed throughout Western North America in river systems draining into the Pacific Ocean. Widely introduced worldwide, including into the Colorado River.

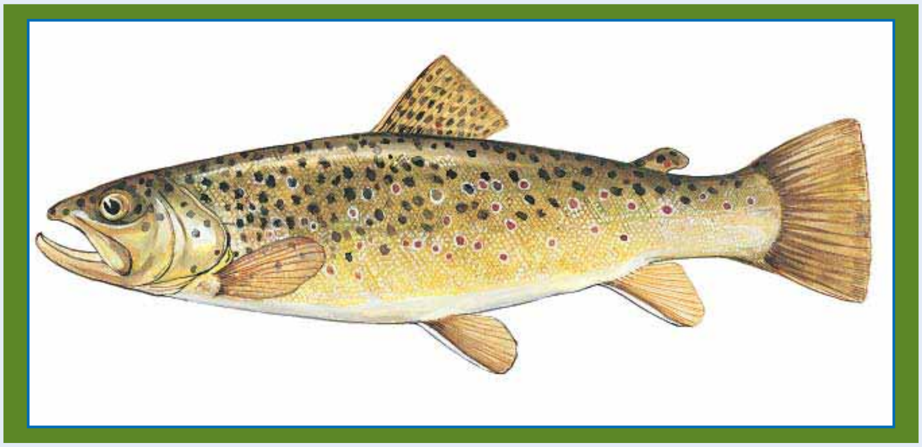
Status–

common.

Natural history–

Rainbow trout (*Oncorhynchus mykiss*) were introduced into the Grand Canyon area in the 1920s for sport fishing. Originally confined to clear tributary streams, the construction of Glen Canyon Dam created cold, clear conditions that allowed trout to colonize the mainstem. Trout were also stocked in the tailwaters of the dam by the State of Arizona shortly after construction was completed in the 1960s. The diet consists mainly of both aquatic and terrestrial insects and other aquatic invertebrates including amphipods. Spawning in Grand Canyon occurs in winter and early spring. After fertilization by males, females excavate a depression, or redd, in gravelly bottoms, and the eggs are buried in the substrate to hatch unattended. Rainbow trout like cold water temperatures and rarely live in water above about 77°F (25°C). The Lees Ferry reach of the Colorado River is where most spawning occurs in the Grand Canyon area and is managed as a "blue ribbon" trout fishery. Trout numbers have been increasing in recent years, possibly to the detriment of the endangered humpback chub.

## Brown trout (nonnative)



Randall D. Babb, Arizona Game and Fish Department

Size–

Arizona State record is 36 inches (91.4 cm). The world record is a 40 lb, 4 oz (18.3 kg) specimen caught in Arkansas.

Distribution–

widely introduced worldwide, including into the Colorado River.

Status–

common.

Natural history–

Native to Europe and Asia, brown trout (*Salmo trutta*) were introduced into the Grand Canyon area in the 1920s for sport fishing. Originally confined to clear tributary streams, brown trout were able to colonize the mainstem of the Colorado River when the construction of Glen Canyon Dam created cold, clear conditions. Brown trout eat a variety of aquatic and terrestrial insects and other invertebrates. Large specimens are highly predaceous on other fish, including smaller trout. Reproduction is as in other species of trout (see text box for rainbow trout). Bright Angel Creek is an important spawning stream for mainstem trout that move into the smaller tributary for this purpose in winter and early spring. Brown trout are capable of tolerating slightly higher water temperatures than most other trout. Most brown trout in Grand Canyon today occur near the confluence with Bright Angel Creek.

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# Chapter 3

# Climatic Fluctuations, Drought, and Flow in the Colorado River

Robert H. Webb

Richard Hereford

Gregory J. McCabe

## Introduction

Climate is the cumulative pattern of daily atmospheric conditions in a particular geographic area, and weather is the daily and seasonal expression of these conditions. Climate varies over periods of years, decades, or centuries, altering weather conditions in a region, particularly precipitation amounts and temperatures. In the arid and semiarid Southwest, climatic fluctuations affect many hydrologic characteristics of watersheds, including the quantity of base flow, the occurrence of large floods, and the timing of snowmelt runoff (Dettinger and Cayan, 1995; Cayan and others, 1999; Stewart and others, 2004, 2005; McCabe and Clark, in press).

Reservoirs in the Western United States, particularly those in the Colorado River Basin, were built to reduce, if not eliminate, annual variations in water supply that occurred historically because of periods of above- or below-average precipitation. A persistent drought beginning in 2000 raised concern that decreases in runoff entering Lake Powell could follow and releases from Glen Canyon Dam could be severely reduced or constrained. Inflows to Lake Powell on the Colorado River were below average from 2000 through 2004, leading to drawdown of both Lake Powell (figs. 1 and 2) and Lake Mead, the primary flow-regulation structures on the river. On January 27, 2005, the level of Lake Powell was at 3,562.5 ft (1,085.9 m) (full pool capacity is 3,700 ft (1,128 m)), and the reservoir contained 8.5 million acre-feet (maf) (10,481 million $m^3$) of water (fig. 1), which is only 35% of the reservoir's capacity and a little more than 1 yr of annual flow releases. Reduction in annual flow releases can reduce the water available for prescribed flow releases—particularly flood releases—designed to benefit riverine habitat within Grand Canyon. By 2004, it was speculated that Glen Canyon Dam would be unable to produce hydroelectric power by 2006 or 2007 if drought conditions persisted and the lake level continued to decline.

Conditions changed in fall and winter 2004–05 as a series of storms led to greatly above-average precipitation in the southern portion of the watershed. The high precipitation may have been associated with the onset of El Niño conditions in the Pacific Ocean, which presumably could have enhanced fall and early winter storms. On February 1, 2005, inflows to Lake Powell were forecast to be 125% of normal, the first above-average forecast since 1999. This reversal of conditions

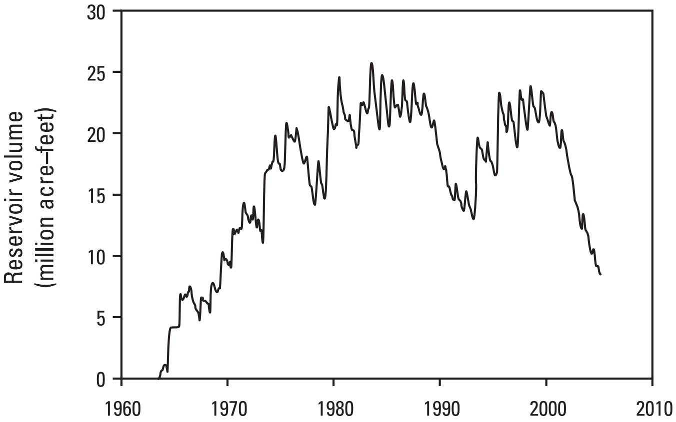

**Figure 1.** Fluctuations in the level of Lake Powell following closure of Glen Canyon Dam in 1963 (from www.summittech.com/LakePowell/LP_waterDB.php, accessed February 20, 2005).

**Figure 2.** Lake Powell at Glen Canyon Dam (photograph by Dale Blank, U.S. Geological Survey).

from the previous 5 yr could suggest that the drought is over, although some long-term records suggest that this may not be the case since average years have occurred within periods of extended dryness. To date, it is unclear whether the early 21st century drought is over or not, and the possible persistence and magnitude of the drought are of great concern for the Glen Canyon Dam Adaptive Management Program.

Unfortunately, the factors that caused and sustained the early 21st century drought have not been positively identified. Although conditions in the tropical Pacific Ocean were considered to be ideal for drought conditions in the continental United States (Hoerling and Kumar, 2003), new studies suggest that the Atlantic Ocean may also influence drought (Gray and others, 2004; McCabe and others, 2004). In the case of the Colorado River, it is possible to examine the drought in a broader historical and climatic context, which can be developed through historical records and statistical models. First, a historical record exists of actual observations and estimates of annual flows in the river at various places, including Lees Ferry. Second, scientists have gained an understanding of precipitation patterns by using annual growth rings in trees to reconstruct the hydrologic conditions in a basin several hundred years before the historical record began. Third, climatologists and other scientists have recently developed statistical techniques and dynamical models that improve understanding of the relations between various ocean temperature patterns and observed precipitation patterns.

This chapter makes clear that the drought beginning in 2000 probably had its origins in several hemispheric-scale atmospheric and oceanic processes that affect moisture delivery to the Colorado River Basin (fig. 3). In this context, the chapter describes the general causes of drought in the Southwest, the long-term perspective on drought duration in the basin based on tree-ring reconstructions, the use of global climate indices to explain Colorado River flows, and scenarios of future climate and runoff in the Colorado River Basin.

**Figure 3.** Moisture sources for the Colorado River Basin (outlined in red). Lees Ferry is the separation point between the upper and lower Colorado River Basins as specified in the Colorado River Compact of 1922.

# Background

Drought is caused by persistent low precipitation over a region. As such, the severity of a drought is a function of spatial extent, duration, and magnitude of the precipitation deficit. Moreover, the area affected by a drought may shift in space and time. This combination of variable factors makes drought prediction and estimation of drought frequency extremely difficult. The causes of persistent drought over a large drainage basin, such as the Colorado River Basin, are particularly difficult to determine because the basin spans a large latitudinal range.

## Sources of Moisture

The most important sources of water to the Colorado River Basin are frontal systems that originate in the North Pacific Ocean and occur in winter and spring. These systems tend to carry moisture at high levels in the atmosphere, and precipitation is orographically controlled, meaning that it typically increases with elevation in the mountains. Cold frontal systems drop substantial amounts of snow at high elevations and rain at low elevations in the Rocky, Uinta, and Wind River Mountains, which in turn become the headwaters of the Colorado River and its principal tributary, the Green River (fig. 3). The frequency and moisture content of frontal systems are strongly affected by the strength of atmospheric circulation patterns and sea-surface temperatures in the Pacific Ocean.

There are two basic types of winter storms that affect flow in the Colorado River. Cold winter storms deliver moisture in the form of snow at most elevation ranges in Utah, Colorado, New Mexico, northern Arizona, and Wyoming. These storms build snowpacks that melt in the spring, providing runoff to the Colorado River. Warm winter storms, originating in the tropical Pacific Ocean, may produce rain on snowpacks, resulting in large runoff events and floods on major rivers, which tend to overwhelm reservoir systems, particularly in Arizona.

Moisture delivered to the Colorado River during summer months typically originates from a combination of the Gulf of Mexico, the Gulf of California, and the eastern North Pacific Ocean. Known variously as the "Arizona monsoon," the "Southwestern United States monsoon," the "summer monsoon," or even the "North American monsoon," this moisture arrives in July and August at low atmospheric levels. The moist air rises rapidly over the desert landscape, spawning high-intensity thunderstorms that produce runoff mostly at elevations of less than 7,000 ft (2,134 m). The thunderstorms tend to be of small spatial extent, and, although they spawn severe flash flooding locally, few floods are generated on larger rivers in the region.

# Status and Trends

## Flow at Lees Ferry

Flow in the Colorado River measured at Lees Ferry (fig. 3), the political boundary between the upper and lower Colorado River Basins, varied substantially during the 20th century. Calendar-year flow volumes (fig. 4a) were combined from three data sets that were measured or estimated by using different techniques. From 1895 through 1922, annual flow volumes at Lees Ferry were estimated by LaRue (1925, p. 108); from 1922 through 1962, unregulated flow was measured at the Lees Ferry gaging station; and from 1963 through 2004, flow was estimated as the sum of tributary flows entering Lake Powell (Webb and others, 2004). Consumptive water use in the basin upstream of the gage at Lees Ferry is not accounted for in these data. As a result, flow values measured at Lees Ferry are due to climatic fluctuations and changes in consumptive water use in the upper basin States of Wyoming, Colorado, Utah, and New Mexico.

The average annual flow volume shown in figure 4a was 12.3 maf (15,166 million m$^3$) from 1895 through 2004. This volume is less than the more-commonly quoted annual volume of 15.0 maf (18,495 million m$^3$) because the time series in figure 4a was not adjusted for water consumed in the upper basin States. The period from 1905 to 1922, which was used to estimate water production allocated under the Colorado River Compact, had the highest long-term annual flow volume in the 20th century, averaging 16.1 maf (19,851 million m$^3$) at Lees Ferry; however, the highest annual flow volume occurred in 1984 (22.2 maf (27,373 million m$^3$)), and the highest 3-yr average is 20.3 maf (25,030 million m$^3$) for 1983 through 1985. The lowest annual flow volume is 3.8 maf (4,685 million m$^3$) in 2002, followed by 3.9 maf (4,809 million m$^3$) in 1934 and 4.8 maf (5,918 million m$^3$) in 1977. The trend in annual flow volume, which decreased by about 0.5 maf (617 million m$^3$) per decade from 1895 through 2003, is due in part to upstream water consumption.

These data show that flow in the early 21st century is the lowest in more than a century. The current drought has contributed to the lowest flow period on record, producing an average of only 5.1 maf (6,288 million $m^3$) for the 3-yr period from 2002 through 2004. In contrast, other low 3-yr averages include 6.2 maf (7,645 million $m^3$) for 1989 through 1991, 6.3 maf (7,768 million $m^3$) for 1988 through 1990, 7.3 maf (9,001 million $m^3$) for 1954 through 1956, and 8.0 maf (9,864 million $m^3$) for 1933 through 1935. The 5-yr average of 5.9 maf (7,275 million $m^3$) centered on 2002 is the lowest in the 110-yr record. By any measure, the early 21st century drought is the most severe in the unadjusted gaging record.

The Bureau of Reclamation (BOR) adjusted the flow record at Lees Ferry to account for consumptive uses in the upper basin (fig. 4b). In the BOR record, flow volumes are available by water year (October 1 through September 30) for the period of 1905 through 2004, a 99-yr record. The adjusted average annual flow volume at Lees Ferry is 15.0 maf (18,495 million $m^3$), and the decrease in flow is 350,000 acre-feet (431,550,000 $m^3$) per decade (fig. 4b). Using this adjusted data, the lowest flow year was 1977 with 5.6 maf (6,905 million $m^3$), followed by 2002 with 6.4 maf (7,891 million $m^3$). The 3-yr averages for 2002 through 2004 (9.2 maf (11,344 million $m^3$)), 2000 through 2002 (9.45 maf (11,652 million $m^3$)), and 2001 through 2003 (9.51 maf (11,726 million $m^3$)) are the lowest in the period of record. Similarly, the lowest 5-yr average is 9.9 maf (12,207 million $m^3$) for 2000 through 2004, which is 1 maf (1,233 million $m^3$) less than the average flow of the second lowest 5-yr period (1988 through 1992). Using either the actual or adjusted flow values, the early 21st century drought produced the lowest flows of the past century.

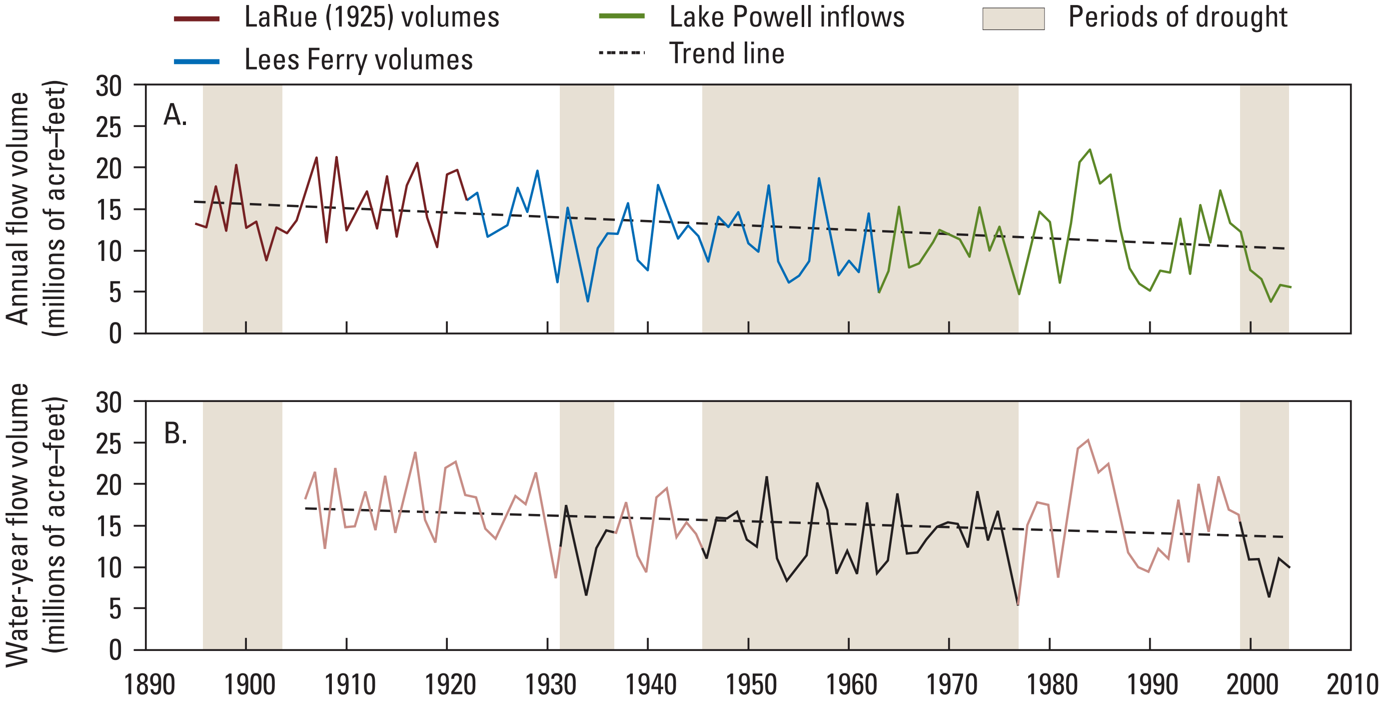

**Figure 4.** Colorado River flow volume at Lees Ferry (before 1963) and inflows to Lake Powell (after 1963). A. Actual calendar-year flow volumes derived from three sources. From 1895 through 1922, annual flow volumes at Lees Ferry were estimated by LaRue (1925). From 1922 through 1962, flow volumes were measured at Lees Ferry, Arizona. From 1963 to 2004, inflow to Lake Powell was estimated from gaging records on the Colorado River and its major tributaries. B. Water-year flow volumes for Lees Ferry adjusted for consumptive use in the upper basin (Bureau of Reclamation, unpub. data, 2005).

## Tree-ring Reconstructions of Drought

Considerable research has addressed the question of the magnitude, frequency, and duration of droughts affecting the Colorado River Basin, including studies examining the effects of the most severe known droughts on record at Lees Ferry (Tarboton, 1995). Many of these studies are based on the seminal work of Stockton and Jacoby (1976), who used dendrochronology to reconstruct long-term river flows using the actual flow record at Lees Ferry for calibration. Recent large-scale work (e.g., Cook and others, 2004), as well as efforts within the drainage basin (Woodhouse, 2003; Gray and others, 2003, 2004), while suggestive, remains insufficient to resolve the basic magnitude-frequency questions concerning the early 21st century drought and its effects on the Colorado River Basin.

What is clear from the Stockton and Jacoby (1976) work and other studies (Salzer, 2000; Woodhouse, 2003; Cook and others, 2004) is how unusual the high precipitation of the early 20th century was in terms of runoff in the Colorado River. The unusually wet period of the 20th century accentuates the severity of the dry conditions experienced during the early 21st century drought. The difference between extreme wet and extreme dry conditions is accentuated because observational records of climate and hydrologic conditions in the Colorado River Basin generally span 100 yr or less, limiting our ability to quantitatively understand the current drought in a long-term context. It is possible, however, to qualitatively view this drought in a long-term context from analysis of tree rings, which provide an indication of moisture conditions going back several centuries.

Using dendrochronological reconstructions from tree rings from the Western United States, Cook and others (2004) analyzed long-term changes in the area affected by drought from A.D. 800 to 2003. Although the region they considered is far larger than the Colorado River Basin and subject to a larger array of climatic influences, their reconstruction provides some perspective on the 2000 through 2004 drought in the Colorado River Basin. Cook and others (2004) concluded that the present drought is not comparable to the so-called “megadroughts” of A.D. 936, 1034, 1150, and 1253, primarily because of its short duration; however, the early 21st century drought may not yet be over. At the very least, their drought-area reconstruction (Cook and others, 2004) suggests that the present drought may surpass other 20th century droughts in the Western United States, including the droughts of the midcentury and the 1930s, and be comparable to droughts of the mid-19th or late 16th centuries.

Several researchers (Tarboton, 1995; Cook and others, 2004; Gray and others, 2004) have noted that decadal-scale persistence of below-average precipitation is of paramount importance when considering drought frequency. Tarboton (1995) and Meko and others (1995) provided data based on the Stockton and Jacoby (1976) reconstructions that, when compared to conditions of 2001–04, suggest that the low-flow conditions of the early 21st century may be the lowest since the drought of A.D. 1579 to 1600.

# Recent Findings

Several indices of atmospheric and oceanic processes are used to explain climate variability in the Western United States, including the Southern Oscillation Index (SOI), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO). These indices reflect short- to long-term conditions that can affect the discharge of the Colorado River.

## Southern Oscillation Index

Perhaps the most well known of the climatic indices is the Southern Oscillation Index (SOI), which is often used to indicate the status of the El Niño-Southern Oscillation (ENSO) phenomenon in the Pacific Ocean. The SOI is the measure of the strength of tropical Pacific atmospheric circulation based on the sea-level pressure difference between Tahiti, French Polynesia, and Darwin, Australia (fig. 5a). Negative values, implying weakened trade winds, are mainly the result of higher-than-normal surface pressures at Darwin and are associated with El Niño conditions. The impacts of ENSO are felt worldwide through disruption of the general circulation of the atmosphere and associated global weather patterns. In terms of the Colorado River Basin, ENSO affects interannual variation of climate and precipitation in Arizona (Andrade and Sellers, 1988) and helps to explain the occurrence of floods and droughts in the Western United States (Cayan and others, 1998, 1999).

The ENSO is a change between three basic states of the ocean. The warm phase, called El Niño, involves warming of the eastern Pacific Ocean off Peru and the northward spread of warm surface water to the west coast of the United States. Because warming of sea-surface temperatures (SSTs) is a hallmark of El Niño conditions (Knutson and others, 1999), several indices based on SSTs have been developed, including the NINO3 index (fig. 5b). Reduced sea-level pressure over the eastern tropical Pacific Ocean combined with increased sea-level pressure over Indonesia (negative SOI) leads to a weakening in the trade winds, enabling warm water from the central equatorial Pacific Ocean to move toward and along the west coast of South America (positive NINO3 index). The cold phase, called La Niña, is the opposite of the warm phase. Thus, El Niño and La Niña are the warm and cold phases of the ENSO system, which also includes a neutral condition that can persist for several years between the two polar phases. ENSO phases typically last 6–18 mo and are the single most important factor affecting interannual climatic variability on a global scale (Diaz and Markgraf, 1992).

The ENSO also affects atmospheric circulation and SSTs in the eastern Pacific Ocean, which in turn affect the transport of moisture across the Western United States. During El Niño conditions, the warmer-than-average water in the eastern tropical Pacific Ocean and a shift in storm tracks tend to produce above-average precipitation (Redmond and Koch, 1991), above-average runoff (Cayan and Webb, 1992), and, potentially, floods in the Southwest. Not all El Niño events lead to increased runoff, however; during the 2003 El Niño, runoff was below average.

During La Niña events, cooler-than-average SSTs in the eastern tropical Pacific Ocean tend to cause less moisture to flow over the continent, typically causing below-average flow in the Colorado River and predictable below-average precipitation in the Southwestern United States. This below-average precipitation occurs despite a tendency for above-average precipitation in the headwaters of the Colorado River Basin, although precipitation gained is negated by most of the basin having below-average precipitation.

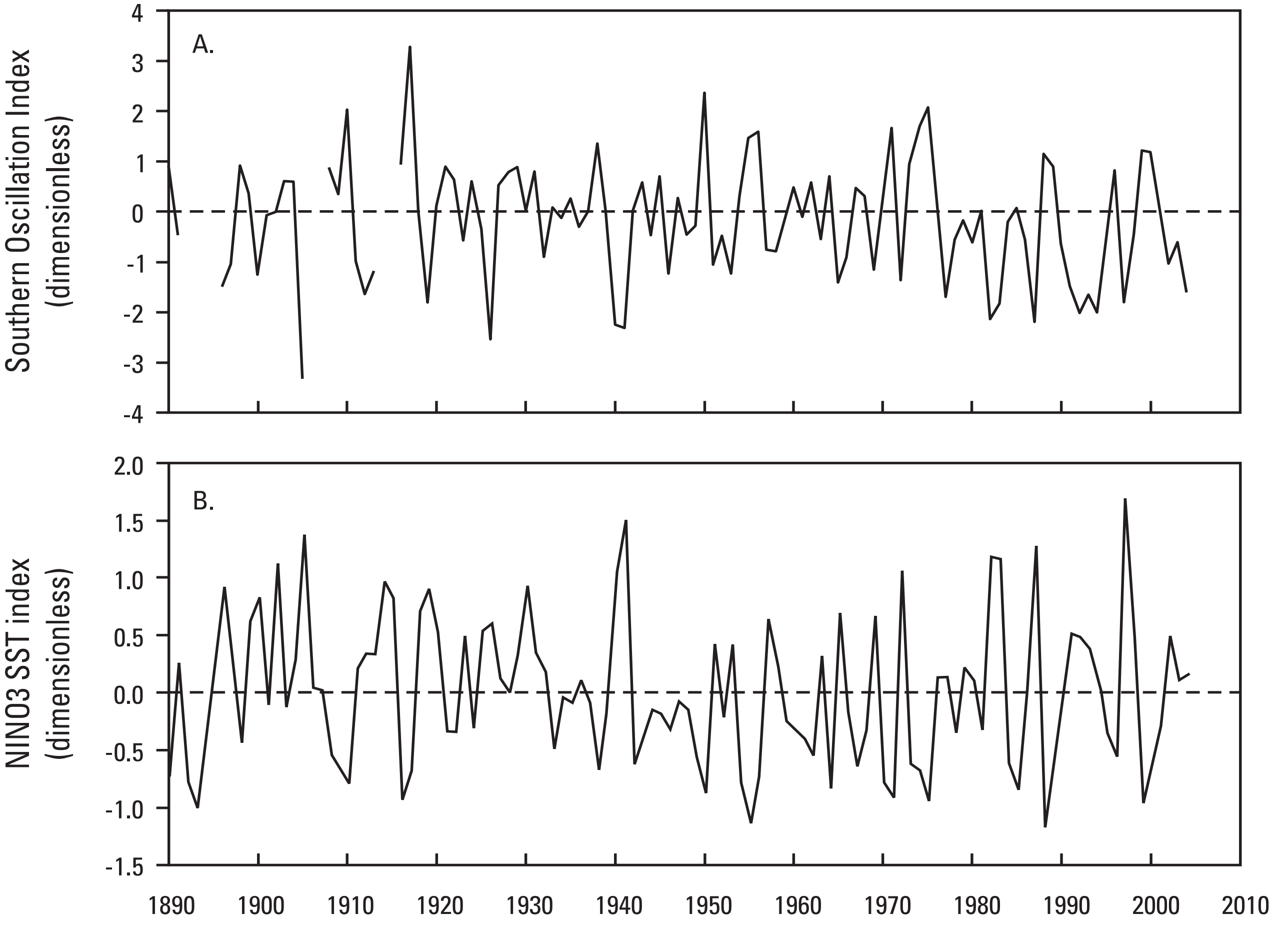

**Figure 5.** A. The Southern Oscillation Index (SOI) varies with a 4- to 7-yr periodicity between negative (El Niño) and positive (La Niña) states. B. The NINO3 index is a standardized anomaly index of sea-surface temperatures (SSTs) in an area of the equatorial Pacific Ocean from 150°W to 90°W longitude and ±5° latitude centered on the equator. Comparison of these diagrams shows that when SOI is negative, the NINO3 index generally is positive.

## Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) index (fig. 6) was developed from SSTs in the Pacific Ocean north of 20ºN latitude (Mantua and Hare, 2002). Two main characteristics distinguish the PDO from ENSO: (1) the PDO state (positive or negative) persists for decades, while typical ENSO events persist for 6 to 18 mo; and (2) the climatic signal of the PDO is most visible in the North Pacific Ocean instead of the tropics. The PDO index is commonly used to explain long-term periods of above- or below-average precipitation in the Western United States. When the PDO is positive, there is colder water in the central and western Pacific Ocean and warmer waters in the eastern Pacific Ocean; under negative PDO, the reverse is true. Positive PDO values are usually associated with wetter conditions in the Southwestern United States, while negative PDO values are suggestive of persistent drought in the Southwest. Long-term changes in the PDO may also influence snowmelt runoff in the Western United States, which is occurring earlier in the year, particularly in the Pacific Northwest and in the Sierra Nevada Range of California (Stewart and others, 2005).

Shifts in the phase of the PDO occurred in about 1944 and 1977 (Hereford and others, 2002; McCabe and others, 2004); from 1999 through 2004, PDO values have varied from negative (1999–2001) to positive (2002–04). While this might be viewed as an inconsistency with the persistent drought conditions during that period, the geographic center of drought conditions shifted towards the Pacific Northwest in a manner consistent with a positive (warm) PDO. At present, neither the causes of the variations in PDO values nor their predictability are well known; although, recent studies indicate that the PDO may be associated with decadal-length periods of above- and below-average precipitation and streamflow in the Colorado River Basin (Hidalgo and Dracup, 2004).

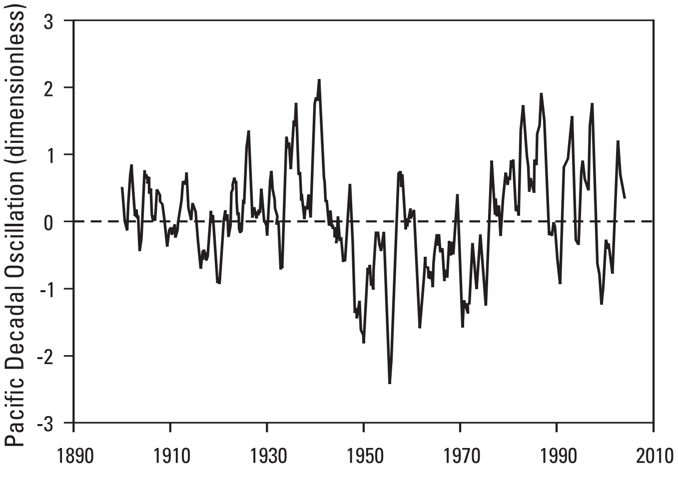

**Figure 6.** The Pacific Decadal Oscillation (PDO) is typically associated with long-term climatic variation in the Western United States. Positive PDO values suggest wetter periods (e.g., 1976 through 1995) for the Southwest and drier periods for the Northwestern United States. In contrast, negative values suggest persistent drier-than-average conditions in the Southwest (e.g., mid-1940s through mid-1970s).

## Atlantic Multidecadal Oscillation

The Atlantic Multidecadal Oscillation (AMO) (Kerr, 2000) reflects conditions in the Atlantic Ocean that may affect climate in the continental United States (fig. 7). The AMO is discussed only to point out that it is an interesting and possibly significant index; much additional research is needed to demonstrate its usefulness. As its name implies, AMO events have a persistence of 20 to 35 yr. Warm conditions indicated by positive AMO values are thought to be associated with drought conditions (Enfield and others, 2001), such as the Dust Bowl on the Great Plains (Schubert and others, 2004) and other periods of drought during the last century (McCabe and others, 2004).

Cool phases in the Atlantic Ocean occurred from 1902 to 1925 and from 1970 to 1994; these periods coincide with generally above-average precipitation and runoff in the Colorado River Basin. A warm phase occurred almost continuously from 1926 to 1963, which coincides with persistent average or below-average rainfall and runoff in the Colorado River Basin between the early 1930s and 1960s. More recently, the Atlantic Ocean warmed in 1996 and remained so through 2004. Fluctuations in the AMO combined with those of the PDO may help explain long-term drought frequency (Gray and others, 2003, 2004) and, therefore, fluctuation in runoff in the Colorado River Basin.

## Climate Indices and Drought

As knowledge increases about the influence of the oceans on the climate of the United States, so too does the awareness of the enormous complexity of the ocean-atmosphere system, particularly its variation over time. After intense scrutiny, scientists have learned that no single index of the system can explain all climate variations. It is increasingly evident that the various factors occur together in a complicated fashion. As a result,

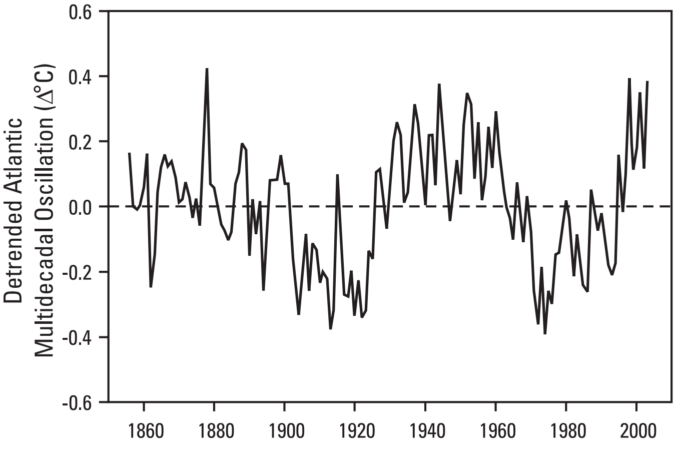

**Figure 7.** The detrended Atlantic Multidecadal Oscillation (AMO) is related to persistent sea-surface temperature (SST) conditions in the Atlantic Ocean. Positive values are associated with higher-than-average drought frequencies in the United States.

researchers attempt to use a combination of indices to explain the occurrence and spatial extent of droughts (e.g., McCabe and others, 2004).

In terms of the Colorado River Basin, the river's flow is related to the indices of global climate change in a complex way (Hidalgo and Dracup, 2004). From an interannual perspective, large floods and high runoff volumes typically occur during strong El Niño conditions (e.g., 1916–17, 1983–84), whereas La Niña conditions typically cause low-flow conditions (e.g., 1934, 1996). Above-average precipitation during El Niño, however, tends to occur in the southern part of the watershed while the northern part remains dry, a situation that tends to reverse during La Niña conditions.

Furthermore, the watershed of the Colorado River spans more than 10° of latitude, and precipitation patterns over that range do not necessarily respond in concert to regional climatic fluctuations. For example, above-average runoff in part of the watershed (e.g., the northern half) may overcome low runoff in other parts (e.g., the southern half) during some low-flow periods. As a result, much of the variability in the annual flow record is not easily explained by climate indices. For example, the midcentury drought, which was severe on the Colorado Plateau (Hereford and others, 2002), caused only slightly below-average runoff in the entire basin; the average runoff volume during this period was 11.1 maf (13,686 million $m^3$) for the period from 1948 to 1963. The response of Colorado River flow to the interaction of these climate indices is complicated, underscoring the concept that hydrologic drought results from an integrated set of climatological factors that are not easily predicted or explained.

The predicted effects of future climatic change suggest overall warming conditions and decreased average annual runoff in the basin (Christiensen and others, 2004), although a simple hydrologic response to this complex climatic framework seems unlikely. Predicted temperature increases suggest that snowmelt runoff may be less prevalent and may occur earlier in spring (Stewart and others, 2004, 2005). These analyses raise the possibility that legally mandated flow releases from Glen Canyon Dam may be possible in only 80% of future years owing to climatic change.

## Drought Persistence and Relation with Indices of Global Climate

Dendrochronological analyses show that since A.D. 1226, nine droughts have occurred in the Colorado River Basin lasting 15–20 yr and four droughts have occurred lasting more than 20 yr (Gray and others, 2003). Several of these droughts were punctuated by above-average precipitation related to discrete El Niño events, which could be analogous to the effect of current El Niño conditions on the Colorado River Basin. Moreover, tree-ring records indicate that some past droughts in the Colorado River Basin persisted for several decades (Meko and others, 1995), leaving open the possibility that the present drought could resume after the ongoing El Niño ends and continue for many more years.

By using tree-ring records spanning 700 yr, Gray and others (2003, 2004) found 30- to 70-yr multidecadal oscillations in drought frequency in the area that includes the headwaters of the Colorado River Basin. They also found a strong relation between drought occurrence and SSTs in the North Atlantic Ocean as manifested particularly in the AMO index (fig. 7) but which also included the PDO index (fig. 6). While neither index has a strong statistical relation to annual Colorado River flow (fig. 8), the combination may provide a context for the potential duration of the early 21st century drought. The broad relation between the PDO index and drought suggests that the present drought could persist for several decades after the end of the present El Niño period.

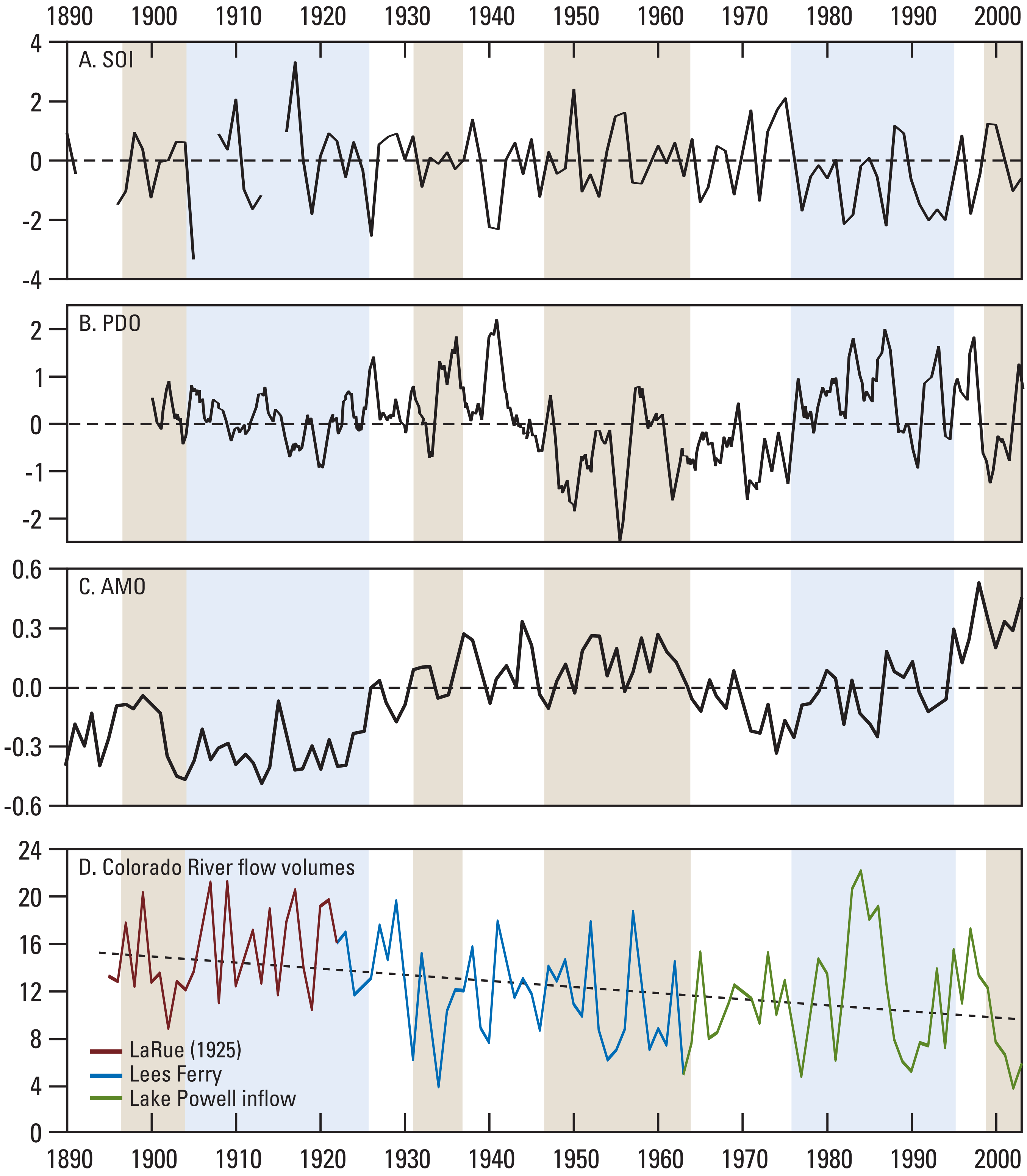

**Figure 8.** Time series showing the complex interrelations among indices of global climate and annual flow volumes of the Colorado River from 1895 through 2003. Colored vertical bars delineate dry (tan) and wet (light blue) climate periods. A. Southern Oscillation Index (SOI, dimensionless). B. Pacific Decadal Oscillation (PDO, dimensionless). C. Atlantic Multidecadal Oscillation (AMO, deviation in °C), not detrended as in figure 7. D. Actual annual flow volume (in millions of acre-feet (maf)) passing Lees Ferry or entering Lake Powell (fig. 4).

## Discussion and Management Implications

From 2000 through 2004, the early 21st century drought caused abnormally low flows in the Colorado River and its tributaries upstream from Lake Powell. By using either actual annual flow data or annual flow records adjusted for consumptive uses in the upper basin, it was found that runoff from 2000 through 2004 was the lowest in the period of record (99–110 yr). This low flow has caused considerable concern about the ability of the reservoirs on the Colorado River to deliver water from upper basin States to lower basin States. Water managers increasingly want to know the predictability of climate and its effects on water resources over annual, decadal, and longer term spans.

Climate, drought, and streamflow in the Colorado River are linked in poorly understood ways. Initial understanding of flows in the system was based on a relatively short historical record that is now believed to be a period of above-average precipitation. Examination of long-term records based on tree-ring analyses suggests that drought magnitude and persistence patterns are associated with much broader hemispheric climate patterns; however, these correlations are imperfect and do not provide a clear understanding of long-term precipitation patterns.

Currently, there is no reliable way to predict how long the early 21st century drought will last in the Colorado River Basin. Components of the climate system, such as sea-surface temperature of the Atlantic and Pacific Oceans, provide some context for understanding past variations in precipitation and streamflow, but they are insufficient for predicting the fate of the ongoing drought. Time series of the relevant climate indices indicate a large amount of year-to-year variability and relatively rapid changes from one regime to another. Above-average precipitation for winter 2004–05 and forecasts for above-average runoff may signal the end of the drought, or the drought conditions may resume after the present El Niño ends. Both outcomes underscore the unpredictability of climatic shifts affecting the Colorado River Basin.

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Andrew Pernick, Bureau of Reclamation

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# Chapter 4

# Water Quality in Lake Powell and the Colorado River

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Steven P. Gloss

## Introduction

Water temperature, nutrient concentrations, turbidity, and other water-quality parameters are of interest to managers and scientists because these parameters influence a range of ecosystem components, from support of aquatic microorganisms and invertebrates to the behavior of native and nonnative fishes. For example, declines of Colorado River Basin native fishes and changes in their condition have been attributed, in part, to low water temperatures downstream from dams, such as Glen Canyon Dam, that release water from deeper portions of the reservoir (Clarkson and Childs, 2000). Similarly, water quality is an important determinant of food-web structure in aquatic habitats and abundance of consumers like fish in those food webs (Carpenter and Kitchell, 1996; Wetzel, 2001).

Any investigation of the dynamics of the Colorado River ecosystem in Grand Canyon must not only document and understand the water quality in Grand Canyon itself but also the water quality in Lake Powell, the reservoir created by Glen Canyon Dam. The impoundment of a river system in a reservoir alters downstream water quality in many ways (Nilsson and others, 2005). The formation of Lake Powell in 1963 was accompanied by reductions in suspended-sediment and nutrient transport and by changes in seasonal temperatures, discharge levels, and benthic community structure of the Colorado River (Paulson and Baker, 1981; Stevens and others, 1997; Topping and others, 2000 a, b). More recently, reservoir and downstream water quality has been affected by reservoir drawdown from a 5-yr basinwide drought in the Western United States. Water released from Glen Canyon Dam in 2003 and 2004 was the warmest recorded since August 1971, when Lake Powell was in its initial filling period (initial filling of the reservoir began in 1963 with the closure of Glen Canyon Dam, and it reached full pool of 3,700 ft for the first time in 1980). Changes in stratification and the fate of inflow currents in Lake Powell under various storage conditions, as well as various operational scenarios such as experimental releases and a proposed temperature control device, could have significant effects on the quality of water released from Glen Canyon Dam.

This chapter provides an overview of water-quality trends and conditions in Lake Powell and the Grand Canyon ecosystem. Because Lake Powell and Glen Canyon Dam operations have a strong influence on downstream water quality, the water quality of the reservoir is discussed in some detail. The chapter also addresses recent drought-induced changes and the effects of the modified low fluctuating flow (MLFF) alternative. The monitoring of water quality in Lake Powell is conducted by the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center under separate funding from the Bureau of Reclamation and is not funded by the Glen Canyon Dam Adaptive Management Program.

## Background

Glen Canyon Dam has a structural height of 710 ft (216 m). This high, concrete-arch dam backs up water for 186 mi (299 km) to form Lake Powell, the second largest reservoir in the United States. Lake Powell had an original capacity of 27.1 million acre-feet (maf) (33,414 million $m^3$) and a surface area of 161,390 acres (65,315 ha) at full pool elevation of 3,700 ft (1,128 m). By 1986, this capacity had been reduced to 26.2 maf (32,305 million $m^3$) because of an estimated loss of capacity of 30,000 acre-feet (af) (36,990,000 $m^3$) per year resulting from sedimentation (Ferrari, 1988). Water can be released from Glen Canyon Dam through three separate structures (spillways, penstocks, and river outlet works). The majority of water is routed through eight penstocks, which feed the powerplant turbines. The penstock inlets are at an elevation of 3,470 ft (1,058 m) and have a maximum combined discharge capacity of approximately 33,200 cubic feet per second (cfs) when the reservoir is full. Water can also be released from (1) the river outlet works at an elevation of 3,374 ft (1,028 m) and (2) two spillways at an elevation of 3,648 ft (1,112 m), both of which bypass the powerplant turbines and have discharge capacities of 15,000 cfs and 208,000 cfs, respectively (Bureau of Reclamation, 1981) (fig. 1).

## Lake Powell

Glen Canyon Dam began storing water on March 13, 1963, and full pool elevation was reached on June 22, 1980. Ninety-six percent of the reservoir's inflow is received from the Colorado and San Juan Rivers; the majority of this inflow is received from May to July as the result of snowmelt in the Rocky Mountains (Stanford and Ward, 1991). The impoundment of the Colorado River by Glen Canyon Dam altered the quality, seasonal release volumes, and the amount of daily fluctuations for the Colorado River ecosystem downstream of the dam. Colorado River water is now transformed by an approximate 2-yr residence time in Lake Powell and by the structure and operation of Glen Canyon Dam. These factors influence the temperature, suspended and dissolved solids, nutrients, and organisms that pass downstream as well as the volume of water released and the magnitude of fluctuations.

Lake Powell has a maximum depth immediately upstream of Glen Canyon Dam of approximately 515 ft (157 m) at full pool elevation; the lake is vertically stratified into density layers and differs longitudinally as the currents move through the reservoir. Vertical stratification varies seasonally and is determined by the relative density of the different layers of the reservoir. Density is determined by water temperature and the amount of dissolved minerals and suspended solids. The surface layer of the reservoir, or epilimnion, warms through summer and is eventually mixed with deeper water by the wind and convective currents during the winter cooling period, which extends from October to early March. The epilimnion exhibits the highest level of biological activity because of warm temperatures and light availability. Water temperature decreases with depth in the metalimnion, the layer that separates the epilimnion from the bottom layer of the reservoir, or hypolimnion. The hypolimnion consistently exhibits lower temperatures, lower dissolved oxygen levels, and higher salinity concentrations than the other layers of the reservoir. Because of the subsurface position of the penstocks, water may be withdrawn from the epilimnion, metalimnion, or hypolimnion depending on reservoir level, reservoir hydrodynamics, timing and strength of stratification, and magnitude of withdrawals.

Longitudinal variation in water quality is the result of currents moving through the reservoir. The portions of the reservoir farthest from the dam exhibit characteristics similar to those of the river entering the reservoir, with more variable temperature and salinity patterns and higher sediment and nutrient concentrations. Primary productivity from photosynthesis is limited by light availability in this more turbid riverine zone. The deeper portions of the reservoir closest to the dam, or the lacustrine zone, exhibit characteristics similar to those of a lake system, with more stable temperature and salinity patterns, low suspended-sediment concentration, and lower nutrient concentrations. Primary productivity in this zone is limited by nutrient availability. A transition zone of intermediate characteristics separates the riverine and lacustrine zones (Kimmel and Groeger, 1984; Department of the Army, Corps of Engineers, 1987; Ford, 1990). The relative location of these zones depends on reservoir levels and the magnitude of inflows. In the

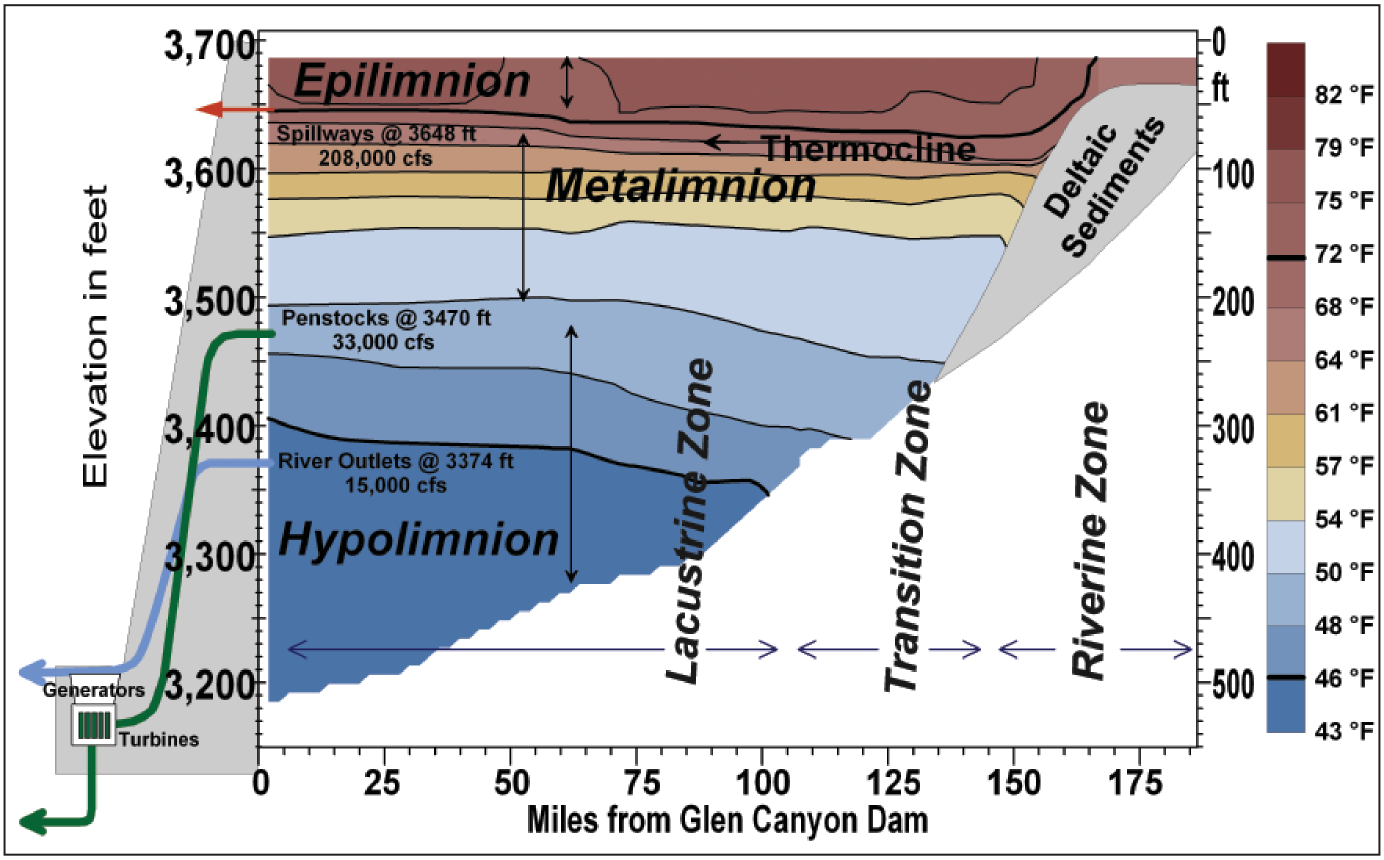

**Figure 1.** Profile of Lake Powell from Glen Canyon Dam to the inflow of the Colorado River, illustrating the vertical stratification and horizontal zonation of the reservoir at or near full pool elevation, September 1999. Also shows the elevations of each of the three release structures and their capacities as well as an approximation of the wedge of deltaic sediments. Y axis on left is measurement of elevation above mean sea level and on right is actual depth.

main channel of Lake Powell, the riverine zone extends from the Colorado River inflow to Hite Bay, the transition zone extends from Hite Bay to the Bullfrog Bay area, and the lacustrine zone extends from Bullfrog Bay to Glen Canyon Dam (figs. 1 and 2).

The depth at which river water enters the reservoir is dictated by its density relative to the density of the water already in the reservoir. Spring and early summer snowmelt runoff entering the reservoir tends to be dilute, has warmed during its passage through the canyonlands, and represents the lowest density water entering the reservoir during the year. Consequently, this water travels through the reservoir as an overflow density current. During the winter months, inflows are colder and more saline and represent the highest density water entering the reservoir. Depending on the relative density of the hypolimnion, winter inflows will either flow along the bottom of the reservoir, routing fresh water to the hypolimnion and displacing older water upward, or flow into intermediate layers, leaving deeper waters stagnant.

Convective mixing takes place in the epilimnion as the reservoir cools during the fall and winter months. By the end of the calendar year, convective mixing in the upper layers progresses to the point that penstock withdrawals begin to exhibit characteristics of the epilimnion, which contains the warmest water in the reservoir at that time of year, despite the cooler weather conditions. This convective mixing results in the warmest release temperatures of the year occurring in late fall or early winter.

## Downstream of Glen Canyon Dam

Changes to the chemical and physical quality of the water of the Colorado River after its release from Glen Canyon Dam are affected by ambient meteorological conditions, primary production and respiration from the aquatic environment, aeration from rapids, inputs from other tributary sources and overland flow, and various aspects of the operation of Glen Canyon Dam.

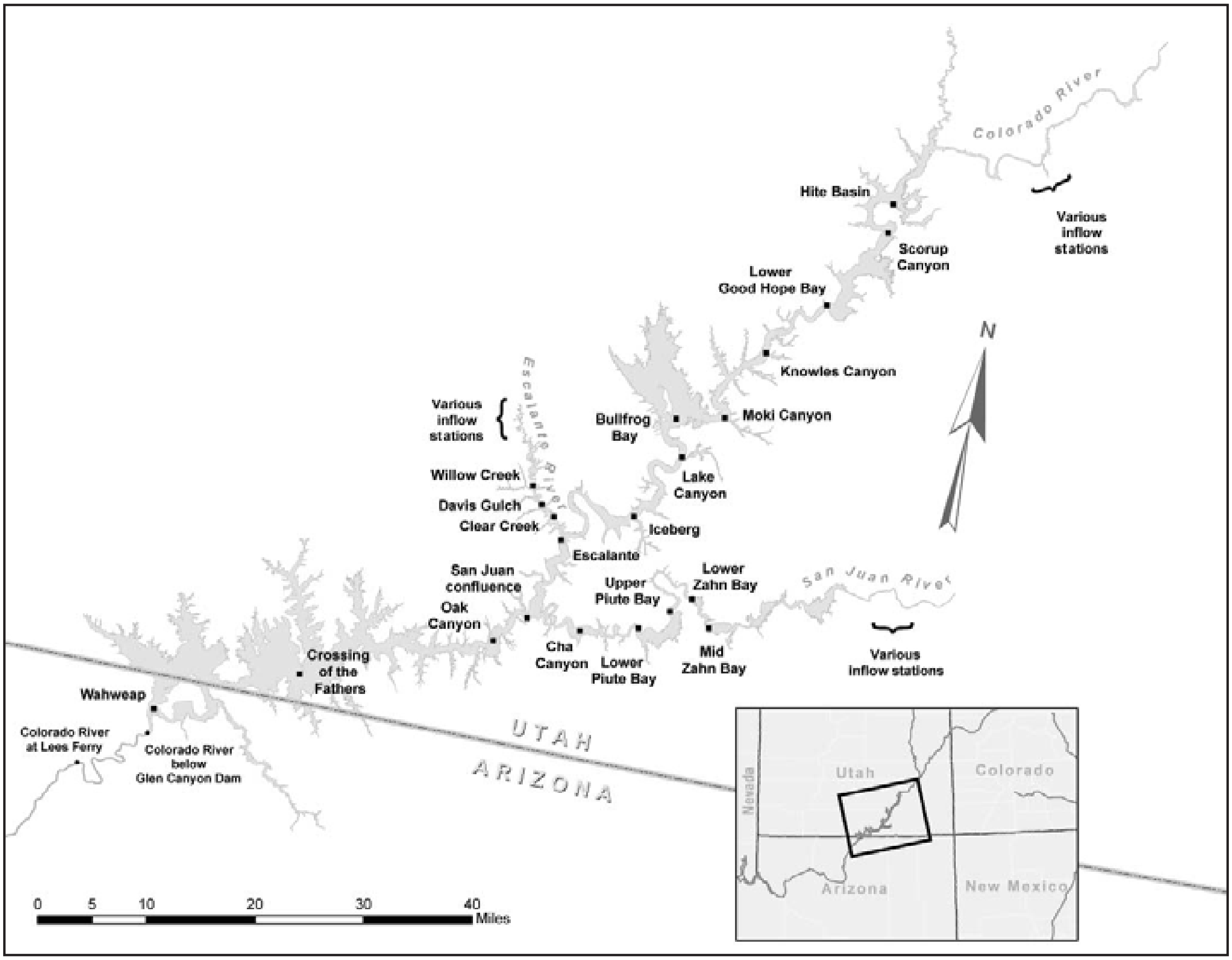

**Figure 2.** Lake Powell water-quality sampling sites.

Water released from Glen Canyon Dam is usually colder than the surrounding environment and warms as it flows downstream with exposure to solar radiation and warmer ambient air temperatures. The exception to this pattern is during portions of the winter months when dam releases are slightly warmer than the surrounding environment and cool as they flow downstream before warming again in lower elevation reaches.

The aquatic environment affects dissolved oxygen concentrations and pH in the tailwater (referred to as the Lees Ferry reach elsewhere in this report), which is the 15 mi (24 km) of the river that extends downstream from Glen Canyon Dam to Lees Ferry. This area is free of significant tributary sediment inputs that limit light availability for primary production (Yard and others, 2005). As a result of photosynthetic activity, therefore, dissolved oxygen concentrations and pH in the tailwater display daily oscillations at Lees Ferry. During daylight hours dissolved oxygen concentrations and pH increase because of the addition of oxygen and removal of carbon dioxide during photosynthesis. The opposite occurs at night when respiratory processes become dominant (Marzolf and others, 1999; U.S. Geological Survey, 2001).

Under normal powerplant discharges, limited aeration of the river occurs in the tailwater reach of the river compared to downstream reaches. Generally, released water that may be lower in dissolved oxygen does not reach full saturation until the first rapids in Marble Canyon, where the water is aerated by turbulence; however, during periods when the river outlet works are operated, such as during the 1996 beach/habitat-building flow or the 2004 experimental high flow, turbulence immediately below the dam is sufficient to bring release water up to full oxygen saturation (Hueftle and Stevens, 2001).

Various tributaries that enter Grand Canyon can significantly affect water quality of the Colorado River below Glen Canyon Dam. The Paria and Little Colorado Rivers can carry large amounts of fine sediment that limit light availability for primary production and may enhance conditions for native fish that use turbid water for cover from predation (Shannon and others, 1994; Topping and others, 2000 a, b). Some tributaries, such as the Little Colorado River, are significant sources of salinity to the mainstem Colorado River (Cole and Kubly, 1976).

# Water-quality Monitoring

## Lake Powell

The purpose of water-quality monitoring in Lake Powell is to document and understand the water-quality changes that occur during the residence time of the water in the reservoir and how those changes may affect the quality of water being released from Glen Canyon Dam under various conditions.

Water-quality monitoring of Lake Powell currently has two main components. Monthly surveys of the forebay, the pool of water in front of the dam, take place at the mouth of Wahweap Bay, approximately 1.5 mi (2.4 km) upstream of Glen Canyon Dam, to document the quality of water in dam releases. Reservoir-wide surveys are conducted quarterly to describe seasonal changes in the stratification and hydrodynamics of the reservoir and to better understand the reason for observed changes in downstream releases.

Water-quality sampling in Lake Powell was initiated by the Bureau of Reclamation in 1964 and continued through 1990, including several phases of differing sampling frequencies for the reservoir and forebay. Glen Canyon Environmental Studies conducted the monitoring from 1990 to 1996. The USGS Water Resources Discipline conducted monitoring in Lake Powell on several dates in 1992, 1994, and 1995 (U.S. Geological Survey, 1998). Since 1997, monitoring has been conducted by the USGS Grand Canyon Monitoring and Research Center.

Monthly monitoring of the forebay allows for the observation of conditions immediately upstream of Glen Canyon Dam and for the description of the dynamics of the water column that is the immediate source for downstream releases. Quarterly reservoir-wide sampling describes seasonal conditions at 20–25 stations throughout the reservoir during the maximum extent of winter convective mixing, spring runoff, post runoff/late summer stratification, and early winter conditions during the early phases of convective mixing (fig. 2, table 1).

At each station, data on basic water-quality parameters—temperature, specific conductance, dissolved oxygen, pH, oxidation-reduction potential, and turbidity—are collected through the water column. At selected depths, chemical (major ions and nutrients) and biological (chlorophyll and plankton) sampling is performed to characterize the major strata in the water column. Major ions are the common negative (e.g., chloride) and positive (e.g., calcium) ions that constitute the majority of minerals dissolved in water. Nutrients represent the total and dissolved fractions of compounds of phosphorus and nitrogen, which are essential for the production of plant life (algae or phytoplankton).

## Glen Canyon Dam Tailwater

Water-quality monitoring activities in the dam's tailwater assess the initial quality of water leaving the reservoir and entering Grand Canyon. These baseline measurements are important for detecting changes occurring in Grand Canyon and for understanding the relationship between the quality of water leaving the reservoir and its relationship to the downstream aquatic ecosystem (fig. 3).

The USGS recorded daily instantaneous water temperatures at Lees Ferry from 1949 to 1977 (U.S. Geological Survey, 2004). Since then, temperatures recorded at Lees Ferry reflect mean daily values of multiple observations (U.S. Geological Survey, 1985–2004). Glen Canyon Environmental Studies began monitoring the temperature and conductivity of dam releases in 1988 by using remotely deployed, continuously logging monitors. In 1991, this program was expanded to include continuous monitoring at Lees Ferry. Dissolved oxygen and pH measurements were added to the monitoring protocol shortly afterwards.

Tailwater monitoring activities currently include the continuous measurement of temperature, salinity, dissolved oxygen, and pH and monthly sampling for phosphorus, nitrogen, major-ion chemistry composition, and biological indicators such as chlorophyll and plankton.

**Table 1.** Lake Powell and tailwater sampling sites.

| Site name | Distance in miles (kilometers) from Glen Canyon Dam | Chemical and biological sampling |
|---|---|---|
| **Tailwater** | | |
| Colorado River below Glen Canyon Dam | 0 | X |
| Colorado River at Lees Ferry | -15.5 (-24.9) | X |
| **Colorado River main channel** | | |
| Wahweap | 1.5 (2.4) | X |
| Crossing of the Fathers | 28.1 (45.2) | X |
| Oak Canyon | 56.2 (90.5) | X |
| San Juan River confluence | 62.2 (100.1) | |
| Escalante | 72.6 (116.9) | X |
| Iceberg | 86.7 (139.5) | |
| Lake Canyon | 98.6 (158.7) | |
| Bullfrog Bay | 104.3 (167.9) | X |
| Moki Canyon | 111.8 (179.9) | |
| Knowles Canyon | 120.1 (193.3) | |
| Lower Good Hope Bay | 129.6 (208.5) | X |
| Scorup Canyon | 140.1 (225.5) | |
| Hite Basin | 148.3 (238.7) | X |
| Colorado River inflow | 149.1–185.8 (240.0–299.0) | X |
| **San Juan River arm** | | |
| Cha Canyon | 12.0 (19.3) | X |
| Lower Piute Bay | 20.4 (32.9) | |
| Upper Piute Bay | 26.8 (43.1) | X |
| Lower Zahn Bay | 38.8 (62.5) | |
| Mid Zahn Bay | 42.6 (68.6) | |
| San Juan inflow | 32.3–54.1 (52.0–87.0) | X |
| **Escalante River arm** | | |
| Escalante at Clear Creek | 4.5 (7.2) | |
| Escalante at Davis Gulch | 7.4 (11.9) | X |
| Escalante at Willow Creek | 12.4 (20.0) | |
| Escalante inflow | 13.7–24.8 (22.0–40.0) | X |

## Downstream Thermal Monitoring in Grand Canyon

Downstream thermal monitoring provides an indication of status and trends in water temperature and how warming is affected by river reach, seasonality, and dam operations. Concerns about the effects of the thermal regime on both native and nonnative fish resulted in the development of a continuous thermal monitoring program in Grand Canyon beginning in 1990. Thermal monitoring was conducted at 10 mainstem stations at intervals of roughly 30 mi (48 km) and at 8 additional sites on major tributaries. Tributary sites have been monitored since 1994, providing thermal baseline data for streams that may act as warmwater refugia for many aquatic species, particularly native fish. In 2005, thermal monitoring in tributaries was reduced to four sites, the Paria River, the Little Colorado River, Kanab Creek, and Havasu Creek.

In 2002, the thermal monitoring program in the mainstem Colorado River was expanded to include multiparameter monitoring stations throughout Grand Canyon to collect time-series measurements of water temperature, specific conductance, dissolved oxygen, and pH at five sites where suspended-sediment transport is also monitored. In 2005, mainstem monitoring was reduced to temperature and specific conductance measurements (fig. 3).

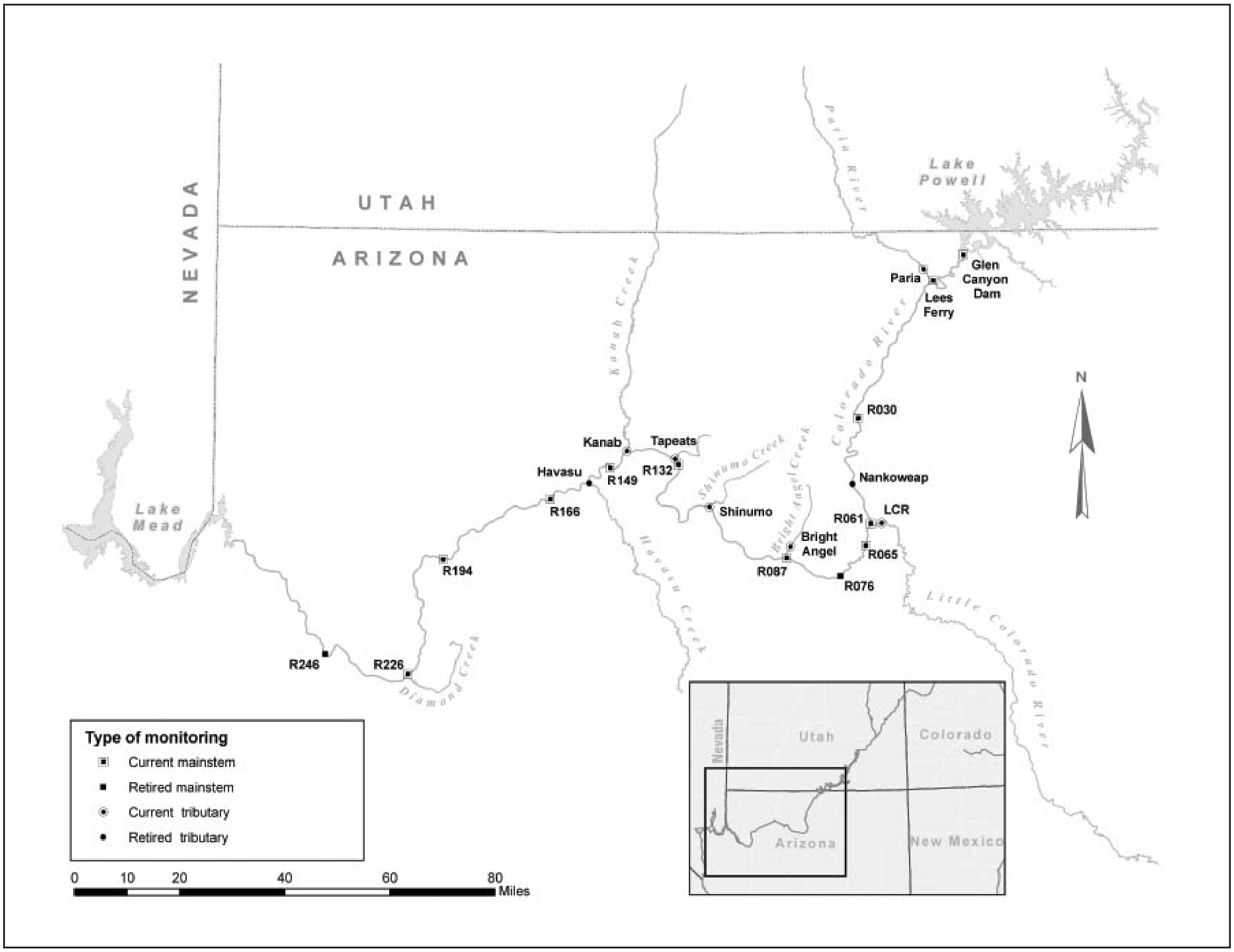

**Figure 3.** Grand Canyon water-quality sampling sites.

# Trends and Current Conditions

## Hydrology

Because of a prolonged drought between 2000 and 2005, Lake Powell water storage was reduced by approximately 60%. Water year (WY) 2004, which ended on September 30, 2004, was the fifth consecutive year of below-normal inflows to Lake Powell; inflows were at 51% of average in WY 2004 (table 2). Inflow in WY 2002 was the lowest observed since the completion of Glen Canyon Dam in 1963. This drought period resulted in a 130 ft (40 m) drop in reservoir elevation and a 13 maf (16,029 million $m^3$) decline in storage in Lake Powell by the end of WY 2004 (fig. 4). While precipitation in the upper Colorado River Basin increased substantially during the first part of WY 2005, storage in Lake Powell continued to decline until the reservoir reached an elevation of 3,555 ft (1,084 m) on April 8, 2005, after which snowmelt runoff and reduced dam releases increased the reservoir elevation. Average unregulated inflow to Lake Powell is 12.056 maf (14,865 million $m^3$), as determined from the 30-yr record that spans WY 1971 through WY 2000 (Tom Ryan, Bureau of Reclamation, oral commun., 2005); however, the average inflow for the water years from 2000 to 2004 was 5.962 maf (7,351 million $m^3$) (table 2).

**Table 2.** Recent inflows and releases at Glen Canyon Dam (maf = million acre-feet).

| Water year (WY) | April–July unregulated inflow (maf) | Percent of average | WY unregulated inflow (maf) | Percent of average | Glen Canyon Dam release (maf) | End of year storage (maf) | End of year elevation (ft) |
|---|---|---|---|---|---|---|---|
| 1998 | 8.625 | 112 | 13.661 | 116 | 13.511 | 22.403 | 3687.7 |
| 1999 | 7.621 | 99 | 12.71 | 108 | 11.202 | 22.997 | 3691.6 |
| 2000 | 4.352 | 56 | 7.310 | 62 | 9.380 | 20.939 | 3677.8 |
| 2001 | 4.301 | 56 | 6.955 | 59 | 8.238 | 19.135 | 3664.8 |
| 2002 | 1.115 | 14 | 3.058 | 25 | 8.230 | 14.468 | 3626.5 |
| 2003 | 3.918 | 51 | 6.358 | 53 | 8.228 | 12.110 | 3603.8 |
| 2004 | 3.640 | 46 | 6.128 | 51 | 8.231 | 9.169 | 3570.8 |

## Salinity

Salinity levels are of concern throughout the entire Colorado River Basin because high salinity can be damaging to soils and crops. Furthermore, treaty obligations with Mexico limit the salinity of water that can be delivered to that country. As the Colorado River flows to the Gulf of California, it leaches salts from soils and other geologic substrates through and over which it flows. Salinity levels are also increased by irrigation returns, by evaporation in storage facilities, and by rate of flow (slow-flowing water picks up higher levels of dissolved solids than do high flows during runoff).

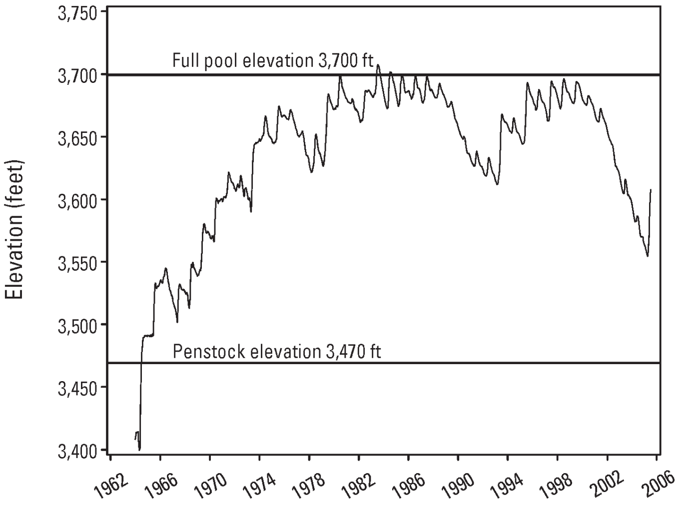

**Figure 4.** Lake Powell surface elevation, 1963–2005.

Periodically the salinity of water released from the dam increases as a result of drought. This increase is due to a combination of factors, including increases in the salinity of base flows into the reservoir, lack of large volumes of dilute snowmelt runoff, and reduced reservoir volume to dilute the effects of reservoir inflows. At the end of WY 2004, releases from Glen Canyon Dam had a specific conductance of approximately 850 microsiemens per centimeter (µS/cm) at 25°C, corresponding to a total dissolved solids concentration of 575 mg/L (fig. 5).

## Water Temperature

Impounding water in Lake Powell significantly affected the water temperature of dam releases to the Colorado River ecosystem because of reservoir stratification and the location of the penstock release structures (fig. 1). During the summer months, the epilimnion of Lake Powell warms considerably from inflows, ambient air temperature, and solar radiation, reaching temperatures as high as 86°F (30°C); however, the hypolimnion is isolated from these processes, maintaining temperatures between 43°F and 48°F (6°C and 9°C).

Before closure of the dam, mean water temperature for what is now the tailwater was approximately 57°F (14°C), ranging from 32°F to 80°F (0°C to 27°C) over the course of a year (U.S. Geological Survey, 2004). Before 1973, during the reservoir's initial filling stage, release temperatures were affected by surface or epilimnetic withdrawals because of the proximity of the reservoir's surface to the penstock withdrawal zone. Max-

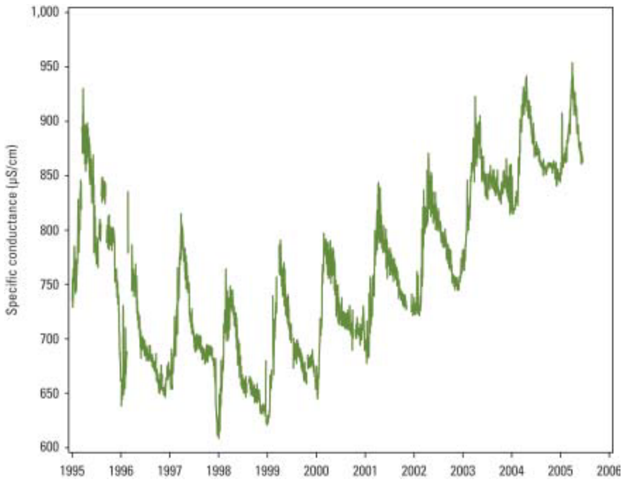

**Figure 5.** Mean daily specific conductance (in microsiemens per centimeter (µS/cm) at 25°C), an indicator of salinity, below Glen Canyon Dam, 1995–2005.

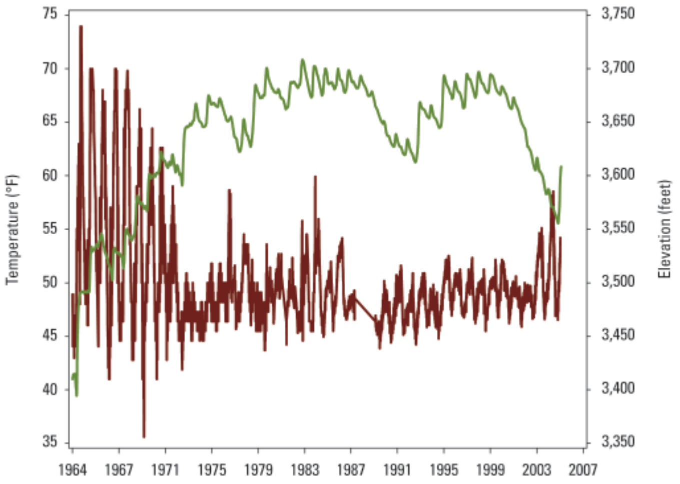

**Figure 6.** Daily water temperature (red line) at Lees Ferry as affected by changes in Lake Powell's elevation (green line).

imum release temperature during that period occurred during the months of August and September, reflecting the surface warming of the reservoir.

Trends in water temperature of the tailwater stabilized from 1973 to 2003, when the reservoir surface elevations were above 3,600 ft (1,097 m) and the epilimnion was situated above the penstock withdrawal zone. During this period, release temperatures as measured at Lees Ferry averaged 48.7°F (9.3°C). Temperatures fluctuated between 44°F and 54°F (7°C and 12°C), with minor excursions beyond this range during periods of spillway releases (fig. 6). Under these conditions, there was some seasonality to Glen Canyon Dam release temperatures, with slight warming beginning in May and June and increasing through the year. The highest temperatures occurred at the end of December as a result of the influence of the relatively warm, convectively mixed epilimnion on penstock releases. Peak temperatures under these conditions appeared to be affected by the volume of the previous year's snowmelt runoff, which affects the thickness of the warm epilimnion near the dam during the latter months of the year. Although seasonality in temperature patterns exists in the postdam era, the annual variation has been reduced to approximately 9°F (5°C) from approximately 48°F (27°C) in the predam era. Also, the highest river temperatures immediately below the dam now occur in late fall or winter instead of in summer, which is when they occurred in the predam, unregulated river.

The water level of the reservoir dropped more than 140 ft (42 m) between 1999 and 2005 as a result of a basinwide drought that began in 2000 (fig. 4). This drop placed the warmer epilimnetic water much closer to the penstock withdrawal zone and resulted in reservoir releases being drawn from this epilimnetic layer. Substantially warmer release temperatures have occurred in the fall and early winter months since 2003. An annual maximum mean daily release temperature of 55°F (12.9°C) was observed on November 14, 2003; on November 6, 2004, the annual maximum mean daily temperature reached 59°F (15°C) (fig. 6). These values represent the highest release temperatures from Glen Canyon Dam since August 1971, when the reservoir was filling. As of July 11, 2005, the mean daily release temperatures had reached 56.4°F (13.6°C), showing earlier warming and higher temperatures than had occurred in the past 2 yr.

Seasonal and longitudinal water temperature patterns in Grand Canyon have been measured from 1994 to 2005 from Glen Canyon Dam to Diamond Creek, 241 mi (388 km) below Glen Canyon Dam (fig. 7). During summer months, gradual downstream warming occurs because of the transfer of heat from the warmer surrounding air mass, heat stored in the canyon walls adjacent to the river, and solar radiation.

A comparison of weekly average increase in water temperature between Glen Canyon Dam and Diamond Creek to average weekly discharge during mid-June from 1994 to 2004 demonstrates the effect of Glen Canyon Dam releases on warming patterns in the Colorado River in Grand Canyon (fig. 8). High steady flows of approximately 26,000 cfs in 1997 resulted in 9°F (5°C) warming at Diamond Creek, while low steady flows of

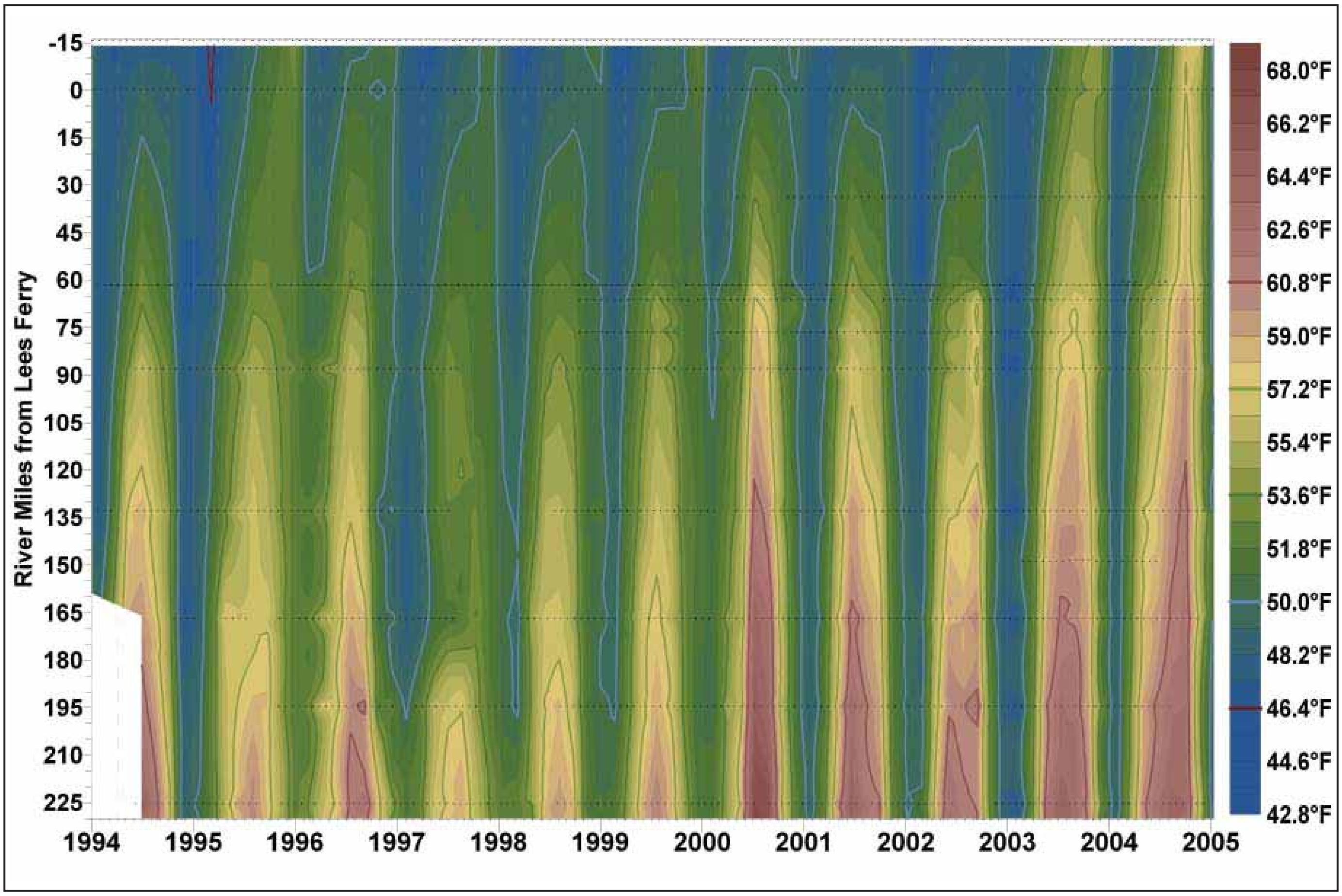

**Figure 7.** Water temperatures along the Colorado River from Glen Canyon Dam to Diamond Creek, 1994–2005. Black dots represent monitoring locations.

8,000 cfs in 2000 exhibited 18°F (10°C) warming. This difference is because large volumes of water have greater mass and a lower surface area to volume ratio as well as less exposure time for atmospheric heat exchange that is due to higher velocity, reducing the amount of warming from ambient temperatures and solar radiation. The warming occurring at low discharges affects water temperatures in lower Grand Canyon to a greater degree than the elevated release temperatures observed in the past 2 yr.

Lateral variation in river temperature also occurs throughout Grand Canyon. Substantial warming occurs in various nearshore environments, ranging from shallow, open-water areas to enclosed backwaters. Water in certain nearshore environments becomes isolated from mixing with the main channel current and warms with solar radiation and equilibration with ambient temperatures. These environments may be important to the survival, growth, and eventual recruitment of the larval life stages of native fish (see chapter 2, this report).

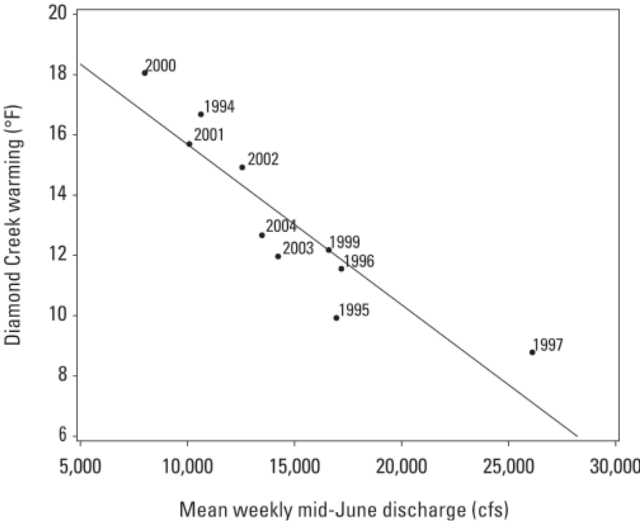

**Figure 8.** Mid-June warming above release temperatures at Diamond Creek, 1994–2004, as a function of mean weekly discharge (in cubic feet per second). Warming at Diamond Creek = 0.000532 * Q + 21.01.

## Turbidity and Suspended Sediment

Construction of Glen Canyon Dam dramatically altered the sediment-transport processes of the Colorado River. Before the completion of Glen Canyon Dam, the total sand supply to Grand Canyon, from the Colorado River upstream from Lees Ferry, with the Paria and Little Colorado Rivers combined, was approximately 29 million tons (26 million Mg). Today, because Lake Powell traps all of the sediment upstream from Glen Canyon Dam, the Paria River is the primary source of sand to Marble Canyon, supplying approximately 6% of predam sand levels (see chapter 1, this report). Only a small portion of the suspended sediment entering Lake Powell is transported for any distance because most of it is deposited near the inflows of major tributaries.

Turbidity and suspended-sediment concentrations are of interest in the downstream environment because water clarity affects the amount of light available for photosynthesis for downstream algal communities, which are an important part of the overall food base for native and nonnative fishes. Turbidity also affects the behavior and distribution of various native and nonnative fishes in providing cover from various predators or by affecting sight-feeding abilities. Turbidity is measured in both Lake Powell and downstream. Turbidity measurements in Lake Powell indicate the location of advective tributary inflows and also can be used as an indicator of primary productivity in the reservoir because increased turbidity indicates the presence of phytoplankton. The rather abrupt decrease in filamentous green alga below Lees Ferry most probably results from inputs of sediment from major tributaries, including the Paria and Little Colorado Rivers, which reduce light penetration (Cole and Kubly, 1976; Stevens and others, 1997).

## Nutrients

Nutrients such as phosphorus, nitrogen, and silica are essential for microbial production and algal growth. Most phosphorus entering Lake Powell is associated with suspended clays in the inflows of river water. The reservoir acts as a nutrient sink, especially for phosphorus. More than 95% of phosphorus reaching Lake Powell is in particulate form or is associated with suspended sediment particles. A large fraction of this phosphorus load is deposited within the reservoir by sedimentation (Gloss, 1977). Most of the remaining dissolved phosphorus is removed from the water by uptake from biological activity.

Bioproduction in Lake Powell apparently is directly related to the intensity and duration of enriched spring inflow events that are responsible for delivering the bulk of nutrient capital to the reservoir (Gloss and others, 1980). Surface concentrations of dissolved phosphorus generally decline from the upper end of the reservoir to the dam because of the uptake from primary production, to the point that dissolved phosphorus is usually below detection limits within 30–60 mi (48–97 km) upstream from the dam in the upper water column. Phosphorus is the limiting factor for primary production near the dam, while low light availability is the limiting factor to productivity in the upper portion of Lake Powell because of turbidity from inflow currents, especially during early summer months (Gloss and others, 1980) (fig. 9a).

Nitrate-nitrogen concentrations from the surface of the reservoir forebay fluctuate in a manner that reflects the utilization of the nitrogen by algae and begin to increase in fall as primary production slows. Nitrate-nitrogen concentrations show a peak in winter when temperatures are coolest and productivity is relatively low. During the summer months, when primary productivity is at a maximum, nitrate-nitrogen concentrations reach a minimum because of uptake by primary producers. From 1999 to 2004, surface nitrate-nitrogen concentrations in the forebay above Glen Canyon Dam averaged 0.09 parts per million (ppm). Nitrate-nitrogen concentrations in the deepest part of the hypolimnion averaged 0.39 ppm, about four times higher than surface concentrations. For the same period, nitrate-nitrogen concentrations in Glen Canyon Dam releases averaged 0.29 ppm (fig. 9b).

The highest productivity in Lake Powell is seen in surface waters of the reservoir and results from a combination of temperature, light availability, and nutrient concentrations. Because primary productivity processes consume nutrients, nutrient concentrations are eventually depleted in the surface waters of Lake Powell and remain at elevated concentrations in the hypolimnion, where there is little primary production taking place. Consequently, hypolimnetic releases from Glen Canyon Dam are relatively nutrient rich. Periods of epilimnetic releases from Glen Canyon Dam may cause a reduction in the amount of nutrients available to the downstream ecosystem.

## Dissolved Oxygen

Dissolved oxygen concentrations in Lake Powell are affected by inflow, seasonal water-circulation patterns, and biological processes (Johnson and Merritt, 1979).

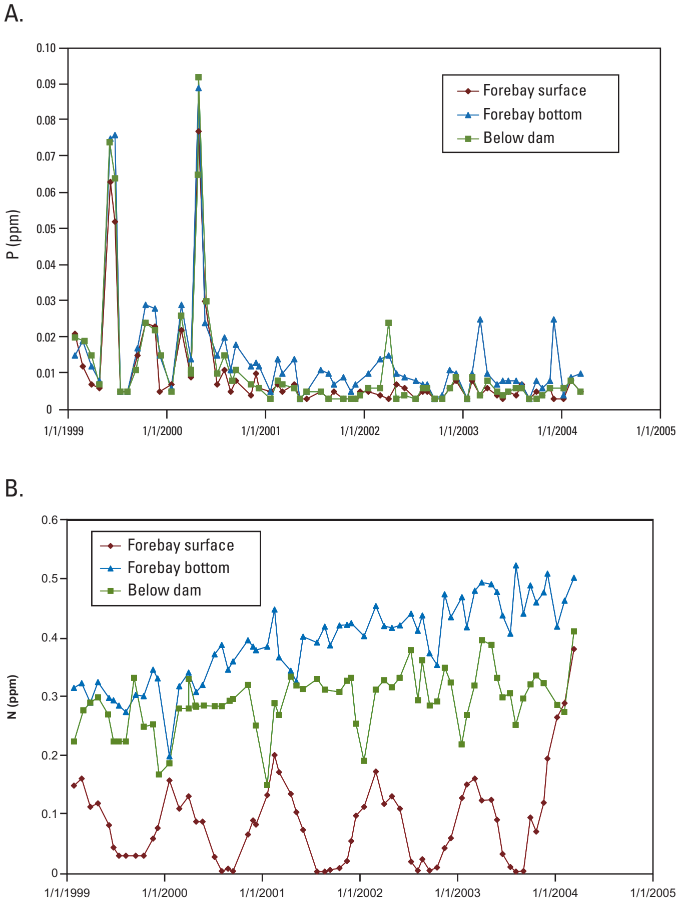

**Figure 9.** A. Total phosphorus concentrations measured (in parts per million) in the forebay of Lake Powell and Glen Canyon Dam releases, 1999–2004. B. Dissolved nitrate-nitrogen concentrations measured (in parts per million) in the forebay of Lake Powell and Glen Canyon Dam releases, 1999–2004.

The spring snowmelt runoff enters Lake Powell as an overflow density current, representing the lowest density water entering the reservoir during the year. This inflow current then travels through the reservoir slightly below the surface, eventually reaching Glen Canyon Dam by late summer or early fall. A large amount of suspended sediment, nutrients, and organic material may be associated with this inflow current. As the inflow current travels through the reservoir, the organic material undergoes bacterial decomposition, removing large amounts of oxygen from this water. This situation, combined with decomposition of plankton from the epilimnion, results in a marked reduction of dissolved oxygen in the metalimnion of the reservoir by late summer.

During periods of reservoir drawdown, as in the past several years, tributary inflows cause the resuspension of exposed deltaic sediments in the upstream portions of the reservoir. This resuspension entrains large amounts of suspended sediment and decomposing organic material in the advective inflow currents that move through the reservoir. In September 2003, the inflow plume extended downstream to Padre Bay, about 28 mi (45 km) above Glen Canyon Dam, at depths of 50–80 ft (15–25 m) (fig. 10). Dissolved oxygen concentrations at or near zero were observed throughout its extent. This plume reached Glen Canyon Dam by October and was eventually dissipated by convective mixing in the following months. The pattern was observed to a lesser extent in 2004 because runoff volumes were smaller.

The hypolimnion of Lake Powell is isolated from photosynthetic oxygenation and reaeration caused by surface mixing and acts as a sink for organic matter falling through the water column. As a result, the water at the bottom of Lake Powell is often oxygen poor throughout the year. Depending on the density of cold winter inflows relative to that of the receiving reservoir, winter inflows will either form an interflow between layers of higher and lower density or may underflow the entire reservoir, displacing hypolimnetic water upwards for withdrawal by dam releases. In the former case, the density of the hypolimnetic water is too great to allow an underflow current, and as a result, the hypolimnion remains stagnant and oxygen concentrations continue to decline. In the latter case, the hypolimnion is refreshed with oxygenated water.

There have been three distinct periods of hypolimnetic stagnation during Lake Powell's history, usually lasting several years and characterized by a buildup of relatively saline water, followed by decreasing dissolved oxygen concentrations. These periods of hypolimnetic stagnation appear to have been dissipated by a series of above-average inflows that flushed the reservoir. Above-normal inflows to Lake Powell during the mid-1990s left the reservoir fairly dilute, and distinct winter underflows have occurred since 1999 (fig. 11).

Dissolved oxygen concentrations in the tailwater are usually slightly below saturation but have not dropped to concentrations low enough to affect the aquatic ecosystem in Grand Canyon. As the reservoir ages or there are periods of extended drought, however, it is likely that the chances of water low in dissolved oxygen being released from Glen Canyon Dam will increase.

## Plankton

The epilimnion of Lake Powell is fairly warm and receives abundant sunlight for photosynthesis through much of the year. As a result, the majority of phyto-

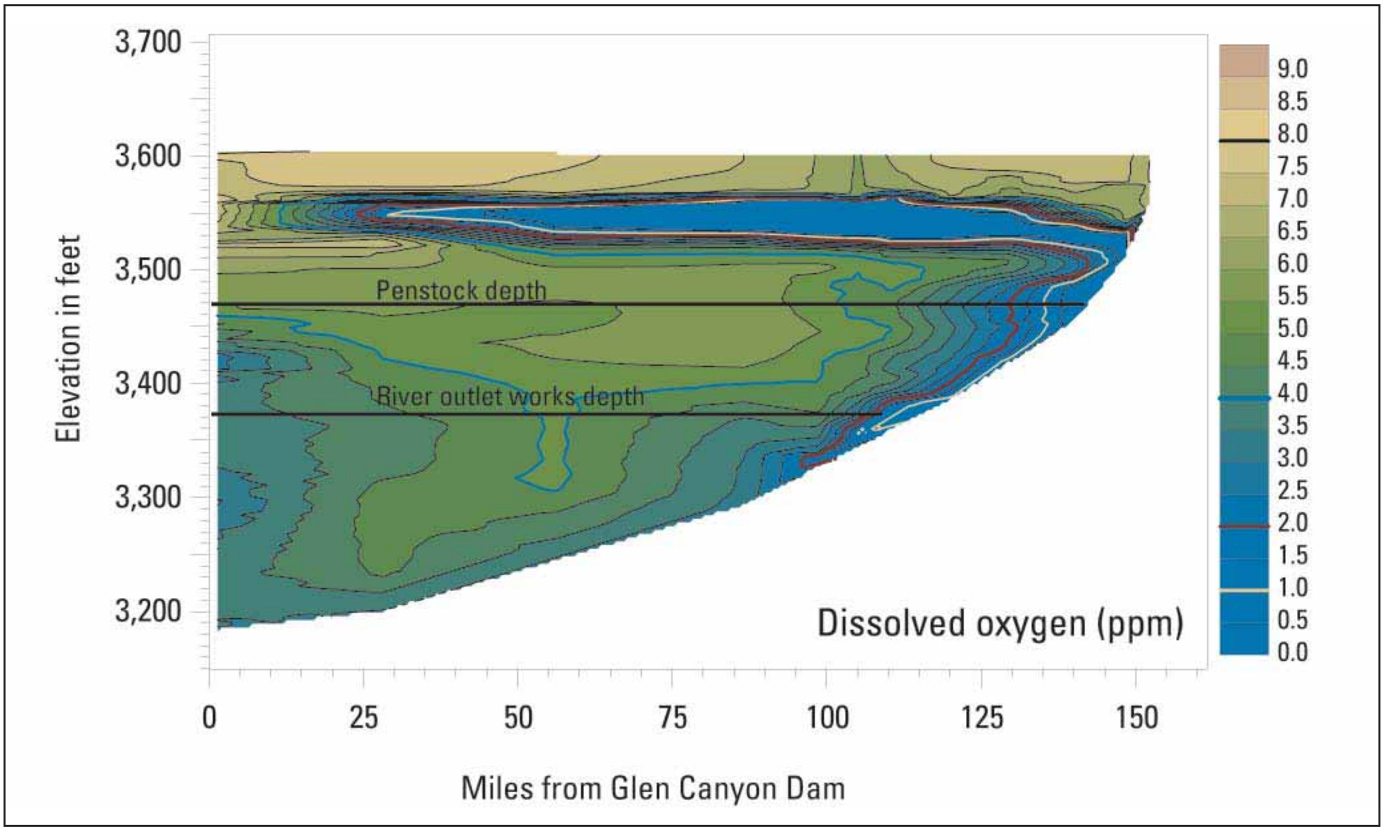

**Figure 10.** Dissolved oxygen concentrations (in parts per million) in the main channel of Lake Powell, from Glen Canyon Dam to the Colorado River inflow, September 2003.

plankton and zooplankton reside in this layer, supporting a recreational fishery in Lake Powell. Under periods of epilimnetic withdrawals—for example during winter mixing or during the recent late-summer events of 2003, 2004, and 2005, when warmer epilimnetic waters are released—plankton from the epilimnion can be released downstream, potentially providing an alternate food source for the downstream ecosystem (fig. 12). Little is known about the downstream importance of plankton and other organic matter released from Glen Canyon Dam.

# Effects of Dam Operations

Operation of Glen Canyon Dam affects the water quality of Lake Powell and downstream releases. High sustained penstock releases during 1973, through the mid-1980s, and under modified low fluctuating flow (MLFF) operations in 1997 acted to route increased volumes of water through the reservoir. The operation of different release structures can affect the downstream environment by withdrawing water of different quality than that at the penstock elevation. Since the implementation of the 1996 Record of Decision and the MLFF alternative, the river outlet works have been used during the 1996 beach/habitat-building flow (Hueftle and Stevens, 2001) and the 2004 experimental high flow. During these events, water of cooler temperature and higher salinity and nutrient content was released, and the turbulence created downstream of the dam increased oxygen concentrations.

During periods of normal operations under the MLFF, daily fluctuations in temperature, specific conductance, and dissolved oxygen can be observed in Glen Canyon Dam releases because of the effects of various discharge volumes and fluctuation patterns on the dimension of the withdrawal zone in the reservoir. Large or fluctuating releases draw water from a thicker withdrawal zone than do small or steady releases (Monismith and others, 1988; Ford, 1990; Casamitjana and others, 2003).

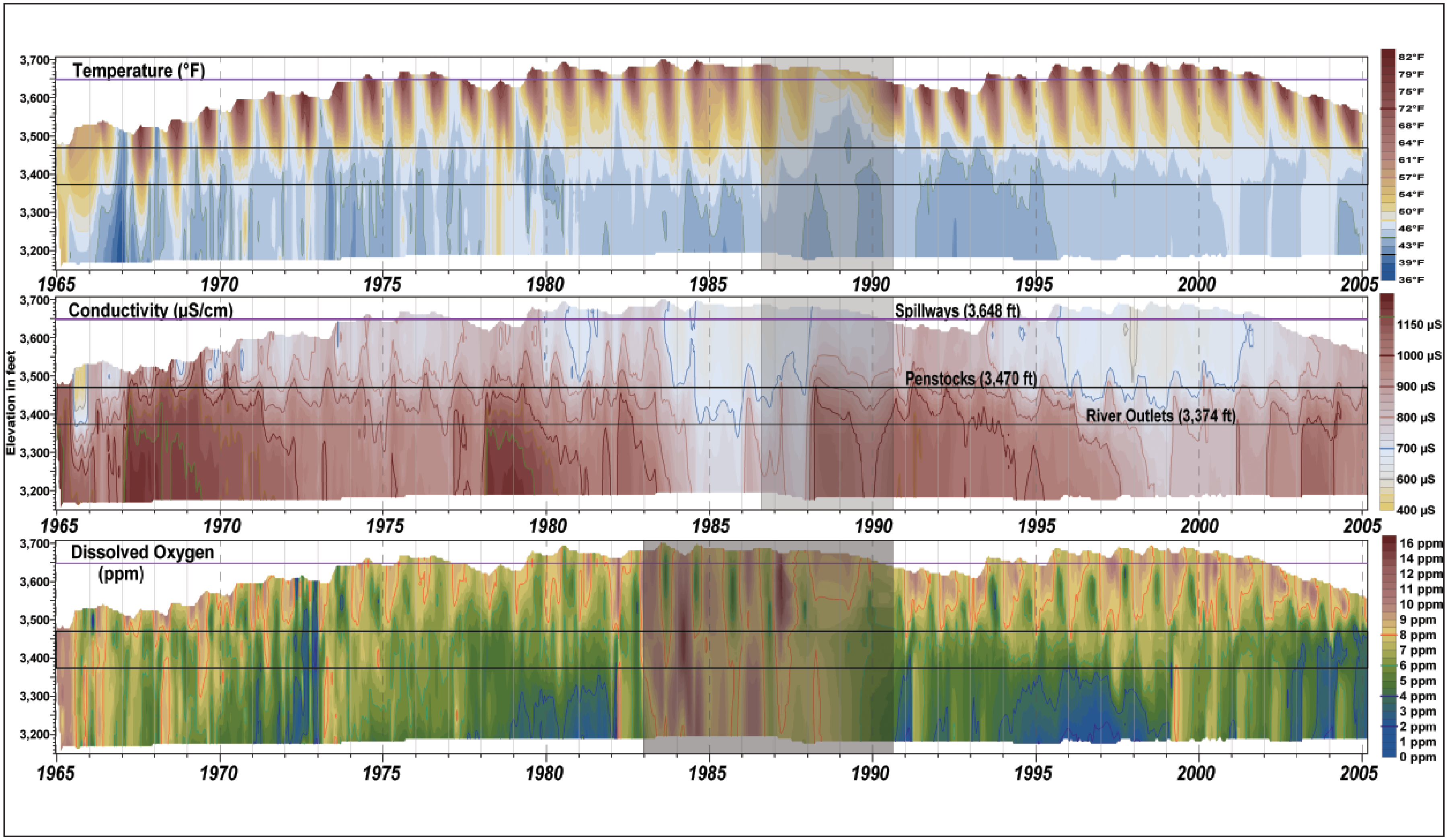

**Figure 11.** Forty-year temperature (degrees Fahrenheit), specific conductance (microsiemens per centimeter (µS/cm) at 25°C), and dissolved oxygen (parts per million) patterns in the forebay of Lake Powell, December 1964 to March 2005. Elevations of spillways, penstocks, and river outlet works are indicated by horizontal lines in each plot. Warmer colors represent higher values for each parameter. Shaded areas represent areas of low temporal resolution or poor data quality. Note three periods of hypolimnetic stagnation (red areas in conductance section), followed by periods of hypolimnetic hypoxia (blue areas in dissolved oxygen section). Dissolved oxygen section shows recent pattern of winter underflows since 1999.

In terms of downstream water quality, the magnitude of discharge and the volume of water in the river determine how much water is exposed to ambient air temperatures and solar radiation, which, in turn, determines the amount of in-stream warming in Grand Canyon. The magnitude of dam discharges also influences the amount of sediment in suspension, which can limit light availability to the downstream aquatic environment.

There are many interactions at work, and the use of a hydrodynamic water-quality model will help understand the changes in Lake Powell and their effects on downstream water quality.

## Conclusion and Recommendations

The current drought demonstrates how long-term climatic trends influence inflows to Lake Powell and affect the quality of dam releases. As the elevation of Lake Powell drops, the warmer surface water is drawn downstream through the penstocks, seasonally increasing downstream temperatures. Furthermore, salinity concentrations increase, more epilimnetic biota are exported downstream, and dissolved oxygen levels may decrease seasonally. Current dissolved-oxygen minimums are within the tolerance limits of tailwater organisms, including rainbow trout (*Oncorhynchus mykiss*). Entrainment of an oxygen-depleted inflow plume or hypolimnion, along with the aging of the reservoir, however, could affect the downstream ecosystem.

If the drought continues, these trends will be exacerbated as summer and fall releases draw increasingly from the warmer surface waters of the reservoir. Release patterns during an extended drought may replicate those of the 1960s when the reservoir began filling, including wider fluctuations in water quality that may begin to mimic predam conditions. These conditions create an opportunity to observe some of the possible effects in the Colorado River ecosystem of a temperature control device, which would route warmer surface waters through the Glen Canyon Dam powerplant.

## Future Monitoring and Modeling

Current understanding of water quality downstream of Glen Canyon Dam in Grand Canyon is limited because more extensive sampling has only recently been initiated and because there has been a lack of modeling for river-water quality. Exceptions are water temperature and sediment concentrations (see chapter 1, this report), which have been more extensively monitored and analyzed. Future water-quality programs should emphasize a model-based approach and close linkages with other sampling programs like aquatic ecology and fine-sediment monitoring.

The extensive 40-yr database available for Lake Powell presents a very clear opportunity to model the hydrodynamic properties of the reservoir under a variety

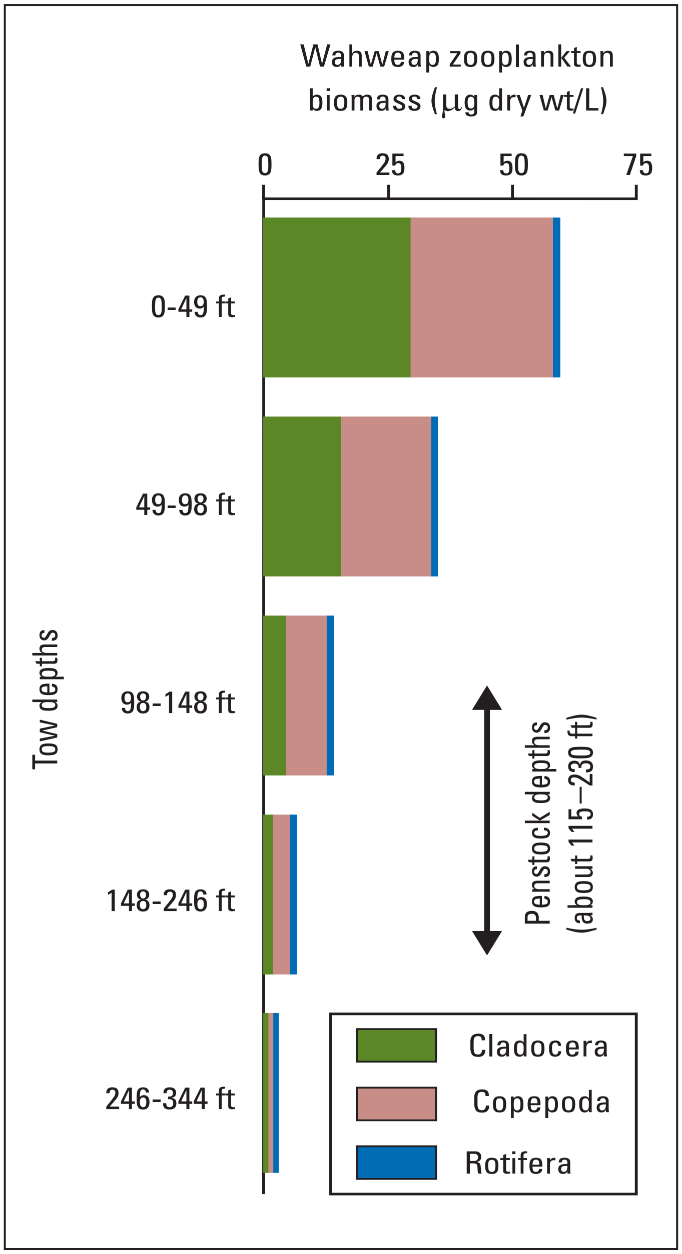

**Figure 12.** Plankton concentrations and biomass in Lake Powell forebay.

of inflow and operational conditions. Such modeling not only would increase the understanding and characterization of reservoir limnology but also would serve as an important predictive tool to anticipate what the quality of water released to the Colorado River ecosystem in Grand Canyon will be. A number of river-flow and water-quality models are available and could be used or modified to better understand and predict downstream changes in water quality and their effects on various components of the ecosystem.

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# Chapter 5

# Aquatic Ecology: the Role of Organic Matter and Invertebrates

Theodore A. Kennedy

Steven P. Gloss

## Introduction

Closure of Glen Canyon Dam and the beginning of flow regulation of the Colorado River through Grand Canyon in 1963 changed the river through the canyon considerably. The river changed from having highly variable discharge rates and temperatures and high suspended-sediment loads to having a relatively constant flow regime (Topping and others, 2003), cold and constant water temperatures, and suspended-sediment loads that are dramatically reduced relative to predam levels (see chapter 1, this report). These changes in the physical environment, coupled with changes in the quantity and types of organic matter present in the Colorado River and intentional introductions of aquatic invertebrates that occurred shortly after Glen Canyon Dam was closed (Blinn and Cole, 1991), have led to substantial changes in the kinds of aquatic invertebrates present in the Grand Canyon ecosystem. Since the closure of the dam, considerable effort has been directed toward understanding the aquatic ecology of this altered ecosystem (Blinn and Cole, 1991).

This chapter describes the results of the research and monitoring activities that have investigated the kinds of organic matter and invertebrate communities in the Colorado River below Glen Canyon Dam. Collectively, organic matter and the aquatic invertebrates that consume it largely constitute the food base for fish in the Colorado River ecosystem. This chapter focuses on patterns, trends, and important controls on the amount and sources of organic matter and invertebrates that are primary food resources for humpback chub (*Gila cypha*) and rainbow trout (*Oncorhynchus mykiss*) in an effort to understand the role that food plays in determining the distribution, population density, and growth of these fish in this ecosystem. Furthermore, most of the research and monitoring that have been conducted on organic matter and invertebrates in this ecosystem have centered on the food items that are important for these two species. This chapter also addresses how organic matter and invertebrates are affected by the timing and magnitude of water releases from Glen Canyon Dam, including the modified low fluctuating flow (MLFF) alternative, which was implemented in 1996 and continues as the operating regime for Glen Canyon Dam today. Finally, this chapter concludes with a brief discussion of recommended research directions and management actions.

## Background

Virtually all food webs, including those in rivers, are fueled by energy that comes from autotrophs (also known as primary producers), which are organisms that can convert sunlight into chemical energy. Examples of autotrophs include vascular plants and algae. Without autotrophs there would be no food energy available to other organisms that lack the capability to fix light energy. In rivers, this autotrophic material can come from two places: the terrestrial environment, such as leaves falling into a river from trees lining the river's banks, or the aquatic environment, such as algae growing on river rocks. Terrestrially derived material is an extremely abundant source of energy in many streams and rivers (Bayley, 1989; Meyer and Edwards, 1990). Although algae often represent just a small fraction of the available energy in river ecosystems, they are frequently an important energy source that contributes to secondary production (Bilby and Bisson, 1992; Lewis and others, 2001; Thorp and Delong, 2002) because they are far more nutritious than terrestrial material (Anderson and Sedell, 1979). Aquatic or terrestrial autotrophic material is also called "organic matter" and provides the energy that supports consumers at higher trophic levels. Trophic levels are groups of organisms that occupy the same position in a food web (fig. 1).

The importance of understanding patterns, trends, and controls of organic matter and invertebrates is reflected in the goals of the Glen Canyon Dam Adaptive Management Program. For example, the program's first goal is to "protect or improve the aquatic foodbase so that it will support viable populations of desired species at higher trophic levels" (Glen Canyon Dam Adaptive Management Program, 2001, p. 11). Two additional goals are to maintain populations of rainbow trout in the Lees Ferry reach and maintain, and ultimately increase, populations of native fish, particularly endangered humpback chub, in sections of the river downstream of the Lees Ferry reach. Recent trends for important fish in the Grand Canyon ecosystem may be partly due to changes in food resources or to an increase in the severity of competition between humpback chub and other fish and highlight the need for continued research on organic matter and invertebrates. The number of rainbow trout in the Lees Ferry reach has generally been high since intensive population measurements began in 1991, but the condition of fish as determined by weight relative to length declined during the late 1990s (McKinney and others, 2001). Also, the average condition (Meretsky and others, 2000) and size of humpback chub populations have declined considerably since intensive measurements began in 1986 (see chapter 2, this report).

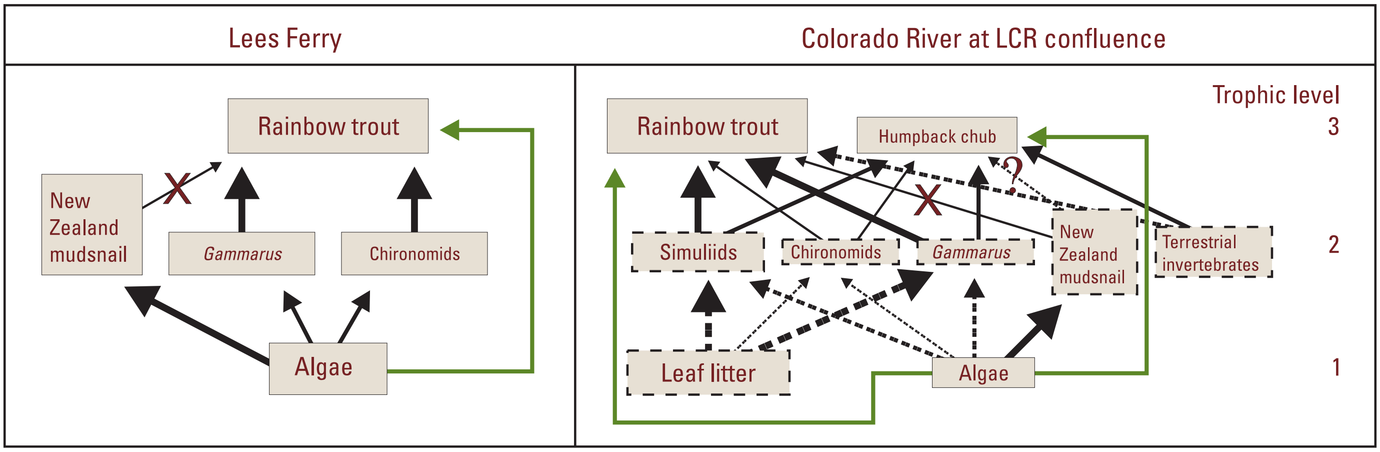

**Figure 1.** Idealized and simplified food-web diagrams for two different sections of the Colorado River ecosystem, the Lees Ferry reach and the Colorado River at the Little Colorado River (LCR) confluence. The sizes of the boxes reflect qualitative differences in the standing mass within trophic levels, and the size of the arrows reflects qualitative differences in the amount of food energy moving between trophic levels. Green arrows linking algae to fish are used to highlight the fact that fish consume algae but do not actually derive significant nutrients or energy from them. Rainbow trout also consume New Zealand mudsnails, but the snails often survive passage through the gut alive and intact, which is noted with the **X**. Humpback chub may be capable of actually digesting mudsnails because they are capable of crushing their shells; however, it is unclear whether humpback chub ingest snails. Areas of greatest uncertainty are noted with dashed lines.

Several of the hypothesized causes of humpback chub decline are, in part, based on the assumption that there is a limited amount of food available in the river to support populations of humpback chub and other fish. For example, Gloss and Coggins (see chapter 2, this report) list competition with nonnative and native fish as one of several possible reasons for the decline of the endangered humpback chub populations. Thus, documenting the food resources that humpback chub and rainbow trout are dependent on and whether these resources vary over space and time will help determine the validity of the food-limitation hypothesis. This information will also clarify the role that food availability plays in determining the population density and condition of both native and nonnative fishes and may prove useful as an indicator of ecosystem health.

**Figure 2.** A preserved *Gammarus lacustris* (also known as a scud or side-swimmer), which is consumed by humpback chub and rainbow trout. Live animals are more translucent (photograph by Michael Booth).

# Status and Trends

## Identifying the Food Items of Fish

A great deal is known about the types of food items consumed by humpback chub and rainbow trout. In general, both fish appear to consume mostly the introduced invertebrate *Gammarus lacustris* (small crustaceans, also called scuds or side-swimmers, hereafter *Gammarus*) (fig. 2), larval chironomids (midges, also called bloodworms), larval simuliids (black flies), terrestrial invertebrates, and the filamentous algae *Cladophora glomerata* (hereafter *Cladophora*) (fig. 3). The small aquatic invertebrates mentioned range from about 0.25 to 1 inch (6 to 25 mm) in length, and individual *Cladophora* filaments can attain nearly 20 ft (about 6 m) in length.

Gut pumping was used to nondestructively investigate the food items consumed by humpback chub collected from two known chub aggregations, the Little Colorado River confluence aggregation (at about RM 61) and the Middle Granite Gorge aggregation (at about RM 127) (Valdez and Ryel, 1995). *Cladophora* represented 24% of gut contents by volume for chub at the Little Colorado River confluence site, with invertebrates representing the remaining 76%. In contrast, humpback chub at the Middle Granite Gorge site consumed exclusively invertebrates. Of the invertebrates, simuliids, *Gammarus*, and terrestrial invertebrates were the most common items consumed. Valdez and Ryel (1995) also quantified the density of algae and specific invertebrates in the drift (fig. 4) and then compared chub diets with the availability of food items in the drift to determine whether chub were "selectively" feeding. These analyses indicated that chub selectively avoided consuming *Cladophora*, even though it represented 88%–93% of potential food in the drift, and chub generally consumed simuliids, chironomids, and *Gammarus* in "approximate proportion to their availability in the drift" (Valdez and Ryel, 1995, p. 9–13).

The feeding habitats of rainbow trout in the Lees Ferry reach were determined by McKinney and Speas (2001). They analyzed the stomach contents of 658 rainbow trout caught in the Lees Ferry tailwater from 1991–97 and found that *Cladophora*, *Gammarus*, and chironomids accounted for more than 90% of the stomach contents by volume. Of the invertebrates consumed by these fish, *Gammarus* and chironomids together accounted for more than 90% of the total by volume.

For a complete understanding of the energy sources that are driving a food web, it is important to know not only what the fish are consuming but also what the invertebrates themselves are consuming. To this end, the diets of some aquatic invertebrates that are commonly consumed by fish have also been investigated by using gut-content analysis and habitat-choice experiments. Pinney (1991) found that diatoms, a class (Bacillariophyceae) of microscopic algae common in aquatic environments, made up more than 93% by volume of gut contents for *Gammarus* in the Lees Ferry reach. Shannon and others (1994) used field and lab-based habitat-choice

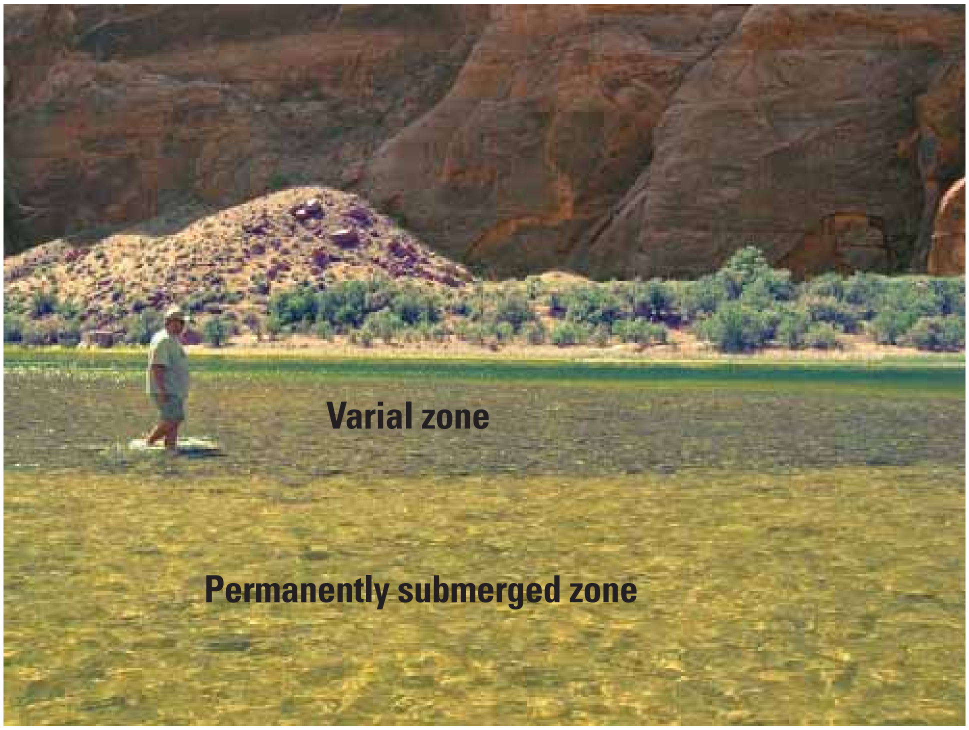

**Figure 3.** Cobble bar in Glen Canyon showing the varial zone (shoreline habitat that is both inundated and exposed to air for long periods each day) and the presence of the filamentous algae *Cladophora* in the permanently submerged zone. *Cladophora* is unable to grow in the varial zone because dam operations result in discharge rates that regularly expose the varial zone to air (photograph by Theodore Kennedy, U.S. Geological Survey).

experiments to determine that *Gammarus* preferred *Cladophora* as habitat over all other choices, including *Oscillatoria* spp. (another species of filamentous algae), gravel, and detritus. These same researchers determined that *Gammarus* were only relying on *Cladophora* as habitat and were actually eating diatoms that were attached to *Cladophora*. Stevens and others (1997) determined the diet composition of chironomids by using gut-content analysis and found that the relative importance of algae in chironomid diets declined with distance downstream from the dam: algae represented 61.4% of chironomid diets at Lees Ferry, 30.7% at RM 32, and only 7.5% at RM 224. This trend is consistent with observed downstream declines in algae biomass (discussed below) and indicates that algae may not be the most common form of organic matter consumed by invertebrates at downstream locations.

Identifying the food items consumed by fish and invertebrates by using gut-content analysis provides an indication of the food resources that are most important to fish; however, relying solely on this approach also has weaknesses. First, gut contents only reflect the items consumed by fish or invertebrates within about an hour of their capture, providing only a “snapshot” of the food items consumed. Even in this short timeframe, however, labile food items may be more readily digested than others, leaving behind the more resistant items and the appearance that these items are the most important food sources. Furthermore, if, for example, rainbow trout consume other fish very infrequently, the snapshot taken through gut-content analysis is unlikely to detect this relatively rare event. Yet these infrequent events of predation may be a significant source of calories and nutrients for the fish and may represent an important type of food that might be overlooked when using only gut-content analysis. Second, just because an item is consumed by a fish does not mean that it is actually an important source of energy or nutrients. For example, both humpback chub and rainbow trout regularly consume the filamentous algae *Cladophora*, but energetic and stable-isotope analyses (discussed below) indicate that this material is not actually assimilated because it is difficult to digest and is low in essential nutrients such as fatty acids, nitrogen, and phosphorus (Angradi, 1994; McKinney and Speas, 2001). It has been suggested that the humpback chub and rainbow trout that consume *Cladophora* may actually be after the more nutritious invertebrates that are imbedded in *Cladophora* (Valdez and Ryel, 1995). Finally, the relative contribution of terrestrial and aquatic organic matter to invertebrate growth

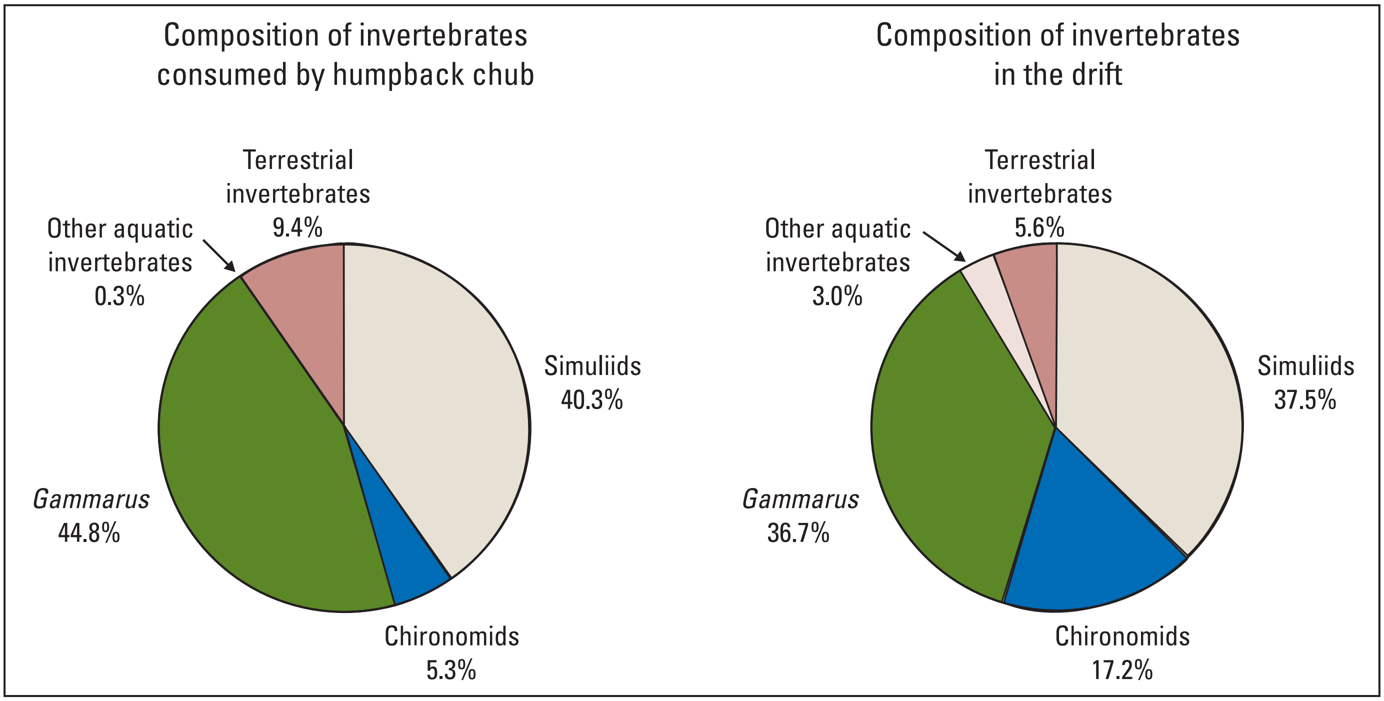

**Figure 4.** Volume of specific invertebrates in humpback chub stomachs from the Little Colorado River confluence aggregation (about RM 61) and composition of these same items in the drift. Data were collected during 1992–93 and exclude algae (*Cladophora*) that were consumed by chub. Modified from Valdez and Ryel (1995).

and production, and hence fish growth and production, is often unclear when only gut-content analysis is used.

To determine what is being consumed and actually assimilated by fish and small invertebrates and to quantify the relative importance of terrestrial and aquatic organic matter in fueling fish growth require a combination of gut-content analysis and a specialized technique known as stable-isotope analysis. Terrestrial and aquatic organic matter often has distinct stable-isotope signatures (Fry and Sherr, 1984) that are largely conserved up the food chain, and these signatures provide information about the source of energy at the base of the food web (Peterson and Fry, 1987). For example, if *Gammarus* consume exclusively algae, then they will have a carbon stable isotope signature identical to that of algae, as will a fish that consumes exclusively *Gammarus*. In contrast, nitrogen stable isotope values change predictably with each link in a food chain, increasing at a rate of 3.4 parts per thousand (‰) with each link, and therefore provide an indication of trophic position (Minagawa and Wada, 1984). Thus, herbivores typically have nitrogen stable isotope signatures that are 3.4‰ higher than plants, and primary carnivores in turn have nitrogen stable isotope signatures that are 3.4‰ higher than herbivores and 6.8‰ higher than plants. Also, stable-isotope analyses provide time-integrated measures of diet. That is, the carbon and nitrogen stable isotope signatures for a large fish will usually reflect the food it has consumed and assimilated over the past several months, which provides a contrast to the snapshot picture of diets obtained with gut-content analysis.

A combination of gut-content analysis of rainbow trout and stable-isotope analysis of the entire food web provided a clear picture of the aquatic food web in the Lees Ferry reach of the Colorado River (Angradi, 1994). Rainbow trout gut-content data collected by Angradi (1994) were remarkably similar to those reported by McKinney and Speas (2001): both studies showed *Gammarus*, chironomids, and *Cladophora* to be the dominant food items. Analysis of stable-isotope ratios showed that rainbow trout were assimilating nutrients from only the *Gammarus* and chironomids and not from the *Cladophora* they consumed (Angradi, 1994). Furthermore, *Gammarus* and chironomids were feeding almost exclusively on benthic algae, which are algae attached to the bottom of the riverbed. Thus, the entire food web of the Colorado River in the Lees Ferry reach, from aquatic invertebrates to fish, was based on algae.

Our understanding of the aquatic food web at sites downstream of Lees Ferry is much more limited.

Although gut-content analysis for humpback chub and rainbow trout collected at downstream locations indicated that both species consume mostly aquatic invertebrates and algae, the relative importance of terrestrial and aquatic energy sources remains unclear. Using stable-isotope analysis, Haden and others (1999) investigated the diet of humpback chub and other fish in the Little Colorado River, the largest tributary of the Colorado River in Grand Canyon and the single most important breeding habitat for humpback chub. They found a complex food web in the Little Colorado River with small chub, less than 6 inches (<150 mm) in length, relying heavily on invertebrates, especially chironomids, mayflies (Ephemeroptera), and caddisflies (Trichoptera), while large chub, greater than 6 inches (>150 mm) in length, were found to be relying on invertebrates and small fish. They also found evidence that terrestrial and aquatic organic matter was fueling the food web, although they were unable to determine the proportional contribution of each energy source. Angradi (1994) investigated food-web structure in tributary streams of the Colorado River and found that the food web in some tributaries was supported by leaf litter from streamside vegetation while others were supported by leaf litter from upland plants. Shannon and others (2001a) collected samples of algae, aquatic invertebrates, and eight species of fish (rainbow trout and humpback chub were collected, but the identity of the other six species was not specified) from seven sites that span the entire Grand Canyon ecosystem and found that carbon isotope values for algae increased consistently with downstream distance. Further, they found that invertebrate and fish isotope values roughly tracked the downstream shift in algae isotope values, providing evidence that algae is contributing to invertebrate and fish growth along the entire length of the Grand Canyon ecosystem.

## Spatial and Temporal Patterns in Organic Matter and Invertebrates

There are very few data on the relative abundance of terrestrial or aquatic organic matter, or the density or kinds of invertebrates present, in the Grand Canyon ecosystem before the construction of Glen Canyon Dam (Blinn and Cole, 1991). In general, aquatic invertebrate diversity (the number of different species) has declined following closure of Glen Canyon Dam, while invertebrate density and biomass have probably, perhaps even dramatically, increased (Blinn and Cole, 1991, and references therein). Comparison of invertebrate diversity in tributaries relative to the mainstem provides an indication of changes in the invertebrate fauna that have occurred following closure of Glen Canyon Dam; Hofknecht (1981) found 52 insect families in tributaries of the Grand Canyon ecosystem, compared to just 5 insect families for the mainstem Colorado River. Haden and others (2003) studied relatively pristine and free-flowing sections of the lower Green River and the Colorado River in Canyonlands National Park in Utah to determine what the food web in the predam Colorado River in Grand Canyon might have looked like. They found that terrestrial organic matter was the primary energy source for aquatic invertebrates in this free-flowing reach because high levels of suspended sediment prohibited algae growth. They also found an invertebrate community that was markedly different from that in the Grand Canyon ecosystem; the invertebrate community in the free-flowing reach was dominated by filter feeders (simuliids and caddisflies) and collectors (mayflies and chironomids), reflecting the importance of terrestrial organic matter to this system. Prior to the closure of Glen Canyon Dam, the Colorado River contained large quantities of coarse woody debris (i.e., whole trees and branches) and other terrestrial plant material that were transported from upstream sources (Valdez and Carothers, 1998). This material accumulated along river banks and in eddies and supported a high diversity and abundance of terrestrial invertebrates. When this material was entrained by the river during spring floods, the terrestrial invertebrates probably served as an important food resource for fish in the Colorado River (Valdez and Carothers, 1998).

Because Glen Canyon Dam has created clear water conditions that allow sunlight to reach the river bottom, algal standing mass is extremely high in the Lees Ferry reach of the Grand Canyon ecosystem. Much of the terrestrial organic matter that formerly moved through the Colorado River system is now trapped behind Glen Canyon Dam. Stevens and others (1997) quantified river-bottom algae and invertebrate standing mass at 11 stations between Lees Ferry and Diamond Creek on a bimonthly basis during 1991. They found that *Cladophora* was the dominant algae throughout the Lees Ferry reach, exhibiting an average of 0.5 oz carbon (C)/yd$^2$ (15.5 g C/m$^2$). Downstream of the Paria River confluence, *Cladophora* standing mass abruptly decreased to 0.01 oz C/yd$^2$ (0.5 g C/m$^2$), and it remained low at the remaining downstream sampling stations (fig. 5). *Oscillatoria* spp., mat-forming algae, tended to dominate aquatic habitats at sites downstream of Lees Ferry with average biomass of 0.02 oz C/yd$^2$ (0.6 g C/m$^2$) at the site immediately downstream of the Paria River.

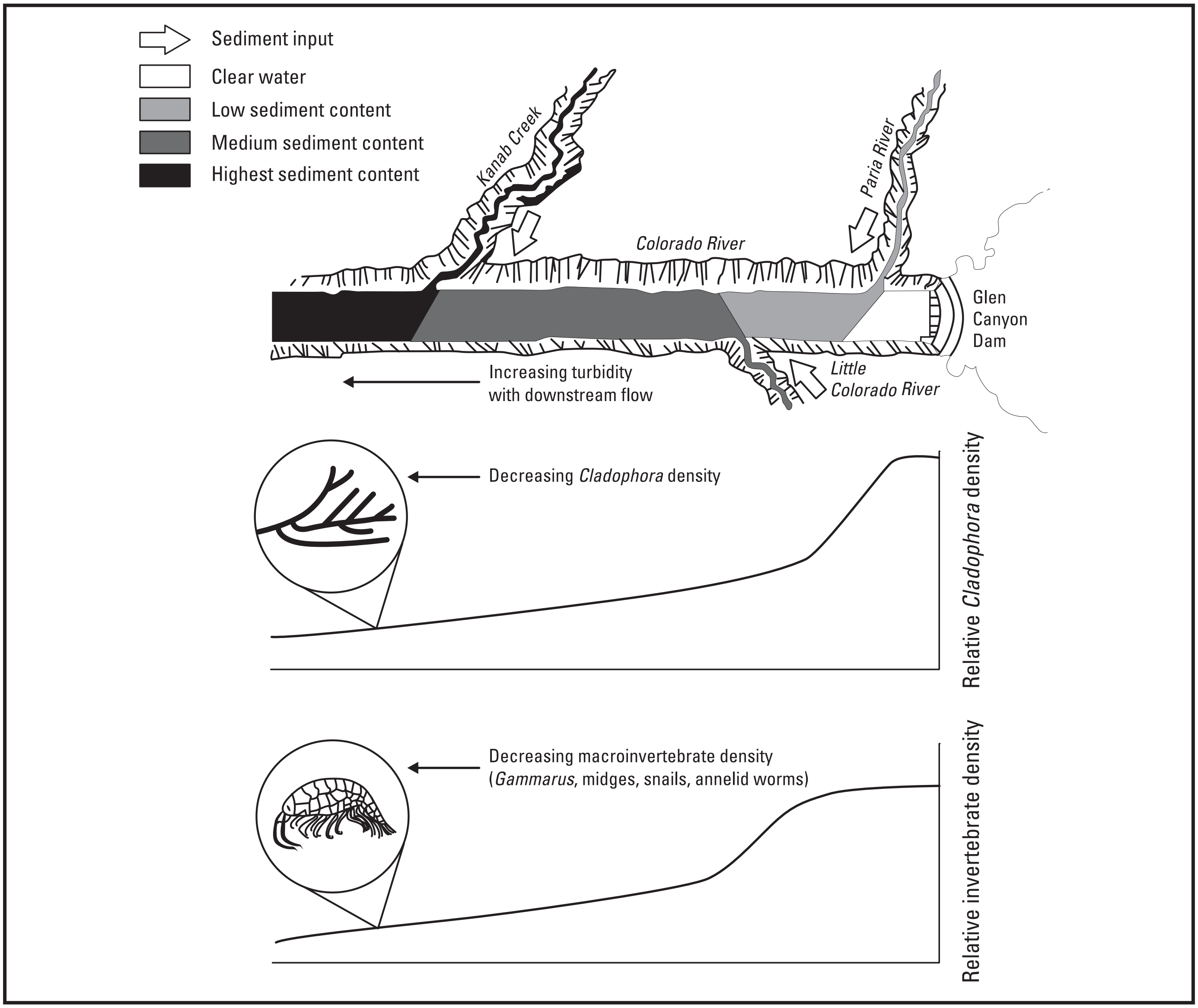

**Figure 5.** Downstream patterns of sediment concentration and biomass of *Cladophora* and macroinvertebrates along the Colorado River ecosystem. Modified from *The Colorado River Through Grand Canyon* by Steven W. Carothers and Bryan T. Brown. © 1991 The Arizona Board of Regents. Reprint by permission of the University of Arizona Press.

The species composition and biomass of aquatic invertebrates also vary with distance downstream. Stevens and others (1997) reported that *Gammarus* and chironomids were the dominant aquatic invertebrates in the Lees Ferry reach, while simuliids were the dominant invertebrates at sites downstream from the Paria River. Sublette and others (1998) identified 38 species of chironomids in the Grand Canyon ecosystem, and Stevens and others (1998) studied the factors that influence chironomid distribution in the Grand Canyon ecosystem. Stevens and others (1998) found that turbidity strongly influenced chironomid diversity, with 11 species present in the clear water of the Lees Ferry reach, 18 species present in what they termed the “variably turbid” segment of the Colorado River (Lees Ferry to Little Colorado River confluence), and 24 species in the “usually turbid” segment (Little Colorado River confluence to Diamond Creek). In contrast, the biomass of invertebrates declined downstream (Stevens and others, 1997), with mean biomass of 0.09 oz C/yd$^2$ (2.9 g C/m$^2$) in the Lees Ferry reach and much lower values, less than 0.003 oz C/yd$^2$ (<0.1 g C/m$^2$), at downstream locations.

Even though the Lees Ferry reach accounted for only 6.9% of the aquatic habitat in the 242 mi (390 km) of river studied by Stevens and others (1997), it supported 63.5% of the primary producer biomass and

87% of the invertebrate biomass in the entire study area. Stevens and others (1997) attributed the downstream decline in *Cladophora* biomass, and hence the invertebrates which are dependent on *Cladophora* and its attached diatoms (i.e., especially *Gammarus* and chironomids), to episodic inputs of suspended sediments from tributaries such as the Paria and the Little Colorado Rivers that reduce water clarity and light penetration enough to limit algal production (fig. 5).

In contrast to the patterns described above, river-bottom detritus (nonliving organic matter), which can be derived from both terrestrial and aquatic sources, peaked at approximately RM 124. This peak could have occurred here because detritus is transported from upstream locations and accumulates in this region of the river. Detritus is an important component of the aquatic food web because fish at downstream locations regularly consume simuliids that feed on detritus via filter feeding. In general, the overall quantity of drifting organic matter increases and the composition changes from predominantly aquatic to terrestrial material with distance downstream (Shannon and others, 1996; Benenati and others, 2001). Shannon and others (1996) noted that tributary inputs of organic matter constituted less than 0.1% of the total organic drift of the Colorado River. We suspect, however, that 0.1% is a gross underestimate of tributary organic inputs because it does not appear that sampling of tributary organic inputs was carried out during periods of flooding. Determining whether tributary inputs of organic matter and energy are important to the food web within the Colorado River will be a major focus of future aquatic ecology efforts, as outlined in the Discussion and Future Research Needs section of this chapter.

The density of many important components of the aquatic food web appears to vary with season. The densities of *Cladophora*, the dominant algae in the Lees Ferry reach, and *Oscillatoria*, the dominant algae at downstream locations, vary over time with peak density occurring during summer (Stevens and others, 1997). The highest density of aquatic invertebrates also occurred during the summer (Stevens and others, 1997). In contrast, the concentration of river-bottom detritus was greatest during autumn (Stevens and others, 1997), perhaps because this is when trees adjacent to the river were dropping their leaves or because lower river flows during this time of year allowed the material to settle out of the water column and accumulate on the river bottom.

It should be noted that because of logistical challenges, samples from only about 10 locations along the entire 241 mi (386 km) of the Grand Canyon ecosystem have been used to characterize spatial and temporal variability of organic matter and invertebrates. Further, much of the sampling (e.g., Shannon and others, 1994, 2001b; Blinn and others, 1995, 1998; Stevens and others, 1997; Benenati and others, 1998; McKinney and others, 1999) focused heavily on quantifying organic matter and invertebrate dynamics at cobble bar habitats; yet, cobble bars make up less than 10% of the aquatic habitat downstream from Glen Canyon Dam (Mietz, 2003). Thus, these results may not accurately characterize spatial and temporal variability of organic matter and invertebrates within the Grand Canyon ecosystem.

Mathematical modeling is a powerful tool that can be used to predict or estimate variables of interest (e.g., algae productivity) across large areas, such as the Grand Canyon ecosystem, where logistics prevent intensive field sampling. Yard and others (2005) measured and modeled the influence of canyon orientation and topographic complexity on solar inputs to the Grand Canyon ecosystem. Light is the resource that most often limits the growth of algae and plants in aquatic environments (Wetzel, 2001), so these results provide an indication of potential algae growth across the entire Grand Canyon ecosystem. One of the most striking results of these modeling efforts is that river reaches that are oriented east-west receive far less solar radiation during the winter months relative to north-south reaches because the sun is lower on the horizon at this time of year. That is, the river has a clear view of the sun as it traces a path across the horizon during the winter months along north-south reaches, but the sun never gets high enough on the horizon to shine on the river along east-west reaches. Thus, Yard and others (2005) forecast that algae production should vary predictably with canyon orientation and season because of differences in solar radiation and because of the general downstream decline in algae production that is associated with tributary sediment inputs that reduce water clarity and light penetration.

## The Influence of Dam Releases on Organic Matter and Invertebrates

Understanding how Glen Canyon Dam discharge regimes influence *Cladophora* and associated invertebrates has been a major focus of recent research efforts (Angradi, 1994; Shannon and others, 1994, 1996, 2001b; Valdez and Ryel, 1995; McKinney and Speas, 2001). With discharge from Glen Canyon Dam fluctuating as much as 8,000 cubic feet per second (cfs) daily, there exists a large varial zone of shoreline habitat that is both inundated and exposed to air for long periods each day (fig. 3). Several studies have determined that the varial zone supports a relatively low density of algae, which is often dominated by *Oscillatoria* spp. because *Cladophora* and associated invertebrates cannot thrive in the varial zone (Blinn and others, 1995; Shaver and others, 1997; Benenati and others, 1998). Specifically, Blinn and others (1995) found fourfold higher invertebrate mass in permanently submerged zones compared to the varial zone. Using a series of in situ experiments, they determined that snails readily recolonized cobbles that were resubmerged after initially being subjected to long-term desiccation; however, the density of *Cladophora*, *Gammarus*, and chironomids on resubmerged cobbles was still less than 30% of control sites after 4 mo.

Fluctuations in river flows also have an impact on drifting organic matter because periodic desiccation can weaken algae and invertebrates, making them more susceptible to fragmentation and entrainment by the river. Moreover, higher river flows lead to more turbulent and faster water that is more likely to entrain organic matter and invertebrates. Shannon and others (1996) found that the quantity of drifting organic matter increased with discharge.

Historical data are insufficient to quantitatively determine what impact the MLFF alternative has had on organic matter and invertebrates; however, it is possible to qualitatively describe the likely impacts of this flow regime based on the research described above. By restricting daily fluctuations in discharge to less than 8,000 cfs and limiting minimum discharge to 5,000 cfs, MLFF flows have reduced the size of the varial zone and increased the amount of river bottom that is permanently submerged. Both of these changes probably increased the productivity and standing mass of important components of the aquatic food web, including *Cladophora* and *Gammarus*; however, abrupt changes in monthly release volumes that are permitted under the Record of Decision and MLFF may be detrimental to algae and aquatic invertebrates. For example, when monthly release volumes are decreased, the amount of river-bottom habitat that is permanently submerged also decreases. It seems likely that there is a subsequent, abrupt decrease in the quantity of food available for fish in the Grand Canyon ecosystem. Further, when monthly release volumes are abruptly increased, algae and invertebrates that were in shallow, nearshore habitats may find themselves under several yards of water. While this increase in monthly volume may eventually lead to an increase in the quantity of food available (by increasing available habitat), it seems likely that there is a short-term decrease in food as algae and invertebrates adjust to the new conditions.

Experimental high flows, or controlled floods, have been used principally as a tool to restore sandbars in the Grand Canyon ecosystem, but these floods also impact organic matter and invertebrates. Blinn and others (1999) found that the 1996 beach/habitat-building flow scoured more than 90% of the primary producer biomass (i.e., algae and submerged aquatic plants) and about 50% of the river-bottom invertebrates from a site at Lees Ferry; primary producers (1 mo) and invertebrates (2 mo) quickly recovered to preflood levels. In contrast, McKinney and others (1999) found that the 1996 beach/habitat-building flow caused short-term reductions in the standing mass of primary producers and invertebrates only in depositional habitats (i.e., areas of sand/silt) and not in more resistant habitats like cobble bars (fig. 6). Brock and others (1999) found that the 1996 beach/habitat-building flow actually led to significant increases in algae production rates (the rate at which photosynthesis is occurring within the algae); they hypothesized that algae production increased because the flood removed senescent, or old, material and detritus from the algae. Marzolf and others (1999) measured oxygen production, a byproduct of photosynthesis, along several river segments within the Lees Ferry reach and found that those segments produced less oxygen after the flood relative to preflood values. These data suggest that the 1996 beach/habitat-building flow did in fact scour large quantities of algae and aquatic macrophytes from the Lees Ferry reach, resulting in a systemwide reduction in primary production. Even though the flood may have reduced the standing mass of invertebrates from some areas in the Lees Ferry reach, the quantity of food items in rainbow trout stomachs was actually greater immediately after the flood relative to before the flood (McKinney and others, 1999). Blinn and others (1999) used stable-isotope analyses to determine that riparian vegetation and upland vegetation were the dominant types of drifting organic matter during the flood, while river-bottom algae were the dominant drifting organic matter during normal dam operations. Thus, experimental high flows can scour benthic algae and invertebrates and capture large quantities of terrestrial organic matter, which may temporarily increase the amount of food available for fish.

# Recent Findings

## New Zealand Mudsnail Invasion

Biological invasions represent a significant threat to the persistence of resident species because invaders are capable of altering food-web structure, rates of disease

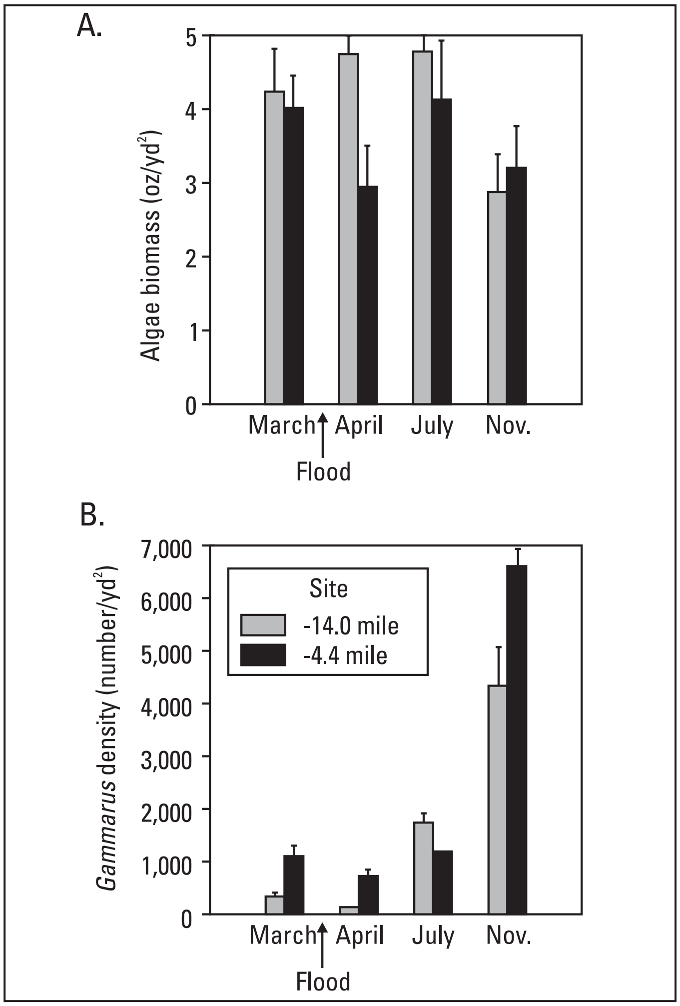

**Figure 6.** Algae (A) and invertebrate (B) response to the 1996 beach/habitat-building flow. The flood occurred between the March and April sampling dates. Bars represent average standing mass (algae) or density (*Gammarus*) at cobble bars in the Lees Ferry reach, while the thin lines on top of each bar represent 1 standard error (an indication of the uncertainty associated with each estimate). Data from McKinney and others (1999), table 1, p. 251.

or parasitism, and the amount or type of energy at the base of a food web (Vitousek, 1990; Wilcove and others, 1998; Kennedy and Hobbie, 2004). Although the food web in the Colorado River below Glen Canyon Dam has already been dramatically changed because of the installation of the dam and intentional introductions of nonnative sport fish, it is still susceptible to the impacts of biological invasions.

The New Zealand mudsnail (*Potamopyrgus antipodarum*), a species that is rapidly spreading throughout North American rivers and lakes (Hall and others, 2003, and references therein), has recently invaded the Grand Canyon ecosystem. The presence of the mudsnail in Grand Canyon was first identified from samples collected in March 2002; however, the analysis of archived collections revealed that mudsnails were actually present as early as May 1995 (Benenati and others, 2002). Presently, this small snail (fig. 7), which measures approximately 0.2 inch (about 5 mm), occurs in high densities throughout the Grand Canyon ecosystem, particularly in the Lees Ferry reach where densities of more than 32,800/yd$^2$ (40,000 snails/m$^2$) have been found (Benenati and others, 2002). Before the New Zealand mudsnail invasion, snails represented a minor component of total invertebrate mass in the Lees Ferry reach (less than 6% of the total in 1992). Snails are now the dominant category of invertebrate in the Lees Ferry reach, representing more than 66% of invertebrate mass in 2001 (Benenati and others, 2002).

The potential impacts of the New Zealand mudsnail invasion on the aquatic food web of the Grand Canyon ecosystem are significant because nonnative rainbow trout apparently cannot easily digest the snails (fig. 1); snails eaten by trout often survive intact after passage through the gut (Mike Yard, oral commun., 2004), perhaps because of the snails' protective operculum. Humpback chub have pharyngeal gills that are capable of crushing snail shells and therefore might be able to more completely digest them; however, the only detailed diet analysis for chub was conducted before the mudsnail invasion of the Colorado River ecosystem. Because

**Figure 7.** New Zealand mudsnails on a concrete anchor in Glen Canyon. The density of snails shown here is typical for the Glen Canyon ecosystem (photograph by Michael Booth).

rainbow trout cannot easily digest the mudsnail, the mudsnail may have a competitive advantage over other herbivores such as *Gammarus*, potentially allowing it to displace these other organisms as it continues to spread. If the density of *Gammarus* and other invertebrates that are regularly consumed by fish declines because of competition with the New Zealand mudsnail, it seems likely that these changes will affect fish density and condition. Even if mudsnails do not compete with or displace herbivores such as *Gammarus*, which seems unlikely given their extremely high density, they dramatically alter important ecosystem functions, including rates of nutrient cycling and primary production (Hall and others, 2003). Unfortunately, historical data are inadequate to determine whether the density or biomass of *Gammarus* and other invertebrates that are important food items for fish in the Colorado River ecosystem has been affected by the New Zealand mudsnail invasion.

## Discussion and Future Research Needs

With recent declines in the size of native fish populations and the condition of rainbow trout (see chapter 2, this report), understanding what food resources drive fish growth and production, as well as what sources of energy drive production of these food resources, becomes increasingly important. Previous research on the aquatic food web has produced a relatively clear picture of the food habits of fish in the Grand Canyon ecosystem. Aquatic invertebrates—particularly *Gammarus*, simuliids, and chironomids—appear to be the most important food items for both rainbow trout and humpback chub. In the upper reaches of the Colorado River near Lees Ferry, it appears that invertebrates, and therefore the fish that consume them, are fueled almost exclusively by algae, particularly diatoms attached to *Cladophora*. Although there is evidence that the invertebrates consumed by fish at downstream locations are relying on both aquatic and terrestrial organic matter, the relative importance and sources of this material remain unclear. This uncertainty prevents a complete understanding of the role that food availability plays in determining the condition and population size of native and nonnative fish.

Food-web analysis provides a framework for quantifying the movement of terrestrial and aquatic material into higher trophic levels, the trophic positions of consumers, and the importance of interactions such as competition and predation. Applied research efforts have repeatedly benefited from studying an ecosystem from a food-web perspective (Winemiller and Polis, 1996). Fisheries management, in particular, can benefit from a food-web perspective because it is critical for accurately predicting the responses of both predators and prey to management actions (Parsons, 1992). Although many food-web studies of terrestrial and aquatic systems have focused on trophic pathways based exclusively on aquatic production, it is increasingly recognized that leaf litter and other types of terrestrial organic matter play a major role in determining ecosystem structure and function (Winemiller and Polis, 1996).

In the case of the Grand Canyon ecosystem, previous research efforts on the aquatic food web have focused almost exclusively on trophic pathways associated with aquatic organic matter, namely the filamentous algae *Cladophora*, the diatoms attached to this algae, and the invertebrate consumers of these attached diatoms (Usher and Blinn, 1990; Hardwick and others, 1992; Shannon and others, 1994). Focusing on these aquatic sources of organic matter seems appropriate for the tailwater section of the Colorado River, that is, from the dam to Lees Ferry. Yet, the tailwater is not representative of downstream portions of the river and accounts for less than 7% of the total wetted area of the Grand Canyon ecosystem. A thorough analysis of the trophic significance of terrestrially derived material has never been conducted, although there are some correlative data that support the contention that the downstream decline in algae production limits secondary production at downstream sites (Shaver and others, 1997; Stevens and others, 1997). Importantly, the one detailed food-web analysis that has been conducted in the Grand Canyon ecosystem indicates that terrestrially derived carbon is contributing to invertebrate and fish production at downstream tributaries (Angradi, 1994).

Given these considerations, it seems clear that future research and monitoring efforts should take a broader view of the food web and attempt to document the relative importance of aquatic and terrestrial organic matter to invertebrate and fish production. For example, if invertebrates, and by extension humpback chub and rainbow trout, are dependent on algae throughout the ecosystem, a systemwide reduction in algae production would likely have strong negative consequences for fish, especially because algae biomass is already very limited at downstream sites. Alternatively, if terrestrial organic matter is fueling production of invertebrates at downstream sites, then findings from the proposed food-web research would provide managers with some of the information necessary to assess the effects of proposed management actions, including sediment augmentation and thermal modifications, on fish production.

Food-web analysis should continue to focus on the two most ecologically and economically important fish species, humpback chub and rainbow trout, and use a combination of gut-content and stable-isotope analysis. To determine whether the resource base of the food web shifts downstream and is affected by tributary inputs of organic matter, a food-web analysis should encompass the entire study area including the major tributaries of the Colorado River, including the Paria and Little Colorado Rivers. Shannon and others (2001a) found downstream shifts in the isotopic composition of algae, invertebrates, and fish. This downstream shift may complicate interpretation of stable-isotope data, but another technique for determining trophic linkages, known as quantitative fatty acid analysis (Iverson and others, 2004), may allow investigators to resolve any uncertainties associated with stable-isotope analysis. Manipulative experiments involving New Zealand mudsnails also represent an important research direction because these experiments could help scientists determine whether or not this invasive species is having a negative impact on important food items for fish and identify the factors that control New Zealand mudsnail density. Collectively, these activities will determine the short- and long-term feeding habits of humpback chub and rainbow trout, the energy resources at the base of the food web, whether humpback chub are consuming and digesting New Zealand mudsnails, and the impact of the mudsnail invasion on the aquatic food web.

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Jeff Sorensen, Arizona Game and Fish Department

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# Chapter 6

# Riparian Vegetation and Associated Wildlife

Barbara E. Ralston

## Introduction

In the Western United States, riparian areas are conspicuous as narrow belts of dense, green vegetation along streams and rivers. Fluvial marshes—areas of wetland characterized by emergent herbaceous plants like sedges (*Carex* sp.), grasses (Poaceae family), and cattails (*Typha* sp.)—can be part of the riparian areas that are associated with erosion and sediment deposition patterns of the adjoining stream or river. The riparian and wetland plant community is dependent on surface water and groundwater flows (Busch and Smith, 1995; Stromberg and others, 1996; Stromberg, 2001) and is transitional between aquatic and upland systems. In Grand Canyon, the upland system is characterized by limited moisture and includes Great Basin desertscrub, Mohave desertscrub, and Sonoran desertscrub plant constituents (classifications per Brown, 1982), such as mormon tea (*Ephedra nevadensis*), sagebrush (*Artemisia* spp.), white brittle bush (*Encelia farinosa*), and barrel cactus (*Ferocactus cylindraceus*). The dry uplands are a stark contrast to the lush plant community along the Colorado River in Grand Canyon (figs. 1a–d).

Riparian areas are a junction between aquatic and terrestrial habitat types. In the West, they tend to exhibit higher levels of species diversity, richness, and population densities than either adjacent habitat. Because of these characteristics, riparian areas are of high value to managers, scientists, and the public, particularly to Native American communities (see chapter 11, this report). The importance of riparian areas in the maintenance of biodiversity is well documented (Nilsson and others, 1989; Naiman, 1992; Nilsson, 1992; Decamps, 1993; Lock and Naiman, 1998; Saab, 1999; National Research Council, 2002). Riparian areas are especially important in the Southwestern United States, where more than 50% of 166 species of breeding birds in the lowlands are completely dependent on water-related habitat (Johnson and others, 1977; Farley and others, 1994). Riparian areas also buffer the movement of materials, such as nitrogen and carbon, between aquatic and terrestrial environments and help retain nutrients along the river or stream channel (Schlosser and Karr, 1981; Jacobs and Gilliam, 1985; Naiman and Decamps, 1990). Vegetation along a water course also provides cover and food such as insects and seeds for animal life. In Grand Canyon, whitewater recreationists and hikers also use the shade of riparian shrubs and trees in the hot summer months. Understand-

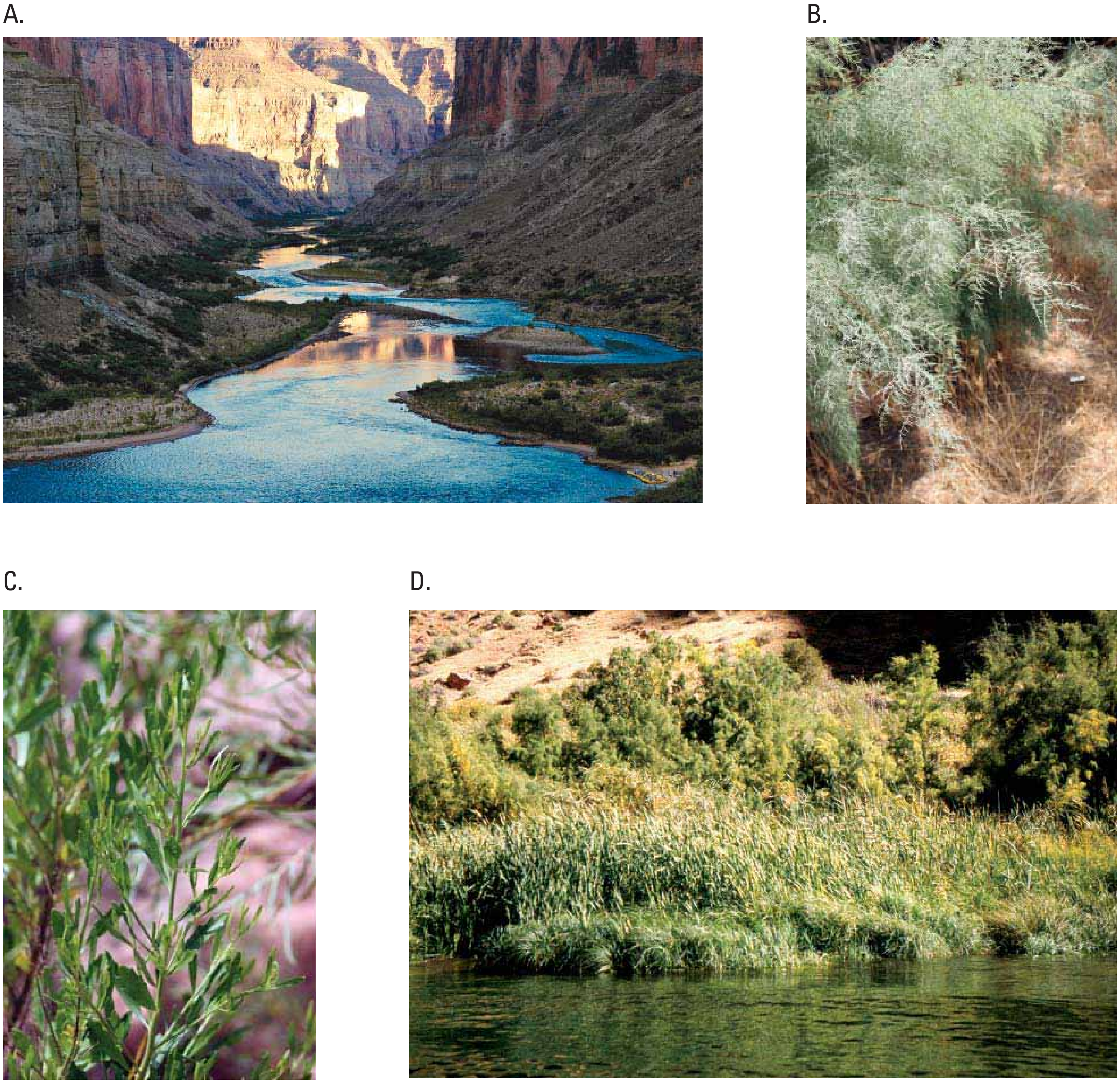


**Figure 1.** A. Riparian zone along the Colorado River in Grand Canyon. The predam high-water zone is noticeable as a line of vegetation well above the shoreline. Postdam riparian vegetation has progressed downslope and become thicker (photograph © 2005 Geoff Gourley; used with permission). B. Tamarisk (*Tamarix ramosissima*), which is one of the species that was found along the predam high-water zone. Tamarisk was introduced to the Colorado River Basin in the 1880s and was present in Grand Canyon in 1938 (photograph by Jeff Sorensen, Arizona Game and Fish Department). C. Seep willow (*Baccharis* sp.), a new high-water zone constituent. This species was also present before the dam, but in lower densities (photograph by Jeff Sorensen, Arizona Game and Fish Department). D. Examples of fluvial marsh and postdam species. The foreground is composed of common reed (*Phragmites australis*) and water sedge (*Carex aquatilis*), but the background shows tamarisk and arrowweed (*Pluchea sericea*) (photograph by Jeff Sorensen, Arizona Game and Fish Department).

ing how this community has changed over time is key to developing appropriate management strategies for this important resource.

This chapter describes changes in the riparian and fluvial marsh communities along the Colorado River in Grand Canyon from the closure of the Glen Canyon Dam and the beginning of the regulation of the river in 1963 to the present. To provide a better understanding of how dam operations have affected riparian vegetation, we examine changes in Grand Canyon riparian vegetation during three periods of time (1963–80; 1981–91; 1991–present) that correspond to major operational changes at Glen Canyon Dam. The effects on riparian vegetation of both the modified low fluctuating flow (MLFF) alternative, which was implemented beginning in 1996, and the recent drought are discussed. The chapter concludes with a summary of the findings with respect to riparian vegetation as habitat and its relationship to other resources and with a discussion of monitoring priorities within the context of the Glen Canyon Dam Adaptive Management Program.

# Background

## Predam Vegetation

Much of what is known about predam vegetation comes from the 1938 investigation of the Colorado River corridor by Clover and Jotter (1944). Predam vegetation in the high-elevation benches (fig. 2), the areas well above the river that are less frequently scoured by floods, was dominated by mesquite (*Prosopis glandulosa*), catclaw acacia (*Acacia greggii*), Apache plume (*Fallugia paradoxa*), and tamarisk (*Tamarix ramosissima*). Tamarisk was introduced to the Colorado River Basin in the 1800s and was present in Grand Canyon in 1938 (Clover and Jotter, 1944). These same investigators noted the presence of coyote willow (*Salix exigua*), rabbitbrush (*Chrysothamnus nauseosus*), four-wing salt bush (*Atriplex canescens*), and Goodding's willow (*Salix gooddingii*) along or close to the shoreline (moist sand) at Lees Ferry. On higher benches, they found arrowweed (*Pluchea sericea*) and four-wing salt bush. Mormon tea and rabbitbrush were found in the talus above the flood plain. The presence of plant cover from the river up to the talus at Lees Ferry (RM 0) in 1938 illustrated the degree of community development. Greater vegetation cover may have occurred previously because the 1930s was the period of the lowest discharges in the record (Topping and others, 2003).

Elsewhere in the river corridor, Clover and Jotter (1944) documented patchy riparian development, including the absence of vegetation in the moist sand zone at President Harding Rapids (approximately RM 43.8) (Stevens, 1990) associated with a recent sand deposit. They also noted the existence of marsh emergent species, including cattails and rushes (Juncaceae family).

The predam riparian zone of Grand Canyon was periodically disturbed with floods of variable frequency and magnitude that redistributed sediment of varying grain size and influenced what plants colonized the bare area. Plants like acacia and mesquite located in the high-water zone were disturbed less frequently than were herbaceous and marsh plants located near the lower benches. The riparian assemblage likely represented different stages of maturity and succession as it progressed either landward or downstream from a tributary source of disturbance. At the higher benches, the vegetation would be the most mature and stable, while at the shoreline, the vegetation would be composed of more flood-tolerant pioneering species. Areas from the channel upslope to the former high-water zone (also known as the old high-water zone) were composed of a mix of perennial and annual plants that corresponded with tolerances to moisture and disturbance. (Hereafter, refer to fig. 2 for references that relate discharge to riparian elevations.)

## Variables Affecting Vegetation Change

The abundance, distribution, and composition of riparian and fluvial marsh vegetation along the river corridor in Grand Canyon are influenced by many variables including yearly discharge, soils, sedimentation, time since disturbance, and temperature (Turner and Karpiscak, 1980; Baker, 1989; Stromberg and Patten, 1991; Busch and Smith, 1995; Stevens and others, 1995; Stromberg, 2001). A conceptual model illustrates some of the linkages between physical processes and riparian habitat (fig. 3); however, the model shown in figure 3 is not comprehensive with respect to all variables that affect riparian habitat.

Following closure of Glen Canyon Dam in 1963, changes in the hydrologic and sediment regime occurred that affected vegetation in Grand Canyon. The operations reduced annual peak discharge and duration and increased the yearly base flow (Topping and others, 2003). The yearly hydrograph was replaced by monthly volume releases that followed energy demands (high releases in December–February and in July–September) rather than seasonal patterns (high flows occurring

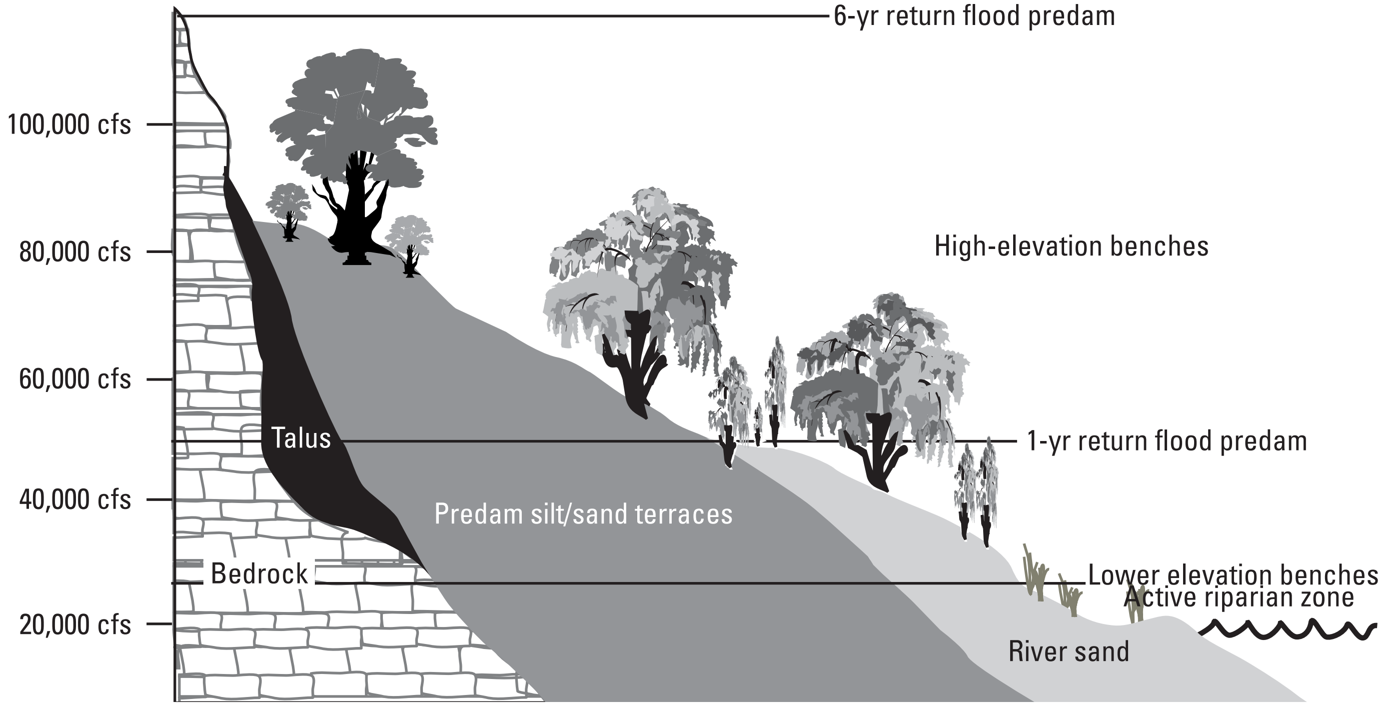


**Figure 2.** Habitat zones according to inundation frequency and flow magnitude (cubic feet per second). Regulation of the Colorado River by Glen Canyon Dam has resulted in reduced flood frequencies and magnitudes. In the postdam setting, the area below 50,000-cfs water-surface elevation is the active riparian zone. (In the postdam period, the active riparian zone remained at 50,000-cfs water-surface elevation during the 1980s, dropping to 45,000 cfs after 1991, when new restrictions constrained dam operations to minimize resource impacts.) Above the active riparian zone are the higher elevation benches, areas well above the river that are less frequently scoured by floods and were subjected to a predam 6-yr return flood frequency. Within the active riparian zone are bands of vegetation that follow a moisture gradient from water-tolerant plants located near shoreline to species that tolerate drier upslope conditions. Figure modified from Carothers and Aitchison (1976) with data from Topping and others (2003).

in June and July). Postdam median daily discharge increased to 12,600 cubic feet per second (cfs), which was 58% greater than the predam volumes of 7,980 cfs (Topping and others, 2003). Larger average discharges increased sediment-export rates (Topping and others, 2000) and reduced sand storage along channel margins and reattachment bars associated with debris fan-eddy complexes (Schmidt and Rubin, 1995). Both channel margins and reattachment bars are substrates for plant colonization. Higher sediment-export rates were most noticeable in Marble Canyon (Topping and others, 2000). Also, the dam reduced the amount of upstream sediment coming into the river by 99.9% (Topping and others, 2000); tributaries below the dam, including the Paria and Little Colorado Rivers, now provide the bulk of sand and smaller sediment fractions (see chapter 1, this report).

Disturbance frequency along a river or stream is one of several variables that affect riparian community development (Stromberg and Patten, 1991; Bendix, 1994; Toner and Keddy, 1997). Scour and sediment reworking within depositional environments like debris fans, channel margins, and return channels (Schmidt, 1990; Schmidt and Rubin, 1995) provided sites for colonization by marsh and riparian plant species (Clover and Jotter, 1944; Turner and Karpiscak, 1980; Gecy and Wilson, 1990; Decamps, 1993). The pioneer assemblage may be from an introduced seed source or from vegetative regrowth following scour (Gecy and Wilson, 1990). Before regulation of the Colorado River through Glen and Grand Canyons, large portions of the river's flood plain were periodically scoured. Predam 1-yr return flood discharge reached approximately 50,000 cfs, with larger discharges of 120,000 cfs occurring every 6 yr on average (fig. 2) (Topping and others, 2003). Yearly flooding reduced vegetation below the 50,000-cfs water-surface elevation, while larger, less frequent floods affected vegetation communities on higher benches. Lower peak flows caused by Glen Canyon Dam allowed species, including nonnative plants, to occupy lower flood-plain

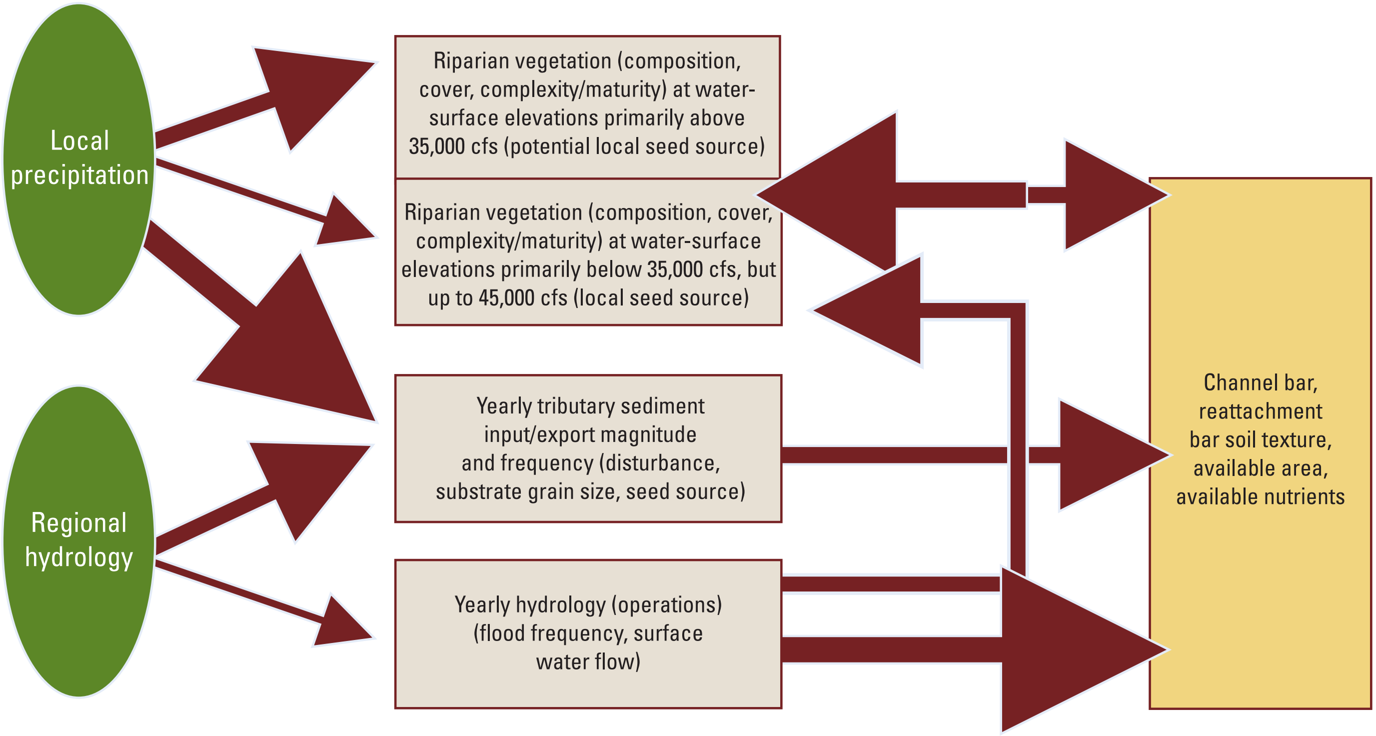


**Figure 3.** A conceptual model of physical factors that affect riparian vegetation development along the river corridor. Thicker arrows indicate a greater degree of effect on riparian vegetation. The closure of Glen Canyon Dam and the beginning of flow regulation of the Colorado River through Grand Canyon in 1963 all but eliminated the mainstem sand supply to Grand Canyon. Also, dam operations are now independent of tributary inputs of sediment. Taken together, dam-induced changes in both sand supply and flow have altered the sedimentary processes that provide substrate for riparian vegetation.

benches. Riparian areas are particularly prone to invasion by nonnative plants because they are frequently disturbed by flood events, which create favorable conditions for the seeds of nonnative plants that can be dispersed long distances by a variety of processes (Decamps, 1993).

## Status and Trends

Riparian community changes following the closure of Glen Canyon Dam in 1963 occurred over three periods.

### Period I: Initial Vegetation Expansion (1963–80)

Immediately following the closure of Glen Canyon Dam, operations focused on filling Lake Powell, delivering water to Lake Mead, and producing peak power. Discharges were reduced to between 1,000 and 20,000 cfs during this period (median discharge was 9,490 cfs in the 1960s). A series of discharges of 50,000 cfs conducted in 1965 cleaned the channel below the dam and raised the elevation of Lake Mead (Topping and others, 2003). Daily fluctuations in the 1970s were large, varying between 4,000 and 25,000 cfs, with a median discharge of 11,600 cfs (Topping and others, 2003). The result of dam operations during this period was to encourage plant colonization along the channel in the low-elevation benches.

Vegetation expansion below the 50,000-cfs water-surface elevation was documented by Turner and Karpiscak (1980), who used repeat photography from historical expeditionary trips through Grand Canyon such as J.W. Powell's second trip in 1872 (Darrah, 1948), the Robert Stanton expedition in 1889 (Stanton, 1965), and the U.S. Geological Survey expedition in 1921 (LaRue, 1925). Although Turner and Karpiscak (1980) did not quantify vegetation change, they did qualitatively demonstrate an increase in vegetation in the postdam fluvial sediment zone (up to 30,000 cfs) and in the predam fluvial sediment zone (30,000–85,000 cfs; 2-yr return period) (Topping and others, 2003). They noted dense stands of tamarisk, coyote willow, and arrowweed throughout the corridor, with desert broom (*Baccharis sarothroides*), Bermudagrass (*Cynodon dactylon*), Emory seep willow (*Baccharis emoryi*), and some cottonwoods (*Populus fremontii*) along the postdam fluvial zone. The expansion of coyote willow, tamarisk, and arrowweed within the predam and postdam fluvial zones was predictable given the creation of a stable water source and exposed land area (figs. 4a and b). The expansion of emergents such as cattails along the channel was also noted by Turner and Karpiscak (1980). The higher bench (land above >50,000 cfs) was found to be changing at a slower rate and composed of predam high-bench species like acacia, mesquite, sand dropseed (*Sporobolus cryptandrus*), and Apache plume.

The qualitative findings of Turner and Karpiscak (1980) are consistent with a land area change study of selected sites in Marble Canyon and upper Grand Canyon through the use of geographic information systems (Waring, 1995). Waring estimated a 100% increase in vegetation in the postdam and predam fluvial sediment zones between 1965 and 1973 (56.5 acres vs. 108.6 acres (228,503 $m^2$ vs. 439,420 $m^2$)). Anderson and Ruffner (1988) examined the predam high-bench terrace vegetation and determined that this zone showed little recruitment of new acacia or mesquite individuals. In other words, this zone was not showing signs of replacement of similar species. They hypothesized that the vegetation was becoming more mature, with individuals becoming larger and more closely spaced. Over time, the vegetation in this zone would become less dense as mature individuals died and were not replaced. Species found in this predam bench would "move shoreward" over time.

## Period II: Inundation and Habitat Reworking (1981–90)

In 1980, Lake Powell reached full pool elevation, and operations over the next decade focused primarily on water delivery and power generation. Because the early 1980s was a wet period, causing a high-release spill of 97,000 cfs in June 1983 (Martin, 1989), however, Glen Canyon Dam was also operated to manage spring inflows and protect the integrity of the dam. As a result, the 1980s produced several years of releases greater than 20,000 cfs for portions of the year (U.S. Geological Survey, 2005), with higher releases occurring in spring to reduce the frequency of spills. Median discharge for the decade was 15,900 cfs (Topping and others, 2003), approximately 32% greater than the median releases of the 1970s. Fine-sediment erosion and export from the Marble Canyon and upper Grand Canyon reaches occurred in this decade (Topping and others, 2000; Schmidt and others, 2004). Sediment export exceeded inputs during these events, resulting in an overall loss of sediment in the system.

The higher peak and median discharge presented situations of sustained inundation of riparian vegetation along the channel and increased water-table elevations that promoted expansion of woody vegetation in this decade (figs. 4b and c). The peak flow likely redistributed seeds from the predam flood-plain surfaces, which may have promoted establishment and growth of acacia and mesquite within the lower elevation benches. Waring (1995) detected a 13% decrease in vegetation occupying area below 50,000-cfs discharge. Waring showed an increase in vegetated area in the higher elevation benches for 1984 compared with 1975; measurements of mesquite in the predam flood plain by other researchers, however, did not indicate a growth response to the flood events of the 1980s (Anderson and Ruffner, 1988).

## Period III: Low Fluctuating Flows and Experimentation (1991–present)

### River Flows

The operation of Glen Canyon Dam since 1991 has focused on meeting water allocation requirements, producing power, and complying with environmental constraints designed to minimize the effects of Glen Canyon Dam on the erosion of recreational and archaeological sites and on the deterioration of habitats for endangered species, particularly humpback chub (*Gila cypha*) (U.S. Department of the Interior, 1995). During this period, flows have been further stabilized, not varying more than 8,000 cfs daily, though median annual flows have decreased only 15% when compared with those of the 1980s (13,500 cfs vs. 15,900 cfs) (Topping and others, 2003). The frequency of high peak flows has diminished with two experimental high-flow events of 41,000 cfs and 45,000 cfs occurring in November 2004 for 2.5 d and in March 1996 for 7 d (Webb and others, 1999). As a result, since 1991 the active riparian zone has been reduced to 45,000-cfs water-surface elevation. Smaller, shorter duration spikes of up to 31,000 cfs occurred in

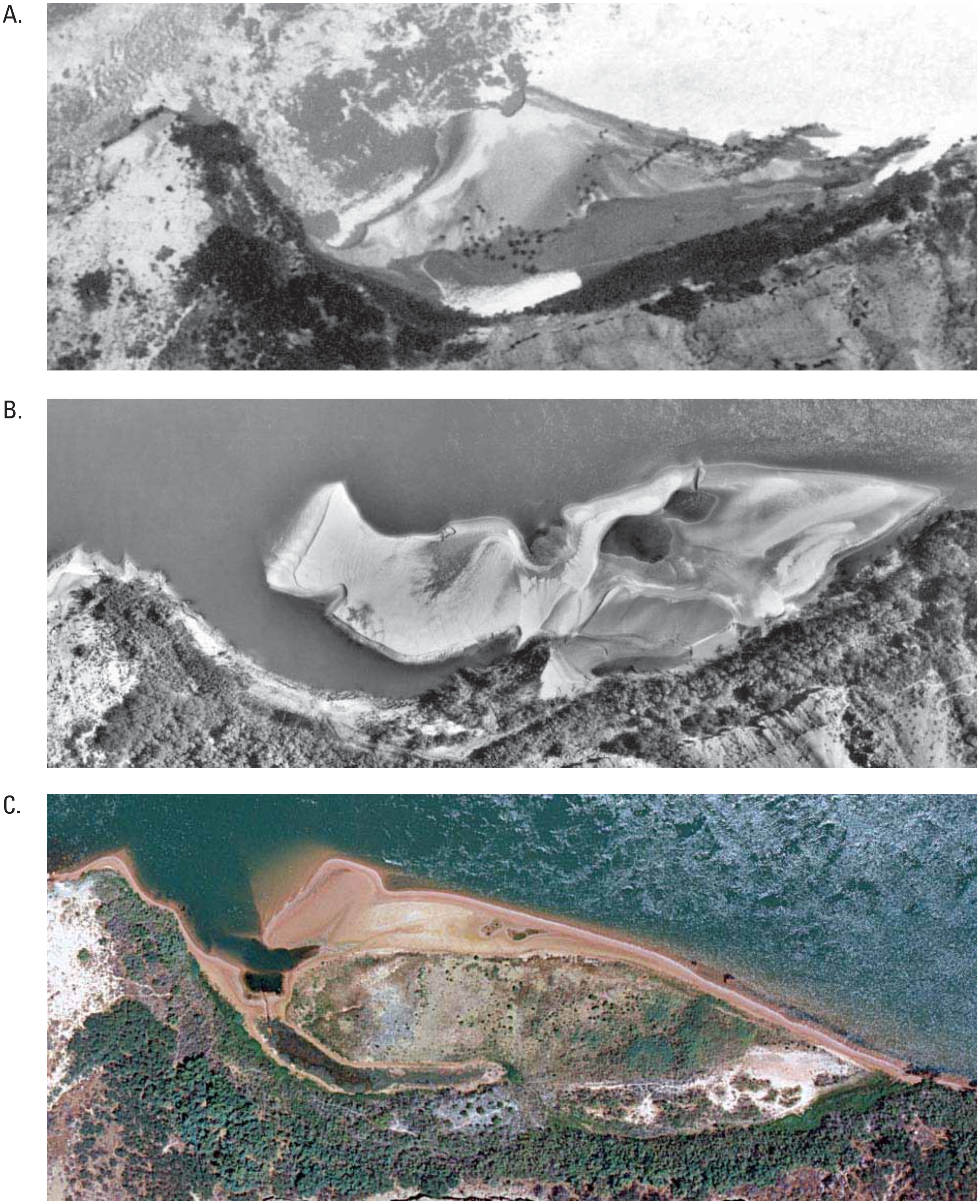


**Figure 4.** A. Aerial photograph from 1965 at RM 55.4 showing sparse vegetation occupying the sandbar and beginning to expand into the postdam fluvial zone. B. Aerial photograph from 1984 of RM 55.4 showing effects of flooding, which scoured low-lying riparian habitats. Vegetation occupies larger expanses along the shoreline and upslope from the river. C. Aerial photograph from 1994 of RM 55.4 showing expansion of riparian and marsh vegetation since 1984 on the sandbar and along the shoreline (source: U.S. Geological Survey file photographs).

1997 and 2000 (Schmidt and others, 2004). Peak flows (flows >120,000 cfs) have also been reduced by more than 50% of mean long-term high flows experienced before 1963 (Topping and others, 2003). As a result, the active riparian zone in Grand Canyon has contracted in width to that area below approximately 50,000-cfs water-elevation stage, with greatest change occurring below 30,000 cfs. The higher elevation bench (>50,000 cfs) persists through yearly rainfall events and is little affected by operations compared to predam hydrology.

## Response in the Plant Community

This 14-yr period of stable but fluctuating flows and experimentation resulted in the expansion of vegetation into open areas, including into campsites and channel margins within the active riparian zone (Kearsley and others, 1994; Webb and others, 2002); the reduction of marsh habitat associated with eddy return channels (i.e., backwaters) (Stevens and others, 1995; Goeking and others, 2003); and most recently (since 2002), a reduction of vegetative cover in low channel positions (Kearsley, 2004b). The community as a whole has become more mature, providing complex habitat for riparian breeding birds. With the onset of the drought in 2000 there has also been a reduction in cover of annual and perennial grasses in areas located above flows of 35,000-cfs elevation (Kearsley, 2004b).

Forty-one percent of camping sites surveyed between 1983 and 1991 were determined to be unusable because of vegetation overgrowth (Kearsley and others, 1994). Vegetation expansion into campsites occurred in reaches that are classified as wide reaches (Schmidt, 1990) or in areas where more sediment is available for plant establishment. Kaplinski and others (2005) discussed trends in vegetation expansion into campsites since 1991; their findings are summarized in chapter 12 of this report. Vegetation expansion between the high-water periods of 1984 and 1992 was supported by Waring (1995), who showed expansion during this period at a percentage of change similar to that which occurred with initial dam closure through 1973. Waring (1995) speculated that the rate of vegetation expansion increased during the early 1990s with the implementation of interim operating criteria. Expansion within the zone between shoreline and up to the 50,000-cfs water-surface elevation included the establishment by nonnative plants and pioneer species like camel thorn (*Alhagi maurorum*) and clonal growth by woody vegetation, including arrowweed and coyote willow. This vegetation expansion resulted in an increase in riparian bird habitat (see chapter 7, this report). Vegetation expansion was greatest in channel margin habitats used primarily by wildlife and was least in sites adjacent to rapids associated with debris fans where disturbance was more likely to occur (Melis and others, 1995; Waring, 1995; Webb and others, 2002).

Debris fan-eddy complexes (Schmidt and Rubin, 1995) are geomorphic features that support fluvial marsh habitat, primarily because they are low-velocity habitats that accumulate silt and clay fractions (Schmidt and Rubin, 1995; Stevens and others, 1995). Daily inundation frequency, soil texture, and distance from the dam influence marsh locations and assemblages (Stevens and others, 1995). Wet-marsh constituents like cattails, sedges, and common reed (*Phragmites australis*) are found in sites with increased inundation frequency, while drier marsh-associated species like tamarisk, arrowweed, horsetails (*Equisetum* sp.), and willows (*Salix* sp.) are associated with lower inundation frequencies. Interim operating criteria, initiated in 1991 and followed by the MLFF alternative in 1996, reduced inundation frequency. This change is coincident with a reduction in wet-marsh habitat since 1991 (Stevens and others, 1995; Kearsley and Ayers, 1996).

## Geomorphic Effects

The effect of geomorphology on plant assemblages is illustrated in marsh plots that were surveyed in the mid-1990s. Narrow reaches of the river such as that of Marble Canyon experienced losses of marsh patches, which correspond to a reported loss of sediment in this reach during the same time (Kearsley and Ayers, 1996; Schmidt and others, 2004). Wider reaches found near the Little Colorado River and in western Grand Canyon that have greater sediment-storage capacities showed gains and losses of marsh patches during these same years in the mid-1990s. The variability in the number of patches within these reaches may reflect local sediment inputs from ungaged tributaries as well as inputs from the Little Colorado River. For these same years, a drying trend (i.e., plants encountered were associated with lower moisture gradients) was noted for riparian plants (Kearsley and Ayers, 1996). Reduced numbers of marshes support a hypothesis that interim flows reduced inundation frequency and that species encountered were more likely to be associated with a lower moisture gradient. Alternatively, the change may reflect infilling and riparian community succession. Marsh census numbers since 1995 are not available, but geomorphic studies of debris fan-eddy complexes detected reduction in backwaters from 1984 to 2000 (Goeking and others, 2003). A reduction in these sites may be an indication that fine-sediment habitats were also declining during this period. Sediment export, particularly silt and clay, and reduced fluctuations likely reduced the area of cover represented by wet-marsh species in the 1990s through 2001.

## Hydrology and Climatic Influences

Reservoir levels, yearly operations, and local precipitation affect riparian vegetation growth and development within all vegetation zones along the river corridor. A persistent, basinwide drought was identified in July 2000 by the National Drought Mitigation Center (www.drought.unl.edu/dm/archive/2000/drmon0725.htm, accessed February 8, 2005). Since then, inflows to Lake Powell have been below average, leading to drawdown of both Lake Powell and Lake Mead (see chapter 4, this report). As a result, Glen Canyon Dam has released the minimum amount of water needed to meet delivery requirements, which is 8.23 million acre-feet (10,148 million m$^3$). While overall volume of delivery has been reduced, monthly median flows have not changed appreciably. Beginning in 2002, the months from January to March and from June to August are dominated by power-generation flows in summer months and fish suppression measures in winter months (U.S. Department of the Interior, 2004a). Fluctuations vary from 5,000 to 20,000 cfs daily in the winter months and by 8,000 cfs daily in summer, with base flow being approximately 10,000–12,000 cfs. Other months have lower volumes allocated with corresponding lower base flow and reduced daily range (e.g., 5,000–10,000 cfs in April). The abrupt shifts in monthly volumes in April and September expose areas in spring for plant establishment but are soon followed by high summer fluctuations in June. By September, the area inundated to 17,000-cfs water-surface elevation is often sparsely vegetated and reduced in sediment (Kearsley, 2004b). Precipitation variability and operational shifts of Glen Canyon Dam resulted in continued changes in the vegetation cover, abundance, and density along the river corridor.

## Recent Monitoring Results

Between 2001 and 2003, riparian vegetation was affected both by changes in dam operations and by a persistent drought. The summers of 2002 and 2003 had higher daily minimum flows than 2001, and these years also had winter (January to March) discharges that varied from 5,000 cfs to 20,000 cfs. Vegetation volume (a surrogate for structure) in the active riparian zone (5,000 cfs to 45,000 cfs) responded markedly each year. Between 2001 and 2002 volume decreased by 15% but had recovered by approximately the same amount between 2002 and 2003 (fig. 5) (Kearsley, 2004a). The recovery was attributable to the operational change that took place in January 2003. How these volumes may influence riparian bird density or abundances between years is not known. In contrast, vegetation at higher water-surface elevations (>45,000 cfs) changed little between years (fig. 5) (Kearsley, 2004a). Vegetation at higher water-surface elevations may respond more to localized precipitation events than to dam operations (Kearsley, 2004a). In general, operations had the greatest effect on vegetation located below the 35,000-cfs water-surface elevation.

Measures of plant abundance, species richness, diversity, and distribution all showed a decline since 2001 (Kearsley, 2004b). Operations and local precipitation differentially affected plants along the elevational gradient. Herbaceous annuals and perennials like cheat grass (*Bromus tectorum*), sand dropseed, and spiny aster (*Chloracantha spinosa*) located above 35,000-cfs water-surface elevation were affected by yearly precipitation and showed the greatest decline in cover (fig. 6a). The effect of the drought on higher elevation plants was also evident when species composition was examined. Species richness changed significantly at sites at 45,000 cfs and 60,000 cfs (fig. 6b) (Kearsley, 2004b); the change was associated mostly with a loss of annual and rarely encountered plant species. Increased summer precipitation in 2003 was responsible for increases in species richness in both of these elevations (fig. 6b). Annuals appearing in wetter years likely contributed to these increases (Kearsley, 2004b). Compositional shifts did not

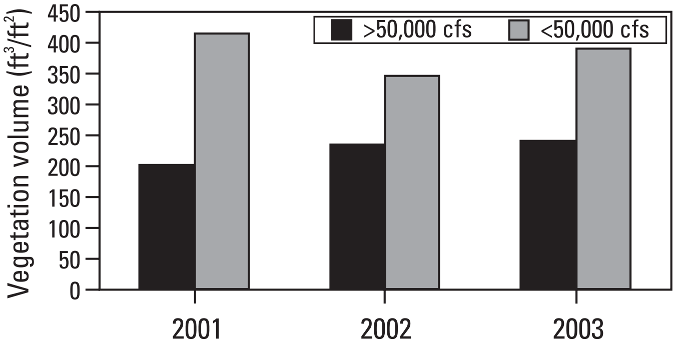


**Figure 5.** Change in vegetation volume (a surrogate measure of structure) from 2001 to 2003 in the riparian zone along the Colorado River in Grand Canyon at surface-water elevations above and below 50,000-cfs surface elevation. Figure modified from Kearsley (2004a).

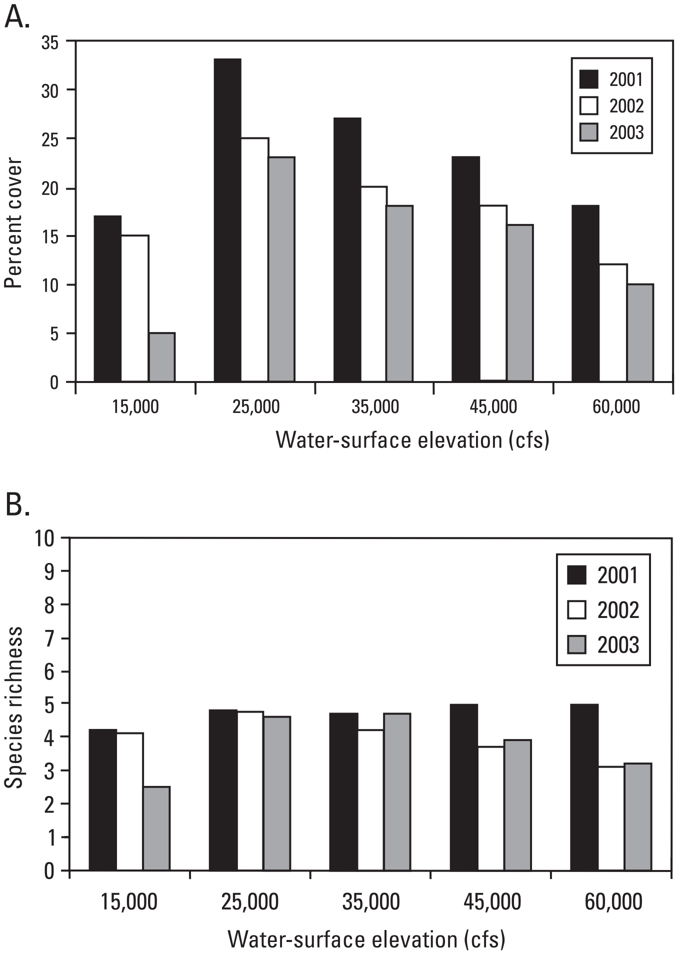


**Figure 6.** A. Percent change in vegetation covers at five water-surface elevations (cubic feet per second) between 2001 and 2003 in the riparian zone along the Colorado River in Grand Canyon. Cover has declined in all zones since 2001. Discharge had the greatest effect on species richness at water-surface elevations from 35,000 cfs to 15,000 cfs. Overall vegetation cover within the riparian zone is not dense although cover is greatest at the 25,000-cfs water-surface elevation, which corresponds with areas used by campers and breeding birds. Figure modified from Kearsley (2004b). B. Species richness in five water-surface elevations (cubic feet per second) from 2001 to 2003 and change between years in the riparian zone along the Colorado River in Grand Canyon. Species richness is a measure of the total number of species found at each water-surface level and is an indication of biodiversity. Species richness in this case is measured from a scale of 0 to 10 with 10 being the highest amount of richness. Overall species richness within the riparian zone is greatest in those zones that are above the 25,000-cfs water-surface elevation where vegetation is not directly scoured by flow. Species richness in the upper water-surface elevations is more affected by yearly precipitation. Species at upper surface water elevations have declined since 2001 because of drought conditions and include annual cheat grass (*Bromus tectorum*) and perennial sand dropseed (*Sporobolus cryptandrus*). Figure modified from Kearsley (2004b).

occur for zones below 35,000 cfs, and these data, in combination with vegetation volume measurements, suggest that changes in this zone were associated with increased growth of established woody species rather than with recruitment or mortality. Moreover, reductions in cover, richness, and diversity in lower water-surface elevation locations (<25,000 cfs) were caused by sediment loss, inundation, or scour that coincided with operational changes in January 2003. Dam operations influenced changes in vegetation beyond recorded discharge levels, possibly up to approximately 15,000 cfs, while local precipitation appeared to have a greater influence, in the short term, on vegetation above the 35,000-cfs water-surface elevation.

Since the 1990s, reservoir levels, yearly operations, and local precipitation have affected riparian vegetation growth and development along the river corridor in Grand Canyon (figs. 3, 5, and 6). Though other factors do affect riparian vegetation dynamics, these variables appear to be significant drivers in riparian vegetation development and change. The riparian zone in Grand Canyon has contracted shoreward as flows have stabilized. Riparian vegetation at water-surface elevations up to about 15,000 cfs above daily maximum discharge responds to operational changes. Vegetation below a water-surface elevation of 45,000 cfs has become denser and has expanded into open sites, including campsites. Vegetation cover and richness at low water-surface elevation locations (below 20,000 cfs) are most directly affected by dam operations. The fluvial marsh community is the most responsive of vegetative communities within Grand Canyon to changes in hydrology and sediment supply. Not surprisingly, cover and richness decline during flow fluctuations that promote scour and sediment export (Kearsley, 2004b). At the same time these flows can increase inundation frequency at higher elevations and can shift plant composition to more water-tolerant species like cattails and rushes as a result of annual changes in operations (Stevens and others, 1995). Essentially, the riparian area has declined quantitatively in some aspects (less spatial coverage, fewer numbers of species) and has changed qualitatively (denser, more mature).

## Riparian Vegetation as Terrestrial Habitat

As stated in the Introduction of this chapter, riparian communities in the Southwestern United States play an important role as wildlife habitat (Carothers and Brown, 1991; Farley and others, 1994; Skagen and others, 1998; Stevens and Ayers, 2002). Along the Colorado River, riparian birds have had a greater emphasis placed on them than other types of wildlife in terms of monitoring and are treated in a separate chapter of this report (chapter 7). Wildlife other than endangered species and birds has not been emphasized to date in the Glen Canyon Dam Adaptive Management Program. For these reasons, the following section addresses threatened and endangered species that occupy riparian habitat marshes and springs within the Colorado River ecosystem. Other faunal constituents are briefly mentioned.

# Threatened and Endangered Species

## Kanab Ambersnail

The Kanab ambersnail (*Oxyloma haydeni* ssp. *kanabensis*) is a terrestrial succineid snail (fig. 7) associated with wetland and spring vegetation on the Colorado Plateau. The snail was listed as endangered in 1992 (England, 1992). Presently, the species is found at three locations: Vaseys Paradise and Elves Chasm (a translocated population), in Grand Canyon National Park, and private land in southern Utah. Data presented here pertain to the snails located at Vaseys Paradise.

**Figure 7.** Kanab ambersnail (*Oxyloma haydeni* ssp. *kanabensis*), which is monitored at Vaseys Paradise (photograph by Roy Averill-Murray, Arizona Game and Fish Department).

Vaseys Paradise (figs. 8a–c) is a small patch of spring-fed riparian vegetation at RM 31.8 (Stevens, 1990). Ambersnails are found in the vegetation, usually associated with cardinal monkeyflower (*Mimulus cardinalis*) (fig. 8b), watercress (*Rorippa nasturtium-aquaticum*) (fig. 8c), and water sedge (*Carex aquatilis*). Ambersnail adults overwinter and reproduce in spring. Recruitment into the adult population takes place during summer and fall (Stevens and others, 1998; Nelson, 2001).

### Habitat

The greatest gains in habitat area, measured by traditional land-survey methods, occurred between fall 2001 and fall 2002 when snail habitat at Vaseys Paradise increased 23% in area (~2,374 $ft^2$ vs. ~3,103 $ft^2$ (220.6 $m^2$ vs. 288.4 $m^2$)) (fig. 9a) (U.S. Geological Survey, unpub. data, 1998–2004). Increases in measured habitat may be attributable to low minimum flows in 2001 that increased area for colonization by watercress, monkeyflower, or other plants; however, watercress, which is a species adapted to disturbance and that requires sustained moisture, has decreased since 1998 because spring discharges declined in association with the drought. At the same time, monkeyflower increased (U.S. Geological Survey, unpub. data, 1998–2004) and accounted for most of the habitat increase measured between fall 2001 and fall 2002. Monkeyflower, while still requiring moisture, appears to be more tolerant of drier habitats. Water sedge is patchily distributed in Kanab ambersnail habitat and is a source of forage for bighorn sheep (*Ovis canadensis*). As a site that provides a reliable source of vegetation in a drought, the springs are now habitually visited by bighorn sheep, resulting in vegetation used by the snails being regularly trampled.

### Snail Abundances

The number of snails has not changed significantly since 1998. Fall numbers generally exceed spring numbers as would be expected with seasonal recruitment (fig. 9b; U.S. Geological Survey, unpub. data, 1998–2004). Curiously, while habitat has increased, snail numbers have not had a correlated increase. The lack of increase in snail numbers may be associated with soil moisture, shifts in plant-species composition, and mortality associated with trampling by bighorn sheep rather than with the amount of habitat available.

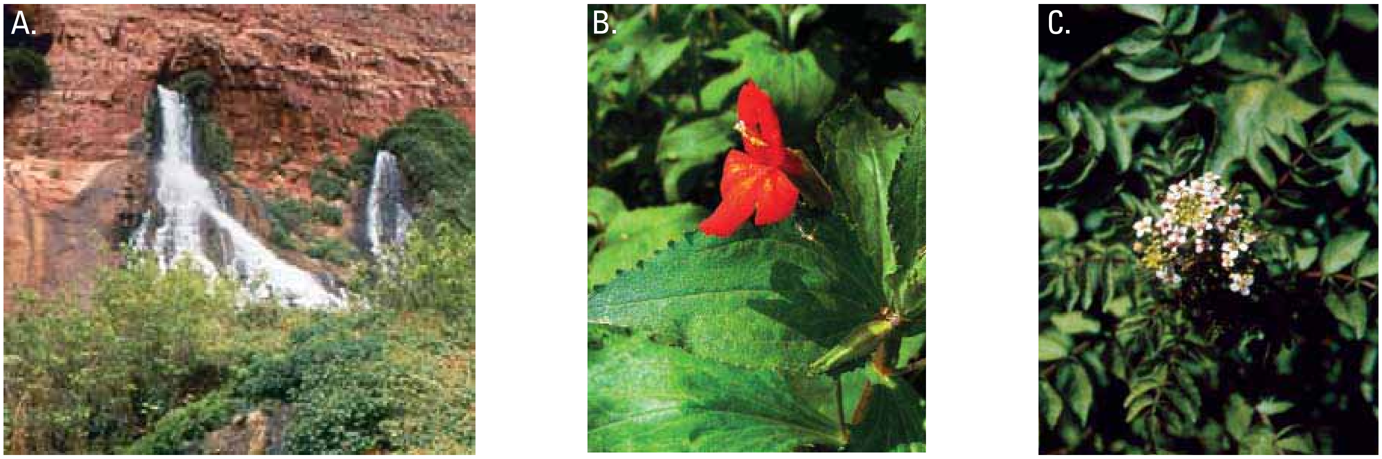


**Figure 8.** A. Vaseys Paradise along the Colorado River, which is one of three locations known to support the endangered Kanab ambersnail (*Oxyloma haydeni* ssp. *kanabensis*). Cardinal monkeyflower (*Mimulus cardinalis*) (B) and watercress (*Rorippa nasturtium-aquaticum*) (C) are primary plant species associated with Kanab ambersnail (photographs by Jeff Sorensen, Arizona Game and Fish Department).

# Other Wildlife

## Invertebrates

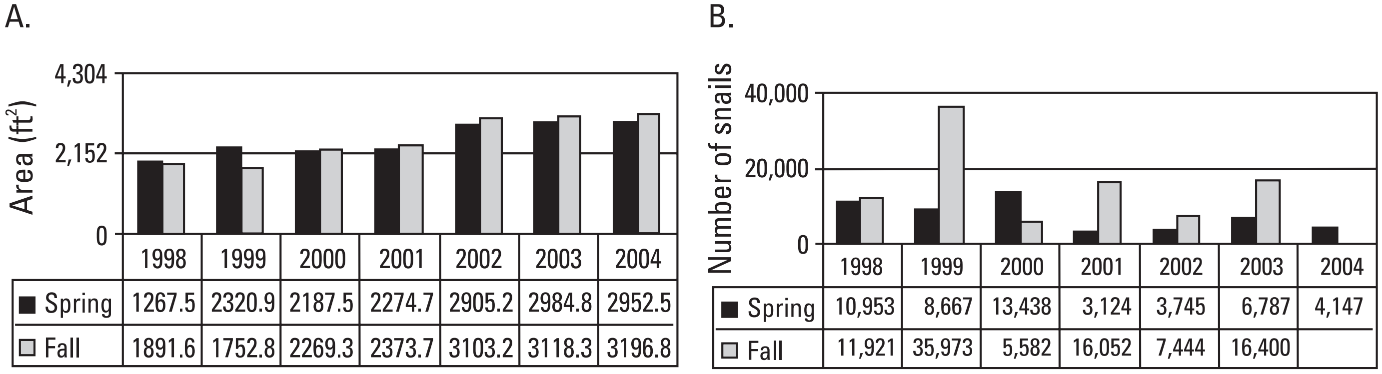
Invertebrate species, as in other ecosystems, account for the greatest number of species found along the river. There are several thousand invertebrate species from over 200 families (Stevens and Ayers, 2002; Lightfoot and others, 2004), including scorpions, spiders, flies, ants, moths, and butterflies. Surveys for invertebrates conducted over the past several years identified either range extensions for species (e.g., butterflies: Arizona powdered-skipper (*Systacea xampa*), piute agave skipper (*Agathymus alliea piute*), desert marble (*Euchloe lotta*), and desert elfin (*Callophrys fotis*)) or species not previously known to exist (e.g., moth, *Schinia immaculate*) (Stevens and Ayers, 2002; Pogue, 2004). Invertebrate composition associated with higher elevation riparian vegetation consists largely of native invertebrate taxa, while the lower elevation riparian vegetation includes a mix of native and nonnative invertebrate species (Lightfoot and others, 2004). The mix of species is not unexpected because vegetation in this area consists of a more pronounced mix of native and nonnative plants.

## Amphibians, Mammals, and Reptiles

Surveys for mammals, reptiles, and amphibians have been sporadic (Carothers and Aitchison, 1976; Warren and Schwalbe, 1986; Frey, 2003). Past surveys found 14 mammal species, 16 reptile species, and 4 amphibian species along the corridor. Amphibians of special concern are detailed in the accompanying text box. Only the deer mouse (*Peromyscus maniculatus*) is restricted to the riparian zone (Frey, 2003; U.S. Department of the Interior, 2004b). Larger mammals include beavers (*Castor canadensis*), coyotes (*Canis latrans*), bighorn sheep, mule deer (*Odocoileus rafinesque*), mountain lions (*Puma concolor*), and bobcats (*Lynx rufus*) (U.S. Department of the Interior, 2004b). Mountain lions and bobcats are seen infrequently. Of these mammals, beavers appear to have expanded their numbers since the 1960s (Carothers and Brown, 1991) in association with riparian vegetation expansion. Beavers appear to be relatively evenly distributed throughout the river corridor (U.S. Department of the Interior, 2004b).

# Discussion and Future Research Needs

A long-term data set associated with changes in riparian vegetation is lacking for the Colorado River ecosystem. The data that are provided here are results associated with specific research questions of 2- to 3-yr duration rather than monitoring to detect trends. Trend detection associated with riparian vegetation requires local and regional scale monitoring because local and regional hydrology and geomorphology affect the riparian zone. The long-term goal for monitoring in the



A.

| | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 |
|---|---|---|---|---|---|---|---|
| ■ Spring | 1267.5 | 2320.9 | 2187.5 | 2274.7 | 2905.2 | 2984.8 | 2952.5 |
| ☐ Fall | 1891.6 | 1752.8 | 2269.3 | 2373.7 | 3103.2 | 3118.3 | 3196.8 |

B.

| | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 |
|---|---|---|---|---|---|---|---|
| ■ Spring | 10,953 | 8,667 | 13,438 | 3,124 | 3,745 | 6,787 | 4,147 |
| ☐ Fall | 11,921 | 35,973 | 5,582 | 16,052 | 7,444 | 16,400 | |

**Figure 9.** A. Change in the area of Kanab ambersnail (*Oxyloma haydeni* ssp. *kanabensis*) habitat ($ft^2$) at Vaseys Paradise from 1998 through 2004 from spring and fall surveys. B. Estimated snail abundances at Vaseys Paradise from 1998 through spring 2004 from spring and fall surveys at Vaseys Paradise (U.S. Geological Survey, unpub. data).

Colorado River should be to use yearly data on cover, species richness, and diversity in concert with semidecadal vegetation mapping data to discern operational versus climatic effects on the riparian vegetation. Large-scale trend detection at the reach or regional scale will be able to provide information about changes in vegetated area, increases and decreases in vegetation patches, and the vegetation classes that have changed the most. The mapping data can also be integrated with bird monitoring, and other faunal resource monitoring that may be developed, to produce information about habitat quality. Habitat quality affects invertebrate communities that are food resources for both riparian breeding birds and fish communities along the river corridor.

Linkages among vegetation, faunal assemblages, and habitat quality are needed before comprehensive assessments of the riparian zone for the Colorado River can be made. One step toward a comprehensive assessment has been initiated by an inventory of invertebrates along the corridor. The intent of the inventory is to determine what types of invertebrates exist along the corridor, whether or not any species can be used to indicate environmental conditions, and in what quantities these potential indicators occur. Both quantity and type of invertebrates encountered are affected by vegetation assemblages. The challenge associated with riparian vegetation is to determine how dam operations affect plant species assemblages and densities, which, in turn, influence habitat quality and food resources for vertebrates found along the river corridor.

In the long term, continued loss of sediment along the shoreline and changes in the size fraction of the substrate will reduce available colonizing substrate and affect subsequent species establishment (i.e., marsh communities may shift to constituents that persist in coarser substrates) (Stevens and others, 1995). At elevations above the 20,000-cfs flow but still in the active riparian zone, woody vegetation is becoming more mature and less diverse in association with the reduction in high flow frequency. Under current operations (modified low fluctuating flows), precipitation affects vegetation above the 35,000-cfs water-surface elevation more than operations do (Kearsley, 2004 a, b). Remnants of the predam high-water riparian zone have remained relatively unchanged, depending on seasonal precipitation rather than on yearly hydrology for its maintenance. Implications for these changes within the river corridor include the potential reduction in numbers of some riparian bird species that depend on wetter marsh-plant species for nesting or food resources, though other riparian bird species may benefit from the more mature, dense habitat (Anderson and Ohmart, 1984; Farley and others, 1994). Furthermore, continued loss of campsite area associated with vegetation expansion may occur. The trade-offs between recreation and wildlife habitats are value-based management decisions that the adaptive management program will have to address. Some of these trends could be ameliorated through higher frequency disturbances up to and above 45,000-cfs discharges, but these events should be timed to coincide with sufficient sediment inputs and existing system supply.

# Declining Riparian Species: Leopard Frogs in Grand Canyon and Glen Canyon

Charles Drost

**Figure 1.** Northern leopard frog (*Rana pipiens*) (photograph by Charles Drost, U.S. Geological Survey).

Amphibians have been relatively neglected in studies of plants and animals and of the effects of dams in Grand and Glen Canyons. Amphibians were surveyed along the Colorado River in Glen Canyon before the construction of Glen Canyon Dam (Woodbury, 1959), but extensive surveys were not conducted in Grand Canyon until well after the completion of the dam (e.g., Aitchison and others, 1974; Suttkus and others, 1976). Over the last 15 yr there has been increasing recognition and concern about declines in amphibian populations in areas throughout the world (Wyman, 1990; Wake, 1991; Vial and Saylor, 1993). The cause of many of these declines is unknown, but they have even occurred in national parks and other protected areas, suggesting that causes are widespread regional ones (Blaustein and Wake, 1990). We describe here the current status of amphibians in the Colorado River corridor of Grand Canyon National Park and Glen Canyon National Recreation Area based on extensive surveys conducted over the last 10 yr throughout Glen and Grand Canyons, from the uppermost end of Lake Powell to the upper end of Lake Mead.

Surveys found healthy, widespread populations of two species of toads (Woodhouse's (*Bufo woodhousii*) and red-spotted (*B. punctatus*)); the canyon treefrog (*Hyla arenicolor*); and the tiger salamander (*Ambystoma tigrinum*). Northern leopard frogs (*Rana pipiens*) (fig. 1), on the other hand, have declined substantially, paralleling losses reported in other areas of western North America. Leopard frog populations have disappeared from 70% of sites where they were formerly found and have declined in numbers at some sites where they still occur (fig. 2). Some of the losses are of riverside populations in Glen Canyon, which were inundated by Lake Powell (Drost and Sogge, 1993); however, other populations have been lost from side canyons off of the lake that are not impacted directly by inundation. Currently, seven leopard frog populations are known to occur in side canyons of Lake Powell, concentrated around the Escalante River area of the lake. The status of the species at some sites is uncertain. Earlier surveys found frogs as far upstream as Dark Canyon, near Hite, but none have been seen there recently. A small population in Wilson Creek off the San Juan River area of the lake has not been seen since 1994.

The predam distribution of northern leopard frogs in the Grand Canyon reach of the Colorado River is unknown because of the lack of early surveys. Compilation of reports from more recent surveys shows that northern leopard frogs occurred at least as far downstream as Cardenas Creek (RM 71) along the river corridor and in side canyons as far as Bright Angel Creek and Kanab Creek. In spite of intensive searches of potential habitat along the river and in side canyons with perennial streams, the only known remaining population is at a spring-fed marsh between Glen Canyon Dam and Lees Ferry. This population was discovered in 1992 (Drost and Sogge, 1993) and has experienced wide year-to-year fluctuations in numbers. The most recent surveys indicate a sharp decline in population size, with only two adult individuals found in 2004. Marsh vegetation at the site has become very dense, reducing areas of open water, and this reduction may be an important factor in the decline of this population.

Although survey work is continuing, it is clear, based on the historical record, that there has been a severe contraction of the northern leopard frog's range in both Glen Canyon and Grand Canyon. A major concern for remaining populations of frogs is that most or all of them are now effectively isolated from each other. No other extant populations have been found along the river below Glen Canyon Dam, so the population below Glen

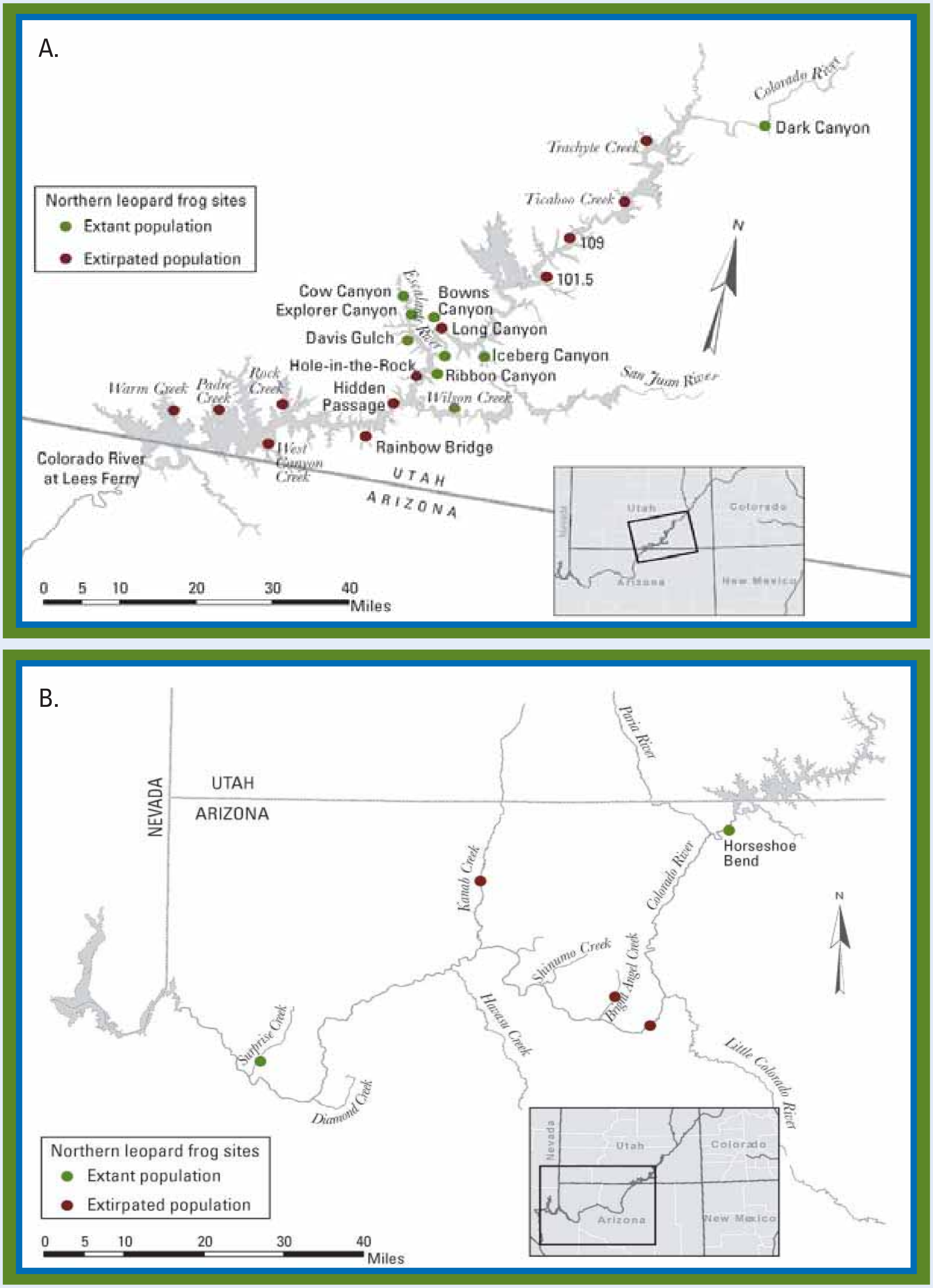


**Figure 2.** Northern leopard frog (*Rana pipiens*) sites in Glen Canyon above Glen Canyon Dam (A) and the corridor of the Colorado River and its tributaries below Glen Canyon Dam (B). Northern leopard frog numbers have declined substantially, paralleling losses reported in other areas of Western North America. Leopard frog populations have disappeared from 70% of sites where they were formerly found and have declined in numbers at some sites where they still occur.

Canyon Dam is completely isolated. In addition, no frogs have been found along the shores of Lake Powell. The combination of deep lake waters, lack of vegetation cover, and large numbers of predatory fish in the lake probably prevents any movement of frogs among side canyons.

One unexpected, positive finding of the surveys was the discovery of a previously unknown population of a second leopard frog species in western Grand Canyon. In spring 2004, small numbers of leopard frogs were found in a pool in Surprise Canyon (RM 248) (Gelczis and Drost, 2004). The frogs are clearly different from the northern leopard frogs found farther upstream. Genetic studies of the population are still in progress, but the frogs are apparently the lowland leopard frog (*Rana yavapaiensis*). This location represents a significant northward extension in range for this relatively rare species. There are potential threats at the site in the form of nonnative predatory fish and crayfish, but this new population appears to be healthy and thriving.

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# Chapter 7

# Birds of the Colorado River in Grand Canyon: a Synthesis of Status, Trends, and Dam Operation Effects

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## Introduction

Riparian habitats, or vegetated areas along streams and rivers, in the Western United States typically support a disproportionately large number of birds compared to adjacent nonriparian habitats, both in terms of bird abundance and the number of species present (also known as species richness). The Grand Canyon ecosystem is no exception and provides important habitat to wintering, migrant, and breeding birds (Brown and others, 1987; Carothers and Brown, 1991; Sogge and others, 1998; Kearsley and others, 2004; Spence, 2004). Importantly, the ecosystem also provides habitat for several bird species of special concern, including the southwestern willow flycatcher (*Empidonax traillii extimus*), California condor (*Gymnogyps californianus*), bald eagle (*Haliaeetus leucocephalus*), and American peregrine falcon (*Falco peregrinus anatum*).

This chapter summarizes the considerable information available from recent studies on the ecology of Grand Canyon bird species and communities. Because changes in riparian habitat undoubtedly influence the abundance and distribution of Grand Canyon birds, the chapter starts by briefly examining dam-induced habitat alterations that may affect birds. The direct and indirect effects of Glen Canyon Dam operations, including the modified low fluctuating flow (MLFF) alternative that was implemented starting in 1996, are considered for how they influence specific bird species and communities. Particular attention is given to the species of special concern listed above. The chapter concludes with a summary and a discussion of research priorities within the context of the Glen Canyon Dam Adaptive Management Program.

## Background

The riparian vegetation of the Grand Canyon ecoregion is complex and dynamic, changing in response to flooding, the invasion of new nonnative species, long-term successional patterns, and climate (Turner and Karpiscak, 1980; Webb and others, 1999). The primary driving variables in the terrestrial riparian ecosystem in Grand Canyon are the flow characteristics and hydrograph of the Colorado River (Carothers and Aitchison, 1976; Stevens and others, 1995; Kearsley and Ayers, 2001). The distribution of the riparian vegetation in the

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Grand Canyon is also strongly influenced by the geography and geology of the region. The river corridor follows a 1,772-ft (540-m) elevation gradient through changing vegetation communities ranging from Great Basin desertscrub (classification per D.E. Brown, 1994) found at Lees Ferry (RM 0) with an elevation of 3,117 ft (950 m) to Sonoran desertscrub at Diamond Creek (RM 226) with an elevation of 1,345 ft (410 m). Type of bedrock geology present and the presence of major side canyons are perhaps the most important geological factors relevant to the distribution of riparian vegetation along the river (Turner and Karpiscak, 1980; Stevens and others, 1995; Spence, 2004). For example, where the bedrock consists of Precambrian schist and granite, which are hard and slow to erode, the river corridor is narrow and tends not to support much riparian vegetation except at the mouths of tributaries.

Before the construction of Glen Canyon Dam, the hydrograph of the Colorado River in Grand Canyon was driven by spring snowmelt floods and occasional large tributary inflows produced by monsoonal late-summer rains (Dolan and others, 1974; Carothers and Aitchison, 1976; Topping and others, 2003). Spring flooding controlled the abundance and distribution of riparian vegetation, producing a distinct trim line at about the 125,000 cfs level. Water-surface elevation, or stage, is typically given in terms of rate of flow (cubic feet per second (cfs)) because elevation varies over the length of the river corridor depending on local channel morphology. Above this line an extensive community of old high-water zone (OHWZ) vegetation occurred, including species such as Apache plume (*Fallugia paradoxa*), net-leaf hackberry (*Celtis laevigata* var. *reticulata*), mesquite (*Prosopis glandulosa*), and catclaw acacia (*Acacia greggii*). Because the lower zone, below 50,000 cfs, was flooded and scoured most years (Topping and others, 2003), sparse vegetation was present below the trim line and consisted of coyote willow (*Salix exigua*), tamarisk (*Tamarix ramosissima*), rushes (*Juncus* sp.), and grasses (Poaceace family) (Clover and Jotter, 1944). Most of the plant species found today in lower vegetation zones were present before the construction of the dam (Clover and Jotter, 1944; Kearsley and Ayers, 2001). Predam conditions resulted in varied riparian vegetation, producing dense riparian stands more than 164 ft (50 m) wide at some tributary mouths, but elsewhere riparian stands were patchily distributed and generally between 10 and 66 ft (3–20 m) wide (Flowers, 1959; Kearsley and Ayers, 2001).

The hydrograph of the Colorado River changed dramatically with the completion of Glen Canyon Dam (Webb and others, 1999; Topping and others, 2003). Of the many changes wrought by the dam and discussed elsewhere in this report, the most influential one in terms of riparian vegetation is the reduction of peak annual flows. In the absence of historical floods that removed lower zone vegetation, perennial plant species were able to move into and colonize these areas. These new areas of riparian vegetation are referred to as the new high-water zone (NHWZ) to distinguish them from the higher predam riparian habitats. The amount of NHWZ riparian vegetation greatly increased between 1963 and 1983 (Pucherelli, 1986), and much of the colonization of the NHWZ was by nonnative species, especially tamarisk (Turner and Karpiscak, 1980). Areas of marsh also developed in return channel-eddy complexes (Cluer, 1997), covering approximately 1% of the NHWZ of the river corridor by 1991 (Stevens and others, 1995).

The floods and subsequent high flows of 1983–85 produced considerable scour and an estimated 13% (Waring, 1995) to 39% (Pucherelli, 1986) reduction in area of the NHWZ. Following the floods, the NHWZ gradually recovered. In 1991, interim flows were established that caused further changes, primarily the stabilization of marshes and riparian colonization of the lower portion of the NHWZ between 25,000–33,000 cfs. The 1996 beach/habitat-building flow through the river corridor was designed to scour tamarisk vegetation in the lower portions of the NHWZ but had only short-term burial impacts on the vegetation, which recovered rapidly (Kearsley and Ayers, 1999; Stevens and others, 2001). Flows under the MLFF alternative have not altered the areal extent of riparian vegetation patches from that established during the period of interim flows in the early 1990s (Kearsley and Ayers, 1996, 1999).

Dam-induced changes to riparian habitat undoubtedly affected the abundance and distribution of riparian birds. These changes are not directly measurable because


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the first surveys of breeding birds along the Colorado River (Carothers and Sharber, 1976) were not conducted until after the dam was completed. Since then, surveys and studies have examined many aspects of the ecology of Grand Canyon birds, including the direct and indirect effects of the dam on specific bird species and bird communities. Riparian breeding bird studies have been conducted along the river corridor since the initiation of the Glen Canyon Environmental Studies in 1982 (Brown and others, 1987; Brown, 1987, 1989; Brown and Trosset, 1989; Spence and Pinnock, 1993; Grahame and Pinnock, 1995; Hualapai Tribe and SWCA, Inc., 1995; Petterson and Spence, 1997; Spence, 1997, 2004; Sogge and others, 1998; Kearsley and others, 2004; Yard and others, 2004). These studies collected data on the composition of bird communities; patterns of species abundance, richness, and diversity; and habitat distribution. They also provided information on habitat associations and identified riparian-dependent bird species.

Species-specific bird studies have also been conducted along the river corridor. Focus was given to bird species that were or are federally listed as endangered or threatened, including bald eagle (Brown and others, 1989, 1998; Brown and Stevens, 1992, 1997; Brown, 1993; Leibfried and Montgomery, 1993; Spence and others, 2002; van Riper and Sogge, 2004), peregrine falcon (Ellis and Monson, 1989; Brown, 1991a; Ward, 2000), and southwestern willow flycatcher (Brown, 1988; Sogge and others, 1997; Johnson, 2000; Yard, 2004a). A number of riparian bird species were also the subject of research, including the Bell's vireo (*Vireo bellii*) (Brown and others, 1983), black-chinned hummingbird (*Archilochus alexandri*) (Brown, 1992), and brown-headed cowbird (*Molothrus ater*) (Brown, B.T., 1994). Studies of the winter riparian bird community (Sogge and others, 1998; Spence, 2004; Yard, 2004b) and the aquatic bird community (Stevens and others, 1997a; Spence, 2004; Yard, 2004b) have also been conducted. These studies provide considerable information on the ecology of Grand Canyon bird communities and the direct and indirect effects of the dam on specific bird species and bird communities.

# Status and Trends

## Breeding Riparian Birds

The breeding bird community associated with the riparian habitat along the Colorado River is made up of bird species generally restricted to riparian habitats and species that can also be found in adjacent upland, nonriparian habitats. More than 30 species have been recorded breeding in the riparian patches along the river within the study area. Most of these are songbirds including warblers, wrens, finches, orioles, and sparrows that nest and forage for insects within the NHWZ and OHWZ vegetation. Of the 15 most common riparian breeding bird species (table 1), 10 are Neotropical migrants that breed in the study area but winter primarily south of the United States-Mexico border. The rest of the breeding birds that use the canyon are year-round residents or short-distance migrants that primarily winter in the region or in nearby southern Arizona.

Repeated research since the mid-1970s has shown that Glen Canyon Dam and its operation have few direct flow-related effects upon the riparian breeding bird community. The primary change influencing these birds has been increased habitat availability caused by the establishment of the NHWZ riparian vegetation in areas that had relatively sparse vegetation before the dam (Brown and others, 1987; Carothers and Brown, 1991; Sogge and others, 1998; Spence, 2004). Brown and Johnson (1985, 1987) also found that flows directly affected some birds that occupied this new habitat during periods of high daily change in the river level or during enormous seasonal fluctuations that occurred before 1991 and the establishment of interim flow operating criteria. For example, they found that flows as high as 31,000 cfs, approximate powerplant capacity, flooded only a few nests, including some common yellowthroat (*Geothlypis trichas*) nests; however, flows of more than 40,000 cfs began flooding nests and nest plants of some riparian breeding species, specifically the Bell's vireo

**Table 1.** The 15 generally most common terrestrial breeding bird species (in alphabetical order) found in riparian habitats along the Colorado River in Grand Canyon.

| Common Name | Scientific Name |
|---|---|
| Ash-throated flycatcher | *Myiarchus cinerascens* |
| Bell's vireo | *Vireo bellii* |
| Bewick's wren | *Thryomanes bewickii* |
| Black-chinned hummingbird | *Archilochus alexandri* |
| Blue grosbeak | *Passerina caerulea* |
| Blue-gray gnatcatcher | *Polioptila caerulea* |
| Bullock's oriole | *Icterus bullockii* |
| Common yellowthroat | *Geothlypis trichas* |
| House finch | *Carpodacus mexicanus* |
| Lesser goldfinch | *Carduelis psaltria* |
| Lucy's warbler | *Vermivora luciae* |
| Mourning dove | *Zenaida macroura* |
| Song sparrow | *Melospiza melodia* |
| Yellow warbler | *Dendroica petechia* |
| Yellow-breasted chat | *Icteria virens* |

and yellow-breasted chat (*Icteria virens*) (Brown and Johnson, 1987).

The interim operating criteria, which were in effect from 1991–96, limited maximum releases to 20,000 cfs and set minimum flows at 8,000 cfs during the day and 5,000 cfs at night. Daily fluctuations were also limited to a maximum of 8,000 cfs. This change in river flows promoted the establishment of a narrow band of vegetation near the edge of the river (Stevens and Ayers, 1994; Sogge and others, 1998). Sogge and others (1998) examined the direct impact of interim operating criteria on breeding birds in the hydrologically active zone (HAZ), the area potentially inundated by flows between 5,000 and 20,000 cfs. They found that few species nested either close to the ground or close to the river; only one common yellowthroat nest was placed low enough to be inundated at 20,000 cfs. The black phoebe (*Sayornis nigricans*), however, places its nests just 3–6 ft (1–2 m) above the water, and some phoebe nests would be inundated by any flows that raised the water level by as little as 3 ft (1 m). For other breeding bird species, Sogge and others (1998) found that nests were placed well away from the HAZ and avoided inundation under the interim operating criteria. Because the MLFF alternative is similar to interim operating criteria (Kearsley and Ayers, 1999), most nests (other than some black phoebe nests) are unlikely to be affected by changing water levels.

Sogge and others (1998) examined the potential long-term effects of dam operations on the Grand Canyon ecosystem bird community. They developed models and identified habitat features that predicted bird abundance, species richness, and diversity. They found that riparian location along the river corridor, patch size, and volume of larger woody species, especially of tamarisk, within a riparian vegetation patch were positively correlated with bird abundance, species richness, and diversity. Specifically, these models predicted the following:

1. Flow patterns that result in smaller, more isolated habitat patches would decrease bird numbers, species richness, and diversity.
2. Flow patterns that create larger and more contiguous habitat patches would increase bird abundance and richness within the constraints of local topography and geomorphology.
3. Loss of mesquite vegetation would decrease bird abundance.
4. Increases in the number of habitat patches would increase overall number of birds and bird species.
5. Changes from tamarisk shrub/tree to willow shrub/tree are not likely to greatly affect bird abundance and species richness of the Grand Canyon ecosystem bird community.

A subsequent study by Spence (2004) modeled riparian bird habitat relationships but did not examine the relationship between riparian patch size and characteristics such as total bird abundance, species richness, and species diversity. Despite the fact that data were being derived from different riparian patches, this study obtained results similar to Sogge and others (1998), concluding that higher woody-species volume and river location were the best predictors of breeding bird abundance and richness.

These two studies (Sogge and others, 1998; Spence, 2004) demonstrate that riparian patch size, the volume of woody species within a habitat patch, and the location of the patch along the river corridor are primary factors that affect the abundance and species richness of birds within a riparian patch. Also, the mix of NHWZ and OHWZ vegetation within a patch probably affects the distribution and abundance of specific bird species because certain species have ecological preferences in nesting and foraging in one or the other vegetation type (Sogge and others, 1998; Spence, 2004). Collectively, the body of research indicates that dam operations with the greatest potential to impact breeding bird species within the Grand Canyon ecoregion are those that would affect the extent and amount of riparian vegetation along the river, such as large-magnitude planned or unplanned floods.

Overall, there has been relatively little change in the distribution of riparian habitat since the initiation of canyon bird studies in the mid-1970s. Likewise, the riparian breeding bird community within the study area appears not to have changed appreciably in species composition during that 25-yr period (Spence, 2004). For the most part, the bird species that were most common in the 1980s are the most common today (Kearsley and others, 2004; Spence, 2004). Two exceptions are the Bell's vireo and the song sparrow (*Melospiza melodia*), which have apparently expanded their breeding ranges within the Grand Canyon ecoregion (Brown and others, 1983; Spence, 2004; Yard and Blake, 2004).

To track trends in riparian breeding bird populations, one long-term monitoring program was initiated in 1996 and continued through 2000 (Spence, 2004) and another from 2001 through 2004 (Kearsley and others, 2004). These studies included baseline monitoring of the breeding riparian birds, southwestern willow flycatcher, and riparian habitat in selected patches along the river corridor. Several species, mostly Neotropical migrants, showed consistent detection rates during the 1996–2000 time period (Spence, 2004). The blue-gray gnatcatcher (*Polioptila caerulea*) showed a steady decline, with detection rates dropping about 30%–50%. Two species, Bullock's oriole (*Icterus bullockii*) in Glen Canyon and yellow warbler (*Dendroica petechia*) throughout the study area, showed statistically significant increases in detection rates (Spence, 2004).

Most birds found in the study area are not year-round residents; therefore, other factors acting outside the Grand Canyon ecosystem influence bird populations, and this influence is especially true for migratory breeding birds. Outside factors—changes in winter and migratory habitat, winter weather events, and climate outside the region—can affect bird survivorship and are independent of the effects of adaptive management (Spence, 2004; Holmes and others, 2005).

## Overwintering Aquatic Birds

Increases in abundance and species richness of the aquatic bird community—loons, grebes, cormorants, herons, ducks, rails, and sandpipers—in the Grand Canyon ecoregion correspond with the increased river clarity and productivity associated with the presence of Glen Canyon Dam (Stevens and others, 1997a; Spence, 2004). These aquatic bird species use the Grand Canyon ecoregion almost exclusively in the winter, nonbreeding season. Two primary foraging guilds are represented: (1) diving species that consume mostly fish and invertebrates within the water column or on the river bed and (2) dabbling species that forage in cobble bars and shallower areas where they can reach aquatic vegetation and associated invertebrates (table 2). These aquatic birds can be directly affected by dam operations that change the distribution of prey species in the water column of the river or, in the case of dabbling species, cover or expose foraging beds. Also, higher discharge rates increase river velocity and potentially increase foraging costs for species in both guilds (Spence, 2004).

Aquatic bird species are distributed fairly predictably within the study area. The upper reaches of the river, from Glen Canyon Dam to about 25 mi (40 km) downstream, tend to be relatively clear and support habitat and food, including an abundance of introduced

**Table 2.** The 10 generally most common overwintering aquatic bird species (in alphabetical order) encountered during surveys along the Colorado River below Glen Canyon Dam.

| Common Name | Scientific Name |
|---|---|
| American coot | *Fulica americana* |
| American wigeon | *Anas americana* |
| Bufflehead | *Bucephala albeola* |
| Common goldeneye | *Bucephala clangula* |
| Common merganser | *Mergus merganser* |
| Gadwall | *Anas strepera* |
| Green-winged teal | *Anas crecca* |
| Lesser scaup | *Aythya affinis* |
| Mallard | *Anas platyrhynchos* |
| Ring-necked duck | *Aythya collaris* |

rainbow trout (*Oncorhynchus mykiss*) for diving species. Dabblers can forage only in wider reaches with extensive shallow, low-turbidity water. Accordingly, dabblers are concentrated in wider reaches above the Little Colorado River (Stevens and others, 1997a; Spence, 2004).

Spence (2004) found that species composition and abundance of the aquatic bird communities within the study area show considerable fluctuations among years. Given similar flows, however, the resources available to waterfowl in the Grand Canyon ecoregion are relatively similar among years. Primary productivity is greatest in the clear water below the dam to approximately 25 mi (40 km) downstream and then drops rapidly as the river becomes more turbid as sediment and organic matter enter the river from tributaries. Hence, it is likely that the large year-to-year fluctuations in aquatic birds noted by Spence (2004) are due to factors outside the region. Outside factors may be numerous and potentially include conditions on the breeding grounds, recreation activities, changes in habitat availability, climate conditions, and hunting. All these factors can interact in complex ways in determining the composition and abundance of the winter aquatic community in the Grand Canyon ecoregion (Spence, 2004).

Because of the high variability in abundance for many species, the power to detect trends in overwintering aquatic birds is low. Comparing results of surveys conducted between 1973 and 1994 by Stevens and others (1997a) to data from surveys between 1998 and 2000, Spence (2004) found strong similarities in the aquatic bird communities, and the most common birds detected during both periods were similar (Spence, 2004).

## Species of Concern

### Southwestern Willow Flycatcher

The willow flycatcher (*Empidonax traillii*) is a small Neotropical migratory bird that breeds across much of North America and winters in portions of Central America and northern South America. The southwestern subspecies (*E. t. extimus*) breeds only in dense riparian habitats in the Western United States, including portions of Utah, Nevada, Colorado, New Mexico, Arizona, and southern California. Breeding generally occurs from late May through early August (Sogge, 2000). When the southwestern willow flycatcher was federally listed as an endangered species in 1995, fewer than 400 breeding territories for the subspecies were known throughout the Southwest; however, by 2001, that number had increased to approximately 1,000 territories distributed among more than 200 breeding sites (Sogge and others, 2003). By 2003, because of increased survey effort and a population increase in central Arizona, there were an estimated 410 territories in Arizona alone (Smith and others, 2004).

Historically, southwestern willow flycatchers were probably found within most major drainages in Arizona (Paradzick and Woodward, 2003) but were uncommon within the Grand Canyon ecoregion primarily because periodic high flows limited dense riparian habitat. The first record of a willow flycatcher in the ecoregion is from Lees Ferry in 1909, but it is not known whether it was a migrant or a breeding bird. The first nest was found in 1935. The next record was of a probable breeder collected in 1953 (summarized in Sogge and others, 1997). Flycatchers have consistently nested along the river corridor in recent years, as new riparian habitat, primarily tamarisk, has developed in response to altered river flow regimes. This expansion of riparian vegetation may have provided additional habitat for the flycatcher. Migrant willow flycatchers also occur along the river corridor, typically in late May and early June, and most of these migrants are probably of the nonendangered northern subspecies (*E. t. adastus*).

There are no direct flow-related impacts to southwestern willow flycatchers because they nest high in tamarisk vegetation, which is well above the level of normal fluctuating river flows. Indirect effects may occur as the result of flow-related changes to riparian patch size, vegetation density, and invertebrate populations that form the flycatcher prey base. The 1996 beach/habitat-building flow did not adversely affect southwestern willow flycatchers or their breeding habitat structure (Stevens and others, 2001). If future flood flows enhance riparian habitat and patch size, flycatchers may benefit. Conversely, if they substantially reduce riparian habitat at current breeding sites, the flycatcher may be impacted.


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Wetland/marsh vegetation has been proposed as important flycatcher foraging habitat in the study area (Stevens and others, 2001). The necessity of wetlands to flycatchers is difficult to evaluate because the species often breeds at sites in the Southwest where extensive wetlands are absent (Sogge and Marshall, 2000).

Other potential impacts to southwestern willow flycatchers include human-related disturbance. Southwestern willow flycatchers are not apparently sensitive to disturbances such as rafts or boats floating past breeding sites; however, people moving through occupied flycatcher habitat can damage habitat, disturb the birds, or impact a nest. During the mid-1990s, visitor closures were instituted at known flycatcher breeding sites in Grand Canyon. To date, there is no evidence of direct, human-related impact to flycatchers along the river corridor. Potential and indirect human-related impacts include the eradication of tamarisk, which the flycatchers use for nesting. Its removal, particularly from known breeding sites, would adversely affect flycatchers.

Brown-headed cowbirds are nest parasites and lay their eggs in the nests of other birds, which then incubate the cowbird eggs and raise the young cowbirds as if they were their own young. B.T. Brown (1994) and Sogge and others (1997) reported that flycatchers in the Grand Canyon ecoregion experienced high rates (>25% of nests) of brown-headed cowbird parasitism, which reduced flycatcher nest success and productivity. There is no evidence, however, that dam operation or river flows affect cowbird populations or nest parasitism rates.

Because southwestern willow flycatchers migrate southward each winter, they are affected by many factors during the migration and wintering periods. Furthermore, flycatchers will regularly disperse long distances and move to different sites between years; however, the reasons behind these movements are not well known (U.S. Fish and Wildlife Service, 2002). These realities complicate interpretation of population trends in the study area and the evaluation of potential impacts of the operations of Glen Canyon Dam.

Over the last 30 yr, the population of breeding southwestern willow flycatchers in upper Grand Canyon has been very small and limited to riparian patches between approximately RM 28 and 71. From 1982 to 1991, 2 to 11 male flycatchers were detected annually, with a maximum of 4 nests in any 1 yr (Brown, 1988, 1991b). Between 1992 and 2003, only 1 to 5 territories were found in any year (Sogge and others, 1997; Johnson, 2000; Paradzick and Woodward, 2003; Yard, 2004a). Flycatchers bred only in the relatively larger patches, and breeding patch size ranged from 1.5 to 2.2 acres (0.6–0.9 ha). Breeding patches were dominated by tamarisk, and all nests had been placed in tamarisk (Sogge and others, 1997; Yard, 2004a). Overall, the southwestern willow flycatcher population in the upper river corridor continues to persist at a very low level, at only one or two sites.

In 1995, breeding flycatchers using one territory were first noted in newly developed native riparian habitat in the Lake Mead delta area, immediately downstream of the Grand Canyon-Lake Mead boundary. The following year this population reached 10 territories, but the delta was flooded during the next 2 yr by rising reservoir levels, and flycatchers were no longer present by 1998. Beginning in 1998, breeding southwestern willow flycatchers were discovered at a variety of upstream sites within lower Grand Canyon between RM 246 and 273 (Paradzick and Woodward, 2003). It is possible that birds found before 1998 breeding downstream, in what is now inundated delta habitat, moved upstream to the lower Grand Canyon reach. Between 1998 and 2001, 7–12 flycatcher territories were recorded in lower Grand Canyon; however, recent surveys in 2002 and 2003 found no breeding flycatchers in lower Grand Canyon (Smith and others, 2003, 2004) and only 2 territories in 2004 (McLeod and others, 2005; Munzer and others, 2005).

Nesting success in the upper Grand Canyon flycatcher population is generally low, and the population is probably not self-sustaining (Sogge and others, 1997). Breeding success in lower Grand Canyon is not well documented, but the lack of detections in 2002 and 2003 suggests that productivity from 1998 to 2001 was probably too low to provide for continued population persistence. Recent habitat changes along the lower river corridor caused by the changing reservoir levels in Lake Mead, however, have probably affected flycatcher site occupancy.


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## California Condor

The California condor is one of the rarest birds in the world and was federally listed as endangered in the United States in 1967. In Arizona, reintroduction was conducted beginning in 1996 under a special provision of the Endangered Species Act of 1973.

Condors are opportunistic scavengers that feed primarily on large, dead mammals such as deer, elk, bighorn sheep

(*Ovis canadensis*), range cattle, sheep, and horses. Condors can soar and glide up to 50 mi/h (80 km/h) and travel 100 mi (161 km) or more per day in search of food. They are long lived, living up to 60 yr, with low reproductive rates. Most nest sites have been found in caves, on rock ledges, or in tree cavities (Snyder and Schmitt, 2002; Arizona Game and Fish Department, 2004).

In prehistoric times, condors ranged from Canada to Mexico, across the Southern United States to Florida, and to the east coast in New York. Based on evidence from bones, feathers, and eggshells found in caves, condors were a resident of Grand Canyon. A dramatic range reduction occurred about 10,000 yr ago, coinciding with the late Pleistocene extinction of large mammals that condors depended on for food (Arizona Game and Fish Department, 2004). Settlement of the Western United States, shooting, poisoning from lead and DDT, egg collecting, and general habitat degradation resulted in further dramatic population reductions (Snyder and Schmitt, 2002). Between the mid-1880s and 1920s, there were scattered reports of condors in Arizona, with the last sighting near Williams, Ariz., in 1924. By the late 1930s, all remaining condors were found only in California, and by 1982 the total population had dwindled to just 22 birds (Snyder and Schmitt, 2002; Arizona Game and Fish Department, 2004).

The U.S. Fish and Wildlife Service, The Peregrine Fund, Arizona Game and Fish Department, National Park Service, and other collaborators established a condor captive-breeding and release program in Arizona. Vermilion Cliffs National Monument is the main reintroduction site, and birds released at this site frequent Grand Canyon. Since December 1996, the Arizona restoration project has released approximately 6–8 birds per year. There are now over 30 condors flying free in Arizona, and natural reproduction is occurring in the Grand Canyon region: in late 2004, 2 wild-hatched chicks stretched their wings and successfully fledged. As part of the continuing reintroduction project, individual condors will continue to be monitored daily (Arizona Game and Fish Department, 2004).

Many of the reintroduced condors have been observed within the Grand Canyon ecoregion. Although typically seen soaring overhead, condors regularly bathe and sun themselves along the banks of the Colorado River (Andi Rogers, Arizona Game and Fish Department, oral commun., 2005). It is likely that the population of condors in the region will continue to increase because of continued reintroduction efforts and natural increase. Since condors make little use of riparian habitat and are not typically found along the edge of the river, there are no likely effects of MLFF operations. The only dam management actions likely to affect this species would be those that resulted in available carrion such as dead fish along the river corridor, which could attract concentrations of feeding condors.


George Andrejko, Arizona Game and Fish Department

## Bald Eagle

Bald eagles are common breeders in Alaska and parts of Canada but are far less numerous in the contiguous United States, where they were once critically endangered. Because of extensive and successful recovery efforts since the 1960s, many bald eagle populations have increased, and in 1995 the U.S. Fish and Wildlife Service downlisted the species from endangered to threatened in the lower 48 States.

Although still somewhat rare as a breeder in Arizona, hundreds of bald eagles migrate into the State each winter; eagle numbers in Arizona increased from 225 in 1992 to 440 in 2001 (Beatty, 2001). Wintering eagles typically concentrate along rivers, lakes, and reservoirs where preferred prey, including fish, waterfowl, and carrion, is readily available (Grubb and Kennedy, 1982; Brown, 1993). The Grand Canyon ecoregion is one such concentration area, and eagles are generally present from November through March, which coincides with trout spawning and an abundance of waterfowl within the corridor. Within the study area, bald eagles are found primarily from Lees Ferry downstream to the confluence of the Little Colorado River. From 1991 to 1995, the maximum daily number of eagles detected during helicopter surveys of this reach ranged from 11 to 24 individuals (van Riper and Sogge, 2004). The Colorado River corridor in Grand Canyon hosted only 5%–10% of the wintering eagles present in Arizona on any given day during this time, but the total number of eagles using the corridor over an entire season may be substantially more (van Riper and Sogge, 2004). Systematic corridor-wide surveys were not conducted before or after the 1991–95 period.

Bald eagles often congregate at Nankoweap Creek (RM 52), a small tributary to the Colorado River in which rainbow trout sometimes spawn in large numbers.

Eagles have concentrated here since the early 1980s (Brown and others, 1989; Leibfried and Montgomery, 1993). From 1986 to 1995, maximum daily eagle counts ranged from 4 to 26, with the number of eagles varying directly with the abundance and availability of trout in the creek (Brown and Stevens, 1992; Leibfried and Montgomery, 1993; van Riper and Sogge, 2004). Neither the size of trout spawn nor eagle abundance at Nankoweap Creek was related to dam release levels (van Riper and Sogge, 2004). There is also no evidence that eagle abundance throughout the river corridor is affected by river flow, although it is likely that river turbidity affects the ability of eagles to forage for fish along the mainstem.

Human disturbance can affect bald eagles. Brown and Stevens (1997) and van Riper and Sogge (2004) documented disturbance of wintering bald eagles by humans, including flushing of eagles by hikers, rafters, anglers, and research activity. Hikers in the Nankoweap Creek delta area caused the greatest disturbance to the eagles there, but such disturbances were reduced in years when a visitor-use closure was instituted.

Evaluating the effects of the operations of Glen Canyon Dam and other management activities on bald eagles is complicated by the fact that eagle abundance in Grand Canyon is influenced by both local conditions and regional factors. Furthermore, bald eagles will travel long distances in search of abundant, easily available prey (Stalmaster, 1987) and can move readily between food concentrations at Grand Canyon, Lake Powell, and other regional lakes and rivers. Nevertheless, habitat use by foraging eagles is strongly influenced by fluctuating river flows; high flows reduce eagle foraging habitat diversity, lower foraging success in river habitat, and restrict foraging opportunities (Brown and others, 1998).

Management changes that alter prey availability could alter eagle abundance and distribution within the Grand Canyon ecosystem. For example, if the selective withdrawal of warmer water from Lake Powell increases the numbers of carp, catfish, and suckers (Hunt and others, 1992), more food resources may be available to eagles. Eagles may have more difficulty foraging along the river, however, if trout numbers decrease and/or spawning is reduced, either through water temperature/turbidity changes or through nonnative fish removal efforts.


George Andrejko, Arizona Game and Fish Department

## Peregrine Falcon

Dramatic declines in peregrine falcon populations led to the addition of the peregrine to the Federal List of Endangered and Threatened Wildlife in 1970, where it was listed as endangered. Following successful recovery efforts, the peregrine falcon was delisted in 1999. The Endangered Species Act requires a minimum 5 yr of post-delisting monitoring in cooperation with State agencies to confirm recovery.

The peregrine commonly breeds in cliffs and uses open landscapes for foraging. Nest sites are usually associated with water (White and others, 2002). In winter, some breeders stay in their nesting areas, and others may migrate.

Diet of the peregrine consists mostly of birds, from songbirds to small geese. They also occasionally eat mammals, especially bats (White and others, 2002). During the breeding season, peregrine falcons in the Grand Canyon ecoregion feed on white-throated swifts (*Aeronautes saxatalis*), swallows, and bats (Brown, 1991a). In winter, they feed mainly on waterfowl. Many of their prey items feed on invertebrate species, especially flies (Diptera), that emerge out of the Colorado River (Stevens and others, 1997b).

Given these life-history traits, any impacts to peregrine falcons from dam operations are likely to be indirect, possibly through influences on the distribution and abundance of aquatic macroinvertebrate populations, which in turn would influence the availability of the peregrine's prey items such as swifts, bats, and ducks.

The Grand Canyon peregrine population was thought to be low in the mid-1970s and apparently increased dramatically in the 1980s (U.S. Fish and Wildlife Service, 1984; Ellis and Monson, 1989; Ward, 2000). In 1981 and 1982, two nests or "eyries" were found during surveys between the Tanner and Bright Angel Trails. In 1998 and 1999, 12 eyries were found in these same areas (R.V. Ward, Grand Canyon National Park, oral commun., 2005). During the same period, the National Park Service conducted surveys throughout appropriate habitat within Grand Canyon National Park, including along the river corridor, and concluded that the peregrine population in Grand Canyon appeared stable since 1988 (Ward, 2000).

## Recent Findings

Kearsley and others (2004) examined the interrelationships between vegetation and animal life, including birds, as part of a monitoring project for terrestrial riparian resources that took place from May 2001 to May 2003. Preliminary findings regarding terrestrial breeding birds showed patterns similar to those of previous studies. More breeding pairs and higher species diversity were detected at larger sites (Yard and Blake, 2004). Vegetation density was found to be an important component of habitat quality for riparian breeding birds in the Grand Canyon ecoregion, with the densities of most bird species positively correlated with the abundance of mesquite and acacia (Kearsley and Lightfoot, 2004). No difference was found in the abundance of birds over the 3 yr of the study although sample sizes were too low to analyze trends (Yard and Blake, 2004). The most commonly detected breeding species were the same as those in previous studies (Brown and others, 1987; Sogge and others, 1998; Spence, 2004).

## Discussion and Future Research Needs

The construction of Glen Canyon Dam and the subsequent changes in the hydrograph of the Colorado River resulted in dramatic changes in the amount of available habitat for both the riparian breeding and the overwintering aquatic bird communities within the Colorado River ecosystem. Perennial plant species, especially tamarisk, colonized areas previously scoured by floods, creating new riparian patches in the high-water zone. These areas provide habitat for over 30 species of breeding birds, including many Neotropical migrants and the endangered southwestern willow flycatcher. Increased river clarity and productivity below the dam provide suitable habitat for many aquatic bird species such as ducks, loons, grebes, and cormorants.

Patterns of abundance and distribution of riparian breeding birds and overwintering riparian and aquatic birds within the study area are now well known. Less well known are the long-term effects of adaptive management and the management activities needed to ensure the continued conservation of riparian resources, their associated avian communities, and bird species of conservation concern. Continued monitoring would be required to address these information needs.

Monitoring riparian breeding birds to detect population changes requires considerable commitments of both time and effort to obtain sufficient data for biological and statistical significance. Data from the 1996 to 2000 breeding bird monitoring program were used by Spence (2004) to determine the adequacy of the monitoring program to detect changes in bird populations. He found that trends could not be detected for 24 of 32 (75%) riparian breeding species and that 5 to 30 yr of sampling were required to detect a 10% change in species abundance. Half of the 16 most common species included in the analysis would require over 10 yr of monitoring to detect a 10% population change, while 5 rarely detected species cannot be monitored by using the sampling protocols tested in the analyses (Spence, 2004).

An alternative approach to continued monitoring of riparian birds would be to use aerial photography, remote sensing, and geographic information systems (GIS) in order to measure habitat variables within the study areas that have been shown to predict bird numbers, richness, and diversity (Sogge and others, 1998). Key variables for monitoring would include the size and distribution of riparian patches, area of NHWZ and OHWZ woody species, and measures of total vegeta-

Mark K. Sogge, U.S. Geological Survey

tion volume; however, simply monitoring habitat quality and extent may miss potential changes in selected bird species caused by factors within the study area other than riparian vegetation dynamics and may miss potentially profound changes in some bird species (Spence, 2004).

Existing data, collected in previous studies, could be used to better model and predict how future changes in the riparian vegetation will affect changes in terrestrial avifauna populations within the Grand Canyon ecoregion. In particular, it would be valuable to extend the current models of bird community and patch-level habitat variables (Sogge and others, 1998; Spence, 2004) to the level of individual bird species. This extension would allow the development of more useful conceptual models and more detailed predictions regarding avian resources in the Grand Canyon ecoregion. For example, models developed by Sogge and others (1998) predicted that changes from tamarisk shrub/tree to willow shrub/tree are not likely to greatly affect overall bird abundance and species richness within riparian patches in Grand Canyon, yet individual species have specific behavior, physiology, and ecology, and some may decline in response to such habitat changes. Extending models to individual species would allow identification of species that may be sensitive to future changes in the riparian vegetation.

Riparian woodlands, such as those within the Grand Canyon ecoregion, provide vital habitat for bird species of conservation concern and support the highest diversity of landbird species of all habitats in the Southwest (Rich and others, 2004). Dam operations affect birds within the ecoregion primarily through effects on breeding habitat. Under the MLFF alternative, these impacts are likely to be fairly minor compared with climate and habitat changes outside the Colorado River corridor. Thus, the Grand Canyon ecoregion is likely to continue to be an important resource for riparian birds. A well-designed monitoring program that takes into account sampling design and statistical power can be used to establish baseline values regarding the distribution and abundance of specific species from which future comparisons can be made over time. If monitoring data are linked to information regarding ecological resources and habitat requirements for specific species and the monitoring is conducted in conjunction with more regional, large-scale monitoring, insight into the causes of population changes and the effects of management actions may result (Holmes and others, 2005).

Dam operations have been shown to be directly linked to overwintering aquatic birds through effects on primary and secondary productivity; thus, they may be a useful resource to monitor. Overwintering aquatic birds can be monitored relatively easily because more than 50% of the aquatic birds occur at or above Lees Ferry in a typical winter. Further study is necessary, however, to determine how to structure any future aquatic bird monitoring program (Spence, 2004).


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Continued monitoring of species of special concern would require continuation or development of monitoring protocols specific to each species. In particular, the southwestern willow flycatcher population in Grand Canyon is extremely small relative to the current range-wide population, which encompasses approximately 1,400 territories (U.S. Geological Survey, unpub. data, 2004). Because flycatcher monitoring must follow a standard, multivisit protocol, conducting such surveys within the study area requires substantial resources. Overlaying this protocol is the challenge of relating river flows to any direct or indirect impacts to the flycatcher and its habitats. The potential impacts of tamarisk removal associated with riparian restoration projects should also be considered. Therefore, the nature and extent of future flycatcher monitoring, and the ability to interpret its results, may be worthy of discussion within the Glen Canyon Dam Adaptive Management Program. Bald eagles have not been systematically or intensively monitored along the Colorado River since 1995; nevertheless, eagles are still noted during some winter research raft trips (Yard, 2004b). van Riper and Sogge (2004) evaluated various monitoring techniques and noted that helicopter-based surveys would be the most effective method in terms of coverage and ability to detect the eagles. On the other hand, aerial surveys would have to be considered in light of potential recreation issues and current and future Grand Canyon National Park policies. Logistical difficulties associated with access make surveying for peregrine falcons in Grand Canyon National Park extremely difficult, and a thorough sample using unbiased or random methodologies has been impossible

(Ward, 2000). Despite these difficulties, the National Park Service will monitor at least five territories within the park (R.V. Ward, Grand Canyon National Park, oral commun., 2005), and Glen Canyon National Recreation Area will monitor one or more territories above Lees Ferry starting in 2005.

Many factors and processes apart from dam operations affect the structure and functioning of the Grand Canyon ecosystem, such as changes in regional climatic and atmospheric conditions, natural disturbances, adjacent land uses, the spread of invasive species, and fire suppression. These natural and human-caused events, along with adaptive management actions, have affected and will continue to affect the abundance, distribution, and composition of the Grand Canyon bird communities and their habitats.

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# Chapter 8

# Debris Flows in Grand Canyon and the Rapids of the Colorado River

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Thomas C. Hanks

## Introduction

Coarse sediment—gravel, cobbles, and boulders—is transported to the Colorado River almost exclusively by debris flows, which are irregularly occurring types of flash flood events. By supplying boulders that exceed the capacity of the river to move them at most discharges, debris flows create and maintain the hundreds of debris fans and associated rapids that control the lengthwise or longitudinal profile of the Colorado River in Grand Canyon. Debris flows occur in 740 tributaries of the Colorado River in Grand Canyon between Lees Ferry (at RM 0) and the Grand Wash Cliffs (at RM 277), the physical feature that marks the western boundary of Grand Canyon National Park and the end of Grand Canyon.

Coarse sediment is of interest within the Glen Canyon Dam Adaptive Management Program because of its relation to key components of the Colorado River ecosystem. The deposition of coarse-grained sediment at tributary junctures builds large debris fans that constrict the river and form rapids. Debris fans and debris bars, which develop below rapids, create the fan-eddy complex that is the cornerstone of the physical framework of the river in Grand Canyon (fig. 1). In addition, the pools upstream and downstream of debris fans slow sediment movement or trap it for temporary storage. The pool-drop system created by debris fans is prime habitat for the endangered humpback chub (*Gila cypha*), while coarse sediment injected into the river during debris flows is used by other aquatic organisms, notably the alga *Cladophora glomerata*. The navigation of the river by whitewater boaters also can be affected by debris-flow events.

Monitoring the input of coarse sediment into the Colorado River ecosystem and its long-term redistribution by the river is critical to understanding how dam operations affect coarse sediment deposition and, indirectly, other ecosystem components. Scientists are able to model debris-flow magnitude and frequency from extensive data sets developed through long-term monitoring. Also, this chapter estimates the amount of sediment contributed by debris flows and models its deposition at tributary junctures to evaluate the effects of debris flows over several temporal and spatial scales, including the recent period of operations of Glen Canyon Dam. Data are combined with modeling to evaluate long-term changes in rapids and to explain large-scale features. The chapter also summarizes data from debris-fan monitoring activities by the U.S. Geological Survey's

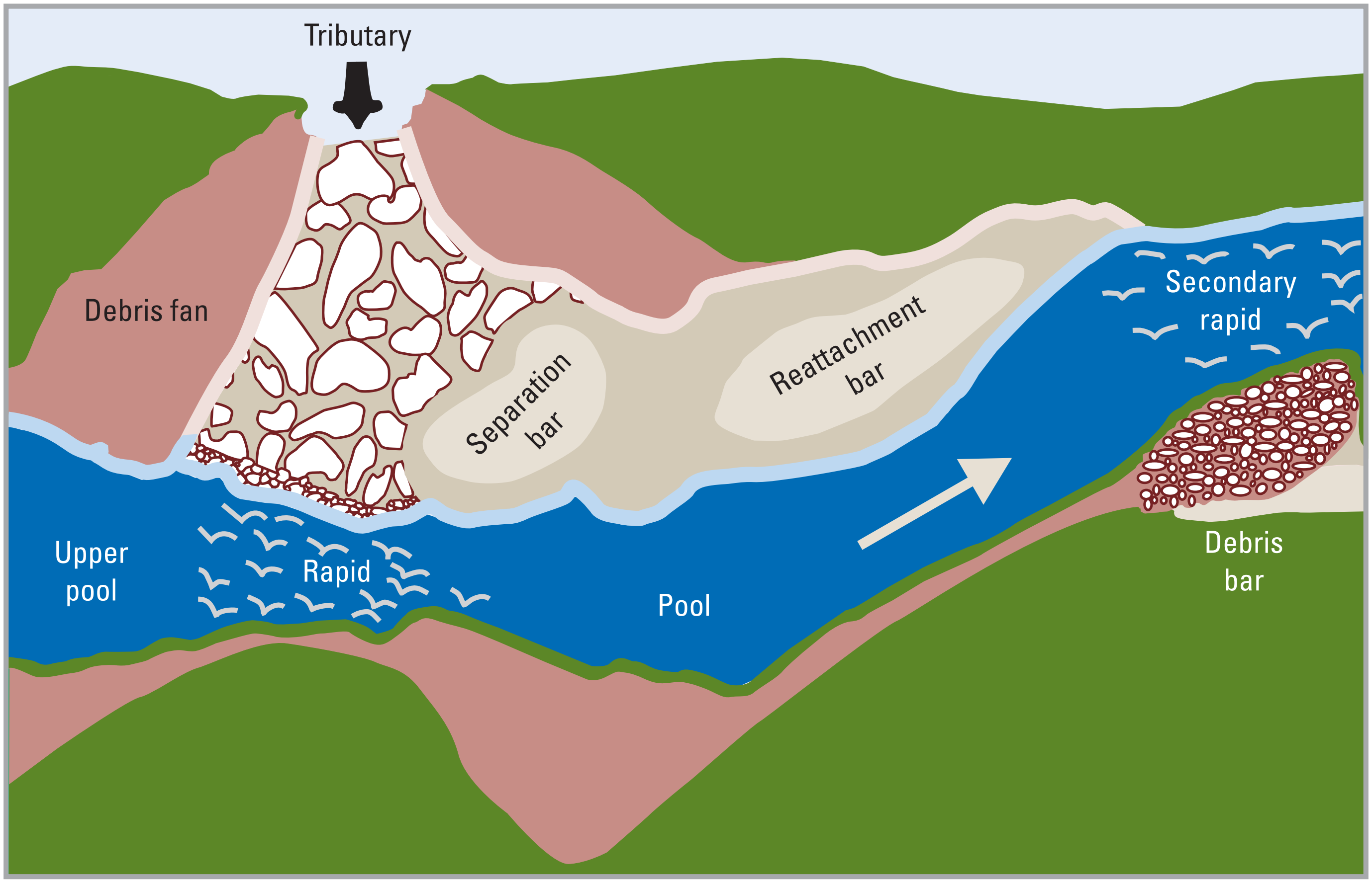

**Figure 1.** Diagram showing a fan-eddy complex in Grand Canyon. Debris flows from tributary canyons carry coarse sediment that is deposited at the juncture with the Colorado River, forming deposits called debris fans. Debris fans constrict the Colorado River and raise its bed elevation, creating rapids. Especially during floods, the river entrains the sediment on the debris fan and transports it downstream through the pool, where the larger particles become lodged on debris bars that form secondary rapids. Between the constrictions of the primary and secondary rapids, pools and eddies form, creating a depositional setting for sandbars.

(USGS) Grand Canyon Monitoring and Research Center (GCMRC) and research by Water Resources and Geology Discipline scientists. Finally, the chapter considers the role of experimental high flows and the modified low fluctuating flow (MLFF) alternative on coarse-sediment reworking.

## Background

Distributed along 277 mi (446 km) of river between the Paria River and Grand Wash Cliffs, the 740 tributaries that produce debris flows drain 4,600 mi$^2$ (12,000 km$^2$) of steep terrain between the north and south rims of Grand Canyon (Webb and others, 2000). Debris flows, which are typically more than 80% sediment by weight, are slurries of clay to boulder-sized sediment mobilized during periods of intense or sustained precipitation. The exposed bedrock landscape of Grand Canyon National Park provides an ideal setting for the initiation of debris flows: high relief combines with differential rock strength to create a high potential for slope failure (Griffiths and others, 2004). Most slope failures that become debris flows (75%) occur in the Hermit Formation and Esplanade Sandstone of the Supai Group and in the Muav Limestone and Bright Angel Shale of the Tonto Group (fig. 2a). Other prominent sources include the Dox Sandstone, Cardenas Lava, Vishnu Schist, and Quaternary Basalts in western Grand Canyon. Tributaries are documented to have produced debris flows throughout the Holocene (Melis and others, 1994; Hereford and others, 1998).

In Grand Canyon, debris flows are initiated by a combination of intense precipitation and subsequent slope failure (Cooley and others, 1977; Webb and others, 1988, 1989, 1999b, 2000, 2004; Griffiths and others, 2004). The most common type of slope failure is termed the “firehose effect” (Melis and others, 1994) (fig. 2b), where streamflow falling over cliffs, typically in the Redwall Limestone, strikes bedrock and accumulated colluvium and causes slope failure and mixes these materials and water to form a slurry. Debris flows that reach the Colorado River deposit their material on debris fans. These enlarged or aggraded debris fans constrict the river and raise the riverbed elevation until mainstem flows rework coarse-grained deposits (Webb and others, 1989). “Reworking” is a term describing river entrainment and transport of particles from debris fans, including the winnowing of fine-grained particles (clay to cobble size) and the movement of boulders, either on the fan surface or into the river. The large boulders that remain after this reworking form the core of rapids that modify the longitudinal profile of the river and locally control the physical framework of the present-day Colorado River in Grand Canyon (Webb, 1996).

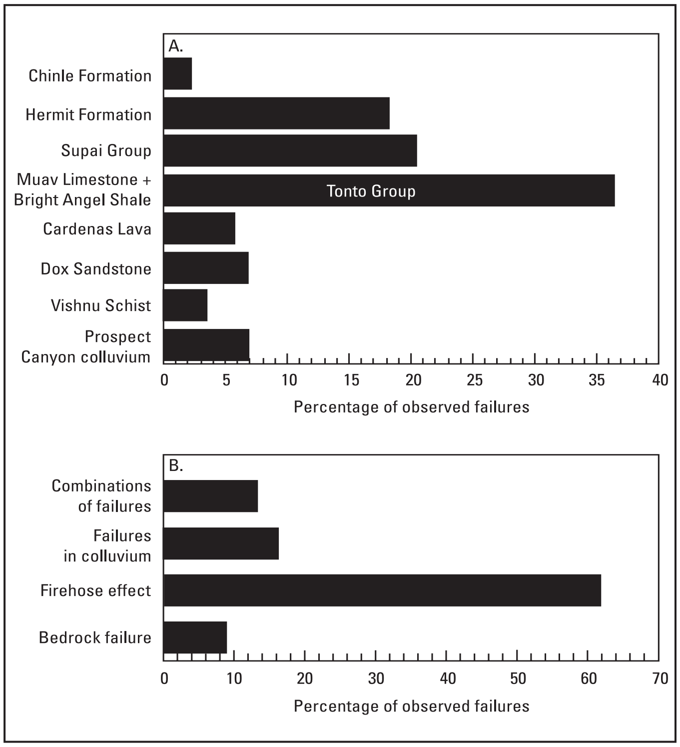

**Figure 2.** A. Relative frequency of the location at which slope failures in bedrock or colluvium resulting in debris flows that reach the river (n = 101, 1939 through 2003) have occurred in Grand Canyon. B. Relative frequency of initiation mechanisms for selected debris flows from 1939 through 2003 in Grand Canyon (n = 68) (from Griffiths and others, 2004).

Debris-fan reworking was extensive before construction of Glen Canyon Dam. Reduced peak flow on the regulated river represents a fourfold decrease in its sediment-transport potential compared to predam conditions (Howard and Dolan, 1981). As a result, ability of the river to erode newly deposited sediment from debris fans has been reduced. Reworking still occurs on a limited basis, typically during maximum powerplant releases or intentional flood releases from Glen Canyon Dam (Webb and others, 1999a). Today, because the reworking by the Colorado River is limited, debris flows from unregulated tributaries are now an effective agent of change in the river corridor (Howard and Dolan, 1981), affecting the water-surface profile, hydraulics through rapids, and the associated pools and eddies downstream.

# Status and Trends

## Debris-flow Frequency

Debris flows in Grand Canyon were relatively well documented in the 20th century (Webb, 1996; Webb and others, 2000; Griffiths and others, 2004). We use the term Grand Canyon loosely to collectively refer to the river corridor from Lees Ferry to the Grand Wash Cliffs, merging Marble and Grand Canyons and their respective subreaches. Direct observations provided a complete record of debris flows from 1984 to 2004 (fig. 3), which was augmented with repeat photography, such as that shown in figure 4, that provides a separate record (1890 through 1983) of debris flows from 147 tributaries. In this analysis, we only documented debris flows that reached debris fans and/or the Colorado River; we did not include debris flows that occurred upstream in tributaries but did not reach the river corridor.

### Direct Observations (1984–2004)

Debris flows, rockfalls, and significant streamflow floods were directly observed or compiled from the accounts of river runners along the river in Grand Canyon from 1984 through 2004. These data provide a complete record of debris flows that reached the Colorado River from all Grand Canyon tributaries for more than 21 yr (fig. 3). During this period, a total of 104 events occurred in 88 tributaries for an average of 4.95 debris flows per year. A total of 14 debris flows occurred in 2001 and again in 2002, the most prolific period in the record. Webb and others (2000) analyzed

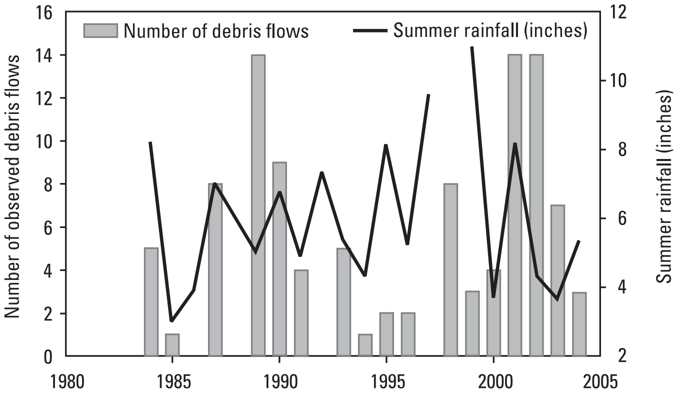

**Figure 3.** Observational record of debris flows in Grand Canyon, from 1984 to 2004, compared with total summer rainfall (July through September) at Grand Canyon National Park airport. No data are available for summer precipitation in 1997.

precipitation records around Grand Canyon and found that the annual number of debris flows is not related to total summer precipitation (as illustrated by the precipitation record shown in fig. 3 in conjunction with annual debris flows). This suggests that antecedent moisture has little effect on debris-flow occurrence (Griffiths and others, 2004).

Most debris flows occurred in Marble Canyon or eastern Grand Canyon, with notable exceptions at Lava Falls Rapid (RM 179) in 1995 (Webb and others, 1999b) and between RM 189 and RM 209 from 1999 through 2001. Several tributaries delivered more than one debris flow to the river between 1984 and 2004. For example, Seventyfive Mile Creek had four debris flows, and Monument Creek (RM 93.9) had three. Multiple debris flows within a drainage basin suggest that slope and channel destabilization caused by the initial event may lead to repeated events until either the loosened sediment is removed or sufficient time elapses between severe storms to allow healing of hillslopes and channel margins.

## Repeat Photography and Debris Flows (1890–1983)

Repeat photography (fig. 4) has been used in numerous studies in Grand Canyon to document long-term changes in both terrestrial ecology and geomorphology (Turner and Karpiscak, 1980; Stephens and Shoemaker, 1987; Webb and others, 1989, 1999a; Melis and others, 1994; Webb, 1996; Griffiths and others, 2004). This type of scientific photography is particularly useful for

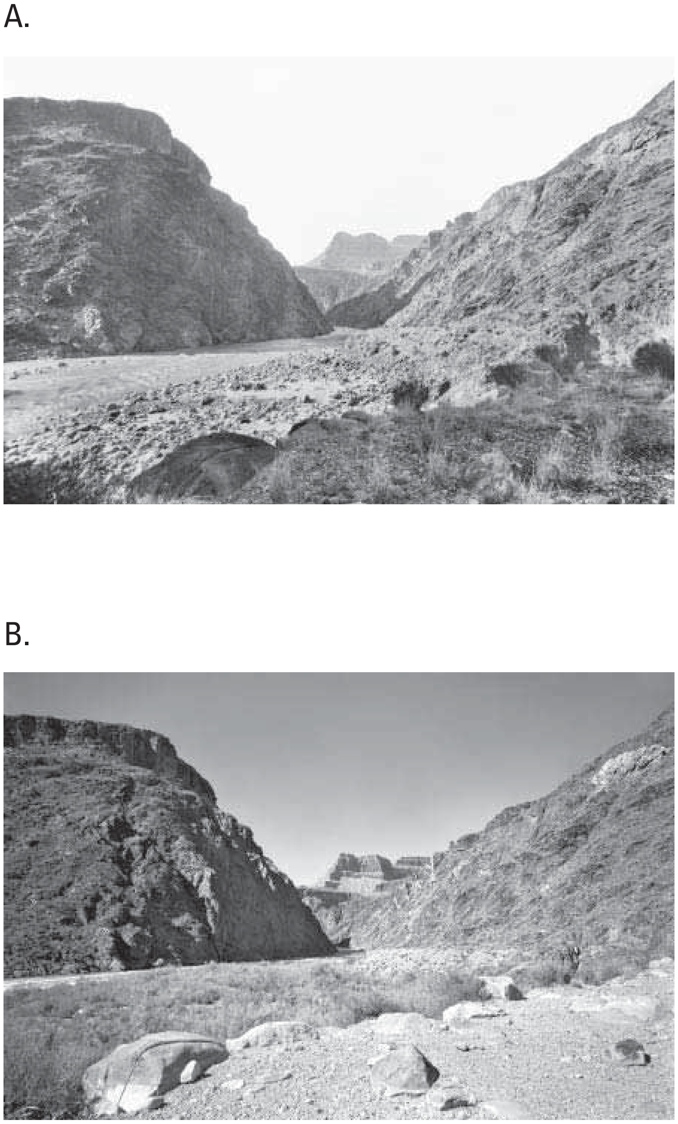

**Figure 4.** Repeat photographs of Crystal Rapid. A. (February 9, 1890) This downstream view from the right scout point at Crystal Rapid (RM 98) shows a wide, gentle rapid during the second expedition through Grand Canyon. This expedition, led by Robert Brewster Stanton, occurred in winter 1890. The deepest water in the rapid is on river right, and emergent rocks are on the left side (R.B. Stanton, courtesy of the National Archives and Records Administration, College Park, Maryland). B. (February 1, 1990) A debris flow in 1966 constricted the river by more than 80%, creating what was considered the most formidable rapid in Grand Canyon. Floods between 1966 and 1986 widened out the constriction, reducing the navigational hazard this rapid posed. Although Crystal Rapid has lost some of its ferocious reputation, it remains one of the largest in Grand Canyon (T. Brownold, stake 1471).

evaluating the types of landscape changes associated with debris flows. Most of the information for historical debris flows was obtained through comparison of repeat photography and historical photographs taken between 1871 and 1964. Between 1989 and 2002, 1,365 historical photographs of the river corridor were matched to determine significant changes to tributary channels, debris fans, and rapids throughout the canyon. The year with the most abundant and widespread coverage is 1890, when the well-documented Stanton expedition occurred (Webb, 1996). Several sets of low-altitude aerial photographs taken between 1935 and 1984 were also analyzed for evidence of debris flows at the river.

To determine the frequency of debris flows at the river from 1890 through 1983, the 1890 photographs and their matches were interpreted for evidence of debris-flow occurrences at 147 debris fans. This process revealed that debris flows occurred at 84 of 147 tributaries (Griffiths and others, 2004), indicating that 57% of the tributaries generated one or more events from 1890 through 1983. Because any of these 84 tributaries could have delivered more than one debris flow, additional data, such as written accounts, were used to identify a total of 93 debris flows from the 84 tributaries over a period of a century. From 1890 through 1983, 6% of tributaries produced two or more debris flows, including five at Lava Falls Rapid (RM 179) (Webb and others, 1999b).

Analysis of aerial photograpy identified an additional 23 debris flows for a total of 107 debris flows that occurred between 1890 and 1983 at the mouths of 167 tributaries from Glen Canyon Dam to Separation Rapid (RM 240), the head of Lake Mead. Using this data set as an unbiased sample of the entire population of 740 tributaries, the rate of debris-flow occurrence at the river is estimated at 5.0/yr for all tributaries from 1890 through 1983. This rate is essentially identical to the 4.95/yr frequency observed between 1984 and 2004. If the results for both records are combined, 211 debris flows are known to have occurred along the Colorado River in Grand Canyon between 1984 and 2003.

## Net Observed Effects of Debris Flows

Of the documented 211 historical debris flows in 172 tributaries, 55 significantly affected the Colorado River by creating rapids or increasing constrictions during the past century (Webb, 1996; Webb and others, 2000; Griffiths and others, 2004). From 1984 through 2004, 8 rapids were created, and 15 were constricted by debris flows. The observational evidence indicates that the occurrence of debris flows is not spatially random in Grand Canyon. Debris flow activity is particularly concentrated in Marble Canyon and other reaches where the river trends towards the southwest or south-southwest. The findings indicate that about 10% of tributaries had two or more debris flows in the last century, with a maximum of six debris flows at Lava Falls Rapid (Webb and others, 1999b) and five debris flows at Seventyfive Mile Creek during the 20th century.

## Modeling Debris-flow Frequency

Griffiths and others (1996) developed a model of debris-flow frequency (1890–1990) in Grand Canyon between Lees Ferry and Diamond Creek (RM 0 to RM 226), and Webb and others (2000) extended that model to the Grand Wash Cliffs (RM 277). The model identified several parameters that are significantly related to the occurrence of debris flows that reach the river, including the presence and location of shale in the basin, drainage-basin area, mean drainage-basin gradient, and the aspect of the river corridor. Drainage-basin variables that are the most significant in influencing the occurrence of debris flows are suggested in a map showing the distribution of debris-flow probabilities (fig. 5). One tendency is for debris-flow frequency to decrease when the river corridor trends away from a southwesterly course; Griffiths and others (2004) attributed this to the regional trajectory of summer storms, which tend to move from the southwest. The effect of drainage-basin area is evident in Marble Canyon, where the largest tributaries have a higher probability of debris-flow occurrence. The height of the Hermit Formation and the gradient from this unit to the Colorado River appear to be especially important in Marble Canyon and reflect the dominant contribution of shale units to debris flows in Grand Canyon.

In eastern Grand Canyon, a greater variety of source materials, combined with structural variability, resulted in a mosaic of probabilities (fig. 5). The presence of and gradient below shales strongly affect debris-flow probability. River aspect and drainage-basin area are significant but less influential in this reach. Certain sections of the river corridor that trend northwesterly generally have tributaries with low probabilities. In western Grand Canyon, the presence of three source formations and the overall gradient of each tributary from headwaters to river strongly influenced debris-flow probability. The height of the Hermit Formation is less influential in western than eastern Grand Canyon or Marble Canyon

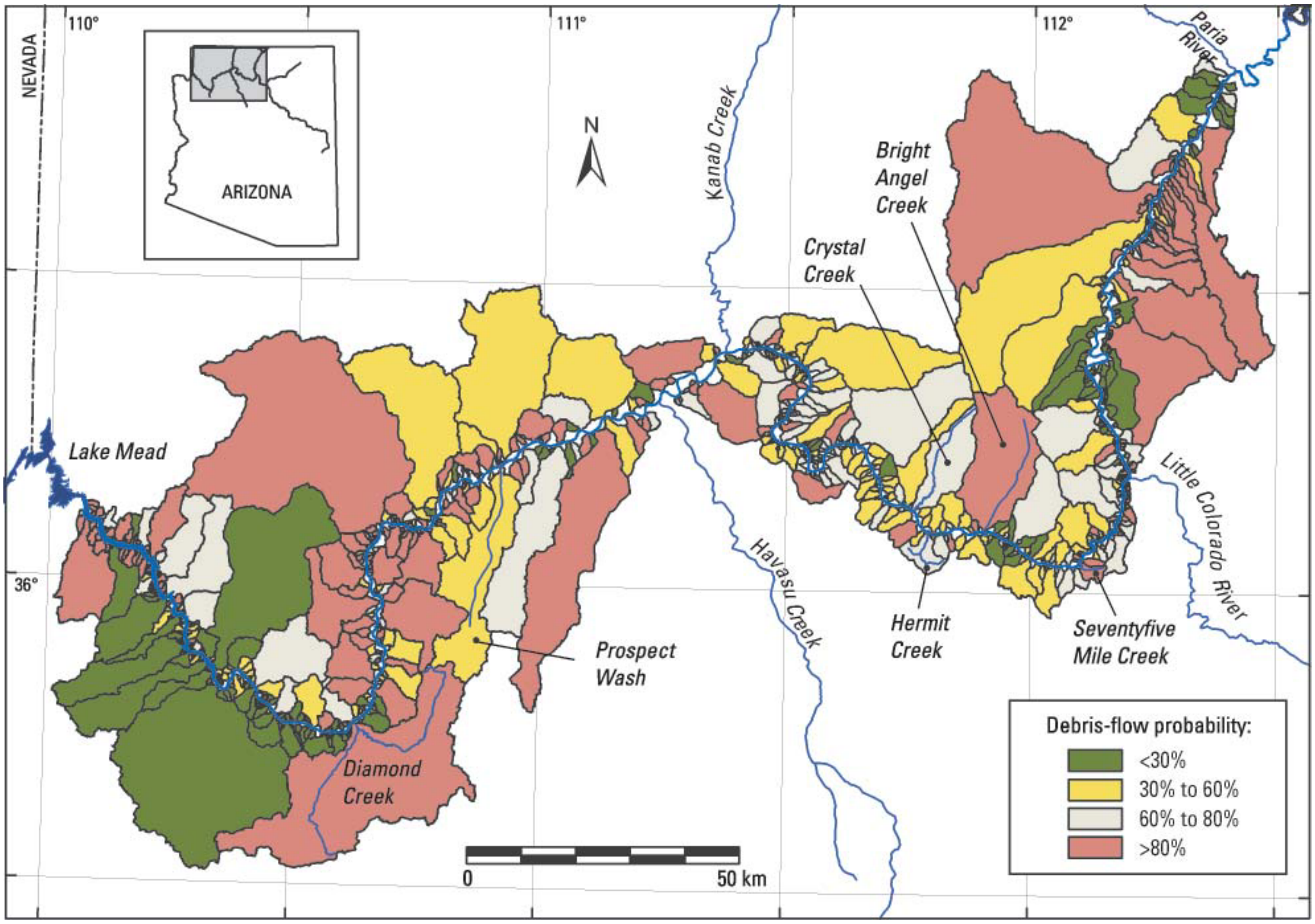

**Figure 5.** Debris-flow probabilities of 740 tributaries of the Colorado River in Grand Canyon (Griffiths and others, 2004). This map depicts group probabilities of the occurrence of one or more debris flows in a tributary during the century between 1890 and 1990.

because that formation is farther from the river. Debris-flow probability is lowest downstream from Diamond Creek, where the river trends northwesterly, except in the reach immediately upstream from the Grand Wash Cliffs, where debris-flow probabilities are high because of the proximity of shales to the river corridor.

Our observations and statistical analyses show that (1) all 740 Grand Canyon tributaries produce debris flows, albeit some at a low frequency; (2) about 60% of tributaries produce one or more debris flows per century; (3) about 10% of tributaries produce two or more debris flows per century; and (4) no tributary has produced more than six debris flows in the last century.

## Debris-flow Sediment Yield

Data on debris-flow frequency, volume, and particle-size distributions were combined to create a model of debris-flow sediment yield in Grand Canyon (Webb and others, 2000). Using this model, it is estimated that debris flows contribute between 155,000 and 325,000 tons/yr (141,000 and 295,000 Mg/yr) of sediment to debris fans in Grand Canyon. Marble Canyon contributes the greatest amount of debris-flow sediment, which is consistent with both empirical observations and the modeled distribution of debris-flow occurrence in Grand Canyon (Griffiths and others, 2004).

Modeling debris-flow sediment yield requires a number of important assumptions. In this case, it was assumed that all debris flows from a given tributary were the same size, which means the model does not realistically depict a magnitude-frequency relation. Furthermore, the sediment-yield model does not account for extreme events not included in the historical record and small events that are inadequately represented. Some of these problems could be resolved by using a fully stochastic model of debris-flow frequency, but objectively determining model constraints based on the limited data would be difficult.

Incorporating an average boulder content of 14% of debris-flow volumes (Melis and others, 1994; Webb and others, 1999b, 2000), the total boulder delivery from all 740 tributaries is 1.1 billion $ft^3$ (31 million $m^3$) per thousand years. Distributing these boulders evenly along the river corridor without removal, dissolution, or erosion raises the bed by 2.4 ft (0.7 m) per thousand years, which we consider to be a reasonable order of magnitude. To distribute boulders more realistically, deposition was limited to the areas of recent debris fans, calculating the area of deposition at each tributary confluence as a rectangle defined by the length and average width of the rapid. For each confluence, local bed rise was calculated by dividing the total volume of sediment delivered by debris flow by the estimated area of deposition; these results were reported in Webb and others (2000, 2004).

## River Reworking of Aggraded Debris Fans

In the years immediately following a debris flow, Grand Canyon rapids are known to be unstable because of reworking by the Colorado River (Howard and Dolan, 1981; Kieffer, 1985; Webb and others, 1989, 1999b; Melis and others, 1994). Before closure of Glen Canyon Dam in 1963, the Colorado River removed most debris-flow deposits during the early summer floods, which averaged 82,000 cubic feet per second (cfs) and were as large as 220,000 cfs. Those flood events swept all but the largest particles downstream and redeposited cobbles and small boulders on debris bars that constrained the extent of eddies and controlled secondary rapids. The interaction between the frequency and magnitude of tributary debris flows and mainstem floods resulted in debris fans and rapids that were relatively stable in the intervening time periods between debris flows.

Lava Falls Rapid offers one of the best documented cases of debris-fan reworking, which occurred during the 1996 beach/habitat-building flow (fig. 6) and during other floods in the predam and postdam periods (Webb and others, 1999b). Most of the reworking that occurred during the 1996 event happened as the discharge increased to its peak; reworking slowed markedly during the first day of peak discharge. Nine radio-tagged boulders traveled an average distance of 262 yards (240 m) from their initial positions on the Prospect Canyon debris fan during the 1996 event (Pizzuto and others, 1999; Webb and others, 1999b). Debris-flow deposits in 1939, 1954, 1955, 1963, and 1966 were also reworked by subsequent floods; some of the aggraded debris fans (1954, 1963, 1966) were completely removed, while some of the deposition (1939, 1955) remained to cause persistent changes in Lava Falls Rapid.

While Kieffer (1985) stated that exceptionally large floods (>400,000 cfs) are required to completely rework some aggraded debris fans, Magirl and others (2005) found several examples of debris flows that were effectively removed by modest floods. For example, an 8 to 10 ft (2.4 to 3.0 m) drop at Doris Rapid was nearly completely removed by a 220,000-cfs flood in 1921. Also, a 3.0 ft (0.91 m) riffle at To Hajisho Wash (RM 28.5) in 1923 was completely removed by the 127,000-cfs flood in 1927. While we do not dispute that the amount of reworking increases with the magnitude of floods, effective reworking and redistribution of coarse sediment can occur at a variety of flood discharges and are heavily dependent on particle size of the aggraded debris fan, the elapsed time between debris flow and reworking flood, and the stream power available to transport sediment from a specific debris fan.

Webb and others (1999a) reported that reworking decreases with the time elapsed between the debris flow and the flood event because average releases may interlock particles into an overlapping network, significantly increasing the force necessary to dislodge and carry particles from debris fans. This process that leads to interlocked particles, which is the net result of physical rearrangement, abrasion of particle-particle contact points, and differential dissolution at contact points, is termed "suturing." Suturing is common on debris fans that have not had debris-flow aggradation historically, and we have observed some suturing on recently aggraded debris fans, such as 18 Mile Wash (1987 debris flow) and 127.6 Mile Wash (1989 debris flow), on the distal margin where submergence occurs frequently. The documented occurrence of suturing provides compelling reason to decrease the elapsed time between controlled flood releases, if reworking of aggraded debris fans is a priority.

To understand how rapids have changed over time, water-surface profiles from 1923 and 2000 were compared to detect geomorphic change (Magirl and others, 2005). Magirl and others (2005) compared the longitudinal profile surveyed in 1923 (U.S. Geological Survey, 1924) with a profile constructed from lidar data taken in 2000. Ninety-one tributary junctures along the Colorado River in Grand Canyon between Lees Ferry and Diamond Creek were evaluated for change. These sites represent 39% of all rapids and 67% of named rapids. At these 91 locations, 11 rapids were known to have not changed between 1923 and 2000, 6 rapids exhibited a rise in the elevation at the head of the rapid of 4.6 ft (1.4 m) or more, and the elevation at the head of 2 rapids

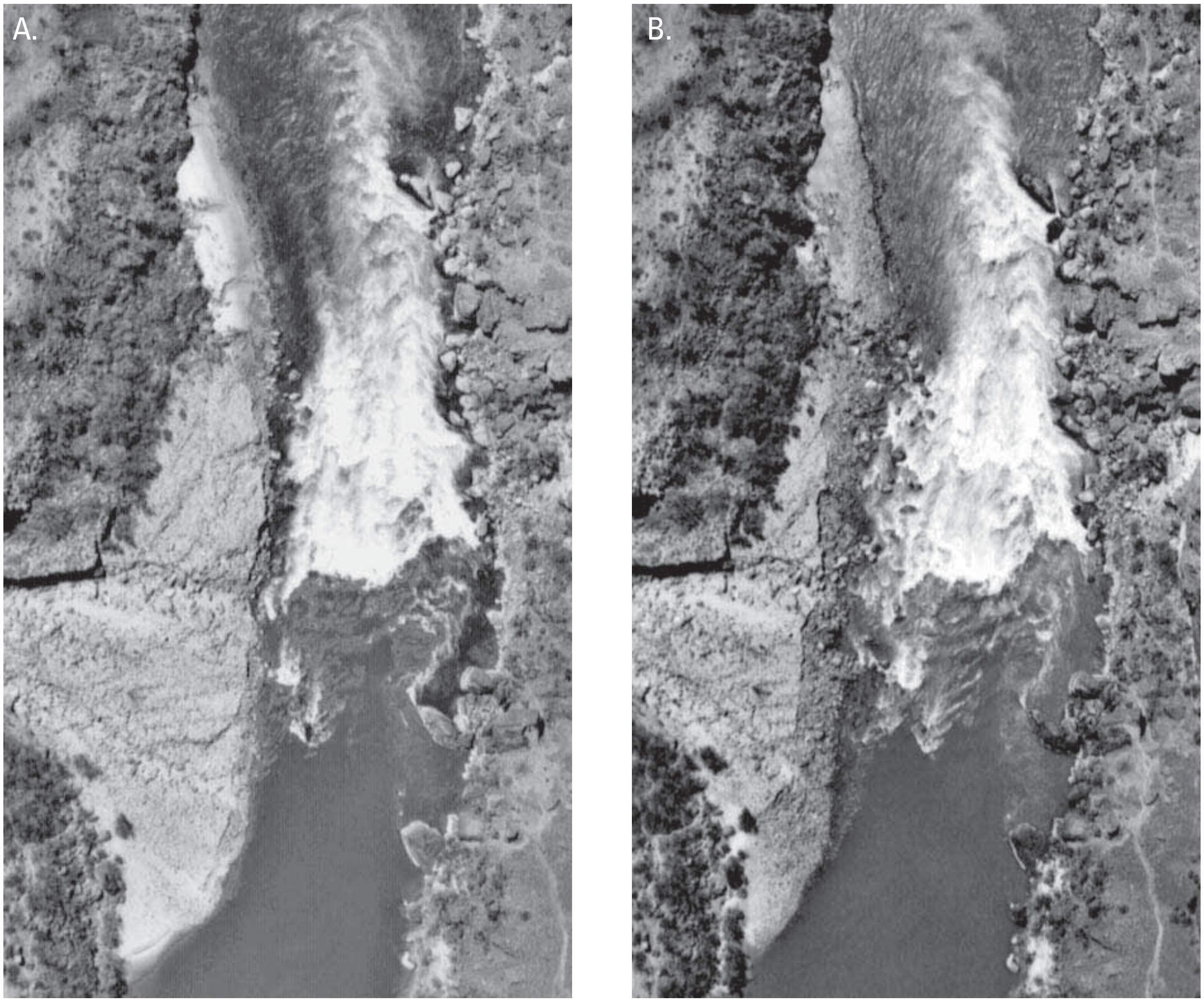

**Figure 6.** Changes in Lava Falls Rapid (RM 179) during the 1996 beach/habitat-building flow. The river flows from bottom to top in these views. A. (March 24, 1996) The 1995 debris flow from Prospect Canyon (left side of the views) constricted the river by about 60%. This view shows the freshly deposited sediments with no vegetation on river left (left side of the view). B. (April 9, 1996) Reworking by the 1996 beach/habitat-building flow, which had a peak discharge of about 47,500 cfs at Lava Falls Rapid, removed 208,000 $ft^3$ (5,900 $m^3$) of the aggraded debris fan, increasing the width of the rapid by an average of 16 ft (5 m) (photographs courtesy of Grand Canyon Monitoring and Research Center, U.S. Geological Survey).

decreased more than 4.6 ft (1.4 m). The net change at 91 rapids is shown in figure 7. More rapids aggraded (18) than degraded (7) for elevation changes greater than or equal to 2.3 ft (0.7 m), which is the threshold of detectable elevation change. Moreover, elevation increases were consistently larger than elevation decreases. Of the 10 debris fans associated with the largest elevation increases, 8 were aggraded by one or more known debris flows since 1923 (table 2 in Magirl and others, 2005). Of the five debris fans associated with the largest elevation decreases, only two had debris flows since 1923 (Magirl and others, 2005). Finally, the average elevation of pools at the heads of rapids was 0.85 ft (0.26 m) higher in 2000 than in 1923.

Comparison of the 1923 and 2000 profiles also reveals the interaction between rapids as a result of debris-flow deposition (fig. 8). The 1966 debris flow at Crystal Rapid (RM 98) caused a rise in river level several miles upstream, which drowned out the tailwaves of Boucher Rapid to create what river runners refer to as “Lake Crystal.” The 1951 debris flow at Boucher Rapid had the opposite effect on the tailwaves of Hermit Rapid. The result was one of the larger hydraulic features in Grand Canyon, the notorious fifth wave in

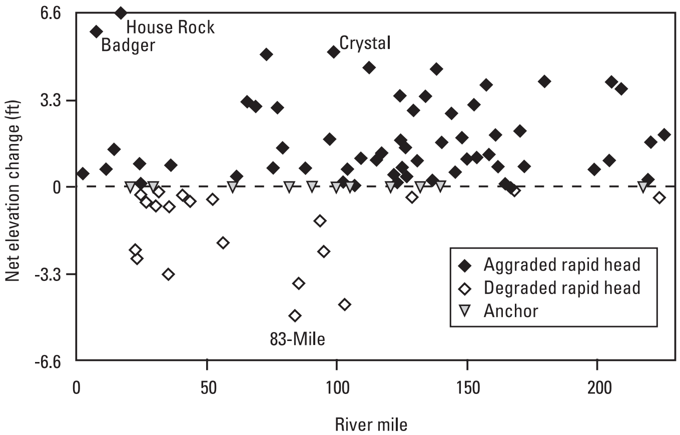

**Figure 7.** Net elevation change in 91 rapids of the Colorado River in Grand Canyon between 1923 and 2000. The locations of rapids that did not change between 1923 and 2000 and were therefore used to anchor the change in longitudinal profiles are shown as inverted triangles.

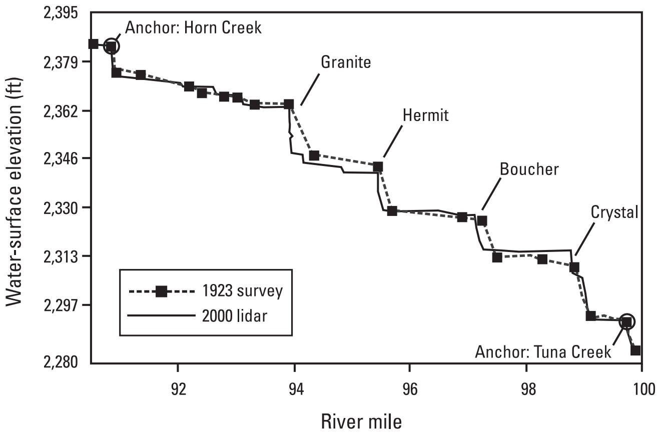

**Figure 8.** Comparison of 1923 and 2000 water-surface elevation profiles in upper Granite Gorge in Grand Canyon. Despite three debris flows, the head at Granite Rapid has changed little in 77 yr, but its drop has steepened. In contrast, aggradation from the 1966 debris flow at Crystal Rapid is clearly visible in the comparison, and this aggradation affects Boucher Rapid upstream. Likewise, a 1951 debris flow at Boucher Creek has affected Hermit Rapid upstream.

Hermit Rapid, which is a compressional wave associated with the jet of the rapid entering a backwater controlled by an aggraded Boucher Creek debris fan.

Leopold's (1969) analysis of the pool-and-rapid morphology of the Colorado River, which is one of the more widely referenced figures, presents the cumulative vertical drop of the river as a function of distance as measured in 1923 for the first 150 mi (241 km) below Lees Ferry. Leopold concluded that 50% of the total drop occurred in only 9% of the length of the river. In 2000, 66% of the total drop in river occurred in 9% of the length over the 227 mi (365 km) below Lees Ferry. When only the first 150 mi (241 km) of river is considered for direct comparison with Leopold (1969), 71% of the total rapid occurs in 9% of the length (fig. 9), reflecting the greater amount of aggradation in Marble Canyon and eastern Grand Canyon compared to western Grand Canyon.

## Impacts of Dam Operations on Aggradation

Operations of Glen Canyon Dam have long been hypothesized to increase aggradation of the riverbed by limiting the reworking of debris fans (Howard and Dolan, 1981; Kieffer, 1985; Webb and others, 1989; Melis and others, 1994; Griffiths and others, 2004). Glen Canyon Dam has reduced peak discharges on the Colorado River, which now has insufficient stream power to transport particles more than 3 ft (0.91 m) in diameter, except during maximum powerplant releases or intentional flood releases and even then only at the largest rapids. Cobbles and boulders carried from debris fans by the regulated Colorado River appear to be redeposited in the pool immediately downstream of the debris fans instead of on the debris bar farther downstream (Pizzuto and others, 1999; Webb and others, 1999b). This altered pattern of redeposition reflects a change in the geomorphic framework of the Colorado River; in the case of Granite Rapid, repeated debris flows and modest reworking from 1984 through 2003 have resulted in a lengthening of the rapid tailwaves through the pool and into the secondary riffle.

Many rapids in the Colorado River system have become larger during the last 30 yr because debris-fan constrictions and individual boulders cannot be totally removed by typical dam releases (Graf, 1979; Howard and Dolan, 1981; Melis and others, 1994; Webb, 1996). Continued deposition of coarse sediment into the river channel by debris flows will likely fill deeper pools above and below rapids while also enhancing the size of eddies; however, with the notable exception of the Crystal Rapid debris flow of 1966, most rapids affected by recent debris-flow aggradation are less hazardous to navigation. Exposed or shallowly submerged rocks are significant navigational obstacles, and debris-fan aggradation tends to narrow the channel, increasing flow depths and either removing or submerging existing rocks. At the same time,

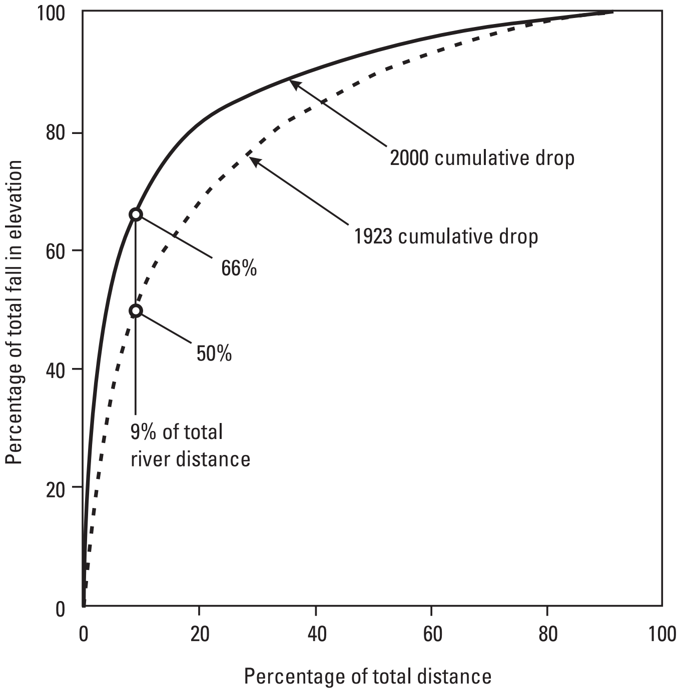

**Figure 9.** Comparison between the cumulative vertical drop of the river in 1923 (data from Leopold, 1969) and the cumulative vertical drop in 2000 (Magirl and others, 2005).

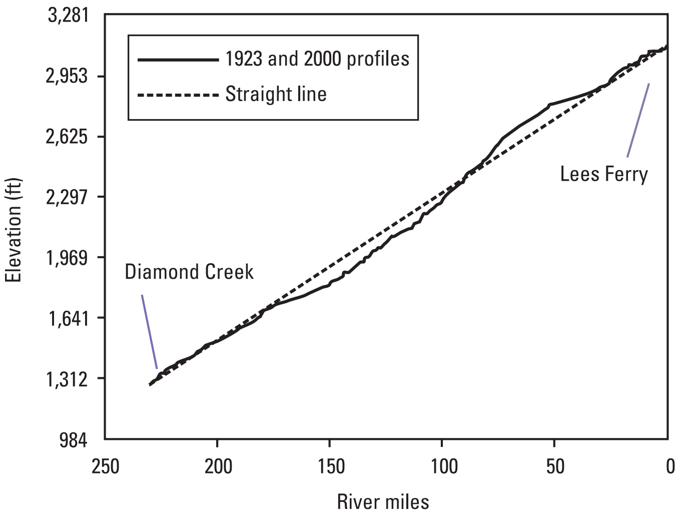

**Figure 10.** The longitudinal profile of the Colorado River through Marble and Grand Canyons (Lees Ferry to Diamond Creek) as surveyed in 1923 (U.S. Geological Survey, 1924) and as measured by using lidar in 2000 (from Magirl and others, 2005; Hanks and Webb, in press). At this scale, differences in the 1923 and 2000 profiles (see fig. 8) are not apparent. The straight line represents the average river gradient and illustrates profile convexities that appear to be related to debris-flow deposition in the Colorado River.

the drops through these rapids are steeper, and sizes of waves are typically larger; these changes could lead to increased incidence of boat flips.

## The Longitudinal Profile of the River

Hanks and Webb (in press) interpreted the longitudinal profile of the Colorado River through Grand Canyon in relation to debris-flow sedimentation at rapids. Rapids represent short-wavelength (about 0.6 mi (1 km)), small-amplitude (less than about 16 ft (5 m)) convexities (areas that round outward from the riverbed) in the longitudinal profile of the river, arising from the shallow gradient in the upstream pool and the steep gradient through the rapid itself. The kinds of changes detected in the comparison of the 1923 and 2000 profiles (Magirl and others, 2005) discussed previously cannot be as easily detected when the longitudinal profile of the Colorado River is displayed for the length of Grand Canyon (fig. 10).

Analysis of the entire longitudinal profile through Grand Canyon reveals two river-profile convexities that are long-wavelength (about 62 mi (about 100 km)), large-amplitude (49 to 98 ft (15 to 30 m)) river-profile convexities (Hanks and Blair, 2003; Hanks and Webb, in press): the eastern canyon convexity between RM 30 and RM 80 and the western canyon convexity between RM 160 and RM 250. Both of these convexities are easily discernable in figures 11 and 12. These large-amplitude convexities have strong spatial correlations with high probabilities of debris-flow occurrence, high densities of debris fans, and the largest debris fans along the river. Convexities of intermediate scale are also identified in the longitudinal profile. River-profile convexities require an active and powerful geologic process to maintain them, in this case the abundant, frequent, and voluminous debris-flow activity in Grand Canyon. Presumably for all of the Holocene and at least some of the late Pleistocene, the Colorado River has been expending its energy transporting sediment within Grand Canyon, integrating short-wavelength convexities into long-wave-

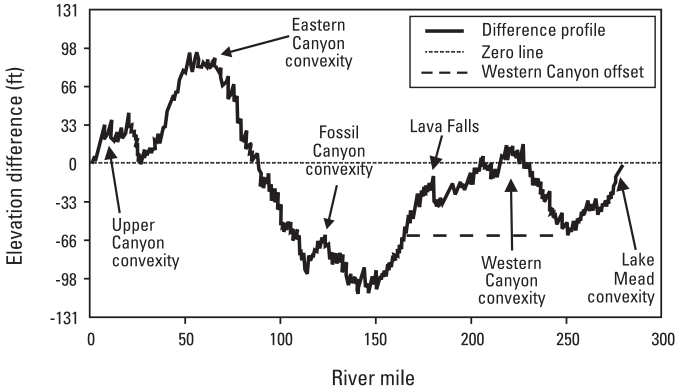

**Figure 11.** A profile of the difference in elevation (ft) between the longitudinal profile of the Colorado River between Lees Ferry and the Grand Wash Cliffs and its average gradient (both are shown in fig. 10). The Western Canyon offset shows that this convexity likely has a larger magnitude if the true bedrock profile were known. Convexities discussed in this chapter are shown on the profile.

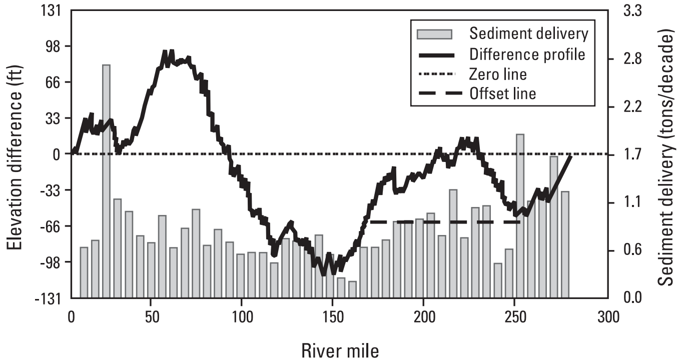

**Figure 12.** A profile of the difference in elevation (ft) between the Colorado River and an average gradient (fig. 11) compared with a reach-averaged sediment yield for debris flows as calculated by using a stochastic model (Webb and others, 2000).

length convexities. This suggests that little or no bedrock incision has occurred during about the last 11,000 yr.

Detrending of the longitudinal profile (fig. 11) reveals the magnitude of convexities and allows comparison with other features along the river corridor. For example, the largest convexities coincide with reaches that contain 13 of the 14 largest debris fans (Hanks and Webb, in press). In addition, the locations and areas of the 444 Holocene debris fans between Lees Ferry and Diamond Creek (Melis, 1997) coincide with fluctuations in the difference profile (Hanks and Webb, in press).

Hanks and Webb (in press) compared debris-flow probabilities (calculated from fig. 5) averaged over 12.4-mi (20-km) intervals with this difference profile and found that the highest debris-flow probabilities have a strong association with intermediate and long-wavelength convexities. The falling limbs of the Eastern and Western Canyon convexities are both associated with decreasing debris-flow probabilities as they enter the upper and lower Granite Gorge, respectively, reflecting the decrease in the rate of tributary sediment delivery in these reaches. As shown in figure 12, the reach-averaged sediment yield from the debris-flow sediment-yield model is also associated with profile convexities, although the association is less than for the probabilities alone.

Several overall characteristics of the river corridor appear to be associated with the characteristics of long-wavelength convexities. The presence of abundant emergent islands in the river is associated with the tops of the convexities where overall slopes are relatively low. Cultural sites on fine-grained sediment deposits appear to be most common on the tops of large-scale convexities as well. The largest rapids on the river appear to be associated with the falling limbs of convexities (Hanks and Webb, in press). This latter characteristic may result from both the increased reach-scale gradient on the falling limbs of the convexities and a greater spacing between rapids, which minimizes interaction between the drops.

# Summary and Management Implications

Debris flows transport poorly sorted sediment onto debris fans in the Colorado River at a frequency that varies through Grand Canyon. Historically, an average of 5.0 debris flows per year has occurred in Grand Canyon. The occurrence of these debris flows does not appear to be related to seasonal precipitation amounts. Modeling debris-flow frequency in Grand Canyon based on the interpretation of 1,365 photographs of the river corridor yielded frequency information in 167 of 740 tributaries (23%). Of the 167 tributaries, 98 (59%) had debris flows during the last 100 yr.

Frequency estimates indicate that 57% of the tributaries had at least one debris flow per century, while about 10% of the tributaries had a frequency of more than two debris flows per century. Estimates of sediment yield to the Colorado River in Grand Canyon by debris flow are as high as 3.3 million tons (3.0 million Mg) of sediment per decade, of which 452,000 tons (410,000 Mg) are boulders larger than 10 inches (>256 mm) in diameter. Distributed evenly throughout the river corridor, these boulders would raise the bed in Grand Canyon by 2.3 ft per thousand years (0.72 m per thousand years). If deposition is limited to existing debris fans at tributary mouths, these boulders would raise the bed by an average of 8.66 ft (2.64 m) per thousand years at each confluence.

By combining the frequency model with relations for debris-flow volume and particle-size distribution, debris-flow sediment yields were calculated for several time periods. On average, debris flows deliver between $0.15 \cdot 10^6$ and $0.33 \cdot 10^6$ tons/yr ($0.14 \cdot 10^6$ and $0.30 \cdot 10^6$ Mg/yr) of sediment to the main channel. Although debris flows deliver only 23,142 to 48,488 tons/yr (21,000 to 44,000 Mg/yr) of boulders to the river, these boulders control the longitudinal profile and geomorphic framework of the river, defining debris fans, rapids, and related sandbars, and are unlikely to be removed by regulated flows. Moreover, the effects of debris flows are shown to affect the river on several length and temporal scales.

Comparison of the two water-surface profiles (one surveyed in 1923 and one in 2000) showed a change in 80 rapids. The average elevation of pools at the heads of rapids was 0.85 ft (0.26 m) higher between 1923 and 2000, indicating net aggradation of the coarse-grained sediment forming the rapids throughout Grand Canyon. Furthermore, comparison of the two water-surface profiles showed enhanced pool-and-rapid structure; while 50% of the total drop of the river occurred in just 9% of the river distance in 1923, that figure increased to 66% by 2000. Reconstruction of water-surface profiles showed that debris-flow deposition can also have large upstream effects, particularly in the cases of reducing gradients between rapids and reducing the fall in the upstream rapid.

Analysis of the entire longitudinal profile through Grand Canyon reveals convexities that reflect sustained debris-flow deposition. Specifically, there are two long-wavelength (about 62 mi (about 100 km)), large-amplitude (49 to 98 ft (15 to 30 m)) river-profile convexities: the eastern canyon convexity between RM 30 and RM 80 and the western canyon convexity between RM 160 and RM 250. These large-amplitude convexities have strong spatial correlations with high probabilities of debris-flow occurrence, high densities of debris fans, and the largest debris fans along the river. These convexities appear to be maintained by debris-flow activity in Grand Canyon, presumably for all of the Holocene. In this period, the Colorado River has been expending its energy transporting sediment within Grand Canyon and integrating short-wavelength convexities into long-wavelength convexities, with little or no bedrock incision.

Coarse-sediment fill in the channel of the Colorado River at any wavelength has its origins in the rapids, which result from the tributary debris flows and fans that feed them. In contrast, the amount of fill in the rapids, either individually or collectively, is a small volume compared to the fill that creates the longer wavelength convexities. Periodic channel maintenance floods are not likely to perform the transport necessary to create the long-wavelength convexities, although reworking of locally aggraded debris fans is clearly feasible. The river-reworking processes by which point-source contributions of debris-flow sediment are aggregated into longer wavelength convexities are as yet unknown and certainly involve a more detailed understanding of the flood dynamics of the predam river. Nevertheless, the close spatial associations of the longer wavelength convexities with the locations and sizes of debris fans and with the frequency of debris flows lead to the conclusion that unusual accumulations of debris fill in the channel are their principal cause, just as they are for the rapids.

In terms of adaptive management and operations of Glen Canyon Dam, reworking of aggraded debris fans has been shown to be feasible. Reworking has been documented during modified low fluctuating flow releases, maximum powerplant releases, and flood releases up to 47,500 cfs. Both reworking and transport capacity increase with increasing discharge, which suggests that flood releases larger than powerplant capacity of about 33,500 cfs are more efficient than smaller events. Because reworking mostly occurred in the rising limb of flood hydrographs, large-magnitude floods designed for debris-fan reworking do not have to have significant duration. As shown in figure 13, a flood designed

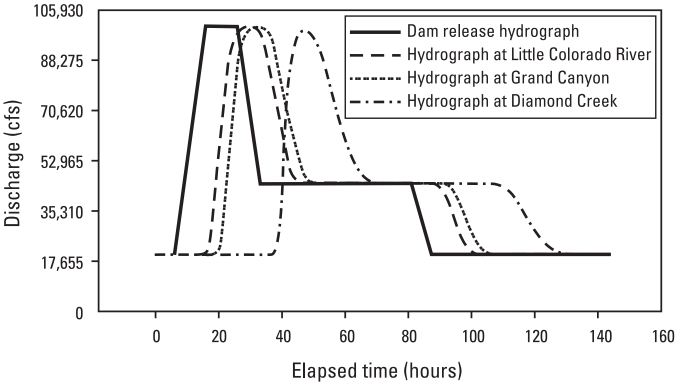

**Figure 13.** Hypothetical Glen Canyon Dam release and flow hydrographs designed to create a peak discharge of 100,000 cfs for 1 min at Diamond Creek, followed by a beach-building discharge of 45,000 cfs for a duration of 2 d.

to rework debris fans could have a peak discharge of 100,000 cfs for only 1 min at Diamond Creek then drop rapidly to a beach-building discharge for several days. This type of management prescription may be only used every 5 to 10 yr, with smaller intervening releases.

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# Chapter 9

# Recreation Use Values and Nonuse Values of Glen and Grand Canyons

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## Introduction

Grand Canyon and Glen Canyon are unique natural environments valued worldwide, providing world-class recreational activities and habitat for wildlife and endangered fish. This chapter discusses the various economic values of the Grand Canyon and Glen Canyon ecosystems, how these values are measured, and what we know about them. The economic value of the services provided by these ecosystems is also discussed. Other chapters in this report address related topics, including the potential effects of Grand Canyon campsite availability on recreation (chapter 12) and the hydropower values of Glen Canyon Dam (chapter 10).

This chapter focuses on how recreation use and economic values are influenced by alternative river flow regimes and Glen Canyon Dam operations. Recreation is of interest within the Glen Canyon Dam Adaptive Management Program for several reasons. First, the Grand Canyon Protection Act (GCPA) of 1992 expressly mentioned recreation as one of the three elements to be monitored. Specifically, the act stated that "long-term monitoring . . . shall include any necessary research and studies to determine the effect of the Secretary's actions . . . on the natural, recreational and cultural resources of Grand Canyon National Park and Glen Canyon National Recreation Area" (GCPA, sec. 1805(b)). Second, because Glen Canyon is a national recreation area and recreation is one of the dual mandates of national parks (Loomis, 2002), the effects of alternative dam operations on recreation should be expected to receive significant attention. Third, recreation use and value are of interest in an integrated scientific research effort because of potentially important linkages between various ecosystem components. For example, it becomes important to understand how changes in river flows influence trout size and abundance and how changes in fish population in turn influence recreation use and value.

As noted previously by the National Research Council (1999, p. 13), however, there has not been regular, systematic, or comprehensive monitoring of the effects of alternative flow regimes and other operational changes on recreation use and public values. Therefore, this chapter draws from research conducted over the last two decades to summarize the available information on recreation use, benefits, and public values of Grand and Glen Canyons. This partial information is the best available at the present time to inform adaptive management (see Overview, this report) of Grand and Glen Canyons about the consequences of operational changes on recreation use and public values.

# Background

## Types of Economic Values Provided by Glen and Grand Canyons

Economic values can be divided into three main categories: (1) visitor use values such as recreation, (2) local economic effects associated with visitor spending that supports commercial outfitters, hotels, restaurants, and towns such as Page, Arizona, and (3) public nonuse values.

### Use Values to Visitors

Most people are familiar with the local economic effects of visitor spending and the positive economic impacts of recreation and tourism in the form of jobs and local income. In addition, the visitors themselves also receive economic benefits from the actual recreation experience in the form of what is termed "consumer surplus." This consumer surplus represents the monetary measure of the increase in economic well being that a visitor receives, and would be willing to pay, over and above the existing cost of the recreational trip. Consumer surplus, or net willingness to pay, is the federally recommended measure of benefits for use by agencies such as the Bureau of Reclamation when conducting benefit-cost analyses (U.S. Water Resources Council, 1983).

As an example of consumer surplus, consider the case of private whitewater boating on the Colorado River through Grand Canyon. A private boater experiencing a long awaited and possibly once-in-a-lifetime trip would likely pay more for the trip than just the travel costs to Grand Canyon in order to enjoy a 2-week float trip. This extra value or consumer surplus realized on these trips may be influenced by the river flows, as minimal flows will reduce the size of some rapids, as well as the time available for stopping at side canyons and visiting cultural sites.

### Local Economic Effects of Visitor Spending

While visitor expenditures are a cost to the visitor, they create positive, direct economic effects in the local area in the form of additional income and employment in the retail sector. The ripple, or multiplier effects, of such spending reverberates to the wholesale and distribution sectors that supply the retail sector. This second round of economic stimulation is known as indirect effects. Further, a portion of the money received by employees as wages and profits to business owners gets respent in the local economy on other consumer goods and services. These respent portions are often referred to as induced effects. The regional multiplier is the sum of these direct, indirect, and induced effects divided by the direct effect (Douglas and Harpman, 1995; Loomis and Walsh, 1997; Minnesota Implan Group, 1997). Thus, the local economic effects of recreation include employment and income that originate from the economic sectors directly catering to tourists but also include many other sectors indirectly affected by recreation spending.

### Nonuse Values

Nonuse values include the benefits that people derive from simply knowing that a unique and irreplaceable natural environment or species exists even if the individual does not visit it or see it. This component of nonuse value is often called "existence value." Nonuse values also include a bequest value from knowing that protection today provides the unique natural resources to future generations. The unique natural environment of Grand Canyon was used as an example in the seminal article on existence value by Krutilla (1967, p. 778). Krutilla also noted that continued existence of a threatened and endangered species (e.g., humpback chub (*Gila cypha*)) would also generate existence values.

The U.S. Department of the Interior officially recognized existence values in 1986 when it included these values in procedures to calculate natural resource damages from hazardous substances (U.S. Department of the Interior, 1986). The inclusion of nonuse values was broadened by the U.S. District Court of Appeals decision (1989), which referred to nonuse values as passive-use values, and indicated that both use and passive-use values must be considered when performing a natural resource damage assessment. The concept of nonuse values and its empirical measurement by using surveys were given a qualified endorsement by a blue ribbon panel commissioned by the National Oceanic and Atmospheric Administration and chaired by two Nobel laureates (Arrow and others, 1993). The potential role of nonuse values in policy analysis for the Glen Canyon Environmental Studies program is discussed in Harpman and others (1993). The growing acceptance of including nonuse values in valuation of ecosystems is evident in the latest National Research Council (2005, p. 6) report, which states, "economic valuation of changes in ecosystem services should be based on . . . both use and nonuse values."

Of course, what is relevant for this chapter is how the nonuse values of Grand Canyon change with alternative dam operations that affect the native species in Grand Canyon for current and future generations. We will discuss the one study, performed in 1994, that measured nonuse values for changes in natural resources in Grand Canyon (Welsh and others, 1995). Unfortunately, there have been no follow-up studies to measure how nonuse values have changed as a result of stabilization of river flows, beach building, and recovery efforts for the humpback chub.

## Empirical Measurement of Use and Nonuse Values

### Recreation Use Values

To estimate visitor benefits or consumer surplus, there are two broad categories of methods: (1) those that rely upon actual behavior or what are called "revealed preference methods" and (2) those that rely upon intended behavior or what are called "stated preference methods." The travel cost method (TCM) for estimating recreation demand is an example of a commonly used revealed preference method. The basic TCM uses variations in visitors' travel costs as a proxy for the price of a trip and the number of trips taken as a measure of quantity to trace out a demand curve for recreation at the particular site. From the demand curve, the consumer surplus or net willingness to pay (WTP) can be measured (Loomis and Walsh, 1997). More recent TCM models involve a random utility model of site choice to reveal the net WTP of visitors for access to a recreation site.

Within stated preference methods is the frequently used contingent valuation method (CVM), as well as newer conjoint and choice experiment techniques. These stated preference methods use a survey to construct a simulated or hypothetical market in which an individual's consumer surplus is elicited. For example, the analyst often asks a visitor what is the maximum increase they would pay to visit a particular site. In most of the CVM studies reviewed below, a popular willingness-to-pay question format, called "dichotomous choice," is used. In this question format, individuals are asked if they would pay a higher trip cost of $X. The amount of $X varies across the sample. At higher dollar amounts, a lower percentage of visitors would pay that amount, and conversely at lower dollar amounts, a higher percentage would pay that amount. By plotting the percentage of people who would pay each dollar amount, a demand-like relationship is traced out from which consumer surplus can be calculated. Conjoint and choice experiments also use a survey to present alternative trips with different levels of trip characteristics (e.g., flow levels, size of beaches) to directly estimate how consumer surplus changes with changes in trip characteristics.

Both methods, the TCM and CVM, are recommended for use by Federal agencies such as the Bureau of Reclamation for valuing recreation (U.S. Water Resources Council, 1983). There have been hundreds of applications of both methods worldwide. Extensive comparison of the consumer surplus estimated by using the TCM and CVM suggests that the two have convergent validity, as estimates of consumer surplus by the two approaches are nearly identical and are highly correlated with each other (Carson and others, 1996).

### Measurement of Regional Economic Effects of Recreation

To calculate the local economic impacts associated with visitor expenditures, an input-output model is used to calculate the multiplier effects (Douglas and Harpman, 1995; Loomis, 2002). The general economic approach of combining expenditure data with an input-output model is called "regional economic analysis" because it usually measures the effect on a local economy (county) or a region (group of counties). The input-output model translates the visitor expenditures into total local income and employment. The regional economic analyses reported in this chapter use IMPLAN® software (Minnesota Implan Group, 1997) to construct an input-output model of the local region. The input-output model captures the ripple, or multiplier effects, of the direct spending on indirect spending of related industries and induced spending of workers receiving additional wages.

### Measurement of Nonuse Values

Stated preference methods such as the CVM or conjoint/choice experiments are the only methods currently available for measuring nonuse values. Much like the recreation application of the CVM, the application of these methods to measure the willingness of a consumer to pay for nonuse values involves using a survey to construct a simulated or hypothetical market or referendum. In this case, however, a random sample of households is interviewed or mailed a survey. They are asked whether they would vote in favor of or against a particular management action or program involving protection of the resource at a specific cost to their household in the form of higher taxes or prices.

# Status, Trends, and Recent Findings

## Recreation Use Values of Glen Canyon

### Fishing Use

Because of the clear, cold water released from Glen Canyon Dam, the 15-mi (24-km) stretch of the Colorado River below the dam provides a significant trout fishery in Arizona. As shown in figure 1, use has fluctuated over the past 10 yr. In part, fluctuating use may be due to increasing populations of trout reaching carrying capacity of the stream, which results in a reduction of the size of fish from their earlier trophy size. Changes in fishing regulations (including greater restrictions in permissible fishing gear and reductions in catch limits) may also be partially responsible for fluctuating use patterns. Shore anglers are less affected than boat anglers because there are threshold minimum flows for floating the boats over the rocks in critical reaches. The downturn in Lees Ferry angler use may be due to a variety of factors and, therefore, suggests the need for an integrated multivariate statistical analysis of the relationship between angler use, catch-per-unit effort, and fish size. Chapter 2 of this report presents a catch-per-unit effort that suggests that the decline in angler days may be due to decreasing angler catch rate, which fell from a peak of nearly 1.5 fish per hour in the 1998–99 time period to 0.5 fish per hour in 2002. At the same time, the size of fish continued to decrease through 2001.

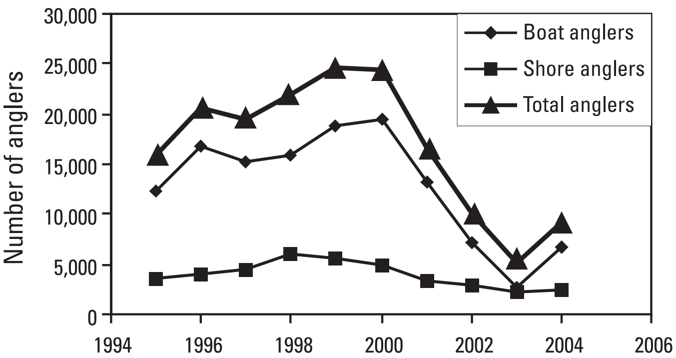

**Figure 1.** Angler use at Lees Ferry, 1995–2004 (developed from data found at http://www2.nature.nps.gov/mpur/ for Glen Canyon National Recreation Area).

### Fishing Values

There are only two economic valuation studies of recreational fishing in the Lees Ferry reach, both of which are fairly old. The first study was by Richards and others (1985) and used the TCM to estimate the consumer surplus of trophy trout anglers and nontrophy trout anglers. The authors calculated net willingness to pay over and above their trip cost of $381 for trophy trout anglers and $272 for nontrophy trout anglers. Using the percentages of trophy and nontrophy anglers that existed at the time of the study (now more than 20 yr ago, and before the change in fishing regulations), the weighted average value was $304 in 1983 dollars. In 2004 dollars, the consumer surplus is $580 per trip.

The second study, and the only one we are aware of that related angler value to river flow levels, was conducted by Bishop and others (1987). During 1985, anglers were sampled at Lees Ferry. The investigators used a dichotomous choice, willingness-to-pay format in their CVM survey of anglers. The net willingness to pay for the anglers' actual trips ranged between $130 for those experiencing constant flows and $104 for those experiencing fluctuating flows. In 2004 dollars this is about $250 per trip for those experiencing constant flows and nearly $200 for those experiencing fluctuating flows.

While the 20%–25% difference in value per trip with constant versus fluctuating flows gives some insight into the effect of Glen Canyon Dam operations on the value of fishing, the study by Bishop and others (1987) also asked anglers their net willingness to pay for a wide range of flow scenarios. The results indicated that angler benefits (WTP) peaked at a flow of 10,000 cubic feet per second (cfs) with constant flows at $126 per trip ($240 in 2004 dollars). This finding is in the same range of benefits as the actual trip experience, where 75% of anglers experienced a flow between 5,000 and 15,000 cfs on their most recent trip (Bishop and others, 1987, p. 121). At low flows, such as 3,000 cfs, the values per trip fell to half at $60 per trip ($114 in 2004 dollars). At high flows of 25,000 cfs, the value per trip was $94 ($178 in 2004 dollars). Thus, there is a nonlinear relationship between angler benefits and flows.

Combining the values per angler trip and the number of anglers yields estimates of annual recreational fishing benefits that range from $2.4 to $4.8 million (2004 dollars) at optimum flow levels, corresponding to the range of past use of 10,000 to 20,000 angler days. At low flows these values drop by more than half to $1.1 million to $2.3 million annually.

While these values suggest that the recent flow experiments such as the low summer steady flows (LSSF) in 2000, which held flows steady at 8,000 cfs, probably did not result in a large reduction in angler benefits from optimum flows, it is not possible to know for sure without conducting surveys of anglers during this period. Judging solely by angler use levels, the LSSF was associated with angler use equivalent to the previous year (1999). This is corroborated by the findings of Hjerpe and Kim (2003), who interviewed fishing guides and found that the 2000 season had slightly higher angler use but in line with the growth in angler use in the past 5 yr.

## Day-use Rafting

The 15 RM of Glen Canyon below the dam provide an opportunity for scenic day-use rafting. At low to moderate river flows, the half-day raft trips launch below Glen Canyon Dam and float downstream to Lees Ferry (Douglas and Harpman, 1995). At very high flows or at times when the national security level reaches red and visitors are not allowed to launch from the dam, they must launch from Lees Ferry and motor most of the way upstream and then float down. As is shown in figure 2, this is a popular float trip, averaging around 40,000 visitors each year.

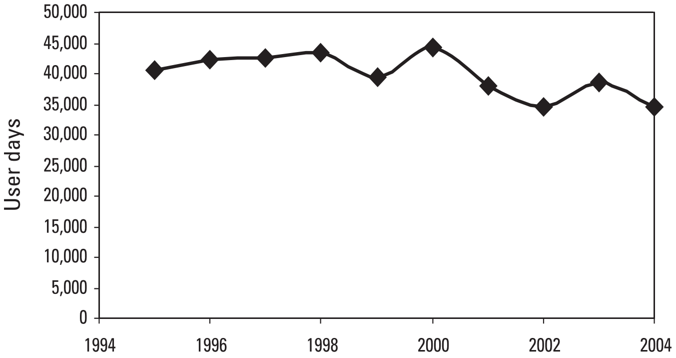

**Figure 2.** User days per year at Glen Canyon National Recreation Area for day-use rafting, 1995–2004 (source: fax from Jacki Blais, Glen Canyon National Recreation Area, to Lara Schmit, U.S. Geological Survey, January 12, 2005).

## Economic Values of Day-use Rafting

The only study of the economic value of day-use rafting was performed nearly 20 yr ago in 1986 by Bishop and others (1987). About half of their sample were rafters starting their trips below Glen Canyon Dam and then floating down, and the other half were motoring up and then floating down. Dichotomous choice CVM was used to estimate the consumer surplus that day-use rafters received. Statistical tests indicated that the WTP functions were not statistically different between the rafters starting their float trip below the dam and those who motored up and then floated down (Bishop and others, 1987, p. 145). Overall, the net WTP or consumer surplus was $26 per day, or nearly $50 in 2004 dollars. These figures translate into an annual value of $2 million.

Based on the attribute survey and the lack of difference in WTP values for the two departure locations, Bishop and others (1987, p. 145–146) concluded that day-use rafting trip values were not sensitive to river flow. This insensitivity to flows may be because visitors lacked prior knowledge regarding river flows and because of the lack of rapids in this section of the river. Obviously, it would be desirable to update these values, especially with the new flow regimes since 1986, and revisit the Bishop and others (1987) finding of no apparent relationship between flow and recreation benefits for the day-use rafting.

## Recreational Rafting Use of Grand Canyon

Grand Canyon National Park is world renowned for its whitewater rafting opportunities (Behan, 2000). Typically, commercial motorized rafting trips navigate the entire 226 RM from Lees Ferry to Diamond Creek (one of the takeout points) in 1 week, although there are also 2-week commercial oar trips. Private boaters typically take about 18 d for this same trip (Hjerpe and Kim, 2003). Passengers of commercial trips and some private oar trips navigate the river either from Lees Ferry to Phantom Ranch (88 RM) or meet their trip at Phantom Ranch and end at Diamond Creek.

The popularity of rafting in Grand Canyon skyrocketed during the late 1960s and 1970s, prompting the National Park Service to place limits on the number of commercial and private boaters. During the 1970s to 1990s, 21 commercial rafting companies took visitors down Grand Canyon. Today, the limits are 115,000 user days for commercial rafting companies and about 55,000 for noncommercial, or private, users. The binding nature of these limits on use can be seen in figure 3.

The number of user days, however, masks the large difference in the number of passengers permitted for the two groups. Since the private trips are often much longer than commercial trips, there are nearly six times the number of commercial passengers (18,500–19,600) as there are noncommercial passengers (3,400–3,600).

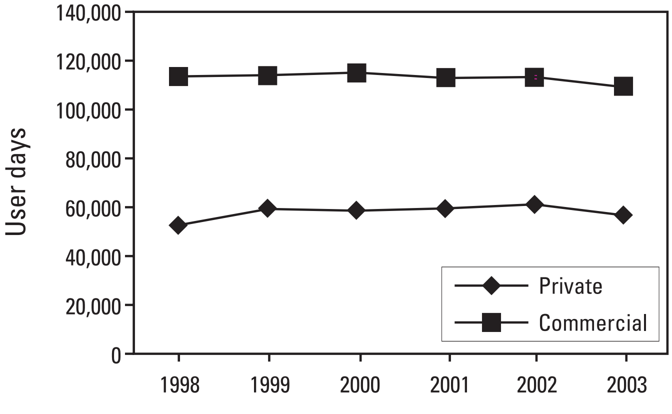

**Figure 3.** Number of private and commercial boater user days, Grand Canyon National Park, 1998–2003 (source: www.nps.gov/grca/crmp/documents/stats/1998-2003ByMonth.pdf).

Over time the demand for private trips has increased substantially relative to commercial trips. This increase has resulted in a substantial and growing wait to obtain a private permit. The wait has grown from about 5 yr in 1991 to 12 yr in 2003, resulting in the National Park Service revisiting its allocation by issuing in October 2004 the Draft Environmental Impact Statement Colorado River Management Plan. The preferred alternative in the management plan nearly doubles the noncommercial user days and the number of private passengers permitted (Grand Canyon National Park, 2004).

Because of excess demand and user limits, one cannot cite visitor use as an indicator of visitor response to alternative flow regimes (Hjerpe and Kim, 2003). Rather, one must conduct surveys to ascertain how visitor experience and economic benefits (i.e., consumer surplus) change with alternative flow regimes and natural resource conditions.

There are two surveys that provide some insights into how visitor satisfaction in nonmonetary terms varies with flow levels. The first survey was performed as part of the original Glen Canyon Environmental Studies program during 1984 and 1985 by Bishop and others (1987). Surveys of river guides, private trip leaders, commercial passengers, and private rafters found that constant flows in the range of 20,000–25,000 cfs yielded the highest satisfaction ratings. In essence, flows in this range allowed for larger rapids, more time for stopping at side canyons and attraction sites, and less time motoring or rowing. Low flow levels frequently resulted in visitors having to walk around certain rapids, which decreased trip satisfaction.

The second survey was by Stewart and others (2000), who during 1998 and 1999 replicated the portion of the Bishop and others (1987) study that dealt with whitewater rafting trips. This more recent study found the same pattern of visitor satisfaction ratings with regard to flow. In particular, the study found that whitewater rafting satisfaction was highest at constant flows of 20,000–25,000 cfs and that several flow-related trip characteristics such as large rapids and time to stop and hike the side canyons were highly important (Stewart and others, 2000). This study also found that large beaches with shade from trees for stopping and camping was rated as moderately important.

Related to these satisfaction surveys are trip diary data collected by Roberts and others (2002) and Roberts and Bieri (2001) to develop a Grand Canyon river trip simulator. In their simulation model, river flows are a key determinant of boat speed and, hence, the amount of time for trip-related activities such as swimming, visiting cultural sites, hiking, campsite selection, and decisions to

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layover part of or an entire day. Roberts and Bieri (2001) also used trip diaries to study the LSSF of 2000. They found that the low flows reduced the amount of time visitors had for swimming, hiking, and visiting cultural sites from 7 h/d on a typical trip (flow averaging 19,000 cfs) to 3.5 h with the 8,000 cfs of the LSSF. Thus, with the 8,000-cfs flows, an additional 3.5 h/d were spent motoring or rowing to make up for lost time because of the slower flows (Roberts and Bieri, 2001, p. 13).

## Economic Values of Private and Commercial Rafting in Grand Canyon

The price of a commercial Grand Canyon rafting trip is substantial, averaging around $215 per person per day (Hjerpe and Kim, 2003). For private trips, the National Park Service requires a $100 payment to get on the waiting list, coupled with a payment of $100 for every person taking the trip (Hjerpe and Kim, 2003). One way to think of the $100 payment to get on the waiting list is as an “option value,” a willingness to pay to maintain the opportunity to raft Grand Canyon in the future.

The payment of commercial fees and related visitor expenditures of commercial and private rafters creates significant positive economic effects in the region in the form of income and employment. These effects are detailed in the regional economic effects section of this chapter.

Our interest here is the amount of benefits received by the whitewater rafters and kayakers themselves. This is their net economic value, or consumer surplus. The first and only primary data study on whitewater rafting economic values and how they change with flow was conducted by Bishop and others in 1987 (see also Boyle and others, 1993). These authors used a dichotomous choice CVM survey of commercial and private boaters. They found that commercial passengers’ willingness to pay for their actual trip experience rose from $127 ($228 in 2004 dollars) at 5,000 cfs to a maximum value of $888 ($1,598 in 2004 dollars) at higher flows and then declined only slightly at 40,000 cfs (Boyle and others, 1993). For private boaters the value of their actual trips rose from $111 ($200 in 2004 dollars) at 5,000 cfs to a maximum of $637 ($1,147 in 2004 dollars) at 28,000 cfs. This value falls to $455 ($819 in 2004 dollars) at 40,000 cfs (Boyle and others, 1993). The larger decline in value at the highest flows is likely because of less experienced private trip leaders compared with professional guides on commercial trips. Nonetheless, these are very high recreation trip values, although less dramatic on a per-day basis (about 7 d for a commercial trip). The relatively high value is commensurate with the high-quality experience and high satisfaction received by the majority of visitors to Grand Canyon.

Summing these updated 2004 dollar values over the nearly 19,000 commercial passengers and 3,500 private boaters, these values at optimum flows are $30 million and $4 million annually in economic value to commercial passengers and private boaters, respectively. Based on Bishop and others (1987), there would be a drop in total whitewater rafting benefits from $34 million to $5 million, or a loss of $29 million, at low flows such as 5,000 cfs (a flow level close to the LSSF of 2000). Unfortunately, the opportunity to evaluate the actual loss in recreation benefits with the LSSF was missed.

There is only one more recent estimate of whitewater river recreation in Grand Canyon that has been made. Hammer (2001) used the TCM with travel costs calculated by using the U.S. Postal Service ZIP Code™ data from the 1998 recreation preference surveys of Hall and Shelby (2000) and Stewart and others (2000). Since these surveys were not originally designed for economic analysis, however, they do not allow for analysis of how the economic value of the rafting trips changes with flow levels. Nonetheless, Hammer (2001) did a very careful job of using ZIP Codes to calculate travel costs of visitors and using this information to estimate a TCM demand curve. This calculation is somewhat challenging because each visitor usually takes just one trip. But by using a zonal or visits-per-capita type demand model, Hammer (2001) was able to calculate an estimate of the value in 1998–99. The value per trip for private boaters was $134 or ($148 in 2004 dollars) and $314 ($351 in 2004 dollars) for commercial trip passengers (Hammer, 2001).

The inability to link recreation benefits from Hammer’s (2001) study to flows is unfortunate. If there is an insufficient budget to fund separate recreation economic surveys, then an integrated social science survey that would allow for data to provide both preference and valuation in relation to flows would be desirable. Such recreation valuation monitoring should be planned into future flow experiments.

## Regional Economic Effects of Water-based Recreation in Glen and Grand Canyons

As discussed previously, recreational fishing and rafting involve tens of thousands of visitors each year to the Glen Canyon and Grand Canyon areas. Commercial rafting on Grand Canyon currently involves 16 different companies. One of these companies also provides day-use rafting in Glen Canyon, and there are support companies providing visitor and shuttle transportation to day-use rafters. Many anglers in Glen Canyon also employ professional fishing guides, who often use boats for guiding. Even the anglers and private rafters who do not use commercial outfitters spend a significant amount of money in the local areas on hotels, restaurants, groceries, ice, gasoline, and supplies.

The local economic effects of recreation on the retail, supporting wholesale, and distribution sectors and on induced spending elsewhere in the economy from river-based recreation expenditures have been calculated in two studies. The most comprehensive regional economics study was by Douglas and Harpman (1995), who used data collected in 1985. Table 1 presents the average trip expenditures, total trip expenditures, the amount spent in the local region (defined by Douglas and Harpman as Coconino County, where Page, Arizona, is located, and Mohave County), and the resulting total employment. The employment effects reflect only visitor spending in the region, and the multiplier effects are calculated by using IMPLAN® (see Douglas and Harpman, 1995). The monetary amounts used in Douglas and Harpman (1995) have been updated to 2004 dollars, but the employment estimates are calculated directly from their data (see Douglas and Harpman, 1995, tables 3 and 6 using 1990 relationships) and are consistent with calculations developed by Douglas (2005) of 438 total jobs in whitewater boating in Grand Canyon National Park.

As indicated in table 1, the total of nearly 600 jobs provided by river-based recreation is a substantial number of jobs. Commercial rafting, particularly the Grand Canyon National Park segment, contributes the majority of the jobs, 438.

Unfortunately, there has been little systematic comprehensive research that links changes in flows to angler use or other visitor use and, hence, to associated changes in economic impacts. There has been one study on the effect of the lower summer steady flows on economic impacts to the rafting and angling outfitters by Hjerpe and Kim (2003). They found that these low flows had minor effects, mostly related to damage to equipment in Grand Canyon and angler boats in Glen Canyon. Day-use rafters in the Glen Canyon reach were apparently not affected (Hjerpe and Kim, 2003). The direct economic consequences of higher outfitter costs because of commercial boat damage were in the range of $25,000, and the loss in fishing guide services during the spike flows that were part of LSSF was in the range of $33,000 (Hjerpe and Kim, 2003). As the result of low flows stranding commercial whitewater trips, there were also three rescue operations, which cost $30,000. Hjerpe and Kim (2003) aggregated these as losses to Coconino County for the regional economic analysis. The IMPLAN® estimated total effects on Coconino County were $117,705 in losses. This estimated total is relatively minor to the local economy; however, Hjerpe and Kim (2003) acknowledged that they may have mixed local economic losses from reduced fishing guide income with increases in economic activity from boat repair and helicopter rescue. There is a problem with using regional economic impact analysis as an indicator of the economic effects of changes in flows: higher outfitter expenses, which are costs, have the potential to actually increase economic activity. Thus, a benefit-cost analysis that would treat higher costs to outfitters as the actual losses that they are to society would probably be more appropriate for monitoring the economic consequences of changes in the flow regime.

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**Table 1.** Local economic effects of river recreation in northern Arizona (2004 dollars).

[Source: Douglas and Harpman (1995). The monetary amounts used in Douglas and Harpman (1995) have been updated to 2004 dollars, but the employment estimates are calculated directly from their data]

| | Glen Canyon National Recreation Area | | Grand Canyon National Park | | Total |
|---|---|---|---|---|---|
| | Day -use rafting | Anglers | Commercial rafting | Private rafting | |
| Average trip expenditures | $115.90 | $355.91 | $2,711.30 | $981.84 | |
| Nonresident total expenditures | $3,803,374 | $3,655,174 | $36,542,901 | $2,872,876 | $46,874,326 |
| Nonresident total expenditures in region | $3,803,374 | $1,810,320 | $15,351,554 | $1,195,997 | $22,161,245 |
| Total jobs | 100 | 48 | 406 | 32 | 586 |

The comparison of these relatively minor local economic effects from the LSSF illustrates the limitation of relying on regional economic analyses: if visitor use does not change much because of the National Park Service limits on passenger days, then the effects of river flow will not be manifested in changes in regional economic effects (Hjerpe and Kim, 2003). Rather, any effects of river flow changes are more likely to be manifested as changes in user satisfaction and use value. Without conducting a valuation survey, the most likely economic effects of changes in river flow regimes in Grand Canyon may be missed.

## Nonuse Values

As noted above, Grand Canyon is also a source of nonuse or existence/bequest values to people who may never or no longer visit Grand Canyon (Harpman and others, 1993). The same is true with the continued existence of endangered species, such as the humpback chub, in their natural habitat. A given household's nonuse values for improving river flow management in Glen Canyon and Grand Canyon can be obtained by using the CVM. To date, there has been only one nonuse CVM survey that asked willingness to pay to improve native vegetation (and associated birds and other wildlife), native fishes, game fish (such as trout), river recreation, and cultural sites in Glen Canyon National Recreation Area downstream of Glen Canyon Dam and in Grand Canyon National Park. This study was conducted in late 1994 and early 1995 by Welsh and others (1995).

There were two main sampling strata in the Welsh and others (1995) study: a sample called market area, reflecting Western U.S. households receiving hydropower from Glen Canyon Dam, and then a national sample, reflecting the rest of the Nation. These sampling strata received different payment vehicles: the market area would pay for protection via higher utility bills, while the national sample would pay via higher taxes. There were three main river-flow scenarios and accompanying changes in five main environmental attributes (beaches, risk of erosion to cultural sites, vegetation/bird habitat, native fish, and trout). At the time the survey was conducted, the main flow regimes under consideration involved degrees by which the fluctuating flows previously associated with peaking power production would be moderated. The three main flow scenarios were (1) moderate fluctuating flows, (2) low fluctuating flows, and (3) seasonally adjusted steady flows. While all scenarios would maintain beaches at current conditions, decrease the erosion risk to cultural sites substantially, and increase streamside vegetation by 10%, the steady flow scenario was described as providing improvements for native fish and trout.

The response rates in the two sample strata were quite high by comparison to most CVM studies in the literature. The national sample had an overall response rate of 74%, and the marketing area sample had a response rate of 83% (Welsh and others, 1995).

To provide a conservative estimate of nonuse values, only those responses that indicated "definitely yes" as yes responses to the dichotomous choice CVM responses were counted and yielded the values per household shown in table 2. Counting only "definitely yes" responses has been shown in actual cash validity test comparisons to yield a valid measure of actual cash willingness to pay (Champ and others, 1997; Ethier and others, 2000).

The steady flow scenario, which was supposed to be the most beneficial for fish, had the highest willingness to pay, especially by households living closest to Grand Canyon (i.e., the market area sample strata). The annual per-household willingness-to-pay values are quite reasonable and, yet, when aggregated up to the number of households in the population, produce estimates in the $3 billion to $4 billion range. Thus, the nonexcludable and nonrival nature of protection of the Grand Canyon environment is evident in the fact that modest willingness to pay per household across the country adds up to a substantial total. In some sense this response is not unusual; after all, Grand Canyon is a national park and Glen Canyon a national recreation area. In fact, Grand Canyon was designated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a World Heritage Site in 1979, suggesting that limiting the aggregation of benefits to just U.S. households probably significantly understates the total economic value received from Grand Canyon by people around the world.

This survey is now nearly 10 yr old, and much has been learned in that decade about the response of the Grand Canyon environment to changes in flow regime, including the decreasing trends in humpback chub populations. Several of the ecological responses to moderate or steady flows described in the survey, while based on the best available science at the time, have not been fully realized. As the name “contingent valuation method survey” suggests, the values obtained from such a survey are contingent upon the description of the environmental effects. Since the actual and anticipated environmental effects associated with different flow regimes are somewhat different from those envisioned at the time of survey, it may be appropriate to update the nonuse value survey to more current ecological estimates that are associated with different flow regimes. The facts that the alternative flow regimes currently being implemented are somewhat different from those described in the survey and that quite different management actions, such as temperature control devices, are being considered suggest that to keep nonuse valuations current, it would be worthwhile to update this survey. The National Park Service Organic Act of 1916 has been interpreted as a dual mandate of recreation and preservation of the national parks (Loomis, 2002). This dual mandate suggests that it is insufficient to only measure economic values of a national park by recreation use value. More recent legislation such as the Redwoods Act—as amended in 1978 to the General Authorities Act of 1970 (16.U.S.C. 1a-1), which governs the National Park Service—provides that, when there is a conflict between recreation use and preserving the parks unimpaired, preservation is the primary objective. The preservation value of a national park, therefore, is also reflected in its nonuse values. As suggested previously by the National Research Council (1999), these nonuse values reflect values to nonrecreation stakeholders and should be used by managers in decisionmaking.

## Discussion and Future Research Needs

Based on past studies, it appears that economic values for natural and cultural resources in Grand Canyon and Glen Canyon amount to nearly $40 million of use values and several billion dollars worth of nonuse values each year. With 12-yr waiting lists to raft Grand Canyon National Park and tens of thousands of anglers and boaters using Glen Canyon National Recreation Area each year, recreation is obviously an important public use of these two areas. The now nearly 10-yr-old study

**Table 2.** Estimates of nonuse value for three flow scenarios (2004 dollars) (updated from Welsh and others, 1995).

| | National sample | | Market area sample | |
|---|---|---|---|---|
| **Flow scenario** | **Per household** | **Annual value (millions)** | **Per household** | **Annual value (millions)** |
| Moderate fluctuations | $17.06 | $2,858 | $27.94 | $79 |
| Low fluctuations | $25.19 | $4,219 | $27.17 | $77 |
| Steady flow | $25.69 | $4,303 | $36.57 | $103 |

suggested that preservation of natural environments in Grand Canyon provides nonuse values (e.g., existence and bequest values) to citizens nationwide. Given that nonuse values are nonrival goods available to all, the rapid population growth in the Southwestern United States suggests that nonuse values have probably risen substantially as well.

Unfortunately, studies of the recreation and nonuse values are between 10 and 20 yr old and reflect the flow regimes in place before the Grand Canyon Protection Act of 1992. Recreation use values and nonuse values in the current flow regime and how they change with experimental flow regimes have not been studied. With proposed increases in whitewater rafting use levels in Grand Canyon National Park, it is time to begin regularly monitoring recreation satisfaction and use value. The Grand Canyon Protection Act specifically lists recreation monitoring, and the omission of systematic recreation use value monitoring has been previously pointed out by the National Research Council (1999). Behan (2000) provided detailed suggestions on the type of recreation monitoring that is needed. If the spirit of adaptive management and the function of the Grand Canyon Monitoring and Research Center are to be more fully realized, the call in the Grand Canyon Protection Act of 1992 to monitor recreation needs to be given the same consideration that has been given to other resources discussed in this report. If integrated adaptive management of all resources is to be performed, then it is important to monitor recreation satisfaction and value since recreation is directly affected by flow regimes, changes in sand deposits for beaches, and trout size and abundance. For example, a better understanding of changes in angler use in Lees Ferry could result from an integrated analysis of use in relation to catch rate and fish condition class.

The importance of recreation use and nonuse values is becoming more apparent as trade-offs are explored between desired flows to recover endangered humpback chub and those desired for recreation and hydropower. Although the Endangered Species Act of 1973 requires that all reasonable and prudent recovery alternatives be considered, having economic valuation information on recreation, endangered fish, and hydropower may aid in finding a suitable balance. Federal oversight agencies such as the Office of Management and Budget may require benefit-cost information on temperature control devices being considered at Glen Canyon Dam to aid recovery of humpback chub. Adaptive management requires putting monitoring in place prior to new management actions. Now is the time to do the same for recreation use economic values so that the intended and unintended effects of future management actions can be assessed.

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# Chapter 10

# Status and Trends of Hydropower Production at Glen Canyon Dam

David A. Harpman

Aaron J. Douglas

## Introduction

Approximately 7% of the electricity in the United States is generated by hydroelectric powerplants (Energy Information Administration, 2004, p. 2). These plants are an invaluable component of the Nation's interconnected electric power system in which generation resources consist of thermal, nuclear, solar, wind, and other sources. Hydroelectric powerplants are characterized by exceptionally low costs of operation, are highly reliable, and produce electricity without burning fossil fuels and producing air pollution. In addition, they provide voltage control, system regulation, and other ancillary services which help ensure the reliability and electrical integrity of the system.

Although they play an important role in the electric power system, hydroelectric powerplants, such as the one at Glen Canyon Dam, have some widely recognized environmental effects. Large hydro facilities have blocked the spawning of anadromous and migratory aquatic species, eliminated the downstream transport of sediment, fundamentally altered the seasonal hydrograph, affected water chemistry, and changed the downstream temperature regime (Collier and others, 1996; Poff and others, 1997; Van Steeter and Pitlick, 1998 a, b). Furthermore, the operation of these plants, particularly those used to produce peaking, or variable, power, causes hourly variations in stream flow and elevation, thereby adversely affecting downstream aquatic and riparian communities (Nilsson and others, 1997; Parasiewicz and others, 1998) and recreation (Bishop and others, 1987; Kearsley and others, 1994; Welsh and Poe, 1998). The unveiling of plans to construct Glen Canyon Dam spurred a nationwide protest (Bradley, 1964; Martin, 1989). Construction of the dam started a public environmental discourse which continues to this day (McPhee, 1971; Elfring, 1990; Brower, 1997; Long and Essick, 1997; Jacobs and Wescoat, 2002).

## Glen Canyon Dam

Glen Canyon Dam, shown in figure 1, is a 710-ft-high (216 m) concrete thick arch dam. It is the second highest dam in the United States (Hoover Dam is 16 ft (5 m) higher). Construction of Glen Canyon Dam began on October 1, 1956; Lake Powell started filling on March

**Figure 1.** Aerial view of Glen Canyon Dam (photograph courtesy of the Bureau of Reclamation).

13, 1963; and the first electric power was generated on September 4, 1964.

The outlet works at Glen Canyon Dam are composed of four hollow "jet tubes" and two spillways. These outlet works are used only under special conditions, primarily to accommodate releases from the dam that exceed the amount of water which can be released through the powerplant. Such releases may occur when the reservoir is full and tributary inflows exceed the capacity of the powerplant or they may be ordered for environmental purposes such as the 1996 beach/habitat-building flow.

The hollow jet tubes consist of four 96-inch-diameter (244 cm) pipes. The combined release capacity of the four hollow jet tubes is 15,000 cubic feet per second (cfs). The intake elevation of the jet tubes is approximately 3,374 ft (1,028 m), or 326 ft (99 m) below the surface when the reservoir is full. These elevations are illustrated in figure 2.

Each of the two spillways consists of an intake structure with two 40- by 52.5-ft (12- by 16-m) radial gates and a concrete-lined spillway tunnel. These spillways are located on both sides of the dam, each of which is capable of releasing 104,000 cfs when the reservoir is full (3,700 ft (1,128 m)). The elevation of the spillway crest is 3,648 ft (1,112 m). The spillways cannot be used to release water from the reservoir when the lake elevation falls below 3,648 ft (1,112 m).

## Powerplant

The powerplant at Glen Canyon Dam is made up of eight hydroelectric generation units. Since 1964, these units have been uprated and rewound several times. As of August 2003, the combined generation capability of the powerplant (at unity power factor) is 1,320.0 megawatts (MW) (Seitz, 2004). A separate penstock feeds each of the eight Francis type turbines, which each produce approximately 155,000 horsepower. Current operating rules require at least 40 ft (12 m) of submergence to prevent the entrainment of air into the penstocks, which would cause damage to the turbines. As a result, the powerplant cannot be operated at lake elevations below 3,490 ft (1,064 m). Each turbine has a release capacity of approximately 4,150 cfs when the reservoir is full. The nominal powerplant release capacity is approximately 33,200 cfs.

## Electricity Background

Electricity cannot be efficiently stored on a large scale by using currently available technology. It must be produced as needed. Consequently, when a change in demand occurs—such as when an irrigation pump or a central air conditioner is turned on—somewhere in the interconnected power system, the production of electricity must be increased to satisfy this demand. In the language of the utility industry, the demand for electricity is known as "load." Load varies on a monthly, weekly, daily, hourly, and even second-by-second basis. During the year, the aggregate demand for electricity is highest when heating and cooling needs are greatest. During a given week, the demand for electricity is typically higher on weekdays and lower on weekends, particularly holiday weekends.

The maximum amount of electricity which can be produced by a powerplant is called its capacity. Capacity is typically measured in megawatts. The capacity of thermal powerplants is determined by their design, their location, and the ambient temperature. In the case of hydroelectric powerplants, capacity varies over time because it is a function of reservoir elevation, the amount of water available for release, and the design of the facility. Because the capacity at hydroelectric powerplants is highly variable, the amount of dependable or marketable capacity is of particular significance. The amount of dependable or marketable capacity is determined by using various probabilistic methods (e.g., Ouarda and others, 1997).

The large variation in loads has important implications for the electrical generation system. In particular, it greatly influences the amount of generation capacity required and, therefore, the capital cost of the system. The implications of large variation in loads can be

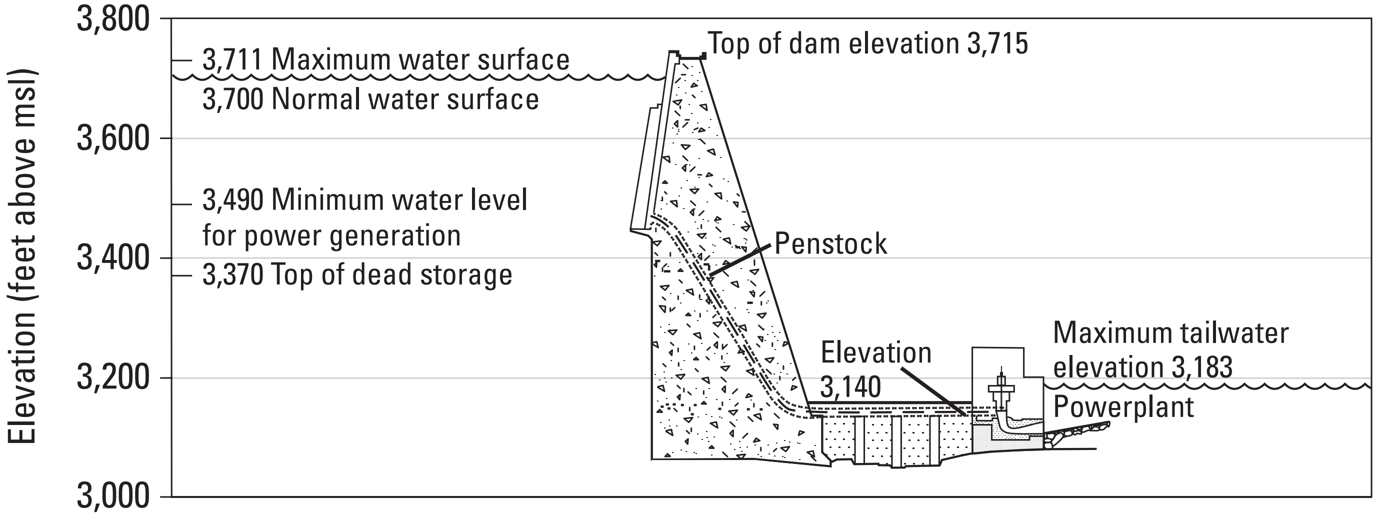

**Figure 2.** Important operating elevations of Glen Canyon Dam and Lake Powell in feet above mean sea level (msl).

readily illustrated by two extreme cases. First, assume the demand for electricity is constant and is 1.0 MW at all times. This assumed demand would imply (ignoring security and reliability concerns) that a utility supplier could supply this demand by building a 1.0-MW powerplant and operating it continuously. For a month (30 d), this situation would imply generation of 1.0 MW for 720 h, which would generate 720 megawatthours (MWh) of electricity. Now assume that the demand for electricity is more variable: assume that it is 1 MW for 1 h of the month and 0.5 MW for the rest of the hours in the month. In this case, the costs of constructing a 1-MW powerplant must also be incurred, but the plant generates only 360.5 MWh of energy (1 MW * 1 h + 0.5 MW * 719 h), or approximately 50% of its potential output. The highly variable nature of the demand for electricity results in the following observable characteristics of the electrical power system: (1) some powerplants are idle for part, or all, of the day or season, and (2) the capital costs of electricity production are quite high relative to operational costs.

Electric energy is most valuable when it is most in demand—during the day when people are awake and when industry and businesses are operating. This period, when the demand is highest, is called the "onpeak period." In the West, the onpeak period is typically defined as the hours from 7 a.m. to 11 p.m., Monday through Saturday. All other hours are considered to be offpeak.

## Hydroelectric Power and the Interconnected Power System

The two most commonly encountered types of hydroelectric powerplants are run-of-river plants and peaking plants. Run-of-river plants typically have little water storage capability. Consequently, generation at run-of-river plants is proportional to water inflow, resulting in little variation in electrical output during the day. Peaking hydroelectric powerplants, such as Glen Canyon Dam, often have significant water storage capability and are designed to rapidly change output levels to satisfy changes in the demand for electricity. Peaking hydroelectric powerplants are particularly valuable because they can be used to generate power during onpeak periods, thereby avoiding the cost of operating more expensive thermal plants such as gas turbine units.

In addition to furnishing capacity and energy, hydroelectric powerplants play an important role in the interconnected electric power system by supplying ancillary services. They contribute to system reliability by furnishing reactive power, voltage support, and system regulation services. These facilities also fulfill part of the regional reserve requirements and provide backup generation in the event of unexpected outages. In addition, they provide extra energy during extremely hot or cold weather periods and help maintain transmission stability during system disturbances.

# The Economic Value of Hydropower

The economic value of operating an existing hydroelectric powerplant is measured by the avoided cost of doing so. In this context, avoided cost is the difference between the total power system cost of satisfying the demand for electricity "with" and "without" operating the hydroelectric powerplant. Conceptually, avoided cost is the savings realized by supplying electricity from a low-cost hydroelectric power source rather than from a higher cost thermal source. These savings arise, in part, because the cost of operating a hydroelectric powerplant is relatively low in comparison to thermal units. For example, the average operating expense for a typical hydroelectric powerplant in 2003 was $7.51/MWh. In contrast, the average cost of operating a typical fossil-fuel steam plant was $22.59/MWh, and the average cost of operating a typical gas turbine unit was approximately $48.93/MWh (Energy Information Administration, 2004, p. 49, table 8.2).

The economic value of operating an existing hydroelectric powerplant varies considerably with time of day. The variable cost of meeting demand varies on a second-by-second basis depending on the load, the mix of plants being operated to meet load, and their output levels. During offpeak periods, demand is typically satisfied with lower cost coal, run-of-river hydropower, and nuclear units. During onpeak periods, the additional load is met with more expensive sources such as gas turbine units. Consequently, the economic value of hydropower is greatest during hours when the demand for electricity, and the variable cost of meeting demand, is the highest.

If the cost of purchasing an additional megawatthour of electricity from a least cost source were observable in the market, then the economic value of producing hydroelectricity could be readily determined. For example, assume that in a particular hour the cost of purchasing a megawatthour of electricity from the least cost source was $30 and that the cost of producing a megawatt of hydroelectricity was $6. The avoided cost, or economic value, of producing an additional megawatthour of hydroelectric power at that time would be $24 ($30 - $6).

In addition to operating costs, the fixed investment (or capital) costs of alternative sources of electricity supply may contribute to the economic value or avoided cost of an existing hydroelectric powerplant. If a hydroelectric powerplant were decommissioned or its operations were restricted, the generation capacity in the system would be reduced. A new powerplant, probably a thermal plant, would need to be constructed to replace this lost capacity. If there were initially excess capacity in the system, the construction of a new powerplant could be deferred until a future date but would be constructed sooner than would otherwise be the case. If there were little or no excess capacity in the system, the need would be more immediate. All other factors being the same, the time of the required replacement capacity has a significant effect on the present worth of these additional costs. The sooner the replacement capacity is required, the higher the present worth of the costs incurred. The further out in the future these construction expenditures occur, the smaller the present worth of the costs incurred.

# Federal Power

There is a long history of Federal involvement in the provision, operation, and regulation of the electric power system. The foundations for this involvement are based on three factors: first, the electric power industry is a natural monopoly (produces a product most efficiently supplied by one supplier in a given area) and hence is subject to regulation under the Sherman Antitrust Act of 1890, the Interstate Commerce Act of 1887, and other applicable statutes; second, the Federal Government owns most of the Nation's large-scale hydroelectric resources; and third, Federal economic development programs facilitated the provision of electricity to large areas of the rural United States (Energy Information Administration, 1996).

During the Great Depression and the Dust Bowl years (ca. 1930s), the Federal Government became much more active in the provision and regulation of electricity. This involvement was consistent with the widespread belief that electricity should be inexpensive and readily available to the public. Federal power- and water-development projects were also promulgated for purposes of creating employment, resettling the landless, improving agricultural production, and fostering business and industry. A number of large public works projects were begun during this period; among these were the construction of Hoover Dam and the construction of Grand Coulee Dam, which remains the Nation's largest hydroelectric facility. A hallmark of the era was creation of the Rural Electrification Administration (REA). The Rural Electrification Act of 1936 (Public Law 74-605) established the REA to provide loans and assistance to organizations providing electricity to rural areas and towns with populations under 2,500. REA-backed cooperatives were instrumental in tripling the proportion of rural homes and farms served by electricity between 1932 and the entry of the United States into the Second World War in 1941 (Energy Information Administration, 1996).

The Bureau of Reclamation constructed and operates Glen Canyon Dam. The Western Area Power Administration (hereafter Western), an entity established by the Department of Energy Organization Act of 1977, now markets and transmits the electricity produced by the dam.

In compliance with the Colorado River Storage Project (CRSP) Act of 1956, power generated at Glen Canyon Dam and other CRSP facilities is first provided to CRSP-participating projects. These are typically Bureau of Reclamation irrigation projects, and generation is used to meet their pumping needs. Generation that is surplus to these "project uses" is then marketed by Western to about 200 wholesale power customers entitled to preference allocations. These preference customers are generally municipal and county utilities, rural electric cooperatives, Federal reservations, Indian Tribes, and certain other authorized entities (see General Accounting Office, 2001, for further details on preference). A list of current preference customers and their allocations can be found in Western Area Power Administration (2004a). These preference customers, in turn, sell electricity to approximately 1.7 million residential, commercial, industrial, and agricultural users located predominantly in a six-State region comprising Nevada, Utah, Arizona, Wyoming, Colorado, and New Mexico.

Each of the preference customers is allocated an amount of energy and capacity based on Western's determination of the marketable power resource. The most recent such determination, the "Post-2004 Determination of Marketable Resource," is described in Western Area Power Administration (2004b). If these preference customers require additional energy and there is additional energy available, Western may sell additional power to them on a short-term basis. If energy is available beyond the needs of the preference customers, Western may exchange energy with other suppliers or make sales on the spot market. If generation is insufficient to meet the allocations of preference customers, Western must exchange energy with another supplier or purchase additional energy on the market.

Western's rate-setting procedure for power differs from that of a non-Federal utility (General Accounting Office, 2000). By statute, power must be marketed at the lowest possible rates that are consistent with sound business practice. Administratively, Glen Canyon Dam is located in Western's Salt Lake City Area/Integrated Projects (SLCA/IP) region. The preferred customer rate is known as the SLCA/IP rate. The SLCA/IP rate is set to ensure that revenues are sufficient to repay all assigned costs within a prescribed period. These costs include annual power operation and maintenance costs, power facility construction costs including interest, certain environmental costs, and other nonpower-related costs that power users were assigned by Congress to repay (including irrigation costs that water users are unable to repay). The current SLCA/IP (F7) rate is $20.72/MWh.

The SLCA/IP rates charged by Western are designed to recover the taxpayer investment. They are lower than current wholesale market rates for electric power. Comparisons of the electric power rates are relatively difficult because of differences in contractual terms, commitment lengths, products provided, and fluctuations in electricity market conditions. Because of these complexities, the average revenue per megawatthour of wholesale electricity sold is widely used in the industry as a metric for comparison purposes. Two studies compared Western's average revenue received per megawatthour of wholesale electricity sold against those of other utilities. In a 1994 study, the General Accounting Office (1996b, p. 105, table V.1.) estimated Western's average revenue per megawatthour of wholesale power sold to be 47% of the revenue received by publicly owned utilities and 52% of the revenue received by investor-owned utilities. A 1999 assessment by the Energy Information Administration estimated Western's average revenue per megawatthour of wholesale power sold to be 42% of the average revenue received by utilities in the West (Energy Information Administration, 2000, p. 44, table 13).

## Monitoring of the Hydropower Resource

The hydropower resource at Glen Canyon Dam is monitored rather intensively. Since the plant's supervisory control and data acquisition (SCADA) system was installed in the early 1980s, it has monitored and recorded a voluminous amount of information about power production and operations. At each of the eight units, these data include generation, release, reservoir afterbay water-surface elevations, voltage, frequency, circuit breaker status, gate positions, bearing temperatures, transformer settings, and the temperatures and operational status of a variety of appurtenant equipment.

These data are sampled at time increments ranging from 1 to 4 s. Selected data are recorded and archived at larger time intervals. This level of monitoring is standard business practice in the electric power industry.

## The Effects of Environmental Constraints

The single most important determinant of hydropower production and economic value at Glen Canyon Dam is the amount of water released during the month. Based on projected hydrologic conditions, monthly and annual release volumes for Glen Canyon Dam and all major CRSP facilities are established by the annual operating plan (AOP) at the beginning of the water year (see www.usbr.gov/uc/water/rsvrs/ops/aop/aop05draft.pdf for an example). Monthly release volumes under the modified low fluctuating flow (MLFF) operating regime are identical to those under historical operations (1963–91) except for water years in which an experimental flow occurs. In years when experimental releases occur, monthly release volumes may vary substantially from the historical pattern, and there may be differences in monthly releases across the entire water year.

The environmental constraints that are part of the MLFF operating regime affect hydropower production at Glen Canyon Dam to varying degrees under different circumstances. Typically, these constraints are most limiting for moderate monthly release volumes and less constraining at either very high or very low release volumes. The maximum release constraint of 25,000 cfs is binding or constraining only when the reservoir elevations and monthly release volumes are sufficiently high to permit releases of 25,000 cfs or greater. The upramp rate of 4,000 cfs/h and the downramp rate of 1,500 cfs/h limit the hour-to-hour ability of the powerplant to respond to changes in load the majority of the time. At extreme high and low monthly release volumes, these ramp-rate restrictions have less effect. The maximum daily change in flow constraint limits the 24-h change in flow to 5,000; 6,000; or 8,000 cfs depending on the monthly release volume. This constraint greatly reduces the ability of the powerplant to respond to load changes within any given 24-h period. At very high and very low release volumes, the maximum daily change constraint has less of an effect on hydropower operations. Readers wishing to explore the effects of the MLFF constraints at Glen Canyon Dam in conjunction with different monthly release volumes and reservoir elevations can do so by using an interactive computer model developed by Harpman (2002). A rigorous mathematical exposition of hourly hydropower models is presented in Edwards and others (1999). A Microsoft Excel spreadsheet example of such a model is described in Edwards (2003).

The relative effects of the hourly constraints at Glen Canyon Dam and changes in monthly release volumes are illustrated in figure 3, which is constructed from Harpman (1997, 1999b) and from unpublished results. The interim low fluctuating flow (iLFF) operation regime (interim operating criteria elsewhere in this report) was a precursor to the MLFF. The iLFF maximum release constraint was 20,000 cfs, and the iLFF upramp rate was 2,500 cfs. Otherwise, these two operational regimes are identical. Figure 3 compares the monthly economic value of hydroelectricity produced at Glen Canyon Dam in water year 1996 under three conditions: historical operations of Glen Canyon Dam, operation under the iLFF, and operation under the iLFF with the beach/habitat-building flow (BHBF) of 1996. Although the 1996 BHBF experiment started on March 22 and ended on April 8, to facilitate this 7-d high-release experiment, changes in water-release volumes were required over much of the water year. As shown in figure 3, the changes in monthly release volumes necessitated by the 1996 BHBF created a significant effect. Relative to historical operations, the economic effects of the iLFF hourly constraints are less pronounced.

## The Costs of Environmental Constraints

Relative to historical operations, the MLFF hourly environmental constraints on hydropower operations (see Overview, this report) have both short-run and long-run effects. In the short run, the MLFF reduces the maximum generation ability of the powerplant to respond to changes in load. As a result, more of the load must be met by other generators in the system, typically thermal generators. Since operation of thermal powerplants is more expensive than hydropower, additional costs are incurred. In the long run, new or replacement powerplants are needed earlier than would otherwise be the case. Increased capital costs associated with the construction of new and replacement powerplants may be substantial.

A number of economic analyses of changes in the operation of Glen Canyon Dam have been undertaken. Only three of these contain analyses of the MLFF alternative. Of these, only one study contains an estimate of

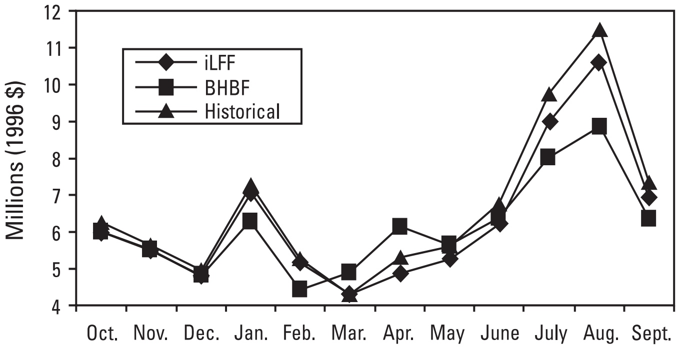

**Figure 3.** Comparison of the monthly economic value in water year 1996 of hydroelectricity produced at Glen Canyon Dam under different operating regimes (interim low fluctuating flows, iLFF; beach/habitat-building flow, BHBF; and historical operations, 1963–91).

both the short-run and long-run power system impacts of the MLFF. The Bureau of Reclamation Power Resources Committee (PRC) estimated the long-run cost of several alternative operating regimes at Glen Canyon Dam by using a production expansion model. Using regression analysis to interpolate between modeled alternatives, the PRC estimated that the annualized economic cost of changing from historical operations to the MLFF was $36.1 million (annualized value, 1996 dollars) per year. Because of excess capacity in the system, most of these costs were projected to be incurred late in the 50-yr analysis period (Power Resources Committee, 1995).

Two very detailed short-run studies of MLFF effects at Glen Canyon have been undertaken to date. These studies differ in conceptual approach and intended application. To correctly interpret their results, it is important to distinguish between the approaches they employ.

A study by Harpman (1999a) estimated the short-run economic effect of the MLFF relative to historical operations. This effect is conceptually equivalent to the difference between the historical line and the iLFF line in figure 3. The purpose of this study was to estimate the economic cost to all power users in the interconnected system. Using an hourly constrained nonlinear optimization model and spot market prices, Harpman estimated that the economic cost of the MLFF was $6.173 million (1996 dollars) for a representative 11.3 million acre-feet (maf) (13,933 million $m^3$) water year.

A short-run, ex post study of the 2000 low steady summer flow (LSSF) experiment was undertaken by Palmer and others (2004). Their approach was to estimate the difference in hydropower value between the MLFF and the 2000 LSSF relative to MLFF operations in the absence of the LSSF. The approach employed is conceptually equivalent to estimating the difference between the BHBF and the iLFF in figure 3. The goal of the Palmer and others (2004) study was to estimate the ex post financial cost of the LSSF to Federal power users, a subset of the power users in the interconnected system. Early in water year 2000, additional water was released from Lake Powell to create storage space in advance of expected spring inflows and to facilitate low steady flows during the summer experiment period. Because of the onset of the drought, approximately 605,000 acre-feet (af) (745,965,000 $m^3$) of this water was not replaced by inflows during water year 2000. Although some of the inflow deficit was subsequently recovered as of December 2004, a 228,000-af (281,124,000 $m^3$) storage deficit remains, and the reservoir elevation is 2.9 ft (0.9 m) lower than it would have been without the LSSF (Thomas Ryan, Bureau of Reclamation, written commun., 2005). Technically, the effects of the LSSF experiment are still ongoing. In order to complete their study, Palmer and others (2004) were forced to make several assumptions about when this inflow deficit would be recovered and the LSSF experiment would be concluded. Using these assumptions, observed prices, and an hourly linear programming model, Palmer and others (2004) estimated that the ex post cost of the LSSF experiment to Federal power users was approximately $32 million (2000 dollars).

## Status and Trends in Hydropower Production

The average release at Glen Canyon Dam from water year 1978 through 1999 was approximately 10.93 maf (13,477 million $m^3$). Since the onset of the drought in 2000, releases have been much lower than average, and hydropower production has fallen annually. In water year 2000, the annual release was 9.38 maf (11,566 million $m^3$). The annual release from 2001 to 2004 has reflected the minimum objective release of approximately 8.23 maf (10,148 million $m^3$). As illustrated in figure 4, diminished inflows to Lake Powell combined with this nearly constant annual release have resulted in markedly lower reservoir elevation levels.

The average annual hydropower production from 1978 to 1999 was approximately 5,196,113 MWh. As shown in table 1, in recent years the production of hydropower at Glen Canyon Dam has been considerably below average. Generation has diminished since the onset of the drought in 2000. Although the annual

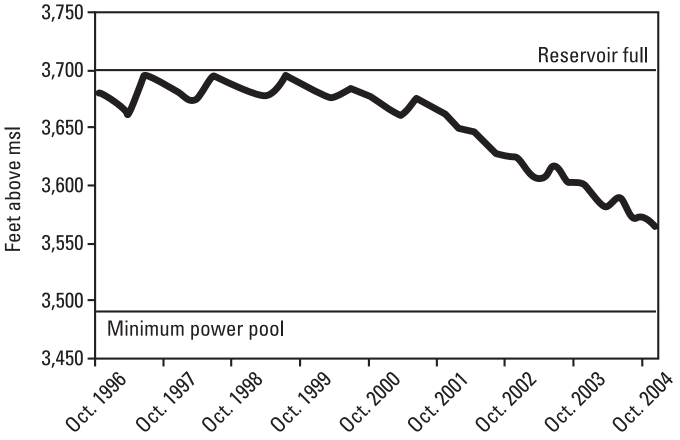

**Figure 4.** Lake Powell end of month (EOM) elevation in feet above mean sea level (msl).

release over the last 4 yr has been approximately the same (8.23 maf (10,148 million m$^3$)), decreasing head, or the distance water falls, has adversely affected annual generation. In 2001, approximately 3,940,247 MWh were generated. By water year 2004, only 3,320,196 MWh were generated.

Water year 2004 unregulated inflows to Lake Powell were approximately 51% of the 30-yr average (1971–2000). By the end of December 2004, the elevation of Lake Powell had fallen to 3,564.6 ft (1,086.5 m), and reservoir contents were approximately 8,678.0 thousand acre-feet (kaf) (10,699,974 thousand m$^3$), or 36% of capacity. This decrease in storage capacity is 135.4 ft (41.3 m) below full pool and 74.6 ft (22.7 m) above the minimum elevation necessary for power generation. These conditions last occurred in 1969 when the reservoir was being filled. Hydropower generation at Glen Canyon Dam is a function of both the amount of water released through the turbines and the head (for example, see Harpman, 2002, appendix 5).

**Table 1.** Average and recent net hydropower production at Glen Canyon Dam.

| Water year | Net generation (MWh) |
|---|---|
| 1978–99 average | 5,196,113 |
| 2000 | 4,600,453 |
| 2001 | 3,940,247 |
| 2002 | 3,772,544 |
| 2003 | 3,518,297 |
| 2004 | 3,320,196 |

As the reservoir elevation has fallen, the head available for hydropower production has declined, and this decrease has adversely affected generation capacity. When the reservoir is full (elevation 3,700 ft (1,128 m)), at a release level of 25,000 cfs the generation capability at Glen Canyon Dam is approximately 1,017 MW. At an elevation of 3,564.6 ft (1,086.5 m) and a release level of 25,000 cfs, the generation capacity at Glen Canyon Dam is approximately 749 MW, a reduction of 268 MW or approximately 26.4% (John Brooks, Bureau of Reclamation, written commun., 2005).

# The Basin Fund

The Colorado River Storage Project, authorized by the CRSP Act of 1956 (Public Law 84-485), is a program to develop, and make available for use, the water resources of the upper Colorado River Basin. The CRSP is composed of 4 multipurpose storage units—Flaming Gorge Dam, Wayne N. Aspinall Unit, Navajo Unit, and Glen Canyon Dam, often referred to as the “mainstem units”—and 21 authorized participating projects in the States of Colorado, New Mexico, Utah, and Wyoming.

Financial exchanges necessary to the operation of the CRSP are facilitated by the Upper Colorado River Basin Fund (Basin Fund). The Basin Fund was established by section 5 of the CRSP Act. The Basin Fund is a financial instrument that obviates the need for congressional actions to pay for project operation and maintenance. It is a dedicated Treasury account for the deposit of project revenues, which would otherwise be deposited in the general fund, and a source of funds for the payment of project expenses, which would otherwise need to be appropriated. Existence of the Basin Fund greatly streamlines the financial operations of CRSP and participating projects.

As described in the CRSP Act, all revenues collected in connection with the operation of the CRSP and participating projects are credited to the Basin Fund. Revenues are available, without further appropriation for defraying the cost of operation, maintenance, and replacements of and emergency expenditures for all CRSP facilities, with the exception that for participating projects, such costs are paid for with revenues generated from that project. Funds in excess of those needed for project operation and maintenance needs, certain environmental programs, and assigned costs of the salinity control program are paid annually to the general fund of the Treasury to repay CRSP investment costs with interest. Funds in excess of those requirements are then apportioned to each of the upper Colorado River Basin States to help defray investment costs associated with developing the irrigation components of the 21 authorized participating projects. There are a number of complex provisions, clauses, and details associated with the CRSP Act, the Basin Fund, and project repayment, but they are all outside the scope of this chapter. A description of these aspects of the CRSP Act and their implications for the recovery of the taxpayer investment can be found in General Accounting Office (1996a).

As dictated by prudent business practice, the SLCA/IP power rate is set at a level sufficient to meet operational and repayment needs while accommodating foreseeable variations in generation and resultant revenue. Sometimes unforeseen, adverse hydrologic conditions occur, necessitating greater than expected replacement power purchases. Purchases of replacement power, in excess of revenues, are made with funds from the Basin Fund. If adverse hydrologic conditions continue, the Basin Fund may be depleted and an increase in the SLCA/IP rate would be required. Conversely, favorable hydrologic conditions can result in greater than expected revenues from hydropower sales; these additional revenues are deposited into the Basin Fund. Funds in excess of those needed for project operations are treated as described in the CRSP Act. If favorable hydrologic conditions persist for a number of years, repayment on investment is accelerated, and a downward adjustment to the SLCA/IP rate may be initiated.

The status of the Basin Fund fluctuates monthly, thereby reflecting the timing of project revenues and expenditures. Exclusive of replacement power purchases, about $95 million is needed to fund CRSP project operational needs on an average annual basis. The vast majority of these revenues are derived from hydropower sales in the CRSP system. Since 2000, extensive and unplanned purchases of replacement power have been required because of the drought. These purchases have drawn down the cash reserve balance in the Basin Fund. In mid-January 2005, the Basin Fund held approximately $50 million (David Taylor, Western Area Power Administration, oral commun., 2005).

In addition to replacement power purchases, the Basin Fund is used to meet CRSP payroll and other operational and maintenance expenses. Certain environmentally related expenditures, including the costs of the Glen Canyon Dam Adaptive Management Program, are also made from the Basin Fund. To the extent that the Basin Fund is depleted during a period of adverse hydrologic conditions, funding for all of these purposes could be jeopardized. Western has taken two steps to bolster CRSP revenues and improve the status of the Basin Fund. First, Western has lowered their determination of marketable power resource (Western Area Power Administration, 2004b). The lower determination reduces the amount of replacement energy that they are required to purchase and shifts more of the risk of being energy-short in times of adverse hydrologic conditions to power users. Second, Western has initiated a substantial rate-increase action (Western Area Power Administration, 2005). As proposed, the new rate is $25.77/MWh, a 24.4% increase over the current rate. Western's rate proposal also includes a provision for cost recovery charge, which can be implemented when revenue shortfalls are projected. These steps will increase the amount of revenue derived from hydropower sales and bolster the position of the Basin Fund.

The Grand Canyon Protection Act of 1992 contains special provisions establishing and funding the Glen Canyon Dam Adaptive Management Program. Section 1805 of the act establishes the long-term monitoring program now carried out by the Glen Canyon Dam Adaptive Management Program, and section 1807 of the act declares expenditures for this program to be nonreimbursable. These provisions shift the burden of paying these costs from project beneficiaries, such as water and power users, to taxpayers in general. Expenditures by the Glen Canyon Dam Adaptive Management Program are drawn from the Basin Fund. These payments are then credited towards project repayment, thereby reducing the repayment obligation of all project beneficiaries. As a result, these environmentally related expenditures are indirectly paid for by all taxpayers in the United States.

## Outlook for the Future

In the years to come, the amount of hydropower generated at Glen Canyon Dam is largely dependent on future hydrologic conditions. While future hydrologic conditions can never be known with certainty, probabilistic forecasts can provide some important insights. The Bureau of Reclamation uses the RiverWare™ modeling system (Zagona and others, 2001) for CRSP multiyear planning studies. These multiyear planning studies employ the indexed sequential method (described in Ouarda and others, 1997) for simulating future hydrologic conditions. RiverWare™ modeling runs completed in January 2005 use December 2004 CRSP end-of-month reservoir elevations as starting conditions and simulate monthly operations for 90 different monthly inflow sequences, each of which is 90 yr long. Statistical analysis of these simulations suggests that the median time required to refill Lake Powell (achieve an elevation of 3,695 ft (1,126 m) in July) is approximately 19 yr (Thomas Ryan, Bureau of Reclamation, written commun., 2005). This evidence suggests that several decades may pass before hydropower production at Glen Canyon returns to the level of the late 1990s.

The scheduled replacement of the turbine runners at Glen Canyon Dam will increase hydropower generation from 1% to 7% (John Brooks, Bureau of Reclamation, written commun., 2005). Turbine runners are the large fan-like blades turned by the force of water falling through the penstocks. The existing turbine runners at Glen Canyon Dam have reached the end of their design life and are now scheduled for replacement. Improvements in runner technology, design, and fabrication methods now allow for improvements in efficiency (more electricity produced for a given amount of water released), greater generation capacity (higher generation level for a given head and water release level), or both. Analysis of alternate turbine runner designs, their costs, and benefits is now underway. Installation of new turbine runners on two of the generation units at Glen Canyon Dam is expected to begin within 2 yr, and all of the turbine runners are expected to be replaced within the next 10 yr.

The potential installation of temperature control devices (TCDs) at Glen Canyon Dam is expected to reduce generation by less than 1% (Bureau of Reclamation, 1999). Thermal and chemical stratification develops in Lake Powell during the summer months. The penstock intakes are located at an elevation of 3,476 ft (1,059 m) and are typically within the cold, hypolimnetic strata (see chapter 4, this report). As a result, releases from Glen Canyon Dam remain at about 50ºF (10ºC) all year long. Native fish populations persist at these relatively low temperatures, but it is believed that their spawning and rearing success is drastically reduced (see chapter 2, this report). The Bureau of Reclamation is studying the feasibility of installing TCDs at Glen Canyon Dam (Bureau of Reclamation, 1999). The purpose of these TCDs is to allow for the management of downstream temperatures to benefit existing and remnant populations of native fish. Current plans call for installation of TCDs on two of the eight generation units at Glen Canyon Dam.

Given current drought conditions, the outlook for hydropower production at Glen Canyon Dam is somewhat bleak in the near term; however, conditions are expected to improve in the future. Easing of the current drought and subsequent gradual improvements in hydrologic conditions in the Colorado River Basin are expected to refill reservoirs and increase the amount of hydropower that can be generated at Glen Canyon Dam and other CRSP units. At any given reservoir elevation and release, the planned installation of new turbine runners will result in an increase in hydropower generation. Although the amount of CRSP generation has been reduced by the drought in recent years and CRSP rates are slated to increase, the hydroelectric energy produced at Glen Canyon Dam has been, and continues to be, one of the lowest cost sources of electric energy available in the West.

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# Chapter 11

# Cultural Resources in the Colorado River Corridor

Helen C. Fairley

## Introduction

Cultural resources along the corridor of the Colorado River include archaeological sites and other types of historic properties, as well as resources that are of traditional concern to Native American peoples such as springs, landforms, sediment and mineral deposits, native plant concentrations, and various animal species. All of these resources have the potential to be affected indirectly, and in some cases directly, by the operations of Glen Canyon Dam.

The principal cultural resource goal of the Glen Canyon Dam Adaptive Management Program is to "preserve, protect, manage and treat cultural resources for the inspiration and benefit of past, present and future generations" (Glen Canyon Dam Adaptive Management Program, 2001). The National Park Service (NPS) goal for managing archaeological and historic resources in the Colorado River corridor is in-place preservation with minimal impact to the integrity of the resources. When in-place preservation is not possible, the NPS and other Federal agencies consider data recovery through excavation of archaeological remains to be an appropriate alternative in certain cases. The six Native American tribes who actively participate in the Glen Canyon Dam Adaptive Management Program and have long-standing traditional ties to the Grand Canyon region—Hopi Tribe, Hualapai Tribe, Kaibab Band of Paiute Indians, Paiute Indian Tribe of Utah, Navajo Nation, and Pueblo of Zuni—are generally supportive of in-place preservation goals for cultural resources, but they have widely varying opinions regarding the appropriateness of undertaking intervention measures to mitigate dam and visitor impacts, such as installing check dams to control erosion or conducting excavations to recover information from archaeological sites.

This chapter describes research, monitoring, and mitigation activities during the past 15 yr that have evaluated and addressed ongoing impacts to cultural resources in the Colorado River corridor because of dam operations and other agents of deterioration, such as visitation and rainfall-induced erosion. The chapter begins with a summary of research and inventory activities prior to the early 1990s, which is followed by a summary of the monitoring and research activities initiated in response to the Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) and the Secretary of the Interior's Record of Decision (ROD)

(U.S. Department of the Interior, 1995, 1996). The chapter ends with some recommendations for the future.

## Background

Current information concerning cultural resources is based on a number of previous investigations within the Colorado River corridor in Glen and Grand Canyons. Comprehensive overviews of previous investigations are included in Ahlstrom and others (1993), Fairley and others (1994), and Fairley (2003). These studies documented evidence of human occupation in the Grand Canyon region extending back as far as the Paleo-Indian period, at least 11,000 yr before present. Starting around 4,500 yr ago, petroglyphs, spear points, and uniquely crafted artifacts known as "split twig figurines" were placed at various locations along and near the Colorado River in Glen and Grand Canyons, indicating intermittent use of the area by Late Archaic hunters and gatherers. Sparse and somewhat controversial evidence for use of the canyon by early farming cultures before 1000 B.C. is present in eastern Grand Canyon (Davis and others, 2000); however, the best documented and most intensive use of Grand Canyon by farmers occurred during the 11th and early 12th centuries A.D., during a time period known as Pueblo II. During this time, people with ancestral ties to modern Puebloan cultures built numerous small masonry dwellings, irrigation ditches, erosion control features, and granaries for storing corn, squash, and cotton throughout Grand Canyon (fig. 1). For reasons not yet fully understood (but that are likely due at least in part to climate-induced stressors), these ancestral Puebloan farmers moved away from Grand Canyon around the end of the 12th century, although small groups continued to visit the canyon for seasonal hunting, plant gathering, trading, and ceremonial pilgrimages into the first decades of the 20th century. Following the departure of the ancestral Puebloan occupants, ancestors of the Hualapai, Havasupai, and Southern Paiute moved into the region. Numerous campsites and food processing areas dating to the late prehistoric (A.D. 1300–1540), proto-historic (A.D. 1540–1776), and early historic (A.D. 1776–1850) periods testify to their extensive, and at times intensive, seasonal use of inner Grand Canyon. Descendants of these Yuman and Numic speakers were still residing in and around Grand Canyon when the first European settlers arrived in the region in 1848, and Havasupai, Hualapai, and Southern Paiute people continue to live in and near Grand Canyon to this day. After 1880, however, as Euro-Americans became increasingly enamored with the spectacular scenery and economic potential of the region, the archaeological record becomes increasingly dominated by the material remains of Euro-American miners, trappers, homesteaders, government explorers, and tourists (fig. 2).

**Figure 1.** Pottery dating to the Pueblo II period is commonly found at archaeological sites along the Colorado River. These formerly buried pot sherds have become exposed by wind (photograph by Amy Draut, U.S. Geological Survey).

## Previous Cultural Resource Research and Inventories

Euro-Americans first noted archaeological remains in the river corridor during the Powell expeditions of 1869 and 1871–72 (Powell, 1875). Powell and his crew found traces of previous human occupation in the canyon in the vicinity of the Little Colorado River, Unkar Creek, Bright Angel Creek, and Shinumo Creek. In the 1950s and 1960s, investigations of archaeological remains in the river corridor became more focused under the direction of the NPS, in part because of anticipated dam developments in Grand Canyon (Taylor, 1958; Euler, 1967a). In the late 1960s and early 1970s, researchers affiliated with the School of American Research, New Mexico, and Prescott College, Arizona, conducted surveys and excavations in the river corridor and adjacent areas to investigate prehistoric settlement patterns (Schwartz, 1965; Euler and Taylor, 1966; Euler, 1967b; Schwartz and others, 1979, 1980, 1981).

**Figure 2.** The remains of Bert Loper's boat came to rest on the banks of the Colorado River in 1948, shortly after Loper drowned in 24 and 1/2-mile Rapid. This boat is an example of the varied historic artifacts found along the Colorado River in Grand Canyon (photograph by Jeff Sorensen, Arizona Game and Fish Department).

Together, these studies provided the foundational information concerning the numerous and diverse cultural resources existing within the river corridor.

In 1984, NPS archaeologists conducted test excavations at five archaeological sites along the Colorado River in advance of their stabilization (Jones, 1986). Three of these sites were deteriorating primarily because of visitor use, one was deteriorating because of both human and natural impacts, and one was being damaged by erosion from a side channel, all resulting in the need for stabilization measures. At all of these sites, excavations revealed the presence of subsurface stratigraphic cultural deposits extending back many centuries earlier than surface evidence indicated. For example, at one site (AZ B:10:4) near Deer Creek, a buried roasting feature produced calibrated radiocarbon dates ranging between A.D. 610 and 380 B.C., whereas the overlying surface structure contained ceramics dating to the Pueblo I-II period (about A.D. 800–1150) (Jones, 1986, p. 105). At another site (AZ B:16:1) near Whitmore Wash, surface materials of Southern Paiute affiliation were found in association with a fire pit that was radiocarbon dated to A.D. 1230–1340, overlying a roasting feature with a calibrated radiocarbon age of 1365–905 B.C. (Jones, 1986, p. 51). This project was important for highlighting the presence of deeply buried cultural deposits at numerous archaeological sites in the river corridor (fig. 3). These older, underlying deposits are often invisible on the surface because floods, slope wash, and aeolian (wind) processes have deposited sediment on top of earlier cultural remains, obscuring them from view.

In 1990–91, an intensive archaeological inventory was conducted by NPS archaeologists (Fairley and others, 1994) in preparation for the writing of the EIS (U.S. Department of the Interior, 1995). This inventory located 475 sites within the assessed area, which extended from Glen Canyon Dam to Separation Canyon, about 255 RM, and up to the estimated 300,000 cubic feet per second (cfs) flood level. The sites ranged in type from isolated hearths and dispersed lithic scatters to complex multiple-component habitations, many with associated roasting features or masonry structures. The sites ranged in age from Late Archaic, about 2500–1500 B.C., to the mid-20th century. Many sites date to the ancestral Puebloan occupation between A.D. 950 and 1200, while many other sites are affiliated with the ancestral Pai and Paiute use of Grand Canyon from about A.D. 1250 to 1870.

Of the sites within the surveyed area, approximately 336 were considered to be situated within the area of potential effect from dam operations, and many of these sites had identifiable impacts that were believed to be related to dam operations (Fairley and others, 1994, p. 148). Dam-related impacts were categorized as direct, indirect, or potential. Direct impacts included sites where inundation or bank cutting from dam-controlled

**Figure 3.** The curved masonry wall of a deeply buried prehistoric structure was uncovered during excavations at site AZ C:13:10 in April 1984. No evidence of this structure was visible on the site surface prior to excavation (photograph by Helen Fairley, U.S. Geological Survey).

river flows had occurred within the site in recent years. Indirect impacts included (1) bank slumpage or slope steepening from river flows immediately adjacent to the site, (2) arroyo cutting or other erosion phenomena tied to the effects of dam-controlled flows, and (3) effects of visitor impacts at sites because of changes in recreational use patterns related to recent dam operations. Potentially impacted sites included all those located within the estimated area of inundation from a 300,000-cfs flood. This flood level reflected the former estimated volume of the highest historical flood on record (in 1884) (Hereford and others, 1993; cf. Topping and others, 2003, p. 31) and also the maximum release level possible from Glen Canyon Dam, estimated at 256,000 cfs, combined with a hypothetical 40,000-cfs flood event from the Little Colorado River and other tributary streams.

Of the 336 sites considered to be within the area of potential effect, 33 showed evidence of direct impacts, 138 revealed evidence of indirect impacts, and 238 were categorized as potentially impacted based on their location below the estimated 300,000-cfs level or based on their location in or on unconsolidated Holocene sedimentary deposits (Fairley and others, 1994, p. 148). (The impact numbers exceed total number of sites because many sites exhibited more than one category of impact.)

Participating Native American tribes also conducted cultural resource inventories in the early to mid-1990s to identify resources with important traditional cultural values, including but not limited to prehistoric Native American archaeological sites. These studies were conducted by the Hopi Tribe, the Hualapai Tribe, the Navajo Nation, the Southern Paiute Consortium (comprising the Kaibab Band of Paiute Indians and the Paiute Indian Tribe of Utah), and the Pueblo of Zuni (Stoffle and others, 1994, 1997; Hart, 1995; Roberts and others, 1995; Ferguson, 1998; Stevens and Mercer, 1998). Numerous locations of cultural importance were identified and evaluated by the individual tribes, including areas with culturally important biological resources, significant landscape features, mineral locations, and specific archaeological resources. Assessments were conducted by the tribes to identify potential impacts resulting from dam operations and to formulate possible treatment options. These studies have subsequently been used by the Bureau of Reclamation for the identification and preliminary evaluation of traditional cultural properties within the area of potential effect as defined by the Programmatic Agreement for Cultural Resources (see discussion below) (U.S. Department of the Interior, 1995, p. Att-23); however, studies to formally define and evaluate traditional cultural properties have yet to be completed.

# Monitoring and Research

## Monitoring of Cultural Resources

Before the 1990s, the NPS annually monitored a sample of archaeological sites in the Colorado River corridor. These initial monitoring efforts focused primarily on sites prone to impacts from visitors. After the comprehensive inventory of the river corridor was completed in 1991, the NPS expanded its monitoring program to encompass the full suite of resources located within the hypothetical area of potential effect from dam operations. In the mid-1990s, the Southern Paiute Consortium and the Hualapai and Hopi Tribes also initiated their own monitoring programs to track changes in resource conditions at culturally important locations in the river corridor (Stoffle and others, 1995; Ferguson and others, 1997).

Since 1994, monitoring of historic properties that are eligible to be listed in the National Register of Historic Places—nationally, regionally, and locally significant prehistoric and historic sites, structures, objects, and places of traditional cultural importance—has been conducted under the auspices of a Programmatic Agreement for Cultural Resources. The agreement exists between the Bureau of Reclamation, NPS, Advisory Council on Historic Preservation, Arizona State Historic Preservation Office, and six affiliated Native American tribes. Current monitoring protocols, established under interim guidelines of the Programmatic Agreement for Cultural Resources, document the presence of all types of impacts occurring to archaeological resources in the river corridor, regardless of ultimate cause.

In addition to the NPS monitoring efforts, the Hopi Tribe, Hualapai Tribe, and Southern Paiute Consortium conduct annual monitoring trips to assess changes to their traditional cultural resources and to assess the general health of the ecosystem through their own traditional value system. Tribal monitoring has been conducted both through and outside of the programmatic agreement, as not all resources of tribal concern meet the established definitions of National Register-eligible historic properties.

The Programmatic Agreement for Cultural Resources is concerned with tracking and mitigating dam effects at approximately 318 National Register-eligible archaeological sites in the river corridor: 54 in Glen Canyon National Recreation Area and 264 in Grand Canyon National Park (Leap and others, 2000, p. I-8). Approximately 160 of these sites are actively monitored at the present time. All sites currently monitored fall within the affected environment as defined by the EIS (U.S. Department of the Interior, 1995). The monitoring is carried out by staff from the NPS, working with cooperators from Northern Arizona University. National Park Service archaeologists conduct monitoring trips several times each year and produce annual monitoring reports, which are submitted to the Bureau of Reclamation in partial fulfillment of an ongoing cooperative agreement (Leap and others, 2000). Currently, archaeological sites above Lees Ferry are not being monitored (Chris Kincaid, Glen Canyon National Recreation Area, oral commun., 2004); only sites downstream of Lees Ferry are routinely monitored.

Archaeological sites are currently selected for monitoring and remedial treatments based on interim protocols established under the programmatic agreement. These protocols include judgmentally selecting sites for monitoring based on perceived susceptibility or likely vulnerability to erosion or visitor impacts. Sites are monitored on a cycle that varies from semiannually to annually, biennially, or once every 3, 4, or 5 yr (Leap and others, 2000). Monitoring cycles are assigned on the basis of perceived levels of stability or visitor use, but the monitoring cycles are not rigidly adhered to and frequently change. For example, of the 91 sites monitored in fiscal year 2001 (FY01), 55% (n = 50) were monitored more or less frequently than their assigned monitoring cycle, and 18% were reassigned to a new monitoring cycle based on perceived changes in their stability. Sites that are stable or show no signs of visitor use are not included in the current monitoring program. This bias in site selection was intentionally designed to focus attention on those sites that were theoretically at greatest risk from damage from visitor use and erosion and were most likely to require preservation treatments in the foreseeable future; however, the deliberate emphasis placed on monitoring sites that are assumed to be most threatened limits the usefulness of the resulting data for drawing systemwide conclusions about status and trends of site condition, rates of impacts, or overall effects of dam operations on historic properties.

The main goals of the current monitoring program are to document site impacts and evaluate the need for site protection measures such as erosional control check dams. Changes in the numbers, types, and locations of site impacts are documented in yearly reports prepared by the NPS and Northern Arizona University cooperators (see Leap and others, 2000, for a listing of annual reports through 1999; see also Leap and Kunde, 2000; Dierker and others, 2001, 2002; Leap and others, 2003). These reports discuss the results of site-specific evaluations, identify specific changes occurring at individual sites, and make recommendations about future protection measures, including data recovery. The reports do not track systemwide trends in site condition or evaluate changes in site condition relative to dam-controlled flows.

Currently, archaeological site-monitoring activities conducted under the programmatic agreement involve repeat site visits, visual assessments of site impacts, and qualitative assessments of overall condition, which are documented through the use of repeat photography and completion of a two-page checklist of impacts. As described in the FY02 annual monitoring report (Dierker and others, 2002, p. 2),

> Archaeologists qualitatively assess impacts to sites via repeat observations. The degree of impact is categorized as "present" or "absent," with physical erosion further categorized as "active" or "inactive." Active erosion is defined as obvious recent movement, disturbance, or rearrangement of sediment or artifacts onsite. Inactive erosion is defined as a (less obvious) perception that past geophysical processes are discernable at the site, but are not presently at work.

Visitor impacts are recorded as present or absent in five categories: social trails, artifact collection piles, evidence of onsite camping, criminal vandalism, and other impacts (fig. 4). Physical impacts are recorded as present or absent and either active or inactive within the following eight categories: surface erosion, gullying,

**Figure 4.** Visitors frequently remove artifacts from their original locations and concentrate them in "collection piles," resulting in loss of information about the original context of the artifacts (photograph by Helen Fairley, U.S. Geological Survey).

**Figure 5.** An erosional gully cutting headward into a prehistoric roasting feature (photograph by Amy Draut, U.S. Geological Survey).

arroyo cutting, bank slumpage, aeolian/alluvial erosion or deposition, side canyon erosion, animal-caused erosion, and other erosion (fig. 5). Impacts that the NPS views as being directly related to dam operations include bank slumpage and gullying/arroyo cutting in locations where drainage systems are actively entrenching to achieve grade with the present-day "highest discharge" terrace levels formed under dam-controlled flows. The precise role of dam operations relative to other erosional forces—precipitation events, human trampling, wind, and other "natural" and "cultural" agents of erosion—in causing or exacerbating erosion of archaeological sites in the river corridor remains a topic of continuing controversy in the scientific community.

Because the current archaeological site monitoring program does not measure or otherwise attempt to quantify impacts or rates of change in either a relative or absolute sense, it is difficult to draw any specific conclusions about overall trends in resource condition in relation to either the interim operating flows of 1991–95 or the modified low fluctuating flow (MLFF) alternative implemented in 1996 (U.S. Department of the Interior, 1996). Two conclusions can be drawn, however, by using the currently available monitoring information: (1) archaeological sites continue to receive impacts from visitor use and erosion, and (2) archaeological site conditions are likely to continue to deteriorate (at an unknown rate) because impacts from visitor use and erosion are ongoing and not likely to diminish in the foreseeable future.

## Erosion Control with Check Dams

Beginning in 1995, the NPS began installing rock and brush check dams at selected archaeological sites in the river corridor in an attempt to control erosion. Check dams were first piloted as an erosion control measure in an area below the Little Colorado River known as "Palisades," where gullies bisect two archaeological sites (AZ C:13:99 and AZ C:13:100). National Park Service archaeologists had monitored and documented a progressive deepening and widening of the drainages in the Palisades area since 1978. Continuing channel erosion caused the collapse and disappearance of numerous slab-lined cists and portions of masonry structures in the late 1980s and early 1990s, hence the decision to initiate erosion control measures. With assistance and supervision from the Zuni Conservation Project (a team of soil conservation experts from the Pueblo of Zuni), NPS archaeologists installed 70 check dams at the two sites by using a variety of local materials and construction styles (Leap and Coder, 1995; Leap and others, 2000).

Since the initial pilot project in 1995, NPS archaeologists have installed approximately 280 check dams at 29 different archaeological sites (Leap and others, 2000). Currently, 260 erosion-control features are actively monitored and maintained at 27 sites (Leap and others, 2003, p. 58). An evaluation of check dam effectiveness conducted in 2002 (Pederson and others, 2003) found that the brush checks built with a "basket weave" technique seemed to work best and caused less damage to surrounding terrain upon failure than did check dams built

**Figure 6.** Members of the Zuni Soil Conservation Project constructing a check dam by using the basket-weave technique (photograph courtesy of Grand Canyon National Park).

with rocks or logs (fig. 6). The researchers observed that brush checks tended to fail in their central sections or get ripped out as a woody mass, whereas the more rigid rock and log checks were often flanked by the gullies via lateral slope erosion, further exacerbating erosional impacts to the sites. Pederson and others (2003) concluded that brush checks were less damaging than stone checks and that check dams, without routine maintenance, could cause more harm than good; however, check dams could temporarily slow rates of erosion provided they were routinely maintained. These findings are considered somewhat tentative and in need of further verification because they were based on observations conducted over the course of a single monsoon season in 2002, which was one of the driest monsoon seasons on record.

## Test Flow Impacts on Cultural Resources

Many of the archaeological resources along the corridor of the Colorado River are situated on or contained within the Holocene sedimentary deposits, which form dunes and terraces (fig. 7). The sediment resource has declined, and the alluvial terraces have eroded since the completion of Glen Canyon Dam. A systemwide method for regenerating the river terraces and redistributing sediment is considered an essential component to maintaining integrity of cultural resources in place.

The 1996 beach/habitat-building flow, or controlled flood, presented an opportunity to study the effects of high-flow discharge from Glen Canyon Dam on alluvial terraces and margin deposits along the river corridor. Although the effects of the 1996 beach/habitat-building flow of 45,000 cfs on archaeological sites could not be predicted, the hope was that it could provide systemwide mitigation to most cultural sites in the Colorado River corridor through the accumulation of additional sediment at higher elevations than normally would occur under the MLFF alternative (Balsom and Larralde, 1996, p. 3). Mitigation and monitoring of archaeological sites, ethnobotanical resources, and sediment accumulation at the mouths of arroyos were undertaken to evaluate the effects of this experimental high flow. In addition, rates of terrace retreat were studied in the Glen Canyon reach to determine whether terraces containing archaeological sites were negatively affected by the high flows (Balsom and Larralde, 1996).

**Figure 7.** A buried Pueblo II structure is becoming exposed by erosion near Unkar Delta (photograph by Amy Draut, U.S. Geological Survey).

The overall findings of the cultural resource studies done in conjunction with the 1996 beach/habitat-building flow were that the 45,000-cfs flow had either no effect, no adverse effect, or in some instances a beneficial effect on cultural resources (Balsom and Larralde, 1996, p. 25). In a few locations, however, especially in the Glen Canyon reach, loss of sediments occurred in a manner that, in the long run, could be detrimental to cultural resources. Follow-up studies conducted by the Hopi Tribe (Yeatts, 1998) and by Northern Arizona University researchers (Hazel and others, 2000) found that sediment deposited in arroyo mouths by the 1996 beach/habitat-building flow persisted in some locations for several years, especially where brush check dams had been installed in the lower reaches of the drainages. These studies, however, did not specifically evaluate whether the sediment plugs diminished the rate of down-cutting in upper reaches of the affected gullies. Nevertheless, the studies demonstrated that backfilling of some erosional channels could be accomplished by periodic high-flow events and that high, sediment-enriched flows offer one potential means of conducting systemwide mitigation for effects of dam operations on cultural resources.

Since 1996, several additional test flows have taken place, including the 2000 low summer steady flows experiment, the 2003–05 fluctuating nonnative fish suppression flows, and the November 2004 experimental high flow. No specific cultural resource monitoring programs were conducted in conjunction with the 2000 low summer steady flows or the 2003–05 fluctuating nonnative fish suppression flows; however, analysis of the sediment mass balance under the 2003 and 2004 winter nonnative fish suppression flows showed that the fluctuating flows eroded material above and beyond the amount supplied by tributaries within the previous year. Also, analysis showed that higher levels of very fine grained material were entrained during the initial few days of the 2003 and 2004 high fluctuating flows, suggesting the possibility that fine sediments that were derived from predam deposits contributed to the sediment being transported out of the system (David Topping, U.S. Geological Survey, oral commun., 2005). Although not conclusive, this information suggests that there may be some additional loss of predam terrace deposits, where most archaeological sites are situated, occurring under the experimental fluctuating nonnative fish suppression flows.

During the 2004 experimental high flow, one of the areas monitored during the 1996 beach/habitat-building flow and two additional sites upstream in Marble Canyon were monitored to determine whether sandbars would be created in the vicinity of archaeological sites, in locations where the new sandbars could serve as sources of sediment for windborne redeposition on downwind archaeological sites. An additional aim of this research was to document whether sediment would be deposited in the mouths of arroyos that currently bisect some archaeological sites and whether these sediment "plugs" would be retained long enough to help reduce the rate of downcutting in affected arroyos because of the temporary elevation increase at the arroyo mouths. Preliminary observations indicate that large sandbars did form upwind of the site areas and that sediment did backfill arroyos; however, at the time this report was being written, it was still too early to determine whether the 2004 experimental high flow would benefit the archaeological sites over the long term. U.S. Geological Survey scientists will be monitoring the fate of the new sandbars and associated archaeological sites over the next year to determine whether and to what degree the newly formed sandbars contribute sediment to the windborne deposits that blanket sites located at higher elevations.

## The Role of Windborne Sediment in Preserving Archaeological Sites

In addition to the monitoring activities previously described, several research projects have been initiated and supported through the Glen Canyon Dam Adaptive Management Program over the past decade to improve overall understanding of how Glen Canyon Dam operations may be affecting archaeological sites in the Colorado River corridor below the dam (Thompson and others, 2000; Draut, 2003; Pederson and others, 2003; Draut and others, 2005; Wiele and Torizzo, 2005).

Of particular interest is whether and how postdam changes in overall sediment supply and flow regimes downstream of the dam may be contributing to the erosion of high-elevation dunes and terraces bordering the Colorado River, where many archeological sites occur. These terraces are bisected by numerous arroyos and gullies draining to the river, and many of the erosion channels pass through or by archaeological features. Pieces of anecdotal and empirical (aerial photography) evidence indicate that these gullies have been increasing in size, depth, and abundance over the past four decades (Hereford and others, 1993). The question that both dam managers and NPS managers are seeking to answer is, "To what extent is the ongoing erosion of these higher elevation terraces related to dam operations?"

Scientists generally agree that gullies are formed in response to specific, and often unusually intense, precipitation events (e.g., Webb, 1985). If precipitation is responsible for the establishment of gullies and arroyos, what might dam operations have to do with the ongoing erosion of the predam terraces? The answer lies in understanding the dynamic nature of the predam fluvial system in contrast with the present-day, dam-controlled hydrologic system, which is also very dynamic but in fundamentally different ways (Topping and others, 2003). The predam system was generally characterized by high seasonal variability and low daily variability. Flows during the winter months were typically quite low, often running at less than 3,000 cfs. The flows usually stayed low until late April or early May, when runoff from the Rocky Mountains started making its way to the Gulf of California. Spring flows typically peaked in June or early July, with additional spikes in late summer in response to localized monsoon storm events. The annual spring snowmelt floods ranged between about 35,000 and 120,000 cfs and averaged around 55,000 cfs, with peak flows of 120,000 cfs reoccurring about once every 6 yr (Topping and others, 2003). The highest known flood in historic times occurred in 1884 with an estimated flow of 210,000 ± 30,000 cfs. In 1921, a flood of 170,000 cfs was measured at the Grand Canyon gage (Topping and others, 2003, p. 31). Floods even larger than this are known from the geomorphic record (O'Connor and others, 1994).

The high spring flows typically carried huge sediment loads. An analysis of the historical predam sediment transport records from the Lees Ferry gage and Grand Canyon gage shows that the monthly sediment loads during May averaged around 13.9 to 17.6 million tons (12.6 and 16 million Mg) per month, respectively, which is close to 20% of the annual amount transported each year (Topping and others, 2000b). As flood waters receded, sand was deposited at and below the flood stage along the river banks. After these flood deposits dried out, wind transported the fluvial sediment farther inland, where some of it covered archaeological sites and formed coppice dune fields around mesquite thickets.

Today, virtually 100% of the sediment load that used to be transported by the river through Grand Canyon is trapped upstream in Lake Powell. Two major tributaries below Glen Canyon Dam, the Paria River and the Little Colorado River, contribute the bulk of the current sediment coming into the river system. Taken together, the contributions of sand from various sources provide Grand Canyon with approximately 16% of its predam levels (see chapter 1, this report). Compounding the effects of this drastic reduction in sediment, the dam is operated to meet peak power demands, so in the postdam era prior to the Record of Decision (1963–96) the Colorado River fluctuated by as much as 25,000 cfs on a daily basis, and the daily discharge range exceeded 10,000 cfs on 43% of all days (before the dam, daily ranges in excess of 10,000 cfs occurred on only about 1% of all days) (Topping and others, 2003). Furthermore, flows higher than 9,000 cfs essentially guarantee that any fine-grained sediment coming into the system will be transported downstream to Lake Mead in a period of a few weeks to a few months (Topping and others, 2000 a, b; Rubin and others, 2002), and analysis of the continuous discharge record from Lees Ferry gage and the Grand Canyon gage demonstrates that flows greater than this level have dominated the postdam record (Topping and others, 2003, p. 48).

The reduction in sand supply translates into a reduction in the size, height, and volume of sandbars throughout the river corridor (Hazel and others, 1999; Schmidt and others, 2004). Furthermore, because dam-controlled flows are generally constrained below 25,000 cfs, sand and silt are no longer being deposited at higher elevations where fine sediment would be less susceptible to riverine transport, more readily available for inland transport by wind, and able to backfill the lower reaches of arroyos and gullies that dissect the terraces.

Aeolian (windborne) sediment has previously been shown to play an important role in the formation and subsequent reworking of terraces where many archaeological sites are located (Hereford and others, 1993, 1996), and aeolian deposition has been hypothesized to play an important role in mitigating the effects of runoff erosion (Lucchitta, 1991). In order to improve our understanding of how changes in sediment supply and river flow dynamics are affecting the archaeological sites, a study was initiated in 2003 to examine the role of aeolian sediment in preserving archaeological sites from several different perspectives: (1) the relative importance of aeolian sedimentation in the past compared to today, both as a terrace-forming process and also in backfilling incipient rills and gullies; (2) the extent to which aeolian sand cover may be diminishing throughout the ecosystem under current sediment-limited conditions; (3) the extent to which current rates of aeolian transport vary at different locations under varying ecological and geomorphic parameters throughout the river corridor; and (4) the extent to which aeolian transport rates and downwind aeolian sand cover could potentially increase when new bars are formed in optimal locations relative to the areas where archaeological sites occur.

To study these issues, Draut (2003; Draut and Rubin, in press) established wind-transport monitoring instruments at six locations throughout the corridor of the Colorado River (fig. 8). These monitoring stations measure the amount of sand being transported by varying wind speeds at different times of the year and under different sediment supply conditions. Preliminary results from the first year of data (Draut and Rubin, in press) indicated that wind speeds and predominant directions vary widely throughout the river corridor and that trans-

**Figure 8.** U.S. Geological Survey scientists installing a weather station near RM 65. These devices measure wind velocity and direction at six locations along the Colorado River (photograph by Amy Draut, U.S. Geological Survey).

port conditions are also highly variable, limiting efforts to model sediment-transport rates for the system as a whole.

To determine the extent to which aeolian sediment formed the material in which archaeological sites are embedded, Draut worked collaboratively with NPS archaeologists, U.S. Geological Survey scientists, and other researchers to evaluate subsurface deposits at a nonrandom sample of archaeologically rich locations throughout the river corridor (Draut and others, 2005). These investigations focused on describing the various geomorphic processes that have contributed to the formation and preservation of archaeological sites by closely examining the sedimentary structures preserved in subsurface contexts (fig. 9). Preliminary findings indicated that aeolian deposits were common throughout the prehistoric landscape of the river corridor and were important factors in the formation of many sites but that wind deposition was clearly not the only matrix-forming process at work in the past. Aeolian sediment blankets the surface of many archaeological sites, but often these windborne deposits cover substrates that are both fluvially (from the river) and colluvially (from the slope) derived (Draut and others, 2005).

In terms of understanding how dam operations could be altered to enhance the sediment supply available for redeposition by the wind, Draut is tracking the fate of several sandbars that formed during the November 2004 experimental high flow near previously established sediment-transport monitoring stations (Draut and Rubin, in press). During 2005–06, Draut will evaluate the extent to which aeolian processes may contribute to the erosion of the newly formed sandbars and track the amount of sediment transported by the wind from the sandbars to nearby archaeological features. This information will allow researchers to assess the relative importance of fluvial and aeolian processes in maintaining the sedimentary matrices of archaeological sites located above the level of dam-controlled flows in the river corridor.

**Figure 9.** A U.S. Geological Survey scientist examines stratigraphy exposed in the wall of an arroyo near RM 209 (photograph by Amy Draut, U.S. Geological Survey).

## Ethnobotanical Resources and Other Tribally Valued Resources

The Hopi and Hualapai Tribes and Southern Paiute Consortium have monitored a variety of culturally important resources in the Colorado River corridor since the mid-1990s. The monitored resources of concern include culturally valued plants and plant gathering locations, traditionally valued mineral resources, landscape features, traditional use areas, and archaeological sites.

Since 1995, the Southern Paiute Consortium has monitored culturally important resources in the corridor of the Colorado River to assess their condition relative to Glen Canyon Dam operations and visitor use, to educate and train tribal members in resource monitoring, and to educate tribal members and the general public about the traditional importance of Grand Canyon to the Southern Paiute people (Stoffle and others, 1995; Drye and others, 2001; Bullets and others, 2003, 2004). Approximately 20 individual locations are monitored by the Southern Paiute Consortium on a 6-yr cycle. Some locations are visited every year, while others are visited only once or twice over the 6-yr period. Locations of importance include traditional plant areas, rock art, specific perennial tributaries, and archaeological sites with evidence of use by Southern Paiute ancestors. The general assessment from Southern Paiute Consortium monitoring during the past 5 yr is that most of the monitored resources appear to be in relatively good condition, although concerns about visitor trails at archaeological sites, visitor behavior around certain traditionally significant locations in Grand Canyon, and drought stress on plants have been noted. To date, no specific recommendations regarding Glen Canyon Dam operations have been forthcoming from these monitoring efforts.

The Hualapai Tribe monitored traditional cultural resources in conjunction with the 1996 beach/habitat-building flow (Jackson and others, 1997) and again in 2001, 2002, 2003, and 2004 (Jackson and others, 2004 a, b). Beginning in 2001, the baseline conditions of 15 previously documented traditional cultural locations in Grand Canyon and of 5 previously undocumented locations were evaluated by Hualapai tribal members and consultants using a numerical condition index rating system. Several additional sites were added to the monitoring program in 2002–04, resulting in a total of 28 traditional cultural locations receiving 1 or more years of monitoring. Natural and cultural impacts were ranked on a 5-point scale, from 0 (absent) to 4 (severe). Impact ratings averaged over all 20 sites indicated that human impacts, both visitor- and dam-related, were more problematic than were natural impacts. Negative dam-related impacts included water stress on vegetation because of the lack of periodic inundation of higher elevation plant communities, continuing nonnative plant encroachment, and the loss of beach area from dam-controlled flows. Effects from the diminishing surface elevation of Lake Mead, accompanied by vegetation encroachment of nonnative plants, primarily tamarisk (*Tamarix ramosissima*), were also noted. Throughout the corridor of the river, human impacts from trailing, artifact movement, and onsite camping were observed to be a problem, with the latter impacts rated as heavy to severe in several cases. On Lake Mead, the wakes of motor boats are also thought to contribute significantly to beach erosion (Jackson and others, 2004b). Based only on the 2001 monitoring results, human impacts were the most significant impacts observed at most sites, with 13 of the 20 locations rated as having heavy (3) to severe (4) human impacts. In contrast, only 5 of these 20 locations monitored in 2001 were assigned similar natural impact ratings, and most of the impacts were from rodent burrowing and side canyon flash floods. Overall in 2001, the average rating for all natural impacts was 1.8, whereas the average human impact rating was 2.6. In future years, repeated analyses of the same sites will allow Hualapai tribal members to determine whether or not conditions are improving or deteriorating relative to 2001 baseline conditions, but at this time (2005), comparative data are insufficient for conducting this analysis.

The Hopi Tribe initiated an ethnobotanical project in 1998 to evaluate traditional plant resources in the corridor of the Colorado River (fig. 10). This study, completed in 2001, identified over 128 plant species in Grand Canyon that were traditionally used for ceremonies, medicines, food, and other necessities of daily life (Lomaomvaya and others, 2001). Beginning in 2002, the Hopi Tribe initiated a multiyear project to evaluate whether terrestrial ecosystem data currently being collected by cooperating university scientists (Kearsley and others, 2002) could be useful to the Hopi Tribe for assessing resource conditions from a Hopi perspective. The results of this initial study indicated that the terrestrial ecosystem data could be usefully interpreted from a Hopi perspective, provided that the data were translated from scientific categories and terminology into Native American categories and terminology (Huisinga and Yeatts, 2003). In 2003, the Hopi Tribe initiated a pilot study to begin assessing the terrestrial ecosystem data from a native Hopi perspective. Results of this pilot study are anticipated to be available in spring 2005.

**Figure 10.** Hopi elders discuss and document the uses of culturally valued plants in the Colorado River corridor. The photograph was taken at RM 43 below the 100,000-cfs water-surface elevation (photograph courtesy of Michael Yeatts and the Hopi Tribe).

## Summary

Resource monitoring of archaeological and traditional cultural resources suggests that archaeological resources continue to be impacted both by physical processes such as surface erosion and gullying and by recreational visitors. Although surface erosion and visitor impacts would undoubtedly be occurring without the presence or continuing operation of Glen Canyon Dam, the manner in which the dam is currently operated prohibits the retention of sediment within the river corridor. The diminishing supply of sediment appears to be contributing to and exacerbating the rate and amount of erosion occurring at all levels within the ecosystem. In addition to impacts from Glen Canyon Dam operations, visitor impacts such as trailing, trampling, and collection of artifacts are contributing to the degradation of many archaeological sites in the river corridor and of several locations of traditional importance to Native American people.

Tribal assessments of dam-related impacts to ethnobotanical resources in the river corridor offer somewhat mixed results. For the most part, the Southern Paiute Consortium has identified satisfactory conditions for traditional plant resources, although there is some evidence of plant deterioration, probably from ongoing drought conditions. Meanwhile, the Hualapai Tribe has expressed concern over the condition of certain key botanical resources (e.g., the willow tree (*Salix* sp.) at Granite Park), and they have noted an apparent increase in nonnative plants such as Bermudagrass (*Cynodon dactylon*) and camel thorn (*Alhagi maurorum*) at specific locations in the river corridor.

Under the current NPS monitoring program, frequency of monitoring is tied to perceived levels of erosion or visitor use, with those sites showing more evidence of active erosion or more frequent visitor use being monitored more frequently than those showing less impact. As one would expect from a monitoring program that is weighted towards tracking impacts at the more threatened and heavily visited sites, annual monitoring results show relatively high levels of physical and visitor-related impacts.

Because the current data set is lacking measurements related to rates or degrees of erosion, it is not possible to determine whether or to what degree rates of erosion at archaeological sites may have changed in recent years under the MLFF regime. The NPS monitoring program is undergoing a reevaluation and redesign in 2005 to better meet the needs of the Glen Canyon Dam Adaptive Management Program for information related specifically to effects of Glen Canyon Dam operations on National Register-eligible historic properties. Once revised monitoring protocols are implemented in 2006, it will be possible to track rates and trends in gully formation and downcutting relative to different flow regimes and to make systemwide assessments of resource condition over time.

The limited monitoring, in conjunction with the 1996 beach/habitat-building flow and 2004 experimental high flow, indicates that the creation of sandbars above the level of normal dam operations may have beneficial effects on archaeological sites in two respects: (1) by creating sources of sediment for subsequent wind-borne redeposition at archaeological sites located upwind of the newly formed sandbars and (2) by temporarily raising the effective base level to which terrace channels are downcutting in the short term, thereby temporarily slowing the rates of downcutting and headward migration of erosional gullies. For these measures to be effective over the long term, however, periodic high flows under sediment-enriched conditions would need to be repeated at relatively frequent intervals.

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# Chapter 12

# Recreational Values and Campsites in the Colorado River Ecosystem

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## Introduction

Grand Canyon National Park is one of the best-known wildland preserves in the world. Its designation as a national park in 1919 sought to protect it for the benefit of human visitors as well as to safeguard the physical, biological, and cultural resources contained within its borders. Interest in recreation on the Colorado River has risen dramatically since the mid-1960s, and a 226-mi (364 km) journey through Grand Canyon by boat is now regarded as one of the world's premier wild-river experiences. Recreational use of the Colorado River corridor through Grand Canyon is closely regulated by the National Park Service (NPS), and demand for the corridor, particularly for river trips, greatly exceeds availability.

Beginning with the initial explorations of John Wesley Powell in 1869, river runners and hikers have used sandbars along the Colorado River below present-day Glen Canyon Dam as campsites. These camps, and their associated activities, make up an important element of the modern-day recreational experience within Glen and Grand Canyons. Because of their crucial role, the relative size, distribution, and quality of campsites along the Colorado River are of particular concern to river managers (Bureau of Reclamation, 1995; Stewart and others, 2000; Glen Canyon Dam Adaptive Management Program, 2001; National Park Service, 2004).

This chapter presents an assessment of the current state of knowledge concerning the impacts of Glen Canyon Dam operations on the changing condition of campsite areas and sandbars and the implications of physical changes of the Grand Canyon ecosystem for visitor capacity and quality of experience. After defining the study area and some key concepts, the chapter briefly reviews the relationships between the condition and extent of Colorado River sandbars and the quality of the visitor recreation experience. An overview of historical status and trends of the number and size of campsites along the Colorado River is followed by a summary of recent findings. Discussion focuses on the effects of the modified low fluctuating flow (MLFF) alternative and high-volume experimental flows on campsite area. The chapter concludes with an evaluation of these results relative to the stated recreation goals and management objectives of the Glen Canyon Dam Adaptive Management Program (GCDAMP).

# Background

The Colorado River flows approximately 293 RM from Glen Canyon Dam to the Grand Wash Cliffs, the physical feature that marks the western boundary of Grand Canyon National Park. The focus in this chapter is on the portion of the river from Lees Ferry to Diamond Creek (RM 0–226), even though recreational use of the river corridor extends another 50 mi (80 km) downstream to Lake Mead. Lees Ferry is the launching point for river trips through Grand Canyon, and Diamond Creek, on the Hualapai Indian Reservation, is the typical takeout point.

# Geomorphic Characteristics of Campsites

Debris fans are sloping deposits of boulders, gravel, and sand that form at the mouth of a tributary as the result of flash flood events that constrict the main channel and increase the local bed elevation of the river (Schmidt and Graf, 1990). At most constrictions, recirculation zones or eddies (currents of water moving against the main current in a circular pattern) are formed in the river, and because of lower flow velocities, sand is deposited within eddies. Flow patterns within an eddy define the configuration of sand that is deposited (Schmidt and Graf, 1990). Typically, eddies contain a primary recirculating zone and often have secondary zones of separated flow where the current rotates in the opposite direction of the primary zone or is virtually stagnant. Sand deposits are classified based upon where they are deposited in relation to the primary and secondary recirculating patterns. Two types of deposits are the highest in elevation and are most typically associated with campsites: separation deposits and reattachment deposits. Separation deposits mantle the downstream part of the debris fan near the point where the main current separates to form the eddy. Reattachment deposits are located at the downstream end of the primary recirculating zone where the main-channel current reattaches to the bank.

Channel-margin deposits are not associated with tributary debris fans and occur along the channel banks. These deposits form within small eddies associated with bank irregularities caused by talus and rock outcropping. A small number of these channel margin deposits are used as campsites. Within some reaches of the corridor, flat-lying units of rock crop out along the river, and the ledges are also used as campsites.

# Visitor Capacity and Wilderness Experience

In the context of recreation, carrying capacity is now referred to as “visitor capacity,” defined recently as “. . . a prescribed number and type of people that an area will accommodate, given the desired natural/cultural resource conditions, visitor experiences, and management program” (Haas, 2001). Ecological aspects of visitor capacity usually relate to cumulative ecological impacts, but in places such as Colorado River campsites, actual physical space available, impacted or not, is also a critical factor. These categories have been referred to as “ecological” capacity (e.g., plant, animal, and soil impacts) and “physical” capacity (e.g., people per unit area of flat sleeping area; camping parties per beach) (Shelby and Heberlein, 1986). This distinction is useful for understanding visitor capacity for the Colorado River, where both physical space available and resource impacts are important management considerations.

In addition to resource protection, primary objectives for recreation management include minimizing impacts on, enhancing, and preserving the quality of recreation experiences. Experience quality is complex and affected by an array of factors, some of which are social rather than ecological or physical, so visitor capacity also has a “social” component. Social variables that affect experience quality include the number of people visible at one time in a given area and the number of encounters of one group with other parties or with groups of a particular type or size (Shelby and Heberlein, 1986). Resource protection will always be a primary concern in highly sensitive areas, such as desert riparian zones, where even moderate human activity may cause significant ecological impacts, and in settings where heavy use produces damage. Thus, in ecologically sensitive areas, visitor capacity is limited by the need to protect resources. For a broad range of less sensitive areas, however, social variables that affect recreation experience quality may limit visitor capacity at levels below those at which unacceptable resource impacts occur.

On the Colorado River in Grand Canyon, legal guidelines call for not only resource protection and a quality recreational experience but also an undeveloped, uncrowded, wilderness-type experience. It is clear that on the Colorado River, outstanding opportunities for wilderness experiences are indeed a key factor in the river’s popularity and something that the general public has come to expect when visiting Grand Canyon. This popularity was confirmed during the initial phase of river recreation research in the 1970s (Shelby, 1976) and in subsequent studies (Bishop and others, 1987; Hall and Shelby, 2000).

The National Park Service has explicitly expressed an intention to manage for wilderness-type experiences for Colorado River visitors within Grand Canyon National Park (National Park Service, 1995, p. 11). In addition to the opportunity to experience natural ecological conditions, one of the most important attributes of a wilderness experience is solitude (Hendee and others, 1990). Because the operation of Glen Canyon Dam has eroded sandbars used for camping and has reduced the sand available for maintaining them (see chapter 1, this report), the area available for camping in the river corridor has declined significantly since construction of Glen Canyon Dam in 1963 (Kearsley and others, 1994; Kaplinski and others, 2005). The decrease in campsite area can affect solitude by increasing the level of crowding along the corridor. Crowding reduces the ability of separate river trips to camp out of sight and hearing of one another and also reduces the ability of individuals or small groups within a particular trip to camp out of sight and hearing of one another.

Because tracking changes in recreation resources and experience quality means identifying quantifiable parameters, campsite area has emerged as the preferred parameter for measuring these attributes for recreational monitoring programs in Grand Canyon. Campsite area is not the only factor in Colorado River recreation that affects experience quality, but it is a readily measurable factor that has arguably changed more than any other facet of the river experience in the past 40 yr.

## Status and Trends

Studies of campsite area have been conducted by Weeden and others (1975), Brian and Thomas (1984), Kearsley and Warren (1993), Kearsley and others (1994), Kearsley (1995), and Kearsley and Quartaroli (1997). These studies evolved from qualitative estimates of campsite carrying capacity to quantitative aerial photographic measurements. Weeden and others (1975) and Brian and Thomas (1984) focused on developing an inventory of the size and number of campsites throughout the river corridor. Both of these studies estimated the capacity of each site with dam releases above the 24,000–28,000 cubic feet per second (cfs) stage elevation, with capacity defined as the number of campers that could occupy a campsite for an overnight stay. Researchers have focused on high-elevation campsites because summer demand for energy produces medium to high releases. As a result, lower sandbar elevations are inundated during the height of the commercial rafting season (mid-May through mid-September) and therefore are not available for camping during the time of year when campsites are in highest demand. Kearsley and Warren (1993) repeated the inventory and improved the campsite area measurements by developing techniques to quantitatively measure camp area from aerial photography and videography. Subsequent studies by Kearsley and others (1994), Kearsley (1995), and Kearsley and Quartaroli (1997) improved upon the aerial photographic mapping by using geographic information system software.

Kearsley and Warren (1993) studied camps between Lees Ferry and Diamond Creek and divided them into critical and noncritical reaches. A critical reach was defined as any contiguous stretch of the river in which the number of available campsites is limited because of geologic characteristics, high demand, or other logistical factors. Noncritical reaches were defined as any stretch of the river in which campsites are plentiful and little competition for the majority of sites occurs. These reach definitions closely parallel the geomorphic reach definitions of Schmidt and Graf (1990).

Kearsley and Warren (1993) found that campsites had decreased dramatically in both number and size since Weeden's team completed its initial survey in 1973. Reaches designated as critical because of limited availability of suitable campsites by Kearsley and Warren (1993) (Marble Canyon, RM 11–40.8; upper Granite Gorge, RM 76.5–116; and Muav Gorge, RM 139–164) are nearly the same as the critical sections identified by Weeden and others (1975). Campable area decreased primarily because of erosion in critical reaches; in noncritical reaches, decrease in campsite area was primarily the result of vegetation encroachment (Kearsley and Warren, 1993). An overall trend of increased campsite size and number between 1973 and 1983 was attributed to the high releases in 1983 needed to keep Lake Powell from spilling over Glen Canyon Dam. The 1983 high releases forced sand from the river channel onto sandbars, but the change was temporary; sandbars significantly decreased in size and number less than 1 yr later. Moreover, campsites in the upper Marble Gorge and upper Granite Gorge decreased between 1973 and 1983 and between 1983 and 1991. The inventory documented 226 campsites above 25,000 cfs, which represented a 32% decrease in the number of campsites between 1973 and 1991. The inventory also found a 51% decrease in large camps, resulting in a 44% decrease in campsite area between 1973 and 1991. Campsite area decreased an average of 9% between 1991 and 1994, with disproportionately larger decreases at camps in critical reaches

(Kearsley, 1995). River-induced changes accounted for 80% of lost campsite area above the Little Colorado River and 32% of loss below the Little Colorado River confluence.

Kearsley and others (1994) concluded that loss of Colorado River campsites was an ongoing process that was initiated with the installation of Glen Canyon Dam more than 30 yr ago and that the rate of decline had slowed over time. The overall pattern of change was one of initial systemwide decrease in sites (1965–73), variable change during years of regulated high flows because of high levels of precipitation (1983–86), and a systemwide decrease in campsites between 1984 and the mid-1990s. They noted that not all sandbars in Grand Canyon respond in the same manner to high flows, fluctuating flows, or vegetation encroachment and that campsite availability in critical reaches had decreased the most.

To monitor changes in campsite availability resulting from the 1996 beach/habitat-building flow, 53 camping sandbars were randomly selected from the 218 remaining from the 1991 inventory by Kearsley and Warren (1993). The sites were physically measured 2 weeks before, 2 weeks after, and 6 mo after the 7-d, 45,000-cfs experimental flow (Kearsley and Quartaroli, 1997). Float-by assessments were made of 200 sandbars, including the 53 that were also measured. Results showed a systemwide increase in campsite area. Half (100/200) of the sites assessed were at least 10% larger, 39% (77/200) were the same, and 12% (23/200) were smaller than before the experimental flow. For 53 sites directly measured, 62% (33/53) increased in size, 17% (9/53) were the same, and 21% (11/53) decreased in area. Float-by assessments were less sensitive to measuring change but not biased toward increase or decrease. At many sites, sand was deposited directly on top of existing campable areas and did not increase campsite area. At some sites, new sand was deposited as a mound over previously usable space, and the increase in slope angle resulted in decreased camping area.

Eighty-two new sites were created, in the sense that these sites were not usable just before the 1996 beach/habitat-building flow. Although 33 of these “new” sites were included in previous campsite inventories, all had degraded to being unusable by the time of the experiment. Many new sites consisted of deposition on low-elevation sandbars with little sun or wind protection. These sandbars were theoretically usable but not highly valued as camps and were subject to rapid erosion. Forty of the new sites were between RM 40 and RM 65. More than twice as many sites were created in noncritical reaches than in critical reaches. Six months after the beach/habitat-building flow, only 55% (45/82) of the new sites were still considered usable. The high flow obliterated three previously inventoried campsites. Overall, the 1996 beach/habitat-building flow increased the number, size, capacity, and aesthetic qualities of campsites. These benefits were substantial, but degradation occurred quickly: within 6 mo, nearly half of the new campsites were unusable, remaining new sites were half their initial size, and most of the increased area on measured established sites had eroded. Relatively high-flow releases immediately following the 1996 beach/habitat-building flow in late 1996 and 1997 probably exacerbated erosion.

# Recent Monitoring

Following the Record of Decision in 1996 (U.S. Department of the Interior, 1996) and the establishment of the Glen Canyon Dam Adaptive Management Program, a new campsite monitoring program was initiated by the U.S. Geological Survey’s Grand Canyon Monitoring and Research Center. The following discussion focuses on the results of 6 yr of campsite area monitoring beginning in 1998 and ending in 2003 (Kaplinski and others, 2005).

## Monitoring Objectives and Methods

The 1998–2003 campsite area monitoring program focused on describing changes in the size of camping areas in the Colorado River corridor. Monitoring included annually measuring campsite area at a series of long-term monitoring sites and evaluating the changes in campsite area among years and as the result of different dam releases.

Annual surveys were conducted every October from 1998 through 2003 by crews from Northern Arizona University’s Department of Geology to quantify campsite area change. Surveys at the selected study sites were conducted by using standard total station survey techniques (U.S. Army Corps of Engineers, 1994). The surveyors adopted the criteria of Kearsley (1995) and Kearsley and Quartaroli (1997) to identify campable area. Campable area was defined as a smooth substrate, preferably sand, with no more than 8° of slope and with little or no vegetation. Not all campable areas were mapped at every site. Instead, representative camp spots were selected across a range of stage elevations. Camping areas not represented in the mapping were typically far (>328 ft (>100 m)) from the main mooring/cooking areas.

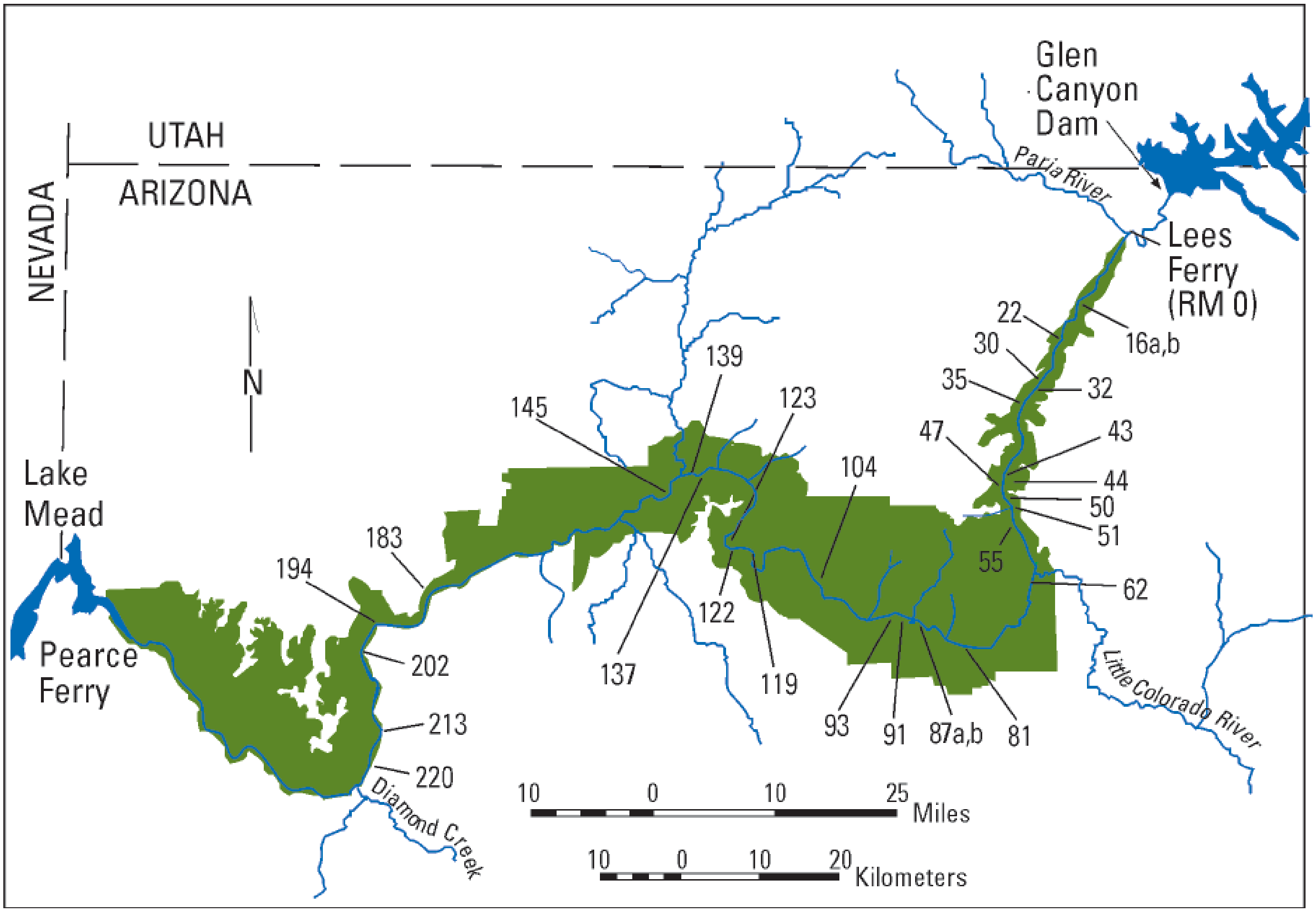

**Figure 1.** The Colorado River corridor below Glen Canyon Dam and locations of 31 study sites from the 1998–2003 campsite area monitoring program. The shaded area represents Grand Canyon National Park. Study site locations are noted by river mileage.

## Study Sites

The study sites are located throughout the Colorado River corridor between Lees Ferry and Diamond Creek (fig. 1) and were selected to coincide with a subset of the long-term study sites used by the Northern Arizona University sandbar monitoring project, which monitors change in sandbar area and volume (Beus and others, 1992; Kaplinski and others, 1995, 1998; Hazel and others, 1999, 2001, 2002). These sites were originally selected on the basis of (1) distribution throughout the geomorphic reaches, (2) size sufficient to guarantee persistence through the period of study, (3) geomorphic diversity within and between sites, (4) availability of historical data, and (5) variation in recreational use intensity and vegetation cover (Beus and others, 1992). Given these criteria, only a subset of the sandbar monitoring sites could be used to monitor campsite areas. These sites, although not chosen randomly, have proven to be representative of systemwide changes in terms of changes in sand volume and area at campsites located above high normal flows (above 20,000 cfs) (Schmidt and others, 2004). Therefore, it is reasonable to assume that changes to campsite areas at these sites are also representative of changes to campsite area systemwide.

The study began with 31 study sites. In 2002, 6 sites were added, for a total of 37 sites. Only the original 31 sites, which have been measured since 1998, were used to summarize the campsite areas, while all sites were used to calculate average percent change between years. Sixteen of these sites are located in Marble Canyon between the Paria River and the Little Colorado River confluence, and 21 are located in Grand Canyon below the Little Colorado confluence. There are 18 sites within critical reaches as defined by Kearsley and Warren (1993), and 19 are in noncritical reaches.

## Dam Releases Before and During the Study Period

Dam releases during the 1998–2003 study period included normal modified low fluctuating flow (MLFF) operations, plus a low summer steady flow (LSSF) experiment during 2000, the habitat maintenance flows (HMF) in May 2000 and September 2000, and fluctuating nonnative fish suppression flows from January to March in 2002 and 2003 (fig. 2). Normal MLFF dam releases fluctuate diurnally and seasonally, based on power demand and water-delivery schedules. Typically, flow releases are higher in winter and summer months and lower during spring and fall months. In 1998 and 1999, daily mean flow releases ranged from an average of approximately 19,400 cfs in high-volume months to approximately 12,400 cfs in low-volume months. The LSSF experiment in 2000 consisted of two high-flow releases in spring and fall and a period of low steady (no diurnal fluctuation) flow during summer. The low steady flow during summer was lowered to a constant 8,000 cfs. The high flows were short-duration (4 d) dam releases of 31,000 cfs. These were the only two flows large enough to reach above the 25,000-cfs stage elevation, or the upper limit for nonexperimental MLFF operation releases, during the study period.

River flow levels during the 1998 and 1999 survey trips fluctuated from 10,000 to 18,000 cfs. Therefore, surveyors were only able to measure camp areas consistently at every site above the 15,000-cfs stage elevation. Subsequent analysis of campsite area below 25,000-cfs stage elevation excluded the measurements made during 1998 and 1999. During the 2000 to 2003 surveys, low-volume releases allowed measurement of camp area above the 10,000-cfs stage elevations at some sites and above 15,000-cfs stage elevation at all sites. Fluctuating nonnative fish suppression flows were conducted from January through March in 2002 and 2003. During these experiments the flows fluctuated from 5,000 to 20,000 cfs. Comparison of camp area change between surveys was conducted by using area measured only above the 25,000-cfs stage elevation.

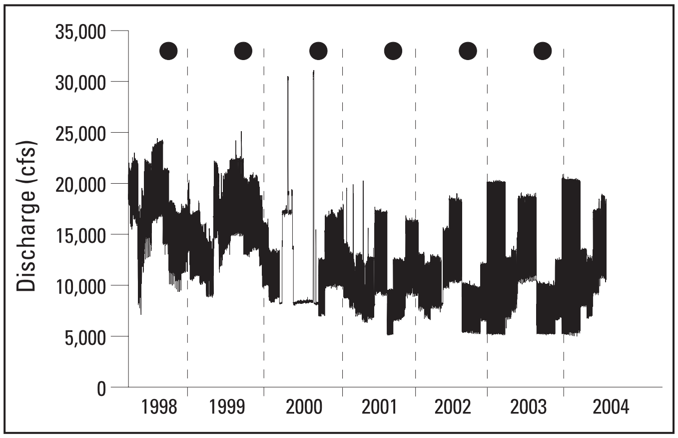

**Figure 2.** Daily mean discharge hydrograph from the USGS gaging station on the Colorado River near Lees Ferry during the period of study. Note the daily and seasonal fluctuations in flow volume during 1998 and 1999 and during the low summer steady flow experiment in 2000 that included two high-flow events.

# Findings

Recent analysis of the 1998–2003 monitoring results by Kaplinski and others (2005) demonstrated that the total camp area above the 25,000-cfs stage elevation significantly decreased during the study period (fig. 3). Total campsite area changes were derived by summing all of the campsite area measurements in a particular reach. Between 1998 and 2003, the total campsite area decreased by 55%. The average decrease was 15% between each survey (fig. 3).

Longitudinal changes were examined by comparing the total campsite area above and below the Little Colorado River (LCR) confluence (fig. 4). In the following discussion, the term Marble Canyon refers to sites above the LCR, while the term Grand Canyon refers to sites below the LCR. Campsite areas in Marble Canyon and Grand Canyon decreased at a similar rate and showed an overall loss of 57% and 53%, respectively. There was a longitudinal difference in the response to the powerplant capacity flows conducted as part of the 2000 LSSF experiment. Camp area in Grand Canyon increased slightly (4%) following the high flows of the LSSF experiment, while campsites in Marble Canyon decreased by 24%. Area increases in Grand Canyon camps are possibly related to greater deposition downstream of the LCR where the sediment supply is presumably greater.

The pattern of campsite area change was different in critical and noncritical reaches (fig. 5). Total campsite area within critical reaches decreased by 37% during the study period for an average decrease of 8% per year. In noncritical reaches the change was greater, with a total decrease of 63% and an average decrease of 18% per year. Campsite area increased slightly in the critical reaches (7%) following the LSSF experiment, whereas sites in noncritical reaches decreased by 18%. Critical reaches are generally narrower than noncritical reaches, and the campsites tend to be smaller and less vegetated

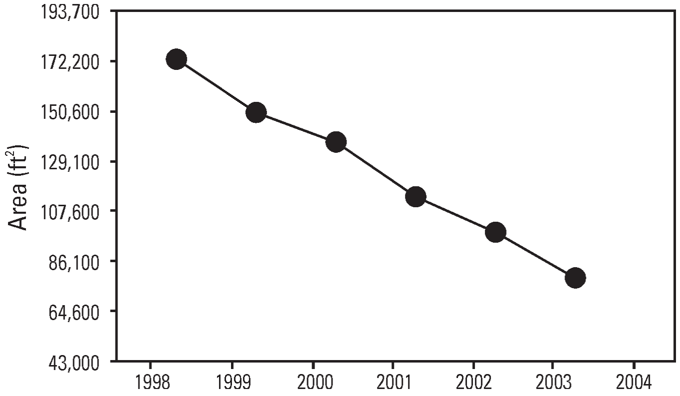

**Figure 3.** Total camp area above the 25,000-cfs stage elevation.

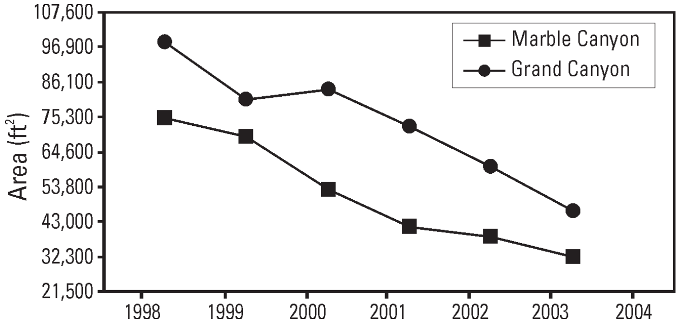

**Figure 4.** Total camp area above the 25,000-cfs stage elevation in Marble and Grand Canyons.

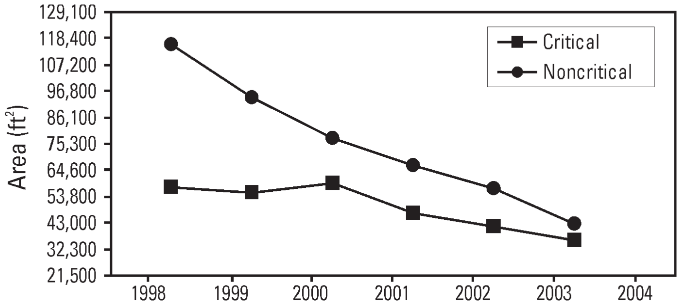

**Figure 5.** Total camp area above the 25,000-cfs stage elevation in critical and noncritical reaches.

because the steep bedrock channels provide little space for sediment deposition.

Campsite area exists across the entire range of normal Glen Canyon Dam releases (5,000 to 25,000 cfs), and the amount of camp area available is greatly dependent on flow levels. Some GCDAMP management objectives are specifically concerned with measuring sandbar area and volume between the 5,000-cfs and 25,000-cfs stage elevation, as well as above the 25,000-cfs stage elevation. In the most recent monitoring study, surveyors measured all campsite areas exposed at the time of the visit, allowing campsite area changes to be divided between discrete ranges of stage elevation (fig. 6).

High-elevation campsite area (above 25,000 cfs) has progressively decreased during the study period, with the exception of a short-lived increase within the 25,000-cfs to 30,000-cfs range following the LSSF experiment. Repeat surveys after 2000 showed that this slight increase in campsite area decreased to levels equivalent to those measured in 1998.

Camp area at lower elevations has increased because of the deposition from high-flow events associated with the LSSF experiment in 2000, the fluctuating nonnative fish suppression flows from January to March 2003, and medium- to high-volume (10,000 to 25,000 cfs) summer dam operations. In fact, the amount of campsite area available at lower elevations is now greater than that available at higher elevations (fig. 7). Since the lower elevation areas are within the zone of flow fluctuation, these increases may not persist because lower elevation sandbars are more susceptible to bank erosion than sand at higher elevations (Hazel and others, 1999).

Campsite area and sandbar volume both decreased during the study period; however, campsite area decreased at a greater rate than did sandbar volume (fig. 8), which indicates that other factors contributed to the

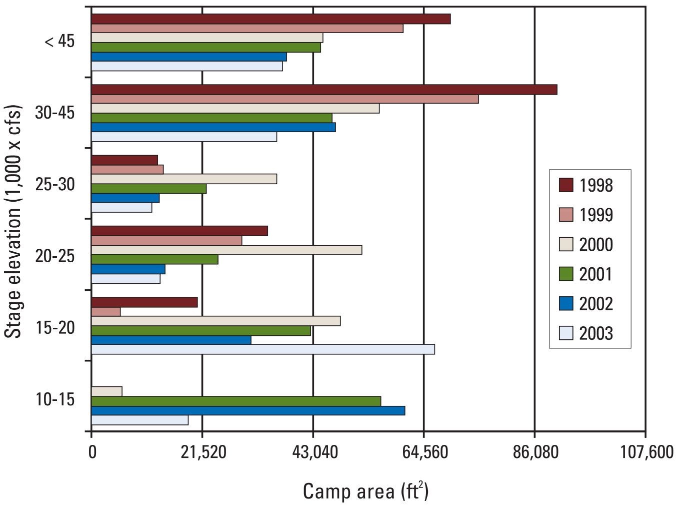

**Figure 6.** Distribution of total campsite area above the 25,000-cfs stage elevation in three different stage ranges.

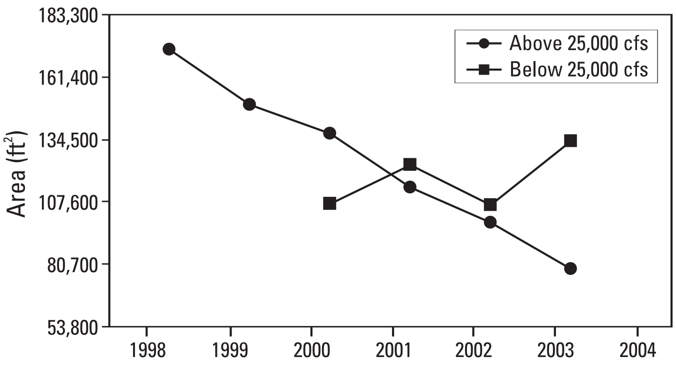

**Figure 7.** Total campsite area above and below the 25,000-cfs stage elevation.

loss of high-elevation campsite area. These factors presumably include vegetation growth, surface water runoff, aeolian processes (wind-caused sediment movement), and human impact.

Although not quantitatively addressed in this study, visual observations and photographic documentation compiled by the Grand Canyon River Guides, Inc., Adopt-a-Beach Program during the same period (1998–2003) indicate that, excluding sandbar erosion, vegetation growth contributes most significantly to the loss of high-elevation campsite area (Thompson and others, 1997; O'Brien and others, 1999, 2000; Thompson, 2001, 2002). Unfortunately, a direct comparison of campsite area change and vegetation colonization during the 1998–2003 study period was not possible because of the incompatibility of vegetation monitoring protocols (M. Kearsley, Northern Arizona University, oral commun., 2004). Kaplinski and others (2005) recommended that, in the future, vegetation coverage changes at campsites should be tracked by using remotely sensed aerial imagery to provide a quantified assessment of the role of vegetation in reducing total campsite area.

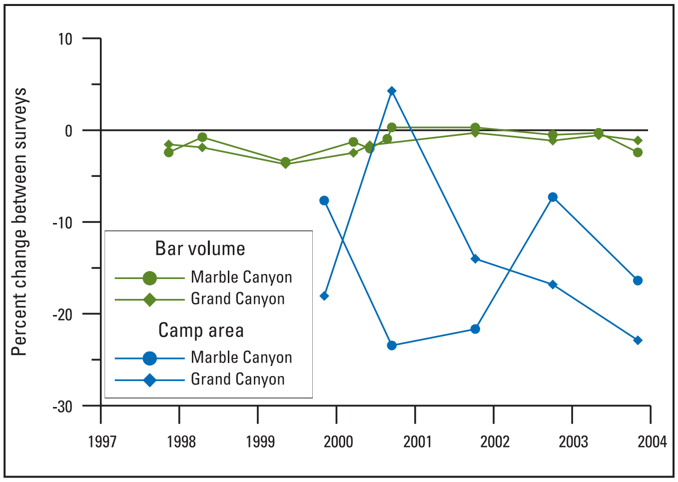

**Figure 8.** Percent change between surveys of sandbar volume and campsite area in Marble and Grand Canyons.

Surface runoff events that significantly decreased campsite area were observed at only three sites during the 6 yr of monitoring. Human impacts were generally minimal, except at locations where vegetation pruning and removal had increased or maintained campsite areas. Aeolian reworking of sandbars did not appear to be a significant factor in affecting campsite area because of the amount of vegetation established along higher elevation sandbar areas.

# Discussion and Conclusions

Campsites within the Colorado River ecosystem exist primarily on sandbars. The size and capacity of camping area are directly related to the areal extent of sandbars and the amount of vegetation colonizing the sandbars (Kearsley and others, 1994). Previous studies by Kearsley and Warren (1993) and Kearsley and others (1994) established that substantial losses in open areas used for camping had occurred because of sandbar erosion and colonization by vegetation. Although both erosion and vegetation reduce campsite area, the processes and their effects are not identical.

Erosion of sandbars is caused primarily by operations of Glen Canyon Dam. The magnitude of daily fluctuations, the ramping rates, and the increased ability of clearwater releases to transport sediment have all been identified as contributing factors (Beus and others, 1992; Rubin and others, 2002).

Vegetation encroachment is leading to higher rates of campsite area decrease than can be attributed to erosion alone. Encroachment by nonnative species such as tamarisk (*Tamarix ramosissima*) and camel thorn (*Alhagi maurorum*), as well as by native species such as arrowweed (*Pluchea sericea*) and coyote willow (*Salix exigua*), has led to colonization on previously open sections of sandbars, thus further decreasing campsite area. In some larger and less frequently visited sites, dense patches of vegetation now make the sites essentially unusable for camping activities. Although this process has substantially reduced available space at many campsites, the effects of these changes on visitor capacity are somewhat less clear than when area is lost to erosion. For example, in some frequently used camps, individual sleeping sites are cleared of and kept free of vegetation by constant use. These individual sites are also often separated by vegetation "screens" that may actually serve to reduce the distance that recreationists feel they need to be separated from one another in order to achieve privacy. Additionally, clumps of mature tamarisk trees along steep riverbanks may serve to reduce sandbar erosion by anchoring sediment in place.

Rainfall-induced flash flooding also reduces campsite area. Flash flood impacts were transient before completion of the dam because the effects of tributary erosion were erased every year or two as flood flows from high spring runoff deposited sediment and reworked sandbars. Today, the effects of tributary flash floods are cumulative and tend to be long lasting because periodic high-flow events that are capable of transferring tributary-derived sediment to higher elevations are infrequent.

The monitoring results of Kaplinski and others (2005) showed that between 1998 and 2003 more than half of the available campsite area at the study sites was lost. Camping area above the 25,000-cfs stage elevation decreased by 55% during this 6-yr period, and the average rate of change was 15% per year. The decrease in high elevation campsite area occurred both in Marble Canyon and in Grand Canyon (above and below the LCR) as well as within critical and noncritical reaches. Notably, lower elevation campsite areas increased after 2000, and the total campsite area below the 25,000-cfs stage elevation now exceeds the area available at higher elevations. The rate of decrease in high-elevation campsite area greatly exceeds the decrease in sandbar volume. This difference indicates that other factors—probably vegetation encroachment—have contributed to the recent loss of high-elevation campsite area. Unfortunately, Kaplinski and others (2005) could not undertake a quantitative comparison of campsite area change and vegetation colonization from 1998 to 2003 because the vegetation study is designed to detect systemwide, rather than site-specific, changes in vegetation cover (Mike Kearsley, Northern Arizona University, oral commun., 2004).

In order to construct a longer term view of changes to campsites in Grand Canyon, Kaplinski and others (2005) compiled the percent change between surveys from the campsite inventories conducted by Brian and Thomas (1984), Kearsley and others (1994), and Kearsley and Quartaroli (1997) and combined them with the results from the 1998–2003 campsite monitoring program. Between 1973 and 2003, the only observable periods of increases in either the number of camps or the size of camps occurred after the high flows of 1983–84, which were needed to keep Lake Powell from overtopping Glen Canyon Dam, and the 1996 beach/habitat-building flow, when flows were greater than powerplant capacity. During years between flood events, both before and after the implementation of the 1996 Record of Decision (U.S. Department of the Interior, 1996), sandbars declined in area, volume, and total number.

The campsite monitoring results showed that current operations of Glen Canyon Dam are not meeting the goals of the GCDAMP with respect to the recreational resources of the Colorado River corridor. Specifically, the GCDAMP seeks to "maintain or improve the quality of recreational experiences for users of the Colorado River Ecosystem, within the framework of the GCDAMP ecosystem goals" (Glen Canyon Dam Adaptive Management Program, 2001). With this goal in mind, the Adaptive Management Work Group developed the following management objectives to maintain or improve recreational resources:

1. Maintain or improve the quality and range of recreational opportunities in Glen and Grand Canyons within the capacity of the Colorado River ecosystem to absorb visitor impacts in ways consistent with NPS and tribal river corridor management plans (objective 9.1) (Glen Canyon Dam Adaptive Management Program, 2001).

2. Increase the size, quality, and distribution of camping beaches in critical and noncritical reaches in the mainstem within the capacity of the Colorado River ecosystem to absorb visitor impacts in ways consistent with NPS and tribal river corridor management plans (objective 9.3) (Glen Canyon Dam Adaptive Management Program, 2001).

3. Maintain or enhance the wilderness experience in the Colorado River ecosystem in consideration of existing management plans (objective 9.4) (Glen Canyon Dam Adaptive Management Program, 2001).

The significant decrease in campsite area during the study period indicates that the second management objective above (objective 9.3) is not being met. While this study does not explicitly link changes in campsite area to the recreational/wilderness experience in Grand Canyon, the significant decrease in campsite area indicates that other management objectives are possibly not being met. For example, a significant decrease in campsite area may indicate a decrease in the range and quantity of recreational opportunities. Also, because existing campsites are smaller and thus more crowded, the quality of campsites is not being maintained or improved. The decrease in campsite area leads to more crowding and less choice for camps, which can negatively affect the wilderness experience (Hendee and others, 1990). On the other hand, conclusions about the inherently sociological aspects of the river experience based solely on changes to campsite area at a limited number of sites are tenuous. Future research and monitoring should be expanded to include sociological aspects of the recreational experience. In addition, future research should investigate the linkages between the sociological aspects of the recreational experience and physical parameters, such as campsite area, in order to evaluate whether GCDAMP goals are being achieved.

The continued existence of sandbars suitable for camping in the Colorado River ecosystem will depend on periodic high flows to redeposit sediment lost through incremental erosion, scour, and vegetation encroachment; therefore, the continuing availability of campsite area is necessarily linked with the frequency and magnitude of flood events from Glen Canyon Dam. Unless vegetation is physically removed, and provided that enough sediment is available for deposition, high-flow events are the only mechanism by which sandbars used as campsites above the 25,000-cfs stage elevation can be built and maintained.

In order to properly address the management objectives of the GCDAMP, the recreational monitoring program should be expanded to include monitoring and research of both physical and psychological parameters of the river experience. Currently, the program consists only of campsite area measurements at a limited number of sites. This limited amount of information makes a complete assessment of the stated goals and objectives of the program currently impossible. One of the largest gaps in the current knowledge base is a complete, systemwide inventory of campsites in the Colorado River ecosystem in Grand Canyon. Since the last inventory in 1991, significant changes have occurred, and a new measurement of the number and size of camps is essential to evaluate the current state of the resource. O'Brien and Roberts (1999) and Roberts and Bieri (2001) used a modified version of the 1991 campsite inventory to develop a numerical river trip simulator model to predict visitor-use dynamics on the Colorado River. This model has been subsequently used by the NPS to assist in developing a management plan of the river corridor (National Park Service, 2004). Unfortunately, an up-to-date measurement of campsite carrying capacity was not available for the planning efforts. O'Brien and Roberts (1999) and Roberts and Bieri (2001) recommended that a method be developed to convert campsite area measurements to carrying capacity of a site; they suggested addressing this key information need by developing a standardized method of estimating carrying capacity for a beach so that onsite estimates are performed consistently. They also recommended that an interdisciplinary team comprising a statistician, a sociologist, a geologist, and surveyors should be included in order to develop an empirically verifiable and repeatable method of measuring and interpreting the campsite area, location, and abundance in relation to other variables such as trip length, attraction sites, number of people, and social aspects of visitor use. Campsite area measurements clearly indicate that campsite area has declined. How does this measured decline relate to carrying capacity of the river corridor? Does the decline in campsite area relate directly to a decline in the quality of the recreational and wilderness experience? Are these parameters linked and, if so, how? Future research aimed at addressing both the physical parameters and the psychological aspects of recreation along the Colorado River would help answer these types of questions and more clearly assess whether or not the goals and management objectives of the GCDAMP are being achieved.

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# Chapter 13

# Lessons from 10 Years of Adaptive Management in Grand Canyon

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## Introduction

Almost a decade ago, the Secretary of the Interior issued a Record of Decision (ROD) (U.S. Department of the Interior, 1996) regarding the operation of Glen Canyon Dam and its impacts on natural, cultural, and recreational resources of the Colorado River below Glen Canyon Dam. This decision was largely in response to mandates of the Grand Canyon Protection Act of 1992. Adaptive management (see Overview, this report, for discussion of adaptive management), sometimes known as "learning by doing," was deemed to be the method of choice after a multiyear environmental impact statement process that included extensive public involvement. Practitioners of adaptive management intentionally see management policies as experimental because of the scientific uncertainties inherent in such large, complex ecosystems (Walters and Holling, 1990; Clark, 2002). The intent in selecting this style of management is reflected in the Operation of Glen Canyon Dam Final Environmental Impact Statement (hereafter EIS) with the following language:

> It is intended that the ROD will initiate a process of adaptive management, whereby the effects of dam operations on downstream resources would be assessed and the results of those resource assessments would form the basis for future modifications of dam operations. Many uncertainties still exist regarding the downstream impacts of water releases from Glen Canyon Dam. The concept of adaptive management is based on the need for operational flexibility to respond to future monitoring and research findings and varying resource conditions (U.S. Department of the Interior, 1995, p. 34).

The very language in the EIS acknowledges that adaptive management is a process of experimentation, monitoring, and evaluation.

The end of a decade of research and monitoring provides an important opportunity to evaluate the effects of Glen Canyon Dam operations on resources of concern and to determine if the desired outcomes are being achieved and whether they are compatible with one another or not. In this concluding chapter we present a summary of adaptive management of the Colorado River ecosystem below Glen Canyon Dam by reviewing predictions contained in the EIS. In table II-7 of the EIS (summarized here in table 1), resource categories are listed and associated with predictions for how those resources would respond under the preferred alternative of modified low fluctuating flows (MLFF) (see table 2 for generalized operating rules). During preparation of the EIS, the best scientific data available were used to generate those prognostications; however, a decade later we have significant new information for evaluating the operation of Glen Canyon Dam in relation to the objectives of the 1995 EIS and the 1992 Grand Canyon Protection Act.

This report is the first systematic attempt to conduct an assessment of the changing state of resources in the Colorado River ecosystem in Grand Canyon over a decadal timeframe. Our objectives are to (1) encapsulate what we have learned about the Colorado River ecosystem over a decade of scientific inquiry, summarizing the most salient conclusions of this report, and (2) discuss, in very general terms, research and monitoring challenges and questions facing the program.

While this report is not meant to be prescriptive with respect to future action for the Glen Canyon Dam Adaptive Management Program, the authors of the preceding chapters presented evidence that dam operations during the last 10 yr under the preferred alternative of the MLFF have not restored fine-sediment resources or native fish populations in Grand Canyon, both of which are resources of significant importance to the program. Some resources of concern, however, have improved under the MLFF, as shown below and also in the preceding chapters.

## What Have We Learned from 10 Years of Adaptive Management?

Adaptive management is an integrated, multidisciplinary approach for confronting uncertainty in natural resources issues. It is adaptive because it acknowledges that managed resources will always change as a result of human intervention, that surprises are inevitable, and that new uncertainties will emerge. Active, experimental learning is the way in which the uncertainty is minimized (Walters and Holling, 1990). Adaptive management acknowledges that policies must satisfy social objectives but also must be continually modified and flexible for adaptation to surprises. Adaptive management, therefore, views policy as hypothesis. That is, most policies are really questions, and management actions become treatments in an experimental sense. Our summary of what is known about the influence of the MLFF on downstream resources examines many facets of the Colorado River ecosystem, especially those resources deemed as most important during the EIS process. Substantial importance is also ascribed to those resources affected by the Endangered Species Act of 1973.

## Fish Response

The Grand Canyon population of the federally endangered humpback chub (*Gila cypha*) has declined during the past decade under MLFF operations. Only eight native fish species were historically found in Grand Canyon. Six of these were desert species endemic (not found elsewhere) to the Colorado River ecosystem, making this one of the most unusual fish communities in the world (Mueller and Marsh, 2002). Of the original eight, only four remain in Grand Canyon, namely the humpback chub, the bluehead sucker (*Catostomus discobolus*), the flannelmouth sucker (*Catostomus latipinnis*), and the speckled dace (*Rhinichthys osculus*). Of these four, only the humpback chub is endangered, and its numbers have dropped dramatically in the last decade. At the same time, nonnative fish have increased in both diversity and abundance. The reasons for the decline of native fish are commonly cited to include dramatic changes in the thermal, sediment, and hydrologic regimes of the river because of the construction and operation of numerous dams in the basin, the introduction of nonnative predatory and competitive fishes, and the introduction of diseases and parasites (Mueller and Marsh, 2002). The actual mechanisms of decline and extirpation are poorly known, in part because of a lack of early data on population numbers.

Our knowledge about the cause and effect between dam operations and chub decline is incomplete; we do know, however, that the current MLFF operation has not resulted in increased survival and recruitment of humpback chub, despite the prediction of the EIS (table 1). Although there is no basis for claiming that the current operation at Glen Canyon Dam resulted in recent and repeated low recruitment and the continued decline of the humpback chub, it is clear that the restrictions on dam operations since 1991 have not produced the hoped-for restoration and maintenance of this endangered species (see chapter 2, this report). During the MLFF, basin hydrology has varied from drought to wet conditions and then back to drought conditions. Through these conditions, the decline of the humpback chub has continued. This trend leads to questions about whether daily, monthly, or even annual patterns of dam

**Table 1.** Natural and cultural resources of the Grand Canyon ecosystem and predictions from the Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) table II-7 (U.S. Department of the Interior, 1995) on how these resources would respond under the modified low fluctuating flow (MLFF) alternative, which is the preferred alternative in the EIS.

[Glen Canyon Dam Adaptive Management Program (GCDAMP) is a federally authorized initiative to ensure that the primary mandate of the Grand Canyon Protection Act of 1992 is met through advances in information and resource management. Resources are ordered in this table as they appear in the EIS. A plus sign (+) indicates that the prediction was correct or exceeded expectations, a minus sign (-) indicates that the prediction was not entirely correct or did not achieve the desired outcome, and plus and minus signs together (+/-) indicate a mixed outcome. Data unavailable are indicated by a question mark (?) and may imply a total absence of data or that the data are not available to the U.S. Geological Survey's Grand Canyon Monitoring and Research Center through the research and monitoring program under the GCDAMP]

| Resource | Prediction | Outcome | Comments |
|---|---|---|---|
| **Sediment and aquatics** | | | |
| **Fine sediment** (sandbars and related physical habitats linked to native fishes (backwaters), terrestrial vegetation, marshes, campsites for recreation, and in situ preservation of archeological resources) | Modest improvement through implementation of constrained daily powerplant operations and periodic implementation of experimental high flows following accumulation of new tributary sand supplies in the main channel of the ecosystem. Sand accumulation was predicted to occur under average-to-below-average hydrology and associated hydroelectric power operations. | - | Sandbars continued to erode, and new sand inputs were not accumulated within the main channel. Experimental high flows were conducted, but the lack of flexibility in the timing and frequency of these controlled floods limited their effectiveness. |
| **Coarse sediment** (debris flow impacts from tributaries and their influence on the navigability of rapids and terrestrial sandbars)<br>This resource was not included in table II-7 of the EIS (U.S. Department of the Interior, 1995), but predictions regarding the fate of this material were given on p. 104–105 of the document. It is included in this tabulation for the sake of completeness. | Inputs of coarse-grained sediment from tributary debris flows will continue to accumulate in the main channel under constrained hydropower operations, causing rapids to worsen and burying sandbars under coarse deposits. High-flow releases may partially rework the new deposits and improve navigation within rapids. | + | The influence of ongoing, naturally occurring debris flows, in terms of aggradation of rapids and burial of sandbars, has been partially mitigated by occasional experimental high flows. The ability of high dam releases to rework new debris flow deposits is related more to peak discharge and timing after debris-flow events than it is to the duration of the high releases. |

**Table 1.** Natural and cultural resources of the Grand Canyon ecosystem and predictions from the Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) table II-7 (U.S. Department of the Interior, 1995) on how these resources would respond under the modified low fluctuating flow (MLFF) alternative, which is the preferred alternative in the EIS. —Continued

| | | | |
|---|---|---|---|
| **Aquatic food web** | "Potential major increase" | +/- | Increases were apparent in Lees Ferry reach but not canyon-wide. Fine-sediment inputs from tributaries below the Lees Ferry reach are most likely the limiting factor in primary productivity. |
| **Native fish** | "Potential minor increase" | +/- | Recruitment and population of adult humpback chub decreased; native suckers may be stable or slightly increasing. |
| **Nonnative fish** | "Potential minor increase" | + | Rainbow trout population increased substantially following the operational change in the Lees Ferry reach and within Marble Canyon. |
| **Interactions between native and nonnative fish** | "Potential minor increase in warm, stable microhabitats"<br>An increase in warm, stable microhabitats would favor native fish and nonnative warmwater fish. | - | Warmer dam releases because of drought-lowered Lake Powell levels may have increased warm microhabitats, but this situation is not directly related to dam operations. |
| **Trout** | "Increased growth potential, stocking-dependent" | - | Rainbow trout numbers have increased in the Lees Ferry reach, but condition factor has declined. Stocking is not required. |
| **Vegetation** | | | |
| **Woody plants** | Modest increase<br>Exotic species included (tamarisk, camel thorn (*Alhagi maurorum*)). | + | Woody vegetation has increased, especially arrowweed (*Pluchea sericea*) and nonnative tamarisk, in the riparian zone that was formerly inundated frequently under the no action period (1963–91) of hydropower operations. |
| **Emergent marsh plants** | "Same as or less than no action" | +/- | Wet marsh species decreased, and dry marsh species increased, likely because of the reductions of daily inundation and without periodic rejuvenation through floods. |

**Table 1.** Natural and cultural resources of the Grand Canyon ecosystem and predictions from the Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) table II-7 (U.S. Department of the Interior, 1995) on how these resources would respond under the modified low fluctuating flow (MLFF) alternative, which is the preferred alternative in the EIS. —Continued

| | | | |
|---|---|---|---|
| **Wildlife** | | | |
| **Wintering waterfowl** | Potential increase | +/- | Trends vary by species and are difficult to distinguish from background variation. |
| **Endangered and other special status species** | | | |
| **Native fish** (humpback chub, razorback sucker, flannelmouth sucker) | "Potential minor increase" | +/- | Recruitment and population of adult humpback chub decreased; native suckers may be stable or slightly increasing. |
| **Bald eagle** | "Potential increase" | ? | Numbers in Arizona have increased overall. |
| **Peregrine falcon** | No effect | + | Numbers have been stable in Grand Canyon since 1988. |
| **Kanab ambersnail** | "Some incidental take" | +/- | Snail habitat increased since 1998, but not snail numbers, which are relatively stable. |
| **Southwestern willow flycatcher** | "Undetermined increase" | - | No increase, but the flycatcher is uncommon in Grand Canyon. |
| **Cultural resources** | | | |
| **Archaeological sites affected** | "Moderate (less than 157)" | ? | Subsequent analyses have not been conducted to fully assess. |
| **Traditional cultural properties affected** | "Moderate" | ? | Subsequent analyses have not been conducted to fully assess. |
| **Traditional cultural resources affected** | "Increased protection" | ? | Subsequent analyses have not been conducted to fully assess. |
| **Air quality** | | | |
| **Effect of emissions on regional air quality** | "Slight reduction" | ? | Not Addressed by Glen Canyon Dam Adaptive Management Program (GCDAMP). |
| **Recreation** | | | |
| **Angler safety** | "Moderate improvement" | ? | No long-term monitoring data. |
| **Day rafting** | "Major improvement" | ? | Pre-EIS study suggests that net willingness-to-pay values were insensitive to flows. More studies are needed. |

**Table 1.** Natural and cultural resources of the Grand Canyon ecosystem and predictions from the Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) table II-7 (U.S. Department of the Interior, 1995) on how these resources would respond under the modified low fluctuating flow (MLFF) alternative, which is the preferred alternative in the EIS. —Continued

| | | | |
|---|---|---|---|
| **Whitewater boating safety** | "Minor improvement" | ? | NPS responsibility—not monitored as part of GCDAMP. |
| **Whitewater boating camping beaches** (average area at normal peak stage) | "Minor increase" | - | Camping areas have been diminished because of vegetation expansion and sandbar erosion, despite the fact that the new operating policy has limited daily peaking release to 25,000 cfs. |
| **Whitewater boating wilderness values** | "Moderate to potential to become major increase" | ? | Potential decrease and decline in campable areas (see chapter 12). |
| **Economic benefits** (not related to hydropower revenue) | Positive | + | Increase to both locally and regionally. |
| **Power** | | | |
| **Annual economic cost** (foregone hydroelectric power revenue) | Acceptable costs relative to other alternatives | ? | Subsequent studies are not available to fully assess. |
| **Wholesale rate of power** | Acceptable costs relative to other alternatives | ? | Not monitored as part of GCDAMP. See Western Area Power Administration (WAPA) for data. |
| **Retail rate of power** (70% of end users) | "No change to slight decrease" | ? | Not monitored as part of GCDAMP. See WAPA for data. |
| **Retail rate of power** (23% of end users) | "Slight decrease to moderate increase" | ? | Not monitored as part of GCDAMP. See WAPA for data. |
| **Retail rate of power** (7% of end users) | Acceptable costs relative to other alternatives | ? | Not monitored as part of GCDAMP. See WAPA for data. |
| **Nonuse value** | "No data" | + | Substantial nonuse value, \$3–\$4 billion, has been demonstrated as willingness to pay for flows to protect fish. |

**Table 2.** Operating limits and general likelihood of occurrence under the preferred alternative (U.S. Department of the Interior, 1995) of modified low fluctuating flows (maf = million acre-feet; cfs = cubic feet per second).

| | General range of hydrologic conditions for Glen Canyon Dam | | |
|---|---|---|---|
| Dam releases under operating rules, as well as constrained by annual hydrology | Dry (minimum of 8.23–10 maf of annual release) | Normal (10–15 maf of annual release) | Wet (15–20 maf of annual release) |
| Minimum releases 7 a.m.–7 p.m. (cfs) | 8,000 (likely only during weekends) | 8,000 (unlikely to occur) | 8,000 (very unlikely to occur) |
| Minimum releases 7 p.m.–7 a.m. (cfs) | 5,000 (very likely to occur on weekends) | 5,000 (unlikely to occur) | 5,000 (very unlikely to occur) |
| Maximum peak under diurnal releases (cfs) | 25,000 (daily peaks reach about 18,000–19,000 cfs, mainly during summer) | 25,000 [1] (daily peaks reach about 20,000–24,000 cfs, mainly during summer) | 25,000 (steady flows at this level occur for 1.5 maf monthly releases) |
| Daily fluctuations (cfs/24 h) | 5,000 (possible)<br>6,000 (possible)<br>8,000 [2] (possible) | 5,000 (unlikely)<br>6,000 (possible)<br>8,000 [2] (most likely) | 5,000 (unlikely)<br>6,000 (unlikely)<br>8,000 [2] (most likely) |
| Ramp rate (cfs/h) | 4,000 up (always)<br>1,500 down (always) | 4,000 up (always)<br>1,500 down (always) | 4,000 up (always)<br>1,500 down (always) |
| Monthly volume (maf) | 480,000–900,000 | 700,000–1,200,000 | 800,000–2,000,000 |

[1] Exceeded during habitat maintenance flows.

[2] Maximums represent normal or routine limits and may necessarily be exceeded during high water years.

operation alone are relevant to native fish recruitment or whether changes in the sediment and thermal regimes of the river imposed by regulation have had the greatest influence on native fishes. Further, the issue of nonnative fishes and their potential to limit recruitment of native fish through predation and competition (although highly suspected by scientists as a significant factor) remains unresolved in Grand Canyon.

Populations of both bluehead and flannelmouth suckers appear to have remained relatively stable under the MLFF operating policy. The reasons for this persistence are also unknown. Conversely, the relatively stable habitat conditions created under the MLFF during protracted drought conditions, coupled with a coarsening of substrate in the river channel (see section below on fine sediment), appear to have greatly favored rainbow trout (*Oncorhynchus mykiss*), particularly in the Lees Ferry reach, as reflected in their increasing numbers during the last decade.

## Sediment Response

Research and monitoring have conclusively demonstrated a net loss of fine sediment from the Colorado River ecosystem under the MLFF. Closure of Glen Canyon Dam eliminated about 84% of the sand that historically entered Grand Canyon (see chapter 1, p. 18, this report). Managing the remaining supply below the dam will apparently require carefully managed experimental high flows that are strategically released immediately following tributary sand inputs. It is not yet clear whether even this strategy will succeed in sustainable restoration of sand resources throughout Grand Canyon (Rubin and others, 2002).

Because physical processes related to hydrology and sediment transport were relatively well studied, a logical question is, “Why did the writers of the EIS predict this outcome incorrectly?” Again, the EIS writers did a commendable job of using the best science available, but three critical monitoring programs for measuring suspended-sediment flux throughout Grand Canyon were discontinued in the early 1970s. This situation, and a lack of analytical or conceptual models (Marzolf and others, 1999), forced the EIS team to evaluate only a limited set of sand-transport data after the dam was built and then work with flawed assumptions rather than with continuous data records of flow and sediment concentration. Clearly, long-term monitoring efforts and good models (see Conceptual Modeling text box, Overview, this report) are essential to the success of adaptive management and accurate predictions.

The EIS assumption that sand would accumulate on the bed of the river over multiple years has been transformed through learning and adaptive management experimentation. Recent research suggests that future management of sediment should involve high-flow releases immediately following inputs of sand and finer sediment from tributaries below the dam. While such releases may be controversial because they bypass the hydroelectric powerplant, recent studies also suggest that the duration of such flows may need to be only a small fraction of what was originally suggested. Such fine tuning in the prescription of experimental high flows that are used for achieving habitat restoration could reduce the financial impacts and controversy associated with such management actions.

A physical habitat component of ecosystem restoration tied to the EIS strategy for restoration of native fish depended on the outcome of modest improvement in fine-sediment resources. As originally proposed in the EIS, restoration of sand-based, nearshore habitats, termed “backwaters,” has also not been realized (see chapter 1, this report) under the strategy of MLFF and hydrologically triggered experimental high flows. Detailed synthesis studies of sediment inputs and outputs to the system (fine-sediment mass balance), intensive field monitoring, and change detection analyses from remote-sensing data all point to a decrease in fine-sediment resources in Glen, Marble, and Grand Canyons in the time since the EIS was implemented. These changes have resulted in smaller and coarser grained sediment deposits that are associated with a net loss of systemwide sand supply and no evidence of accumulating sand from tributary inputs, even under protracted drought hydrology and constrained hydropower operations.

We also know from research on coarse sediment dynamics that there has been an overall trend for the Grand Canyon reach to experience coarsening of the substrate in the river channel since completion of Glen Canyon Dam. As fine sediment is eroded because of dam operations, gravel and larger material remain. The impact of this “coarsening” of the river substrate has two potential biological implications: first is the creation of preferred habitat for benthic invertebrates, which are an important component of the aquatic ecology of the system, and second is the creation of spawning substrate for the nonnative rainbow trout. Both of these changes move the system farther from predam conditions and potentially benefit nonnative species like trout at the expense of natives.

Loss of sand habitats was documented under the no action period (1963–91), and loss has continued since dam operations were altered to reduce sandbar erosion.

Sand-transport data collected from 1999 through 2004 indicate that whenever the monthly flow regime from the dam forces daily peak discharges significantly above 10,000 cfs for extended periods, new and existing sand and finer sediments are being exported relatively quickly (weeks to months), rather than accumulating in the main channel over multiple years.

One alternative test of the MLFF concept for multiyear accumulation of sand supply might be to equalize monthly volumes during droughts in order to further limit daily peaks over such periods. If such a test failed to increase sand supply through accumulation of tributary inputs, then objectives for sand-habitat restoration might have to be reconsidered, or more proactive strategies, such as sediment augmentation, might need to be implemented. Meanwhile, release of short-duration, habitat-building flows following significant tributary sand inputs appears to be the most certain option for restoration of sand habitats below the dam.

## Water Quality and Climate

The presence and design of Glen Canyon Dam caused major environmental changes to the Colorado River ecosystem, including (1) alterations in the timing and variability of the annual, seasonal, and daily flow patterns of the river; (2) drastic reduction of fine-sediment supply to the reaches of Glen, Marble, and Grand Canyons; and (3) reduced variability in water temperature. On the basis of current science information, the MLFF operating alternative has not effectively mitigated the influence of regulation with respect to either the thermal and hydrologic changes or the fine-sediment supply limitation of the downstream ecosystem.

Given the importance of Lake Powell as the major source of water for the Grand Canyon ecosystem below, the lake monitoring program serves as an early warning system for changes in water quality. Although data from Lake Powell indicate that dam operations affect some resources downstream from Glen Canyon Dam, water quality in this large reservoir appears to be largely unaffected by the new dam operations since 1991. Overall, the water quality of the reservoir appears to be strongly linked to climatic annual to decadal variability governing spring inflow events and to the aging of the reservoir. The reservoir does have the potential to exert substantial impacts on downstream resources, however. For example, the current drought that started in the late 1990s reduced the level and volume of Lake Powell to elevations not seen since the reservoir began filling in the 1960s. The lower storage level of the reservoir has brought warmer surface (epilimnetic) waters to the penstocks, causing higher temperature water to be discharged downstream.

The effects of warmer water on downstream biological resources are currently difficult to predict with certainty and potentially include both positive and negative ecological consequences. Potential consequences include the creation of conditions that support the mainstem spawning of native fish, the invasion and dominance of warmwater fishes from Lake Mead, undesirable alteration of the food base, and unknown effects on the coldwater fishery in the Lees Ferry reach. This “natural” warming of Glen Canyon Dam releases that result from falling reservoir levels provides an important opportunity to test system responses to the possible installation of a temperature control device on the dam.

Current understanding of global climate drivers provides little ability to predict the timing or extent of droughts over much of the Colorado River Basin. The current drought may or may not be a so-called “mega drought” because of the limited duration to date. At the time of this writing we are cautiously optimistic about precipitation and runoff predictions for the basin, but the final outcome will have little to do with dam operations.

## Human Use of the River

During the latter part of the 20th century, societal values associated with river regulation began shifting away from a policy focused solely on water supply and energy development to one in which preservation of natural resources was also valued. This shift in values occurred only after river regulation by mainstem dams was well underway on the Colorado River.

River regulation in itself has facilitated the development of an economically significant business associated with whitewater rafting (see chapter 9, this report) by reducing the predam variability in flow extremes of the river and thereby allowing such activities to continue with relative economic safety throughout the year. Recreational use of the river is one of the resources of concern that appears to have benefited most from the stabilizing influence of the MLFF, relative to more variable dam operations. By eliminating very high and very low discharges, the MLFF favors year-round recreational boating and fishing. Although the most comprehensive regional economic study of river-based recreation is now 10 yr old, the figures are impressive: over $46 million (2004 dollars) in nonresident total expenditures and maintenance of 586 jobs, with 438 jobs in commercial rafting alone. Presumably those figures are even higher today.

## Camping

Between 1998 and 2003, camping area above the 25,000-cfs stage elevation decreased by 55%, and the average rate of change was 15% per year. The decrease in high-elevation campsite area occurred in Marble Canyon and in Grand Canyon as well as within critical (campsite-limited) and noncritical reaches. Losses are thought to be attributable both to net sediment exports under current dam operations (see chapters 1 and 12, this report) and to encroachment of woody vegetation (see chapter 6, this report). Notably, lower elevation campsite areas increased after 2000, and the total campsite area below the 25,000-cfs stage elevation now exceeds the area available at higher elevations. The rate of decrease in high-elevation campsite area greatly exceeds the decrease in sandbar volume. Vegetation encroachment most likely contributed to the recent loss of high-elevation campsite area.

The exact relationship and interaction among camping areas, vegetation expansion, and dam operations are unknown and provide a challenge for future researchers. For example, increased vegetation in sandbar areas may also provide greater substrate stability and shade, both limiting campsite erosion rates and enhancing camping areas from an aesthetic perspective. Tradeoffs between vegetation expansion and sandbar stability must also be considered from the perspective that increased vegetation might also limit the potential for wind processes to beneficially blow sand deposits upslope onto cultural sites that are subject to rainfall and runoff erosion.

Overall, in terms of recreation, future research should focus on detailed analyses of how fishing use, catch rates, and fish condition in Glen Canyon National Recreation Area are related to flows. Economic data on fishing and recreational rafting need to be updated to establish current baseline data before new flow regimes are initiated. Finally, studies to quantify the wilderness experiences of recreational users must be initiated so that the benefit of eventually achieving ecosystem restoration can be fully evaluated.

## Nonuse Values

Survey efforts tied to the EIS process found that households across the Nation, including those that might never visit Grand Canyon, were willing to pay additional taxes for flows that benefited native fish and trout. Although the amount that people were willing to pay for these benefits was quite reasonable, when aggregated up to the number of households in the population, it produced estimates in the $3 billion to $4 billion (2004 dollars) range (see chapter 9, this report). The public at large is willing to pay to have flows and other management actions that benefit Glen Canyon National Recreation Area, Grand Canyon National Park, and the resources found in both. While there are those who question the utility of nonuse valuation of Grand Canyon resources, these dollar amounts reflect the iconic values that make Grand Canyon National Park famous throughout the world.

## Hydroelectric Power Generation

Hydroelectric power and revenue associated with its production and marketing are also highly valued resources of concern to society, and environmental constraints on Glen Canyon Dam operations under the MLFF policy have large, annual economic costs (see chapter 10, this report). The acceptability of those costs has to be interpreted within the context of societal values associated with both electrical energy and environmental conservation objectives. Environmental constraints on dam operations have regional economic impacts on power revenue that is generated to pay back the cost of Glen Canyon Dam and to fund related water-resource and energy development. EIS studies on recreational use and nonuse values, however, suggest that dam operations under the MLFF benefit both local and regional economies through stabilization of flows, despite information that suggests that the ecological objectives of the program (e.g., retention of fine sediment, recovery of the humpback chub) remain unfulfilled.

Because of the constraints imposed on dam operations under the MLFF, the economic value of hydropower that was foregone is unknown. Existing scientific data suggest, however, that the policy, no matter how costly, has not resulted in the level of environmental benefits predicted or desired in the EIS for natural resources below the dam.

An ex post facto cost-benefit analysis of Glen Canyon Dam operations is needed to fully assess the economic value of the MLFF operation versus documented environmental benefits below the dam. Additional experimental designs and the eventual implementation of alternative, longer-term changes in the current operating strategy would benefit from such an assessment.

## Water Resources

Water allocation in the Colorado River Basin is governed by the Colorado River Compact of 1922 and subsequent laws and treaties. None of the laws pertain-ing to water management in the basin were superseded by the Grand Canyon Protection Act of 1992 or the 1996 Record of Decision; therefore, delivery of the volume of water required under these laws, including under the MLFF, has remained unaffected by the Glen Canyon Dam Adaptive Management Program.

## Cultural Resources

Under the MLFF operation, sand that is being exported from Grand Canyon is coming not only from new tributary inputs but also from existing beaches and river terraces that contain archaeological sites. Many archaeological sites in Grand Canyon have been covered with windborne (aeolian) sand for centuries. This sand was transported from lower elevation beaches that were frequently resupplied with new sand sources derived from annual floods during the predam era. Before dam operations were constrained, operations in the no action period (1963–91) were optimized for maximum water storage and power revenue (within the constraints of existing law and policies) rather than for strategically conserving limited sand supplies remaining downstream for restoration of sandbars (and, presumably, long-term preservation of cultural sites). The MLFF operation has not mitigated sand export, and therefore the sand supply remains critically limited. With more sand leaving the ecosystem than being supplied, more and more of these archaeological sites are being exposed to the ravages of erosion. As sites are eroded, artifacts and structures are exposed, making them more susceptible to visitor impacts and destabilization because of the loss of the surrounding sedimentary matrix in which they are buried. Such changes make it difficult, if not impossible, for archaeologists to reconstruct and interpret the historical and cultural information contained within these important settings within Grand Canyon.

In addition to being valued by scientists for the information that the archeological sites provide, the sites are also valued by many Native American people who have traditional affiliations with these sites and the Grand Canyon area in general. Other resources along the Colorado River that are also valued by the tribes of the region include traditionally used plants, minerals, water sources, and significant landscape features. The effects of the MLFF on these tribally valued resources remain uncertain; the Native Americans engaged in the Glen Canyon Dam Adaptive Management Program would like to see more emphasis placed on monitoring the effects on these resources in the future.

## Vegetation in the River Corridor

Glen Canyon Dam operations under the MLFF have stabilized flow conditions that were in effect before the EIS in Grand Canyon and that had significant impacts on riparian vegetation. The EIS predicted a modest increase in woody vegetation (table 1), and that prediction has proven largely correct, if not understated. The EIS also predicted that marsh communities would be the same as or less than expected under the no action alternative, which is also largely correct. Since implementation of the MLFF, there has been a decrease in wet marsh vegetation and an increase in dry marsh vegetation.

The stability of flows has encouraged an increase in vegetation density in and near the wetted zone. While an increase in vegetation may appear to be desirable, one of the impacts is a decrease in available camping area for recreational users (see chapter 12, this report). Furthermore, the increase is partially attributable to expansion of nonnative tamarisk (*Tamarix ramosissima*) and arrowweed into the riparian zone. In the terrestrial realm, future research should focus on identifying the responses of wildlife to this fundamental change in habitat structure, striving to understand the relationship between riparian vegetation and insects as related to the food web of the river, and examining the effects of human-mediated removal of nonnative vegetation versus natural disturbance. Understanding the complex interface between dam operations and overlapping elements of both the terrestrial and aquatic parts of the river ecosystem provides even greater challenges.

## Integrated Ecological Factors

Although linkages between native fish recruitment and backwaters are not well documented and strategies for achieving sandbar habitat restoration are still being investigated, it is clear that physical habitat availability does not reduce or diminish the need by native fish for a sustainable food supply. Dam operations under the MLFF have resulted in steadier flows and greater minimum discharges of clearer water than operations in the no action period, and this situation has probably led to increases in the standing mass of algae and invertebrates (table 1).

A critical future research need is to develop a better understanding of the linkages between the organic matter and invertebrates and the actual prey base of fish, both native and nonnative. A large amount of data has been collected on the food items consumed by nonnative rainbow trout, but only limited data are available for the humpback chub because of the endangered status of this fish. Use of stable-isotope analysis will be critical to assessing the energy sources and trophic pathways that are important to fish. Also, critical tests of the hypothesis that competition between nonnative trout and humpback chub is negatively affecting humpback chub populations are not possible because of inadequate data. Eating the same food items is only the first criterion to establish that competition is negatively impacting a particular species. Further research will be required to determine if this hypothesis is supported by data.

## Recent Management Experiments

With respect to native fishes, we have learned that, under the MLFF, focused efforts are still required to understand the importance of the sediment and thermal aspects of physical habitat in the early life history of humpback chub and other species. Focused efforts are also needed to understand the influence of introduced nonnative species on the successful recruitment of humpback chub to the adult life stage. Additional experiments in these areas will require even more commitment to the adaptive management approach by using repeated implementation of both flow and nonflow treatments over an extended period of perhaps 10 or more years coupled with long-term monitoring.

Mechanical removal of nonnative fish, especially rainbow trout, is currently in the third year of a 4-yr implementation strategy to test the hypothesis that reduction of predatory and competitive fish species will result in an increase in survival and recruitment of humpback chub (see U.S. Department of the Interior, 2002, for details of the current experimental design). While the adaptive management program has demonstrated that mechanical removal is an effective way to significantly reduce the number of nonnative trout in the removal reach, it has yet to detect the desired increase in the number of spawning-age humpback chub.

In addition to understanding how aquatic ecology, dam operations, and fish populations of the Colorado River ecosystem are interrelated, scientists need to focus future research on the effects of warming discharges of water from Glen Canyon Dam. An experimental temperature control device has been proposed for the dam later in this decade, and substantial questions remain unanswered as to the efficacy of this experimental treatment with respect to both its risk and its cost benefit.

As linkages between the aquatic ecology of the river and its native and nonnative fishes are defined, new efforts for tracking critical elements of water quality will need to evolve to track bioenergetic pathways and fish responses to flow treatments such as temperature control device operations. Also, as more information becomes available about the role of fine sediment in the preservation of cultural sites, aquatic ecology, and fish recruitment, there will need to be a commitment to modeling and monitoring of long-term fluxes of suspended organic and inorganic materials through the river system.

## Conclusions and Future Challenges

Research and monitoring conducted by U.S. Geological Survey scientists and their cooperators have conclusively demonstrated a net loss of sediment from the system and have documented the decline of the federally endangered humpback chub during the last decade. At this first milestone, both findings are critical pieces of information to assess conditions and adjust management actions in the spirit of adaptive management. It is important to note that water-delivery requirements continued to be met throughout the decade after the EIS, despite increased costs associated with environmental and experimental regulation of flows.

Although incomplete, a substantial body of knowledge now exists for the Colorado River ecosystem in Grand Canyon. The overarching question is, “What will society do with the knowledge now available to move into the next active phase of the Glen Canyon Dam Adaptive Management Program?” The complexity of the natural system presents enormous challenges for determining how resources and population numbers vary in time and space and underscores the importance of long-term studies to describe patterns and processes. The next critical phase of adaptive management requires strategic action on the part of both managers and scientists.

Along with future action come the continuing challenge and need for greater integration of monitoring and research studies. As the complexity of issues in the Glen Canyon Dam Adaptive Management Program becomes more obvious, so does the need for interdisciplinary, not just multidisciplinary, science. Good examples of recent interdisciplinary science include (1) the interface between fine-sediment studies and cultural resources as the result of research efforts to understand the deposition of wind-carried sediment, (2) water-quality studies related to temperature and fish biology, and (3) the developing link between aquatic ecology studies and fish diets. Continued efforts will be required to integrate knowledge across disciplines and scales and to develop a more robust conceptual model for the Grand Canyon ecosystem.

A continued adaptive management approach below Glen Canyon Dam, one focused on systematic experimentation, is recommended as a more efficient strategy for learning than the approach initially undertaken of monitoring the MLFF operation without comparing it to other flow and nonflow (e.g., mechanical removal of nonnative fish) alternatives. Future experimental treatments (flow or otherwise) must be evaluated within a strategic framework of periodic milestones and with rigorous scientific review so as to effectively identify viable management options for achieving the desired mix of resource responses. Success in this approach relies first and foremost on managers and stakeholders identifying what is desired, as well as determining whether identified objectives are measurable by science and attainable through dam operations.

In the context of an adaptive ecosystem management process, the information identified at this milestone should lead to a dialog between managers and scientists about what other flow or nonflow alternatives might be considered to achieve the desired environmental outcomes.

Because of the uncertainty about the cause and effect of MLFF operations on Grand Canyon resources and the even greater uncertainty about other conservation options, such as mechanical removal or thermal modification, the next steps in the process seem best approached as ongoing management policy experiments in the spirit of adaptive management, punctuated with frequent milestones at which the state of knowledge gained is assessed by all interested parties.

## Critical Issues for Further Research

The synthesis of knowledge from over a decade of research and monitoring in Grand Canyon provides an opportunity to identify critical research needs in the Glen Canyon Dam Adaptive Management Program. The purpose of this report is to establish another milestone in our understanding of the state of resources in Grand Canyon; however, we do not attempt herein to provide an exhaustive or prescriptive list of management options. That effort will require another set of processes and products. Instead, we focus on the drivers, or major science questions, that will need to be addressed in the next phase of adaptive management:

- Why is the humpback chub population in Grand Canyon declining? Specifically, what factors or combination of factors are most influential in this downward trend?

- What is the linkage between native and nonnative fish population dynamics and the aquatic and terrestrial food base, and how are these factors related to dam operations?

- Under a potentially continuing drought scenario for the upper basin of the Colorado River, what are the impacts of warmwater discharges on the ecosystem?

- If additional research demonstrates that sediment inputs from tributaries below the dam cannot be manipulated to achieve the desired conservation of sandbars and backwaters with dam operations, is sediment augmentation a viable option?

- What are the specific linkages between dam operations and archaeological site erosion, and what are the options for preserving the significant variety of culturally important resources and the information values associated with nonrenewable heritage resources?

Experimentation and research are needed to determine what role Glen Canyon Dam operations have had in these issues and whether further changes in those operations can benefit key resources.

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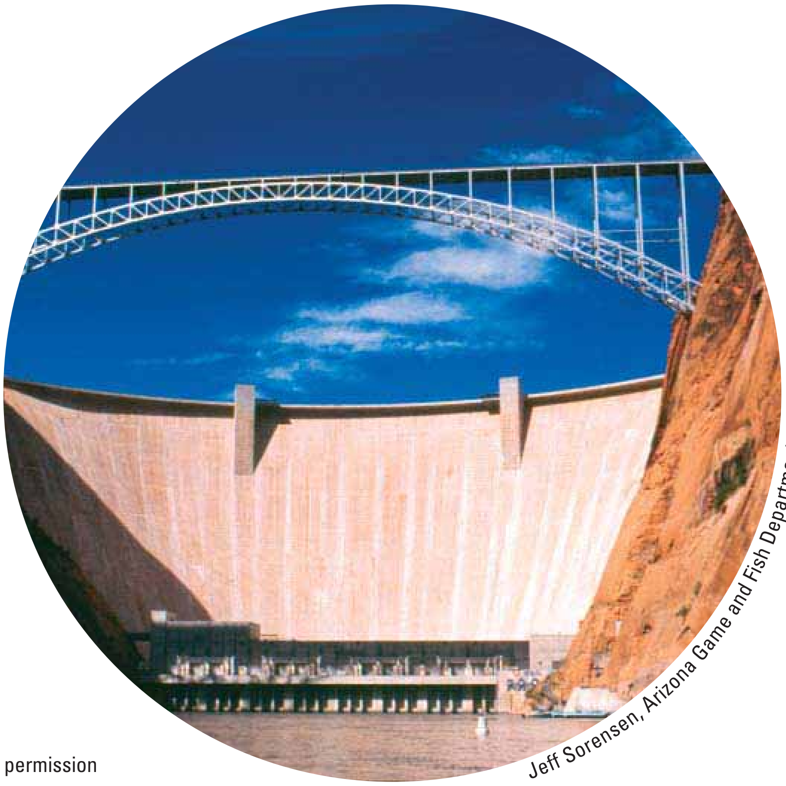

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