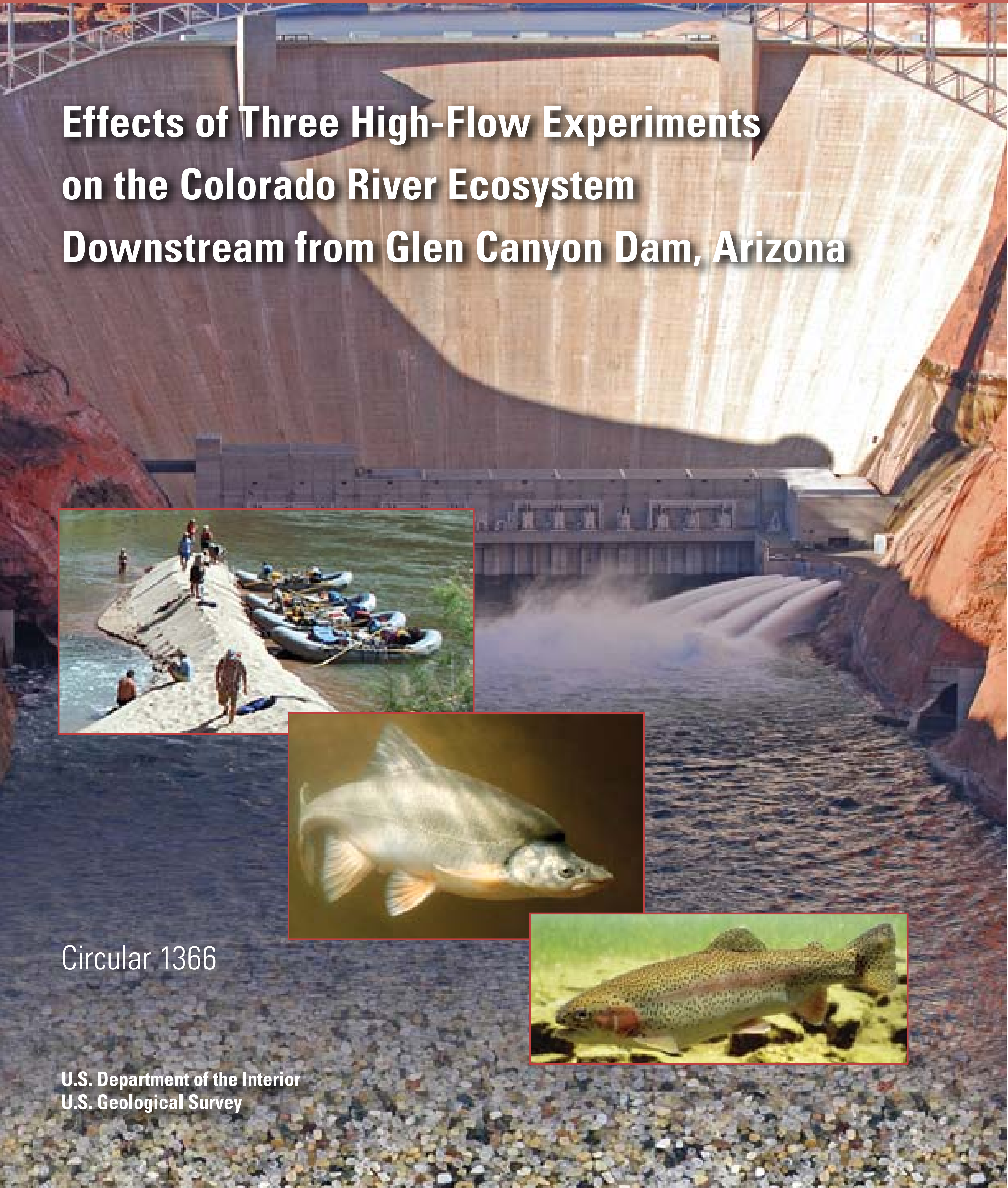
science for a changing world

Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from Glen Canyon Dam, Arizona



Circular 1366

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

Cover photographs:

Background — Glen Canyon Dam during the March 2008 high-flow experiment (Anne Phillips, U.S. Geological Survey).
Inset top — Sandbar and boats (Matt Kaplinski, Northern Arizona University).
Inset middle — Humpback chub (*Gila cypha*; George Andrejko, Arizona Game and Fish Department).
Inset bottom — Rainbow trout (*Oncorhynchus mykiss*; copyright Eric Engbretson, used with permission).
Bottom background — Sand grains (David M. Rubin, U.S. Geological Survey).

Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from Glen Canyon Dam, Arizona

Edited by Theodore S. Melis

National Park Service

Circular 1366

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

This report and any updates to it are available online at:
http://pubs.usgs.gov/circ/1366/

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Melis, T. S., ed., 2011, Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona: U.S. Geological Survey Circular 1366, 147 p.

Contents

CHAPTER 1
Introduction and Overview 1
Lara M. Schmit and John C. Schmidt

CHAPTER 2
Understanding Physical Processes of the Colorado River 17
John C. Schmidt and Paul E. Grams

CHAPTER 3
The High Flows—Physical Science Results 53
John C. Schmidt and Paul E. Grams

CHAPTER 4
Biological Responses to High-Flow Experiments at Glen Canyon Dam 93
Theodore A. Kennedy and Barbara E. Ralston

Text boxes
Richard A. Valdez and illustrations by Joseph R. Tomelleri
Richard A. Valdez, Christopher T. Robinson, and Theodore S. Melis

CHAPTER 5
Science-Based Strategies for Future High-Flow Experiments at Glen Canyon Dam 127
Scott A. Wright and Theodore A. Kennedy

Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	929	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)

SI to Inch/Pound

Multiply	By	To
	Length	
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
	Mass	
megagram (Mg)	1.102	ton, short (2,000 lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: $°F = (1.8 \times °C) + 32$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: $°C = (°F - 32) / 1.8$

In this report, horizontal and vertical coordinate information is referenced in feet above the GRS80 ellipse defined by the North American Datum of 1983 (NAD83).

Elevation, as used in this report, refers to NAD83/GRS80 ellipsoid heights and not traditionally defined North American Vertical Datum of 1988 (NAVD88) orthometric heights.

Project Staff

Editor

Theodore S. Melis, Ph.D.
U.S. Geological Survey
Southwest Biological Science Center
Grand Canyon Monitoring and Research Center
Flagstaff, Arizona

Project Coordinator

Lara M. Schmit
Northern Arizona University
Colorado Plateau Research Station
Flagstaff, Arizona

Production Staff

Kay E. Hedrick
U.S. Geological Survey
Science Publishing Network
Raleigh, North Carolina

David R. Jones
U.S. Geological Survey
Science Publishing Network
Menlo Park, California

Additional Production Support

James E. Banton
U.S. Geological Survey
Science Publishing Network
Nashville, Tennessee

Darlene Ryan
U.S. Geological Survey
Science Publishing Network
Flagstaff, Arizona

Research Assistants

Kyrie L. Fry
Northern Arizona University
Colorado Plateau Research Station
Flagstaff, Arizona

Meredith A. Hartwell
Northern Arizona University
Colorado Plateau Research Station
Flagstaff, Arizona

Special Acknowledgment

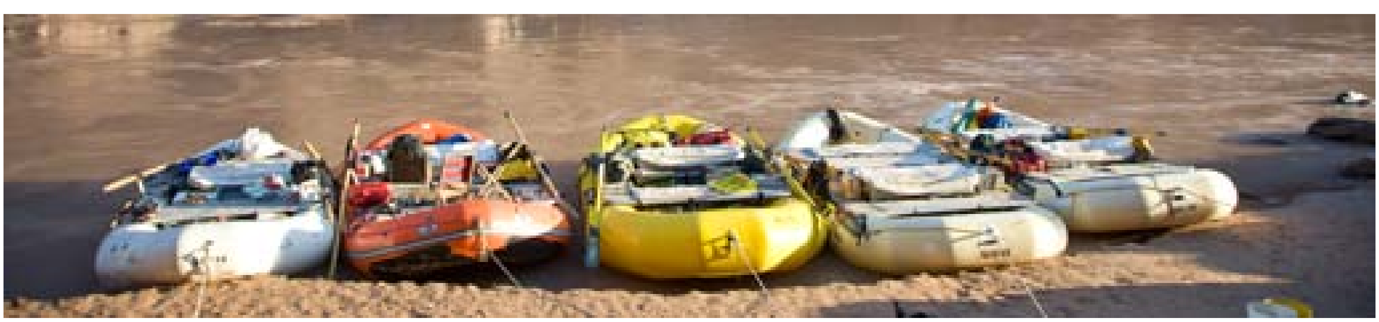
The assistance of Matthew E. Andersen, U.S. Geological Survey; Colden Baxter, Idaho State University; Wyatt Cross, Montana State University; Amy E. Draut, U.S. Geological Survey; Helen C. Fairley, U.S. Geological Survey; Graham D. Foster, U.S. Geological Survey; Thomas M. Gushue, U.S. Geological Survey; Robert O. Hall, Jr., University of Wyoming; John F. Hamill, U.S. Geological Survey; Joseph E. Hazel, Jr., Northern Arizona University; Matt Kaplinski, Northern Arizona University; Kate Kitchell, U.S. Geological Survey; Ronald E. Kirby, U.S. Geological Survey; Josh Korman, Ecometric Research, Inc.; Milada Majerova, Utah State University; Andrew S. Makinster, Arizona Game and Fish Department; Jonathan Nelson, U.S. Geological Survey; William R. Persons, U.S. Geological Survey; Emma Rosi-Marshall, Cary Institute of Ecosystem Studies; Robert Ross, U.S. Geological Survey; David M. Rubin, U.S. Geological Survey; David J. Topping, U.S. Geological Survey; Marijke van Heeswijk, U.S. Geological Survey; Carl J. Walters, University of British Colombia; and Michael D. Yard, U.S. Geological Survey, is gratefully acknowledged.

Peer and Technical Reviewers

The content of the chapters contained in this report was greatly enhanced by the wisdom and research of many colleagues and cooperators. In particular, the project team and the authors gratefully recognize the indepth and thoughtful review of the independent and anonymous scientists who served as peer reviewers for the individual chapters.

Financial Support

This report was funded by hydropower revenues provided by the Bureau of Reclamation as part of the Glen Canyon Dam Adaptive Management Program (GCDAMP). The GCDAMP was established in 1997 to provide for long-term research and monitoring of downstream resources affected by Glen Canyon Dam. Scientific information, such as that contained in this report, is used as the basis for developing recommendations for dam operations and management actions. More information on the GCDAMP is available at http://www.gcdamp.gov/.



Mike Quinn, National Park Service

CHAPTER 1

Introduction and Overview

By Lara M. Schmit[1] and John C. Schmidt[2]

Three high-flow experiments (HFEs) were conducted by the U.S. Department of the Interior at Glen Canyon Dam, Arizona, in March 1996, November 2004, and March 2008 (figs. 1 and 2). These experiments, also known as artificial or controlled floods, were large-volume, scheduled releases of water from Glen Canyon Dam that were designed to mimic some aspects of pre-dam Colorado River seasonal flooding. The goal of these experiments was to determine whether high flows could be used to benefit important physical and biological resources in Glen Canyon National Recreation Area and Grand Canyon National Park (fig. 2) that had been affected by the operation of Glen Canyon Dam. Efforts such as HFEs that seek to maintain and restore downstream resources are undertaken by the U.S. Department of the Interior under the auspices of the Grand Canyon Protection Act of 1992 (GCPA; title XVIII, secs. 1801–1809, of Public Law 102-575). Scientists conducted a wide range of monitoring and research activities before, during, and after the experiments. Initially, research efforts focused on whether HFEs could be used to rebuild and maintain Grand Canyon sandbars, which provide camping beaches for hikers and whitewater rafters, create habitats potentially used by native fish and other wildlife, and are the source of windborne sand that may help to protect some archaeological resources from weathering and erosion. As scientists gained a better understanding of how HFEs affect the physical environment, research efforts expanded to include additional investigations about the effects of HFEs on biological resources, such as native fishes, nonnative sports fishes, riverside vegetation, and the aquatic food web. The chapters that follow summarize and synthesize for decisionmakers and the public what has been learned about HFEs to provide a framework for implementing similar future experiments.

This report is a product of the Glen Canyon Dam Adaptive Management Program (GCDAMP), a Federal initiative authorized to ensure that the primary mandate of the GCPA (GCPA sec. 1802 (a)) is met through advances in information and resource management. The program and its research efforts focus on a study area that encompasses the Colorado River corridor from the forebay of Glen Canyon Dam to the western boundary of Grand Canyon National Park, which is identified as the Colorado River ecosystem elsewhere in this report. The study area includes the approximately 16-mile river corridor between the dam and Lees Ferry within Glen Canyon National Recreation Area and the entire 277-river mile corridor downstream from Lees Ferry and within Grand Canyon National Park (fig. 2). The U.S. Geological Survey's Grand Canyon Monitoring and Research Center (GCMRC) is responsible for the scientific monitoring and research efforts of the GCDAMP, including the preparation of this report. The GCMRC gratefully acknowledges the contributions of those scientists with Federal and State resource-management agencies, academic institutions, and private consulting firms who undertook much of the research presented in the chapters that follow.

[1] Northern Arizona University, Colorado Plateau Research Station, P.O. Box 5614, Flagstaff, AZ 86011.

[2] Intermountain Center for River Rehabilitation and Restoration, Department of Watershed Sciences, Utah State University, Logan, UT 84322–5210.

Figure 1. Glen Canyon Dam during the 2008 high-flow experiment on the night of March 6, 2008. Three high-flow experiments—water releases above powerplant capacity—were conducted in 1996, 2004, and 2008 to determine if water releases designed to mimic some aspects of natural pre-dam seasonal flooding can be used to improve a wide range of natural resources in Glen Canyon National Recreation Area and Grand Canyon National Park. Photograph courtesy of Thomas Ross Reeve, Bureau of Reclamation.

The Colorado River and Grand Canyon

The Colorado River is one of the most iconic rivers in the United States, and its watershed includes parts of seven States—Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming. The river is noted for its striking canyons, especially the part of the river that crosses the southern Colorado Plateau and forms Grand Canyon. Grand Canyon is one of the world's most spectacular canyon systems, reaching depths of more than 6,000 feet (ft). Recognizing the need to protect its world-class geologic wonders and awe-inspiring natural beauty for future generations, Theodore Roosevelt issued Presidential Proclamation 794 in 1908 establishing Grand Canyon National Monument. The monument became the United States' 17th national park on February 26, 1919, when President Woodrow Wilson signed the authorizing bill.

The Colorado River and Grand Canyon also are central to the traditional values and histories of many of the region's Native Americans. In fact, some places in what is now Grand Canyon National Park are identified in multiple Tribal creation stories as the place of origin for the Tribe's ancestors (Fairley, 2003; Dongoske and others, 2010). More than 4,300 archaeological resources have been documented in Grand Canyon National Park, including about 336 sites in the river corridor potentially affected by dam operations (Fairley, 2005). The oldest human artifacts found in the park date to the Paleo-Indian period and are almost 12,000 years old (National Park Service, 2009). In addition to its geologic and cultural legacy, the Colorado River ecosystem downstream from Glen Canyon Dam boasts a diverse array of plants and animals, including federally endangered species, such as the humpback chub (*Gila cypha*) and the southwestern willow flycatcher (*Empidonax traillii extimus*).

Grand Canyon is part of an extensive canyon network through which the Colorado River and its major headwater tributaries flow. The Colorado River watershed covers 15 percent of the conterminous United States, and its channel network is the conduit by which snowmelt originating in the middle and southern Rocky Mountains reaches the Gulf of California (fig. 3). Three large headwater tributary systems—the upper Colorado River, the Green River, and the San Juan River—drain the western slope of the Rocky Mountains and contribute flow to the Colorado River. Southwest of the Rocky Mountains, these rivers cross the Colorado Plateau, a vast uplifted assemblage of sedimentary rocks. The upper Colorado and Green Rivers join just upstream from Cataract Canyon in Canyonlands National Park, Utah. The San Juan River joins the Colorado

River in Glen Canyon National Recreation Area in a part of Glen Canyon inundated by Lake Powell, the reservoir formed by Glen Canyon Dam.

Glen Canyon Dam

Glen Canyon Dam, located just south of the Arizona-Utah border, forms a reservoir that is one of four main-stem water-storage units authorized in 1956 under the Colorado River Storage Project (CRSP) Act (Ch. 203, Public Law 485). The CRSP reservoirs allow the upper basin States—Colorado, New Mexico, Utah, and Wyoming—to store water in wet years and release water during drier periods, thereby allowing the upper basin States to meet their obligations to the lower basin States under the 1922 Colorado River Compact while also maximizing opportunity for future water development. Historically, a minimum of 8.23 million acre-feet (MAF) has been released annually from Lake Powell, the second largest reservoir in the United States, to satisfy Colorado River Compact obligations to the lower basin and also provide the upper basin's share of water to Mexico under a 1944 treaty. Annual releases have exceeded 8.23 MAF during periods of average to above average precipitation levels in the upper Colorado River Basin and to balance storage between Lakes Powell and Mead. In response to recent drought conditions in the Colorado River Basin, interim guidelines have been established to address the possibility of water shortages (U.S. Department of the Interior, 2007).

The CRSP Act included hydropower facilities at three of the four water-storage units it authorized, including Glen Canyon Dam, to produce salable power. The powerplant at Glen Canyon Dam is made up of eight hydroelectric generation units. In 2007, the powerplant produced 3.5 million megawatt hours. Power generated at CRSP facilities is first provided to CRSP participating projects, which typically are irrigation projects (Harpman and Douglas, 2005). The power that is surplus to project uses is sold to approximately 240 wholesale customers—municipal and county utilities, rural electric cooperatives, Federal and State facilities, Native American Tribes, and nonprofit organizations—primarily located in seven States. The revenues generated by the CRSP units are used to pay for annual operation and maintenance costs, including environmental programs such as the GCDAMP, power facility construction costs, and other nonpower-related costs assigned by Congress (Harpman and Douglas, 2005).

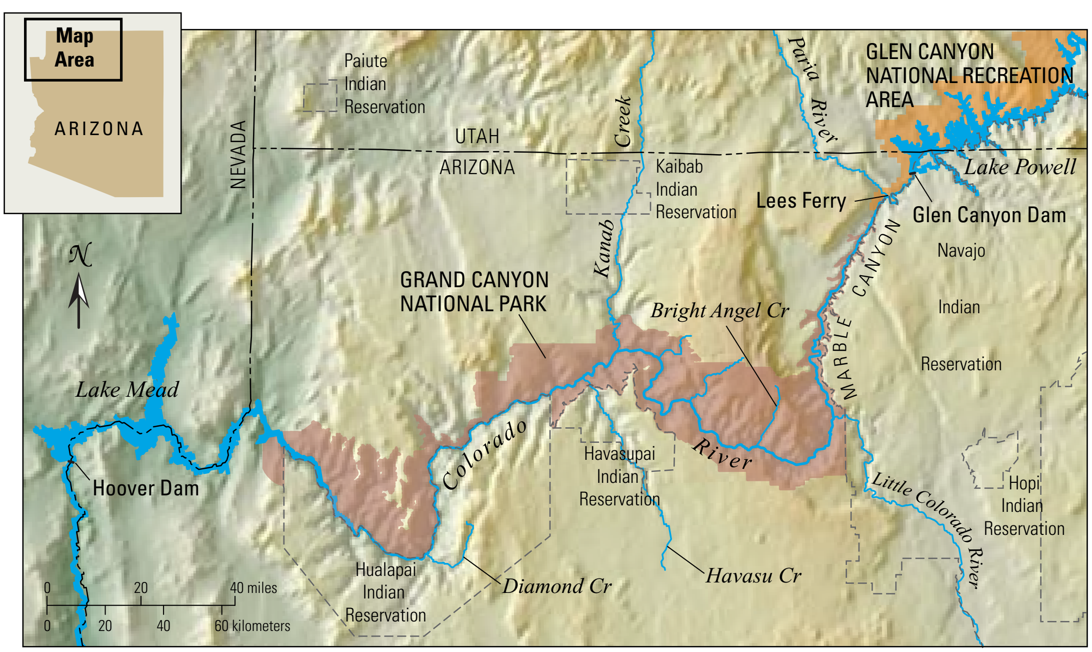


Figure 2. The Glen Canyon Dam Adaptive Management Program study area includes the Colorado River corridor that stretches approximately 293 river miles from the forebay of Glen Canyon Dam to the westernmost boundary of Grand Canyon National Park, Arizona.

Figure 3. The Colorado River watershed covers 15 percent of the conterminous United States. The channel network of the watershed is the conduit by which snowmelt originating in the middle and southern Rocky Mountains reaches the Gulf of California.

Time line photograph credits: Glen Canyon Dam construction, Bureau of Reclamation; Glen Canyon Dam, Anne Phillips, USGS; Colorado pikeminnow, George Andrejko, Arizona Game and Fish Department; Glen Canyon Dam with open jet tubes, Anne Phillips, USGS; Razorback sucker, George Andrejko, Arizona Game and Fish Department; jet tubes, Anne Phillips, USGS; scientists, Paul Alley, USGS; Humpback chub, George Andrejko, Arizona Game and Fish Department.

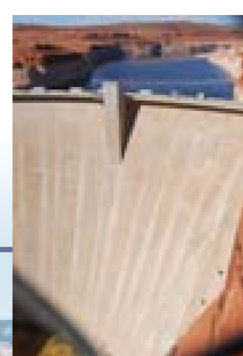
Events Relevant to High-Flow Experiments

Glen Canyon Dam construction begins.

1956

Last completely unregulated spring snowmelt flood, which had a peak flow of about 126,000 ft^3/s, to pass through Grand Canyon is measured at the Lees Ferry gaging station.

1957



Glen Canyon Dam is closed and complete regulation of the river begins; U.S. Supreme Court held in Arizona v. California that, as the 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.

1963

Changing Societal Values and Efforts to Protect Grand Canyon

Until the last half of the 20th century, the goal of Federal policy was to control and use the waters of the Colorado River to create wealth and new opportunities through dam building and hydropower generation. The early 20th century view of the value of the Colorado River was expressed in a 1946 report prepared by the U.S. Department of the Interior entitled "The Colorado River—A Natural Menace Becomes A National Treasure," which stated:

> *In their present state this land, this water, and these minerals are not wealth because they are not being utilized economically. * * * Water can be brought to this land to produce crops; these minerals can be mined and processed with an abundance of low-cost hydroelectric energy made available; trade can be established; and in general, the wealth produced can be converted into more and better opportunities for the American people* (U.S. Department of the Interior, 1946, p. 211).

At the time Glen Canyon Dam was constructed (1956–63), little consideration was given to how dam operations might affect downstream resources in Grand Canyon National Park (Babbitt, 1990). In fact, the dam was completed before enactment of the National Environmental Policy Act of 1969 (42 U.S.C. § 4321 and § 4331–4335, Public Law 91-190) and the Endangered Species Act of 1973 (16 U.S.C. § 1531–1544, 87 Stat. 884, Public Law 91-135). By the late 1950s, public values began to shift, and throughout the 1960s and 1970s recognition of the environmental consequences of Glen Canyon Dam and its operation grew. National Park Service and U.S. Geological Survey scientists and river recreationists observed the physical transformation of the river in Grand Canyon, including the loss of large beaches used for camping, narrowing of rapids so as to reduce navigability, and changes in the distribution and composition of riparian vegetation (Dolan and others, 1974; Cooley and others, 1977; Turner and Karpiscak, 1980; Howard and Dolan, 1981). The humpback chub and Colorado pikeminnow (*Ptychocheilus lucius*), species found only in the Colorado River Basin, were listed as endangered in 1967 under the Endangered Species Preservation Act (Public Law 89-669, 80 Stat. 926) by the U.S. Fish and Wildlife Service, which concluded in 1978 that the dam and its operation jeopardized the continued existence of humpback chub in Grand Canyon.

The status of Grand Canyon as a crown jewel of the National Park System and concerns about the effects of Glen Canyon Dam have inspired lawsuits, agency actions, and legislation. The GCPA, legislation authorizing Federal efforts to protect resources downstream from Glen Canyon Dam, directs the Secretary of the Interior to operate the 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)). The act also clearly states that it was to be implemented in accordance with existing laws, treaties, and

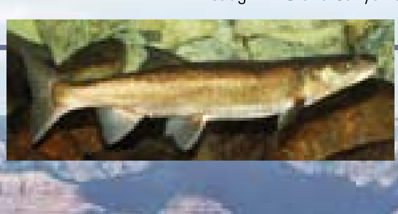
1965
Bureau of Reclamation released a series of 14 short-duration high flows, 6 of which were in excess of 50,000 ft^3/s, from Glen Canyon Dam. These high flows scour fine and coarser sediment from the Lees Ferry reach, which combined with the clear and cold water released from the dam created habitat conditions ideal for a nonnative trout fishery below the dam in Glen Canyon National Recreation Area.

1966
National Historic Preservation Act passed.

1967
Humpback chub and Colorado pikeminnow 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.



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

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 Service (marine species).

institutional agreements that govern allocation, appropriation, development, and exportation of Colorado River Basin waters (GCPA, sec. 1802 (b)).

The “Operation of Glen Canyon Dam: Final Environmental Impact Statement” (hereafter referred to as EIS), which outlined alternative dam-operation strategies for meeting GCPA requirements, was filed in March 1995, and the Record of Decision was signed by the Secretary of the Interior in October 1996. The Record of Decision noted that the goal of selecting the preferred alternative “was not to maximize benefits for the most resources, but rather to find an alternative dam operating plan that would permit recovery and long-term sustainability of downstream resources while limiting hydropower capability and flexibility only to the extent necessary to achieve recovery and long-term sustainability” (U.S. Department of the Interior, 1996b, p. G-11). Having established this goal, the Secretary’s decision was to implement the modified low fluctuating flow (MLFF) alternative, the preferred alternative described in the EIS, with minor changes (U.S. Department of the Interior, 1996b). The Record of Decision also formally established the GCDAMP.

The Colorado River Before and After the Construction of Glen Canyon Dam

Annual spring snowmelt floods were the defining attribute of the pre-dam flow regime (White and others, 2005). Before the Colorado River was regulated by dams, streamflow gradually increased from mid-December to March, precipitously increased in April and May, and reached its peak in early June. The timing and magnitude of the annual pre-dam snowmelt flood depended on how much snow had accumulated in the Rocky Mountains during the preceding winter and the rate at which the snowpack melted in the spring. The largest recorded flood in Grand Canyon occurred in June 1884 and was approximately 210,000 cubic feet per second (ft^3/s; Topping and others, 2003). Approximately every 2 years, however, the largest annual snowmelt flood measured about 85,000 ft^3/s (Topping and others, 2003), which is almost three times greater than flows that occur when Glen Canyon Dam is operated at powerplant capacity. Smaller floods of shorter duration occurred in late summer and fall in many years during the North American monsoon season when moisture from the Pacific Ocean moves northward through Mexico and up to the Colorado Plateau.

Although most of the water in the Colorado River originates from the distant Rocky Mountains, most of the sediment carried by the river originates in nearby desert watersheds of the Colorado Plateau. Tributaries in Colorado Plateau watersheds contribute large amounts of sand, silt, and clay to the Colorado River, and this sediment load is then trapped in Lake Powell. Before extensive European settlement, the Colorado River delivered about 100 million tons of sand per year to its delta at the head of the Gulf of California (Meade and others, 1990) and transported approximately 60 million tons of sand per year past Lees Ferry (Topping and others, 2000).

Photograph courtesy of George Andrejko, Arizona Game and Fish Department

Figure 4. The endangered humpback chub (*Gila cypha*) is a freshwater fish found only in the Colorado River Basin. Reaching 20 inches in length, the humpback chub has features that distinguish it as a native Colorado River fish—large adult body size, small depressed skull, and small eyes.

Pre-dam floods disturbed the aquatic ecosystem, and native fish species developed strategies to survive periods when the velocity in the main part of the channel was high and large amounts of suspended sediment were being transported. For example, several of the native fish species share unusual body shapes, including a large adult body size, small depressed skulls, large humps on their backs, and small eyes, which presumably developed as adaptations to life in a turbid and seasonably variable riverine environment (fig. 4; chapter 4, this volume; Minckley, 1991). During typical floods, the mean velocity of the Colorado River exceeded 10 feet per second (ft/s) at Lees Ferry, five times greater than the velocity during typical pre-dam base flows (Burkham, 1986). Base flow is that part of the stream discharge that is not attributable to direct runoff from precipitation or melting snow and usually is sustained by groundwater. Sandbars, riverbanks, and their accompanying aquatic habitats were reshaped during floods. Additionally, the increased elevation of the river surface during floods provided water to native riparian vegetation otherwise principally dependent on precipitation.

The Regulated River

The regulation of rivers by dams, such as Glen Canyon Dam, results in multidimensional physical and ecological changes to the system. For example, Ward and Stanford (1995) emphasize that river regulation not only alters river characteristics, such as temperature and flow, but also results in changes in interactions between the river and other water bodies and between aquatic and riparian systems, including changes in the movement of nutrients, sediment, fish, and other organisms. Flow regulation of the Colorado River by Glen Canyon Dam effectively

1983 Glen Canyon Dam releases a peak flow of 97,300 ft^3/s 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 Dam Environmental Studies, publishing "River and Dam Management: A Review of the Bureau of Reclamation's Glen Canyon Environmental Studies."

1989 Secretary of the Interior Manuel Lujan, Jr., orders an Environmental Impact Statement on Glen Canyon Dam operations.

1990 The National Research Council sponsors symposium that reviews existing knowledge of the Colorado River ecology and dam management.

1990–91 Research flows used to evaluate a variety of fluctuating and steady flow patterns.

1991 Interim operation criteria for Glen Canyon Dam implemented; razorback sucker and Kanab ambersnail federally listed as endangered.

replaced relatively high and low flows with a greater frequency of moderate flows. The presence and operation of the dam altered the natural timing and magnitude of floods, the most important and dynamic attribute of the pre-dam flow regime. For example, if post-dam floods are defined as "[dam] releases exceeding powerplant capacity [33,200 ft^3/s] for a month or more," a definition used by the Glen Canyon Environmental Studies (U.S. Department of the Interior, 1988, p. A-21), the science organization that preceded the GCMRC, then post-dam floods only occurred in 1983, 1984, 1985, and 1986. The largest of these post-dam floods occurred on June 29, 1983, when a peak flow of 97,300 ft^3/s was measured at Lees Ferry. Additionally, soon after the completion of the dam, the Bureau of Reclamation released a series of six short-duration flows in excess of 50,000 ft^3/s in April and June 1965, which scoured the river channel in the tailwater (the 16-mile section of river downstream from Glen Canyon Dam) and created conditions suitable for a nonnative trout fishery (chapter 2, this volume).

High-Flow Experiments

Beginning in the late 1970s, scientists started exploring and documenting ecological responses to alterations in components of natural flow regimes, including the loss of sensitive species and disruption of spawning and migration signals for fish (Poff and others, 1997). This new information generated a number of projects to restore elements of natural flow regimes throughout the country (Poff and others, 1997). In Grand Canyon, the 1996 Record of Decision included the use of beach/habitat-building flows, which according to the EIS were "scheduled high releases of a short duration designed to rebuild high elevation sandbars, deposit nutrients, restore backwater channels, and provide some of the dynamics of a natural system" (U.S. Department of the Interior, 1995, p. 40). Essentially, resource managers sought to benefit key terrestrial and aquatic resources by simulating one aspect of the pre-dam river—floods. Specifically, beach/habitat-building flows were defined as infrequent high releases that are at least 10,000 ft^3/s greater than the allowable peak discharge in a minimum release year (25,000 ft^3/s for MLFF) but not greater than 45,000 ft^3/s for 1 to 2 weeks. More recently, "high-flow experiment" (HFE), the term used in this report, has been used to describe experimental flows from Glen Canyon Dam ranging from powerplant capacity (33,200 ft^3/s) to 45,000 ft^3/s.

In accordance with the principles of adaptive management, also known as "learning by doing," the EIS identified uncertainties about sandbar building in response to high releases of short duration and required a test of a beach/habitat-building flow before long-term implementation of this element of the EIS (U.S. Department of the Interior, 1995). In reaching a finding of no significant impact, which paved the way for the first test of experimental high flows, the 1996 final environmental assessment reached the following conclusion: "Because all impacts of the proposed action on downstream resources are consistent with natural processes, they are considered to be beneficial to the overall ecosystem" (U.S. Department of the Interior, 1996a, p. iv). Although no significant

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

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 federally listed as endangered; U.S. Department of the Interior establishes the Grand Canyon Monitoring and Research Center in Flagstaff, Arizona.

1996

First high-flow experiment of 45,000 ft^3/s 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.

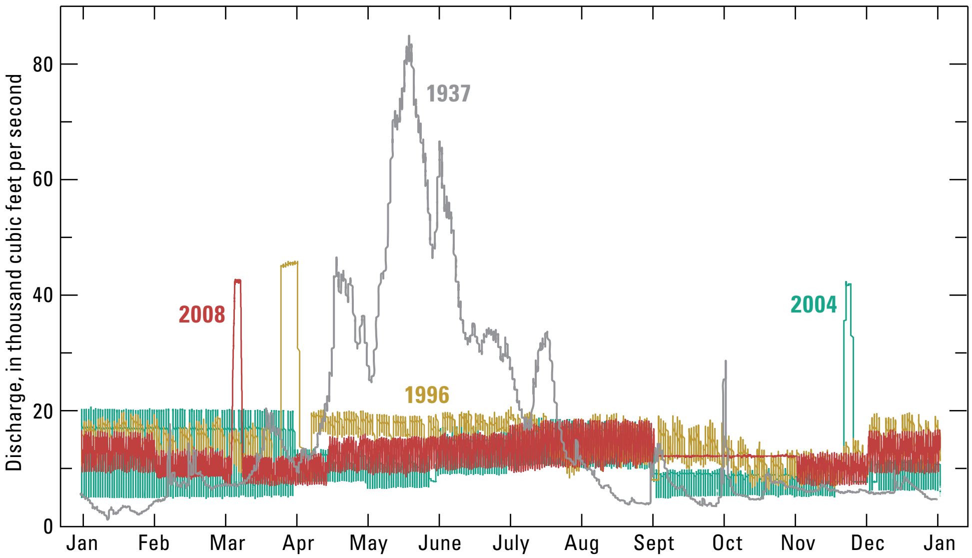


Figure 5. Discharge of the Colorado River at Lees Ferry (U.S. Geological Survey gaging station 9380000) for the calendar years during which the three high-flow experiments occurred—1996, 2004, and 2008—and 1937. The 1937 discharge record is shown because it represents a typical pre-dam year. The 1937 instantaneous peak discharge of 84,800 cubic feet per second was equal in magnitude to an average pre-dam flood likely to occur approximately every 2 years.

impacts were identified, the final environmental assessment identified predicted impacts of the test to resources on the basis of the scientific knowledge that existed at the time (table 1; U.S. Department of the Interior, 1996a). The first HFE was conducted between March 26 and April 7, 1996, just 1 year after completion of the EIS, and involved a 7-day steady release of 45,000 ft^3/s that was preceded and followed by low steady flows of 8,000 ft^3/s for 4 days each to photograph river shorelines (fig. 5; Schmidt and others, 1999). A coordinated team of scientists documented the effects of the 1996 HFE on physical, biological, cultural, and recreational resources; the findings were well publicized and documented, serving to substantially improve the scientific understanding of the effects of the experiment (Webb and others, 1999; Patten and Stevens, 2001).

On the basis of improved scientific knowledge resulting from the 1996 HFE, the timing and duration of the 2004 and 2008 experiments were modified from the 1996 experimental design; projections made for the 2004 and 2008 HFEs (table 1) also were revised to reflect improved understanding. The second HFE occurred between November 22 and 24, 2004, and involved a 60-hour release of about 41,700 ft^3/s. The third HFE occurred between March 6 and 8, 2008, and included a 60-hour release of about 42,800 ft^3/s. The 2004 and 2008 HFE water releases increased from base to peak flows over 30-hour periods, a 50-percent slower rate of rise than for the 1996 event. For comparison, peak flows for each of three HFEs conducted to date have been lower and of shorter duration than the peak flows typical of the pre-dam period or for the unregulated inflow to Lake Powell; the three HFEs also occurred earlier or later in the year than pre-dam seasonal flooding periods (fig. 5).

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 (high, steady flows within powerplant capacity) conducted in spring and summer.

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

2002 — The U.S. Department of the Interior approves an environmental assessment that outlines a new strategy for releasing high-flow experiments that created a triggering threshold linked to sand inputs and retention.

2003–5 — Experimental nonnative fish suppression flows were implemented at Glen Canyon Dam to reduce the abundance of rainbow trout because of concerns about negative effects of high trout abundance on endangered native fish.

2003–6 — Nonnative fish were experimentally removed from critical humpback chub habitat in the Colorado River to evaluate the feasibility of controlling nonnative fish and effects of control on the fish community.

2004 — Fall sediment inputs to Marble Canyon from the Paria River result in the initiation of the second high-flow experiment on Sunday, November 21.

2005 — Grand Canyon Monitoring and Research Center published "The State of the Colorado River Ecosystem in Grand Canyon," which evaluated how downstream resources responded to modified low fluctuating flows and showed that some of the benefits expected under Record of Decision operations have not occurred.

High-Flow Experiments and Adaptive Management

More than 15 years ago, the Secretary of the Interior issued the Record of Decision regarding the operation of Glen Canyon Dam that selected adaptive management as the means of managing the dam and other efforts to meet the GCPA mandate. In selecting adaptive management, the intent of the EIS was to create a process "whereby the effects of dam operations on downstream resources would be assessed and the results of those resource assessments would form the basis of future modifications of dam operations," because it was recognized that "many uncertainties still exist regarding the downstream impacts of water releases from Glen Canyon Dam" (U.S. Department of the Interior, 1995, p. 34). Monitoring and evaluation of the response of downstream resources to the HFEs led to the modification of elements of the experiments over time to incorporate improved scientific knowledge (Lovich and Melis, 2007).

Some of the findings documented in the following chapters were unanticipated. For example, it was concluded in the 1995 EIS that tributary inputs of sand would accumulate over multiple years on the channel bed of the Colorado River in Marble Canyon (fig. 2) and eastern Grand Canyon under the MLFF operating regime during minimum release years (8.23 MAF; U.S. Department of the Interior, 1995), making sand available for redistribution to sandbars by using HFEs. Monitoring following the 1996 HFE indicated, however, that tributary-supplied sand does not accumulate on the channel bed over multiyear periods under typical dam operations; rather, it is carried downstream (Topping and others, 2000; Rubin and others, 2002). Typically, there is insufficient sand on the channel bed in Marble and Grand Canyons to rebuild sandbars by using HFEs. Scientists and resource managers subsequently focused on the need to strategically time HFEs to take advantage of episodic tributary floods that supply new sand to the river downstream from the dam (Rubin and others, 2002). In November 2004, an HFE was timed to follow tributary floods for the first time (see chapter 3, this volume). In the fall of 2004, flooding in the Paria River (fig. 2) enriched the Colorado River with fine sediment in Marble Canyon in advance of the HFE. As a result, the 2004 HFE resulted in an increase in the total area and volume of sandbars in the upper half of Marble Canyon but produced results downstream similar to those seen in 1996. The March 2008 HFE occurred following above-average sand inputs from the Paria River in fall 2006 and fall 2007, but the new sand supplies were partially depleted and coarsened because they were exposed to normal dam operations in the months between inputs and the HFE. Because of these relatively rare multiyear sand inputs, the 2008 HFE was different from both the 1996 and 2004 HFEs (U.S. Department of the Interior, 2008) and resulted in widespread increases in the area and volume of sandbars similar to or greater than the two previous HFEs.

Biological research also produced unanticipated results and the opportunity for increased learning (see chapter 4, this volume). Research conducted in conjunction with the 2008 HFE provided valuable new information about how nonnative rainbow trout (*Oncorhynchus mykiss*) respond to the disruption to flow, habitat, and food sources caused by spring HFEs. For example, the March

2006
Paria River sand inputs exceed the annual average in October and reach levels in excess of those that triggered the 2004 experiment but do not result in a high-flow release. The Long-Term Experimental Plan Environmental Impact Statement was begun to address flow and nonflow actions in the Colorado River below Glen Canyon Dam.

2007
In November, sediment supplies in the Colorado River reach once-in-a-decade levels, initiating National Environmental Policy Act compliance activities in preparation for a third high-flow experiment. In response to basinwide drought conditions, interim shortage guidelines and coordination operations for Lakes Powell and Mead are approved in December.

2008
Third high-flow experiment occurred between March 6 and 8.

2009
USGS estimates that the number of Grand Canyon adult humpback chub increased to between 6,000 and 10,000 fish. The Bureau of Reclamation begins the process of developing an environmental assessment for a protocol for future high-flow experiments.

2010
The Bureau of Reclamation began the process to develop an environmental assessment for nonnative fish control in March.

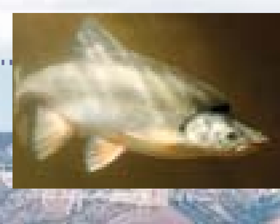


Table 1. Effects on resources downstream from Glen Canyon Dam predicted to result from three high-flow experiments (HFEs) conducted in 1996, 2004, and 2008 on the basis of the science available at the time of each experiment (U.S. Department of the Interior, 1996a, 2002, and 2008). Changes over time in predicted resource responses reflect improved understanding of the effects of high flows on affected resources.

Resource	1996	2004	2008
Water and hydropower	No effect on end-of-year water storage in Lakes Powell and Mead. Two-percent less energy generated during test flow. Little or no effect on wholesale or retail power rates. Total financial cost: $3.1 to $4.3 million; economic cost: $0.5 to $2.2 million.	Annual dam releases will be the same as no action. Bypass of about 93,000 acre-feet of water (about 1 percent of annual output), additional power purchase requirements during steady 8,000 cubic feet per second. Aerial photography flows included in cost of all sediment input scenarios.	2008 water year release unchanged. Predicted changes in levels of Lakes Powell and Mead are minor temporary effects. Projected cost of the high flow test is $4.1 million, or a 9.4-percent increase in purchase power requirement for 2008.
Sediment and sandbars	One to 3 feet sand deposition on most sandbars followed by erosion over time. Net erosion on some sandbars during test flow. Sand transport upstream above Little Colorado River estimated at 850,000 tons in 1996.	More likely to rebuild sandbars and beaches than in 1996, with more diverse grain size; downstream sediment export would be less than in 1996.	Significant positive sandbar building will occur, with likely increase in number and size of sandbars immediately after the event; uncertainty about where and how long the effects will persist. Potential beneficial change in backwaters.
Fish and aquatic food base	Temporary reduction in *Cladophora* biomass with increased drift downstream. Backwaters re-formed. Nonnative populations temporarily disrupted by high flows; interactions between native and nonnative fish rapidly return to no-action conditions. Some trout (*Oncorhynchus mykiss*) eggs, fry, and young lost downstream; mitigation through stocking. Adult trout may be affected for a period following test flow.	Reduction in benthos species; increased drift; primary producers expected to rapidly recover; improved production following removal of detritus. May disrupt ongoing spawning but improve spawning habitat; may displace small-bodied fish. Anticipated positive effect on nearshore rearing habitats used by humpback chub (*Gila cypha*) through rejuvenation; short-term negative effect on food base; limited displacement of juvenile fish, very little displacement of subadults and adults.	No significant adverse effects on movement, habitat use, or diet of humpback chub. No significant impact to standing biomass of benthic invertebrates over long term. For Lees Ferry, temporary reduction in abundance of Lees Ferry rainbow trout smaller size classes, with some downstream displacement of age-1 fish, but no lasting impacts to abundance or condition. Creation and improvement of backwater rearing habitats for native fish.
Vegetation, habitat, and special status species	Some woody and emergent marsh vegetation lost through scouring or burial; vegetation recovery to no-action levels in months/years following test flow. Some wildlife habitat lost; recovery to no-action levels following test flow. No long-term effects on aquatic food base; few wintering waterfowl present during test flow. Habitat improvement for southwestern willow flycatcher (*Empidonax traillii*) and humpback chub. Some Kanab ambersnail (*Oxyloma haydeni* ssp. *kanabensis*) and northern leopard frog (*Rana pipiens*) habitat inundated by test flow; leopard frog population may be lost.	Twenty-percent reduction in cover in riparian zone; drowning of xeric-adapted species and burying low-lying grasses and herbs; scouring weakly rooted plants; increased distribution of seeds; seed scour may initiate germination of native riparian plants; potential ice damage of marshes and wetlands in Glen and Marble Canyons; minimum effects on lake riparian vegetation. Loss of up to 17 percent of primary Kanab ambersnail habitat if not already removed by previous high release.	Minor effects; short term burial of seeds and plants on existing sandbars, some scouring of riparian vegetation, and a short-term increase in groundwater and soil nutrient concentrations. Newly exposed sediment may be subject to exotic species colonization. Moving Kanab ambersnails and their habitat for mitigation could result in adverse effect. Effects on northern leopard frogs uncertain.
Cultural resources	High terrace erosion rates may be reduced in short term. Temporary restoration of natural processes generally beneficial.	No historic properties affected; adverse effect on Tribal cultural resources (marshes, herpetofauna).	No adverse effects expected; one historic property in Glen Canyon National Recreation Area could be adversely affected.
Recreation	River-based recreation activities affected to some degree during test flow. Number and size of camping beaches increased.	The high-flow period will have negligible effect on recreation because of short duration. National Park Service to forewarn boaters and campers; no effect on float trips.	Short-term disruption of Lees Ferry angling (3 days to a week). Loss of about 190 boating user days; improved boater experience for groups on water during high flows. Potential to improve camping beaches.

2008 HFE and the dam operations that followed resulted in more than a 400-percent increase in the survival and growth rates of rainbow trout hatched in the month following the experiment and more than a 200-percent increase in expected trout abundance by 2009 (Korman and others, 2010; Korman and Melis, 2011; Korman and others, in press). Additionally, annual fish monitoring detected an 800-percent increase in rainbow trout catch rates between 2007 and 2009 downstream from Lees Ferry at the confluence of the Colorado and Little Colorado Rivers (Makinster and others, 2010) where most of the Grand Canyon population of endangered humpback chub are found. The influx of nonnative trout, which prey on (Yard and others, in press) and are thought to compete with native fishes for habitat and limited food resources, could reverse recent improvements in adult humpback chub numbers and recruitment rates of juvenile fish into the adult population (Coggins and Walters, 2009).

Although it has been 15 years since the first HFE, uncertainties still remain about downstream impacts of water releases from Glen Canyon Dam. Continued scientific research and long-term monitoring will help address some of the most pressing questions. For example, ongoing monitoring will allow scientists to determine if increased numbers of trout near the confluence of the Colorado and Little Colorado Rivers result in a corresponding decline of adult humpback chub. But some of the answers also raise critical questions: Can dam operations achieve resource goals over the long term? What are the resource tradeoffs of different operations? In the context of the adaptive management program, scientific research can be used to reduce, but not eliminate, the uncertainties inherent in management decisions. The design of future HFEs (see chapter 5, this volume) will require flexibility to respond to some of the unanticipated outcomes that have already been identified since the EIS was completed and others that are likely to emerge as the result of improved scientific knowledge.

Report Organization

The chapters that follow provide a summary and synthesis of the extensive number of studies conducted since 1996 on the effects of HFEs on the physical, biological, recreational, and cultural resources found in the Colorado River corridor downstream from Glen Canyon Dam. Chapter 2 provides an overview of what was known about how floods affect physical processes and resources in the Colorado River ecosystem downstream from the dam before the first HFE in 1996. Chapter 3 examines the experimental use of three high flows greater than powerplant capacity from Glen Canyon Dam in 1996, 2004, and 2008 to rehabilitate the physical setting of the Colorado River in Grand Canyon, tracing the evolution in understanding that has occurred over time about the duration, timing, and frequency of HFEs. This chapter also examines how HFEs affect sandbar size, wind transport of river sand from new sandbars toward archaeological sites, camping beaches, and backwater channel habitats. Chapter 4 considers how HFEs influence the biological components of the system, including the aquatic food web, the native and nonnative fish communities, riverside vegetation, and the endangered Kanab ambersnail (*Oxyloma haydeni* ssp. *kanabensis*). On the basis of the findings presented in the preceding chapters, the concluding chapter outlines what scientists have identified as some of the key resource-management implications associated with HFEs, suggests a strategy for initiating future HFEs, and considers experimentation needed to address outstanding research questions previously identified by river managers.

Units and Place Names

U.S. customary units are used for all measurements provided in this report to facilitate understanding by the general reader. Metric conversions are provided in a table at the front of the report. River mile (RM) is used to describe distances along the Colorado River in the study area. The use of the river mile has historical precedent and provides a reproducible method for describing location. Lees Ferry is considered the reference point, RM 0, with mileage measured for both upstream and downstream locations. Locations upstream from Lees Ferry in the Glen Canyon National Recreation Area (referred to as the Lees Ferry reach) are assigned negative river mile designations;

thus, Glen Canyon Dam is located at RM –16. For purposes of this report, the entire canyon system between Lees Ferry and the Grand Wash Cliffs (RM 277) is referred to as Grand Canyon National Park or simply Grand Canyon. Shorter segments of this canyon system are referred to as Marble Canyon (RM 0 to RM 61), which ends at the confluence of the Colorado and Little Colorado Rivers; eastern Grand Canyon (RM 61 to RM 88); central Grand Canyon (RM 88 to RM 166); and western Grand Canyon (RM 166 to RM 277). For some purposes, Marble Canyon is further divided into upper Marble Canyon (RM 0 to RM 30) and lower Marble Canyon (RM 30 to RM 61).

References

Babbitt, Bruce, 1990, Introduction—Down the imperiled Colorado: Land and Water Law Review, v. 25, no.1, p. 1–9.

Burkham, D.E., 1986, Trends in selected hydraulic variables for the Colorado River at Lees Ferry and near Grand Canyon, Arizona—1922–1984: Flagstaff, Arizona, Bureau of Reclamation, Glen Canyon Environmental Studies, 58 p. (Available from National Technical Information Service, PB88-216098/AS.)

Coggins, L.G., Jr., and Walters, C.J., 2009, Abundance trends and status of the Little Colorado River population of humpback chub—An update considering data from 1989–2008: U.S. Geological Survey Open-File Report 2009–1075, 18 p. (Also available at *http://pubs.usgs.gov/of/2009/1075/*.)

Cooley, M.E., Aldridge, B.N., and Euler, R.C., 1977, Effects of the catastrophic flood of December 1966, North Rim area, eastern Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 980, 43 p.

Dolan, Robert, Howard, Alan, and Gallenson, Arthur, 1974, Man's impact on the Colorado River in the Grand Canyon: American Scientist, v. 62, no. 4, p. 392–401.

Dongoske, K.E., Jackson-Kelly, Loretta, and Bulletts, Charley, 2010, Confluence of values—The role of science and Native Americans in the Glen Canyon Dam Adaptive Management Program, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., 2010, Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 133–140.

Fairley, H.C., 2003, Changing river—Time, culture and the transformation of landscape in the Grand Canyon—A regional research design for the study of cultural resources along the Colorado River in lower Glen Canyon and Grand Canyon National Park, Arizona: Tucson, Arizona, Statistical Research, Inc., Technical Series 79, 179 p.

Fairley, H.C., 2005, Cultural resources in the Colorado River corridor, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 11, p. 177–192.

Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., 2005, The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, 220 p. (Also available at *http://pubs.usgs.gov/circ/1282/*.)

Harpman, D.A., and Douglas, A.J., 2005, Status and trends of hydropower production at Glen Canyon Dam, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 10, p. 165–176.

Howard, Alan, and Dolan, Robert, 1981, Geomorphology of the Colorado River in the Grand Canyon: The Journal of Geology, v. 89, no. 3, p. 269–298, doi: 10.1086/628592, accessed February 18, 2010, at *http://www.jstor.org/pss/30078299*.

Korman, Josh, Kaplinski, Matthew, and Melis, T.S., 2010, Effects of high-flow experiments from Glen Canyon Dam on abundance, growth, and survival rates of early life stages of rainbow trout in the Lees Ferry reach of the Colorado River: U.S. Geological Survey Open-File Report 2010–1034, 31 p. (Also available at *http://pubs.usgs.gov/of/2010/1034/*.)

Korman, Josh, Kaplinski, Matthew, and Melis, T.S., in press, Effects of fluctuation flows and a controlled flood on incubation success and early survival rates and growth of age-0 rainbow trout in a large regulated river: Transactions of the American Fisheries Society.

Korman, Josh, and Melis, T.S., 2011, The effects of Glen Canyon Dam operations on early life stages of rainbow trout in the Colorado River: U.S. Geological Survey Fact Sheet 2011–3002, 4 p. (Also available at *http://pubs.usgs.gov/fs/2011/3002/*.)

Lovich, Jeff, and Melis, T.S., 2007, The state of the Colorado River ecosystem in Grand Canyon—Lessons from 10 years of adaptive ecosystem management: International Journal of River Basin Management, v. 5, no. 3, p. 207–221, accessed August 10, 2010, at *http://sbsc.wr.usgs.gov/products/pdfs/P0151_10sep.pdf*.

Makinster, A.S., Persons, W.R., Avery, L.A., and Bunch, A.J., 2010, Colorado River fish monitoring in Grand Canyon, Arizona—2000 to 2009 summary: U.S. Geological Survey Open-File Report 2010–1246, 26 p. (Also available at *http://pubs.usgs.gov/of/2010/1246/*.)

Meade, R.H., Yuzyk, T.R., and Day, T.J., 1990, Movement and storage of sediment in rivers of the United States and Canada, *in* Wolman, M.G., and Riggs, H.C., eds., Surface water hydrology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-1, p. 255–280.

Minckley, W.L., 1991, Native fishes of the Grand Canyon region—An obituary?, *in* Colorado River ecology and dam management, Proceedings of a symposium, May 24–25, 1990, Santa Fe, New Mexico: Washington, D.C., National Academies Press, p. 124–177.

National Park Service, 2009 Grand Canyon park profile 2009: U.S. Department of the Interior, Grand Canyon National Park, 6 p., accessed October 27, 2010, at *http://www.nps.gov/grca/parkmgmt/upload/ParkProfile2009.pdf*.

National Research Council, 1987, River and dam management—A review of the Bureau of Reclamation's Glen Canyon Environmental Studies: Washington, D.C., National Academies Press, 203 p.

Patten, D.T., and Stevens, L.E., [guest eds.], 2001, Restoration of the Colorado River ecosystem using planned flooding: Ecological Applications, v. 11, no. 3, p. 633–634.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C., 1997, The natural flow regime—A paradigm for river conservation and restoration: Bioscience v. 47, no. 11, p. 769–784.

Rubin, D.M., Topping, D.J., Schmidt, J.C., Hazel, J., Kaplinski, M., and Melis, T.S., 2002, Recent sediment studies refute Glen Canyon Dam hypothesis: Eos, Transactions, American Geophysical Union, v. 83, no. 25, p. 273, 277–278.

Schmidt, J.C., Andrews, E.D., Wegner, D.L., Patten, D.T., Marzolf, G.R., and Moody, T.O., 1999, Origins of the 1996 controlled flood in Grand Canyon, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 23–36.

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport, 1. Natural sediment supply limitation and the influence of the Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515–542, doi: 10.1029/1999WR900285.

Topping, D.J., Schmidt, J.C., and Vierra, L.E., Jr., 2003, Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000: U.S. Geological Survey Professional Paper 1677, 118 p. (Also available at *http://pubs.usgs.gov/pp/pp1677/*.)

Turner, R.M., and Karpiscak, M.M., 1980, Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona: U.S. Geological Survey Professional Paper 1132, 125 p.

U.S. Department of the Interior, 1946, The Colorado River—A natural menace becomes a national resource: Washington, D.C., Bureau of Reclamation, 295 p.

U.S. Department of the Interior, 1988, Glen Canyon Environmental Studies Executive Review Committee, Final report: Bureau of Reclamation, Glen Canyon Environmental Studies, 84 p. + apps. (Available from National Technical Information Serivce, PB88-183348/AS.)

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam—Final Environmental Impact Statement, Colorado River Storage Project, Coconino County, Arizona: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Regional Office, 337 p., accessed November 18, 2010, at *http://www.usbr.gov/uc/library/envdocs/eis/gc/pdfs/Cov-con/cov-con.pdf*.

U.S. Department of the Interior, 1996a, Glen Canyon Dam, Beach/habitat-building test flow, Final environmental assessment and finding of no significant impact: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, 68 p. + attachments.

U.S. Department of the Interior, 1996b, Record of Decision, Operation of Glen Canyon Dam—Final Environmental Impact Statement: Washington, D.C., Office of the Secretary of the Interior, Bureau of Reclamation, 15 p., accessed May 26, 2010, at *http://www.usbr.gov/uc/rm/amp/pdfs/sp_appndxG_ROD.pdf*.

U.S. Department of the Interior, 2002, Proposed experimental releases from Glen Canyon Dam and removal of non-native fish—Environmental assessment: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Regional Office, 112 p.

U.S. Department of the Interior, 2007, Record of Decision, Colorado River interim guidelines for lower basin shortages and the coordinated operations for Lake Powell and Lake Mead, Final Environmental Impact Statement: Washington, D.C., Office of the Secretary of the Interior, 59 p. accessed November 23, 2010, at *http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf*.

U.S. Department of the Interior, 2008, Final environmental assessment—Experimental releases from Glen Canyon Dam, Arizona, 2008 through 2012: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, 59 p. + apps., accessed January 13, 2010, at *http://www.usbr.gov/uc/envdocs/ea/gc/2008hfe/index.html*.

Ward, J.V., and Stanford, J.A., 1995, The serial discontinuity concept—Extending the model to floodplain rivers: Regulated Rivers, Research & Management, v. 10, p. 159–168.

Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., 1999, The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, 367 p.

White, M.A., Schmidt, J.C., and Topping, D.J., 2005, Application of wavelet analysis for monitoring the hydrologic effects of dam operation—Glen Canyon Dam and the Colorado River at Lees Ferry, Arizona: River Research and Applications, v. 21, p. 551–565.

Yard, M.D., Coggins, L.G., Baxter, C.V., Bennett, G.E., and Korman, Josh, in press, Trout piscivory in the Colorado River, Grand Canyon—Effects of turbidity, temperature, and fish prey availability: Transactions of the American Fisheries Society.

Mark Lellouch, National Park Service

CHAPTER 2

Understanding Physical Processes of the Colorado River

By John C. Schmidt[1] and Paul E. Grams[2]

The spring 1996 high-flow experiment (HFE) initiated a new era of scientifically based adaptive management of the Colorado River in the 16 miles of Glen Canyon between the dam and Lees Ferry and the 277 miles of the Colorado River ecosystem within Marble and Grand Canyons (fig. 1). Since the 1996 HFE, releases from Glen Canyon Dam have been used to advance natural-resource goals, such as maintaining populations of endangered fish and rebuilding sandbars, while meeting requirements to transfer water from the upper Colorado River Basin to the lower basin, and to generate hydroelectricity.

The management objectives and the associated scientific hypotheses of the 1996 HFE, as well as the subsequent HFEs in 2004 and 2008, were founded in decades of scientific study of the changing physical and ecological attributes of the Colorado River ecosystem (Carothers and Brown, 1991; Webb, 1996; Webb, Wegner, and others, 1999). The purpose of this chapter is to describe that foundation by summarizing some of the long-standing scientific lines of inquiry related to physical processes. These scientific themes have guided Colorado River scientists for more than 50 years. In the next chapter, the insights gained from the three HFEs are presented within the context that is set in this chapter. Together, the two chapters describe the ongoing Colorado River research program as a continuum that began with observations and measurements made a century ago and now includes new analytical approaches and measurement techniques. In many cases, the questions asked today are the same questions considered by the pioneers of Colorado River science.

Historical Overview

Modern development of the Colorado River began in the late 19th century when diversions were constructed to support agriculture in the Grand Valley in Colorado, the Colorado River valley near Blythe, California, and Yuma, Arizona, and in tributary valleys elsewhere in the basin (Mueller and Marsh, 2002). Construction of the Alamo Canal, which connects the Colorado River to the Alamo River, began in 1900 and allowed part of the lower Colorado River to flow into California's Salton Trough to create an "Imperial Valley" (deBuys and Myers, 1999). Laguna Dam near Yuma was the first dam built on the main stem of the Colorado River and was the first

[1] Intermountain Center for River Rehabilitation and Restoration, Department of Watershed Sciences, Utah State University, Logan, UT 84322–5210.

[2] U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, 2255 N. Gemini Drive, Flagstaff, AZ 86001.

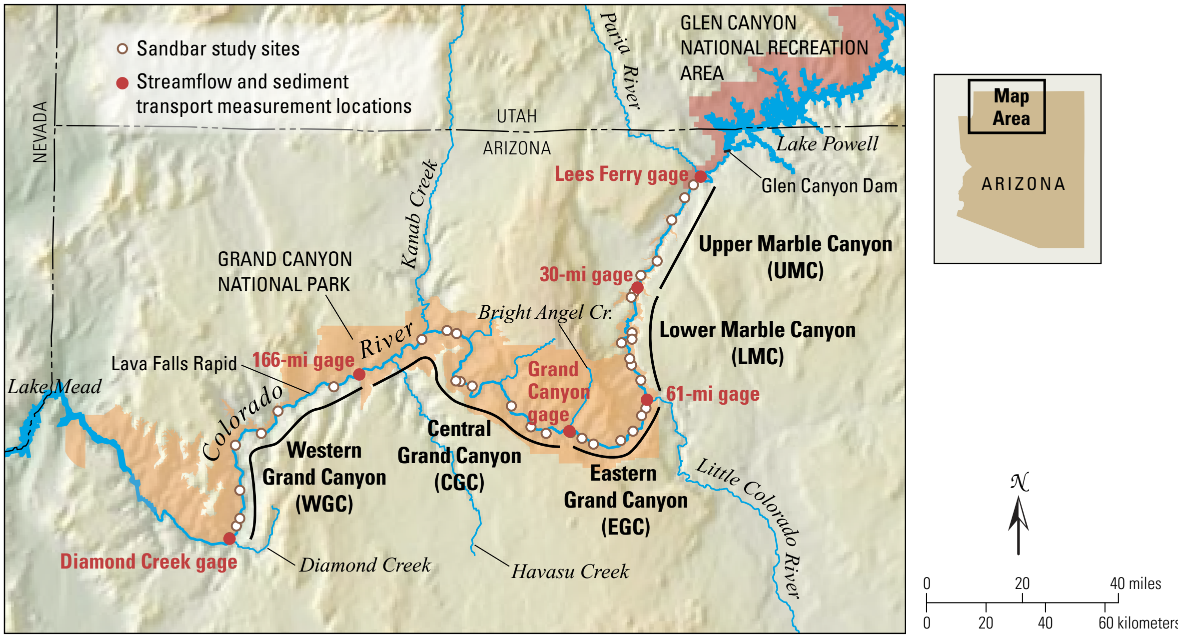


Figure 1. The Grand Canyon region, showing locations of gaging stations and data-collection sites for sandbar topography and channel bathymetry. The Lees Ferry gage (U.S. Geological Survey station 093820000) continuously measures stage and streamflow; supplemental sediment transport measurements have been made during some post-dam floods and all high-flow experiments (HFEs). The 30-mile, 61-mile, Grand Canyon (U.S. Geological Survey station 09402500), 166-mile, and Diamond Creek (U.S. Geological Survey station 09404200) gages continuously measure stage, streamflow, and suspended-sand concentration. During the 1996 HFE, data were collected at the Lees Ferry, 61-mile, Grand Canyon, and 166-mile gages. During the 2004 HFE, data were collected at the Lees Ferry, 30-mile, 61-mile, Grand Canyon, and Diamond Creek gages. Data were collected at all six gages during the 2008 HFE. See Topping and others (2010) for detailed information on the data collected at each gage. The reaches for sand mass-balance calculations between the gages are also identified. Modified from Hazel and others (2010).

permanent dam built by the Bureau of Reclamation (then called the Reclamation Service). The dam was completed in 1909 (Mueller and Marsh, 2002).

Early scientific studies of the Colorado River were used to assess the potential for agricultural development and hydropower production (for example, Davis, 1897; Lippincott, 1900). The first scientific observations of the Colorado River in Grand Canyon were made by John Wesley Powell during his 1869 exploration (Powell, 1875, 1895). Although it may not have been realized at the time, the photographs taken during the second Powell expedition in 1871, as well as photographs taken by early expeditions of the U.S. Geological Survey (Birdseye, 1924), became the basis for subsequent monitoring of geomorphic and ecological change in Grand Canyon when Turner and Karpiscak (1980) and Stephens and Shoemaker (1987) replicated many of the original images from those expeditions (fig. 2). A similar approach to describing long-term change in the Colorado River ecosystem was taken by Webb (1996), who replicated the 1889–90 photographs of Robert Brewster Stanton (Smith and Crampton, 1987).

Streamflow and sediment transport have been measured throughout the Colorado River Basin for more than a century. These data were needed to plan irrigation districts, to strategically locate reservoirs, and to anticipate reservoir sedimentation rates. The first gaging station in the watershed was established on the Gila River at Buttes, Arizona, in 1889. More than 200 gaging stations had already been established, and some had already been abandoned, in the Colorado River Basin when Eugene C. LaRue (1916) summarized the potential for developing the river system. Water-surface elevation measurements were first made at Lees Ferry in May 1921 (Topping and others, 2003).

The first measurements of suspended-sediment concentrations were made in 1892 at Yuma by C.B. Collingwood of the University of Arizona (LaRue, 1916). The U.S. Reclamation Service made the first suspended-sediment transport measurements near Yuma in 1903.

Data concerning the physical structure of the Colorado River channel network were also required to evaluate potential dam sites. The downstream profile of the water surface of the Colorado River in Grand Canyon was the last part of the channel network surveyed (Birdseye, 1924). These data were remarkably accurate and subsequently were used to describe the geomorphology[3] of the channel (Leopold, 1969), as a reference datum in hydraulic models (Randle and Pemberton, 1987), and in an evaluation of long-term changes of rapids (Magirl and others, 2005). McKee (1938) described sedimentary structures typical of Colorado River sandbars in Grand Canyon.

Attributes of the fish community also were described in the late 1800s and first half of the 20th century (Evermann and Rutter, 1895; Miller and others, 1991). These early studies provided the first evidence that many aspects of the life history of native fish species were adapted to the large floods and winter low flows characteristic of the Colorado River, as well as the river's large suspended-sediment load, wide-ranging temperatures, and segmented downstream profile of steep canyons and wide, low-gradient valleys (chapter 4, this volume). The first systematic observations of riparian vegetation in Grand Canyon were made during a river expedition in 1938 (Clover and Jotter, 1944).

As dams and diversions were completed in the Colorado River watershed, scientists and engineers observed changes in channel geomorphology as well as associated changes in the distribution and abundance of native fish species and native vegetation. Using channel survey data, Stanley (1951) and Borland and Miller (1960) demonstrated that erosion of fine sediment occurred immediately downstream from Hoover and Parker Dams on the lower Colorado River, similar to what Cory (1913) observed downstream from Laguna Dam. The sediment eroded from the channel near each dam and accumulated farther downstream (Stevens, 1938). At Hoover Dam, the zone of fine-sediment evacuation extended about 90 miles (Schmidt and Wilcock, 2008, fig. 5).

Completion of Glen Canyon Dam in 1963 initiated similar physical and ecological changes to the Colorado River in Grand Canyon. Scientific studies conducted in the 1970s indicated that alteration of the flow and temperature regimes, complete trapping of the upstream sediment supply, and introduction of nonnative aquatic and riparian species had transformed the pre-dam Colorado River ecosystem (Dolan and others, 1974). The riparian vegetation zone expanded,

[3] Geomorphology is the study of the earth's natural landscapes and how they form. The geomorphology of a river involves descriptions of physical attributes, including channel shape (width and depth), bed material size and distribution, downstream gradient, and meander pattern, as well as the study of physical processes.

Figure 2. Downstream view from the left side of the Colorado River showing changes in channel conditions, including the dramatic increase in riparian vegetation along the Colorado River in Grand Canyon near river mile 217.7. *A*, Photograph taken September 30, 1923, by E.C. LaRue, U.S. Geological Survey. *B*, First matched photograph taken July 4, 1972, by R.M. Turner. *C*, Second matched photograph taken October 24, 1991, by David Edwards. Photographs courtesy of the U.S. Geological Survey, Desert Laboratory Repeat Photography Collection.

nonnative species assumed a dominant role in both the riparian and aquatic communities, populations of several native fish species were lost in Grand Canyon, and humpback chub (*Gila cypha*) were reduced to a small population in an area near the confluence with the Little Colorado River and in the tributary itself (Turner and Karpiscak, 1980; Carothers and Brown, 1991; Webb, 1996). These studies also indicated that the size of bare sandbars was smaller in the post-dam period.

Effects of Dams on Downstream River Channels

Dams cause both erosion and deposition in downstream river channels (Williams and Wolman, 1984). The tendency for a channel downstream from a dam to evacuate or accumulate sediment depends on the river's capacity to transport sediment in relation to the amount of sediment available to be transported (Lane, 1955; Williams and Wolman, 1984; Andrews, 1986; Brandt, 2000a, b; Grant and others, 2003; Schmidt and Wilcock, 2008). Because the greatest amount of sediment transport occurs during floods and because sediment supplied to post-dam channels typically comes only from tributaries that enter the river downstream from the dam, changes in flood characteristics caused by dams and the sediment-supply characteristics of downstream tributaries play an important role in determining channel adjustment.

The relative amount of sediment supply to a given reach and transport out of that reach is commonly referred to as the sediment mass balance. The mass balance of a channel is in deficit downstream from those dams that trap a large proportion of the pre-dam sediment supply; in these cases, sediment is evacuated from the channel (Schmidt and Wilcock, 2008). In contrast, the sediment mass balance is in surplus downstream from a dam where the magnitude of floods is greatly reduced, but sediment continues to enter the channel from tributaries; in these cases, channels tend to accumulate sediment.

At the time Glen Canyon Dam was being constructed, river engineers anticipated that the disruption of the natural flow regime and sediment supply would perturb the mass balance of the channel into deficit immediately downstream from the dam. In 1956, the Bureau of Reclamation began a program of resurveying channel cross sections and measuring bed-material size between the dam and Lees Ferry in order to measure the anticipated evacuation of sediment from this river segment (Pemberton, 1976; Grams and others, 2007). Scientists and engineers did not know, however, if the zone of sediment evacuation would extend farther downstream into Marble or Grand Canyons. As explained below, it took decades of measurement and analysis, including critical observations made during the HFEs, for scientists and engineers to understand that a large part of Grand Canyon was in deficit with respect to fine sediment and that a large amount of fine sediment had been evacuated from much of the river corridor. It also took decades of study to understand the relative roles of changes in flow regime, including reduction in floods and changes in sediment supply, in creating the sediment-deficit conditions.

The Streamflow Regime and How It Has Changed

The magnitude, frequency, duration, timing, and rate of change of hourly, daily, decadal, and century-scale discharge constitute a river's flow regime, and floods are typically an essential attribute of that regime. Native aquatic and riparian ecosystems have developed in response to these attributes (Poff and others, 1997). In some river systems, the flow regime is relatively constant throughout the year, and the amount of sediment transported by the river is small. The native aquatic and riparian ecosystem of Grand Canyon, however, developed in and along a river whose discharge changed greatly throughout the year. The Colorado River typically had a predicable spring snowmelt flood, unpredictable smaller late summer and fall floods, low winter flows, and periods when the transported load of sediment was very large.

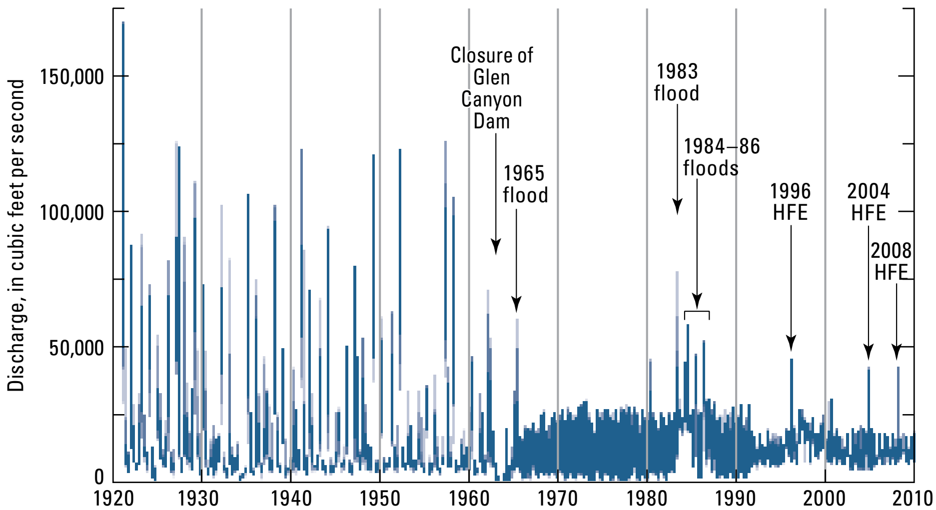


Figure 3. Continuous-discharge record for the Colorado River at Lees Ferry (river mile 0) for 1921 through 2009. With the exception of the first 2 years, the observations used to construct this record are at intervals of 30 minutes or less. Closure of Glen Canyon Dam and post-dam floods and high-flow experiments (HFEs) are indicated. Modified from Topping and others (2003).

The Pre-Dam Colorado River

Before completion of Glen Canyon Dam in March 1963, peak flows of 50,000 cubic feet per second (ft^3/s), which is slightly larger than the magnitude of the post-dam HFEs, occurred approximately every year (fig. 3). In the drought decades of the 1930s and 1950s, however, five annual peak floods were less than the magnitude of the HFEs.[4] Topping and others (2003) estimated that peak flows of 31,500 ft^3/s had a recurrence of approximately 8 months, that the 2-year recurrence peak flow (meaning a flow of that magnitude was equaled or exceeded every 2 years, on average) had a magnitude of about 85,000 ft^3/s, and that a flood of about 120,000 ft^3/s occurred, on average, every 6 years. The largest observed and reported flood in Grand Canyon occurred in June 1884 and was approximately 210,000 ft^3/s (Topping and others, 2003). The second-largest observed flood occurred in June 1921 and was approximately 170,000 ft^3/s. The large magnitude of the pre-dam floods stands in contrast to the low flows that occurred much of the rest of the year. The median flow of the Colorado River for the entire pre-dam period was 7,980 ft^3/s, which means that half of the time flows were smaller than this magnitude, and half of the time flows were larger than this magnitude.

The Post-Dam Colorado River

Flow regulation provided by Glen Canyon Dam "effectively replaced relatively high and low flows with a greater frequency of moderate flows" (Topping and others, 1999, p. 72), because moderate flows are routed through the Glen Canyon Dam powerplant to produce hydroelectricity as water is transferred to the lower basin States. The role of flow regulation provided by Glen Canyon Dam is illustrated in figure 4, which shows the contrast between inflows to Lake Powell and dam releases in the 3 years when HFEs occurred. In 1996 and 2008, HFEs were conducted before the natural spring snowmelt flood. In these years, the magnitude of the HFE releases was less than the magnitude of the natural flood, and the duration of the HFE was much less. In these years, the part of the natural flood not immediately released downstream was used to increase water storage in Lake Powell. In 2004, the HFE release was much larger in magnitude than the natural snowmelt flood for that year. During a typical year, the daily range of flows is large, because usual dam operations consist of daytime releases of water to generate hydroelectricity and smaller nighttime releases. As a result, releases from Glen Canyon Dam typically exceed the magnitude of natural low flows.

[4] These floods occurred in 1931 (34,600 ft^3/s), 1934 (25,300 ft^3/s), 1954 (34,300 ft^3/s), 1955 (35,600 ft^3/s), and 1959 (38,900 ft^3/s).

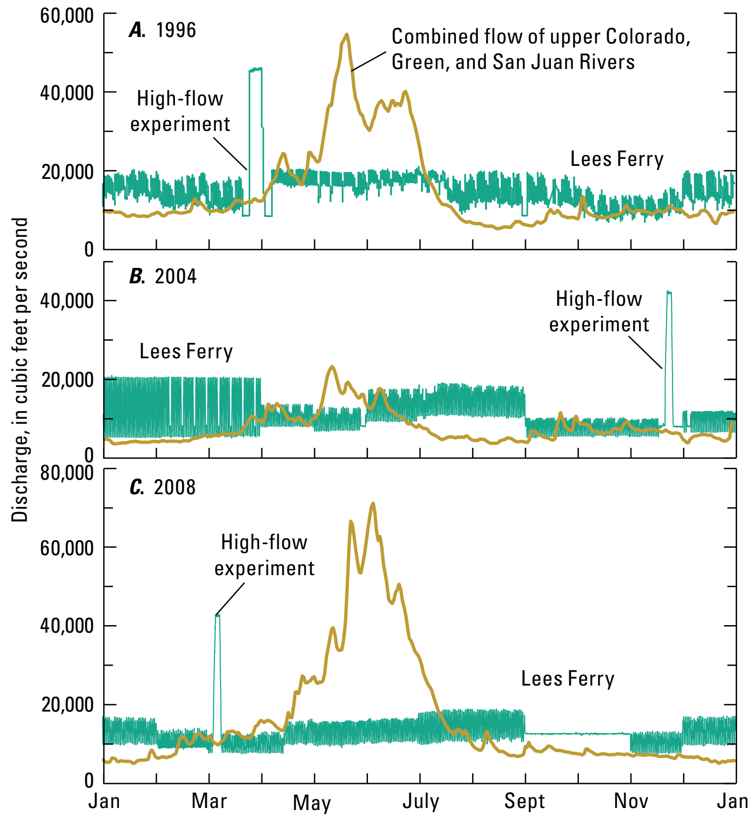


Figure 4. Discharge of the Colorado River at Lees Ferry and the estimated inflow to Lake Powell for the years when the three high-flow experiments occurred. *A*, 1996. *B*, 2004. *C*, 2008. Inflow to Lake Powell was estimated as the sum of measured discharge each day at the Green River at Green River, Utah (U.S. Geological Survey station 09315000), the Colorado River near Cisco, Utah (U.S. Geological Survey station 9180500), and the San Juan River near Bluff, Utah (U.S. Geological Survey station 9379500).

The frequency of large floods has greatly decreased since completion of the dam, and the magnitude of typical low flows has increased. The 2-year recurrence peak flow of the post-dam period was 31,500 ft^3/s, a 62 percent reduction from the magnitude of the 2-year recurrence peak flow of the pre-dam measurement period (Topping and others, 2003). The median flow of the post-dam period was 12,000 ft^3/s, 58 percent larger than that of the pre-dam period.

Post-dam peak flows are not only small relative to the pre-dam peak flows, but they are also small relative to the magnitude of flows that occur during the remainder of the year. For example, the pre-dam 2-year recurrence peak flow was approximately 77,000 ft^3/s larger than the pre-dam median flow, but the post-dam 2-year recurrence peak flow was only 19,500 ft^3/s greater than the post-dam median flow. Thus, pre-dam peak flows were about 970 percent larger than typical base flows, but post-dam peak flows were only about 150 percent larger than typical base flows.

Glen Canyon Dam has not been operated uniformly since 1963. Changes in operation reflect changing objectives of reservoir and river management, as well as wet and dry cycles of watershed precipitation. High flows that have exceeded the capacity of the powerplant have occurred for several reasons. Some of these high flows are considered "floods," as defined by the Glen Canyon [Dam] Environmental Studies (GCES) program (U.S. Department of the Interior, 1988, p. A-21). This program defined post-dam floods as dam "releases exceeding powerplant capacity for a month or more," and these occurred in 1965, 1983, 1984, 1985, and 1986 (table 1).

The 1965 flood (fig. 3) occurred between April and June, when a large volume of water needed to be released downstream in order to equalize the storage contents of Lakes Powell and Mead. For reasons that were not documented at the time (see text box, Channel Change in the Glen Canyon Reach), the high flows were released as a series of short-duration pulses; six of these pulses exceeded 50,000 ft^3/s, and between each pulse, flows were greatly reduced. Releasing this water as a series of pulses maximized fine-sediment evacuation from the channel bed in Glen Canyon, resulting in a dramatic transformation of this segment of the river (Grams and others, 2007).

Floods also occurred each year from 1983 to 1986 (fig. 5); watershed runoff was unusually large in these years. Lake Powell and other reservoirs in the upper Colorado River Basin filled to

Table 1. Summary of post-dam floods and short-duration high flows.

[ft³/s, cubic feet per second]

Year	Number of consecutive days mean daily discharge exceeded 31,500 ft³/s[a]	Dates	Instantaneous peak, in ft³/s	Purpose
		Post-dam floods		
1965	34	May 21–June 25	60,200	Reservoir equalization and channel cleaning
1983	68	June 3–August 10	97,300	Excess runoff
1984	76	May 5–July 20	45,300	Excess runoff
1985	39	May 17–June 28	47,900	Excess runoff
1986	46	May 8–June 24	53,200	Excess runoff
		Post-dam short-duration high flows		
1965	1	April 11	34,200	Reservoir equalization and channel cleaning
1965	8	April 23–30	52,700	Reservoir equalization and channel cleaning
1965	7	May 4–11	52,900	Reservoir equalization and channel cleaning
1965	1	May 16	51,800	Reservoir equalization and channel cleaning
1980	6	June 24–July 1	45,400	Facilities test
1984	3	August 12–15	58,200	Spillway test
1996	8	March 26–April 2	45,900	High-flow experiment
2004	3	November 22–24	42,500	High-flow experiment
2008	3	March 6–8	42,800	High-flow experiment

[a] Consecutive is defined as occurring within 5 days when flows of similar magnitude occurred.

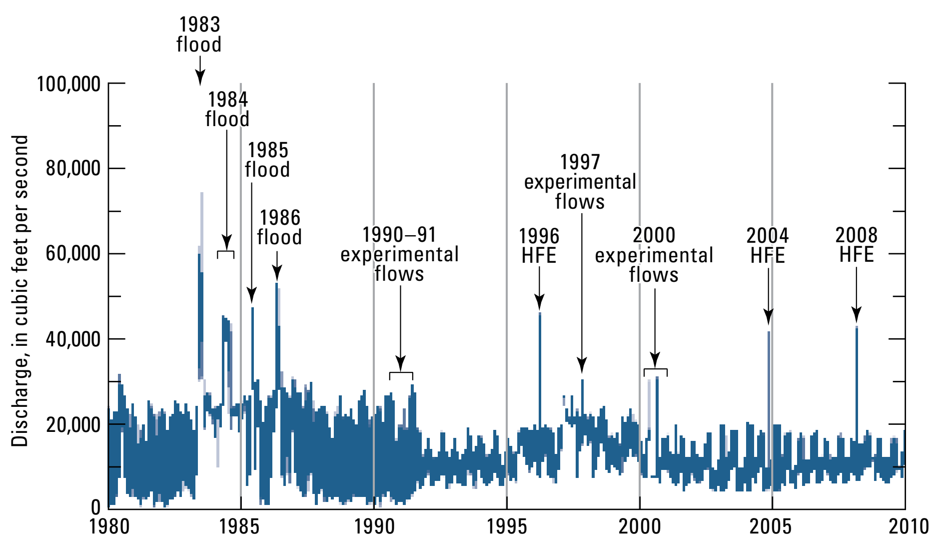


Figure 5. Continuous discharge record for the Colorado River at Lees Ferry for 1980 through 2009. The observations used to construct this record are at 15-minute intervals. Post-dam floods, experimental flows, and high-flow experiments (HFEs) are indicated. Modified from Topping and others (2003).

capacity, and spring snowmelt could not be entirely stored in the reservoirs. The largest dam release occurred on June 29, 1983, when a flow of 97,300 ft³/s was measured in the Colorado River at Lees Ferry. In addition to being unusually large, dam releases in each of these years were of long duration (table 1). Discharge exceeded 31,500 ft³/s for 68 consecutive days in 1983 and for 76 consecutive days in 1984.

Other large post-dam releases were of shorter duration. Two of these releases—in June 1980 and August 1984—occurred so that the Bureau of Reclamation could conduct critical engineering tests of the dam spillways. The other short-duration high-flow releases from the dam were associated with the HFEs that occurred in spring 1996, fall 2004, and spring 2008.

Channel Change in the Glen Canyon Reach

The reach between Glen Canyon Dam and Lees Ferry, locally known as the “Glen Canyon” or “Lees Ferry” reach, is distinct from downstream Marble and Grand Canyons in several important ways, including the jurisdictional boundary that places the upstream reaches in Glen Canyon National Recreation Area and the downstream reaches in Grand Canyon National Park. The differences in channel and canyon character result from the change in geology at Lees Ferry from less resistant Mesozoic rock formations to more resistant Paleozoic rock formations in Marble Canyon. This geologic contact is the reason that Lees Ferry is the point of departure for both downstream travel into Grand Canyon and upstream travel into Glen Canyon. The change in bedrock geology results in a break in the landscape that provides a rare access point to the river, which is engulfed in canyons both upstream and downstream from Lees Ferry. More importantly for the geomorphic character of the river, the change in geology marks the break between the upstream river segment that lacks large debris fans and the downstream segments where debris fans are common. Tributaries to the Colorado River in Glen Canyon supply sand and mud almost exclusively. Beginning with the first small tributary downstream from Lees Ferry, tributaries in Marble Canyon and downstream Grand Canyon deliver boulders composed of resistant rocks, in addition to sand and mud.

Although geology is an important factor in the site selection and design of all dams, in this case geologic context also played a major role in determining how the completed dam affected the river downstream. The fact that the channel in the Glen Canyon reach would be affected by the completion of Glen Canyon Dam was realized by engineers in the 1950s at least as early as when construction began in 1956. Engineers recognized that the bed in Glen Canyon would be subject to scour and that the lack of replenishment from upstream would likely cause progressive bed lowering. It was essential that the bed lowering in the tailwater immediately below the dam be accounted for in the design and

Experimental Flows and High-Flow Experiments

Since 1990, occasional experimental releases from Glen Canyon Dam allowed scientists to measure key physical and biological processes, measure the response of key resources to controlled flow conditions, and test hypotheses. During a 13-month period in 1990 and 1991, different flow patterns were released in 2-week blocks. Measurements, especially of changing sandbar topography, were made during intervening low-flow periods between the blocks. In 2000, a 6-month period of experimentation was executed that included two short-duration pulses at powerplant capacity with an intervening 3-month period when flows were held steady at 8,000 ft^3/s. Very short periods of low releases of approximately 5,000 ft^3/s occurred in October 1984 and June 1990 during acquisition of aerial photography. Subsequent aerial photographs have been taken, and remote data acquisition has occurred during flows of approximately 8,000 ft^3/s.

The first HFE was conducted between March 26 and April 7, 1996, and involved a 7-day steady release of 45,000 ft^3/s that was preceded and followed by low steady flows of 8,000 ft^3/s for 4 days each (fig. 6; Schmidt and others, 1999; see text box, Modeling the Colorado River Shoreline). The coordinated effort of scientists to evaluate the effects of the 1996 HFE on physical, biological, cultural, and recreational resources was documented by Webb, Schmidt, and others (1999). The second HFE was conducted between November 22 and 24, 2004, and involved a 60-hour release of about 41,700 ft^3/s. The third HFE was conducted between March 6 and 8, 2008, and included a 60-hour release of about 42,800 ft^3/s. The rise in discharge from normal dam operations for the 2004 and 2008 HFEs took place over 30-hour periods, a 50-percent slower rate of rise than for the 1996 HFE (fig. 6).

construction of the dam, otherwise powerplant performance and efficiency could be severely compromised.

To be able to predict the scour in this reach with the highest level of accuracy possible, Bureau of Reclamation engineers collected the necessary field data to construct a flow and sediment-transport model—state of the art for the time—that predicted the magnitude of bed scour (Pemberton, 1976). This field campaign included measurement of channel cross sections, water-surface elevations, and samples of surface and subsurface bed material. The effort went so far as to take core samples of deeper bed material. The study was limited to the reach between the dam site and Lees Ferry, because it was already understood that the transition in geology at Lees Ferry meant that scour of the bouldery rapids and riffles downstream was unlikely, even after dam construction. Engineers and scientists at the time were not concerned about the fate of fine sediment, because only the coarse fraction of the bed material controls the gradient of the water surface and can thereby affect the performance of the dam. This effort resulted in predictions that as much as 10.76×10^6 cubic yards of bed material would be evacuated, and this predicted scour was largely realized soon after the dam was completed when a series of pulsed flows were released in the spring and summer of 1965 (Pemberton, 1976; Grams and others, 2007). Bed scour of about 27 feet during the 1965 floods was also documented at the cableway at Lees Ferry by Burkham (1986). Repeated measurements indicated that the bed subsequently filled by 12 feet, such that the bed permanently was degraded by about 15 feet at the Lees Ferry cableway (Burkham, 1986; Grams and others, 2007). Although the primary reason for these high flows was to transfer water from Lake Powell to Lake Mead, it remains unclear why such an extreme and repeated high-flow release pattern was used. The release pattern may have had some secondary purpose, such as testing the water outlet facilities of the newly completed dam and, possibly, testing the prediction of bed scour. Regardless of the purpose at the time, the 1965 pulsed flows (14 in total) were significant in that they were an intentional release of high flows (or floods) from a dam that resulted in a change in the downstream channel that was both predicted and carefully monitored.

Resurveys of the cross sections established for the modeling exercise were completed soon after the 1965 pulsed flows and again in the 1970s, 1980s, 1990s, and finally in 2000. These surveys, together with photographs and measurements of bed-material size, document the transition of the Glen Canyon reach from a highly dynamic sand-bedded channel to a stable gravel- and cobble-bedded channel, which in many respects is more similar to a cold Alpine headwaters trout stream than a lowland desert river (see chapter 4, this volume; Grams and others, 2007).

Pre-Dam and Post-Dam Sediment Supply

Before completion of Glen Canyon Dam, the major sources of sand and mud transported by the Colorado River through Grand Canyon were the sedimentary rocks of the Colorado Plateau upstream from Lees Ferry (Thomas, 1960; Iorns and others, 1965; Howard and Dolan, 1981; Andrews, 1990, 1991b). Sand is defined as particles that are finer than 2 millimeters (mm) in diameter and coarser than 0.0625 mm; mud is finer than 0.0625 mm and can be either silt or clay. The term fine sediment is used to refer to sediment that consists of sand and finer particles. Topping, Rubin, and Vierra (2000) estimated that between 35 and 50 percent of the pre-dam suspended-sediment load of the Colorado River through Grand Canyon was sand and the remainder was mud (table 2). Although sandbars in Grand Canyon may contain discrete mud lenses or layers, primarily they are composed of sand (Schmidt and Graf, 1990; Topping and others, 2005). Thus, sand is the grain size of greatest interest to Grand Canyon researchers and managers.

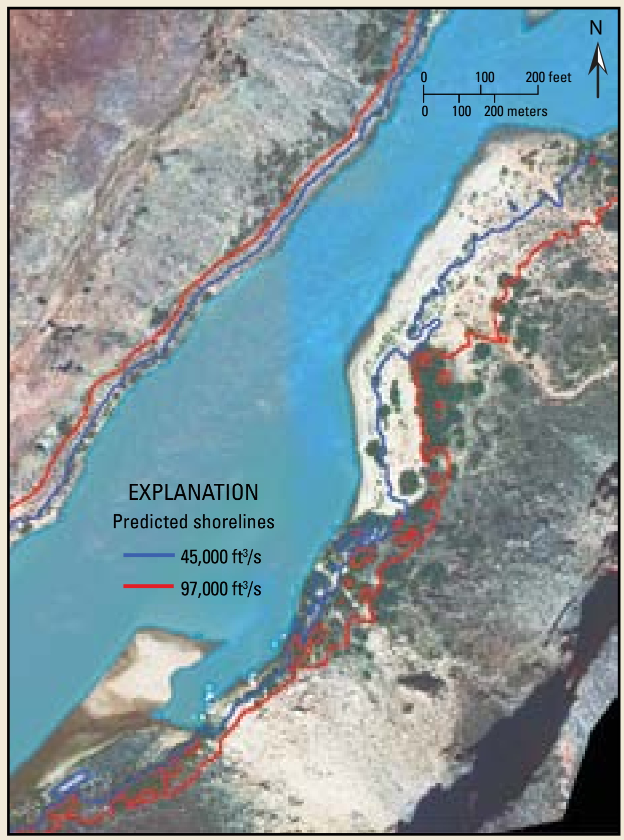
Many investigators recognized that trapping the entire fine-sediment load in Lake Powell that once was transported past Lees Ferry would create a sediment deficit that was likely to scour the 16 miles of the river between the dam and Lees Ferry and result in changes in the size and abundance of sandbars and other sand deposits farther downstream in Grand Canyon. Scientists disagreed, however, in their predictions of the downstream extent of the zone of sediment deficit and on whether conditions of sediment surplus would exist in central and western Grand Canyon (RM 88 to RM 277). The different predictions about downstream sand mass balance conditions arose, in part, because scientists made different assumptions about the amount of fine sediment supplied by tributaries to the Colorado River downstream from the dam.

Modeling the Colorado River Shoreline

"How high will the water get?" is probably one of the most basic and frequently asked questions about high flows in Grand Canyon. Scientists and managers have long relied on the experience of veteran river runners as well as observations made at discrete locations, such as streamgaging stations and sandbar study sites, for information about expected levels of inundation for particular flows. Observations of driftwood lines and other evidence have also provided guidance. Lacking for many years, however, was a means for predicting the level of inundation systematically for any point of interest along the river. Such a depiction of the shoreline requires detailed knowledge of both the water-surface elevation for the flow of interest and the topography of the surface that will be inundated. While models for predicting discharge (Wiele and Smith, 1996; Wiele and Griffin, 1997) and water-surface elevation (Randle and Pemberton, 1987) have been in use for many years, these models lack the level of resolution and coupling with topographic information that would allow their application to the prediction of shorelines.

Completion of high-resolution (about 3 foot (ft)) digital elevation models (DEMs) of the river corridor that were constructed from remote sensing missions in 2000 and 2002 provided data that allowed the construction of a more finely resolved flow model (Magirl and others, 2005, 2008). The model is a traditional one in that it employs basic principles of mass conservation, energy transfer, and flow resistance to predict water-surface elevations. For application in Grand Canyon, Magirl and others (2008) used 2,680 channel cross sections extracted from the remotely sensed topography. Despite the high quality of the topographic data available, below-water channel-depth data were (and still are) lacking. Thus, it was necessary to construct the model by using an approach that relies on the creation of estimated or "synthetic" cross sections for the below-water parts of the channel where remotely sensed data were not available. Randle and Pemberton (1987) used the same approach but with far fewer cross sections. The synthetic cross sections were created by adjusting them such that the model-predicted water-surface elevation matched a water-surface elevation that was measured by airborne lidar[1] during a steady flow of 8,000 cubic feet per second (ft^3/s) in 2000. Observations of water-surface elevations for other discharges were used to further calibrate and verify the model.

The completed model provides predictions of water-surface elevation at spacings of about 300 to 500 ft from Lees Ferry to Diamond Creek (RM 0–225), with uncertainties of about 1.3 ft for flows as high as 45,000 ft^3/s and 3.3 ft for flows as high as about 90,000 ft^3/s (Magirl and others, 2008). The final step in providing maps depicting areas of expected inundation was the overlay of the predicted water-surface elevations onto the DEM to create "virtual shorelines" for the entire river corridor (see figure below). These maps were used by scientists, the National Park Service, and the general public to anticipate areas of potential inundation for the March 2008 high-flow experiment.



Virtual shorelines at Eminence Break camp (river mile 44). The blue shaded area (the river) shows the observed shoreline at a flow of 8,000 cubic feet per second (ft^3/s) in the Colorado River at Lees Ferry, the blue line shows the predicted shoreline at 45,000 ft^3/s, and the red line shows the predicted shoreline at 97,000 ft^3/s. Modified from Magirl and others (2008).

[1]Lidar (light detection and ranging) instruments employ a laser scanning mechanism to measure distances from the instrument, which may be airborne or on the ground, to the ground surface thereby creating a highly detailed topographic map of the area of interest.

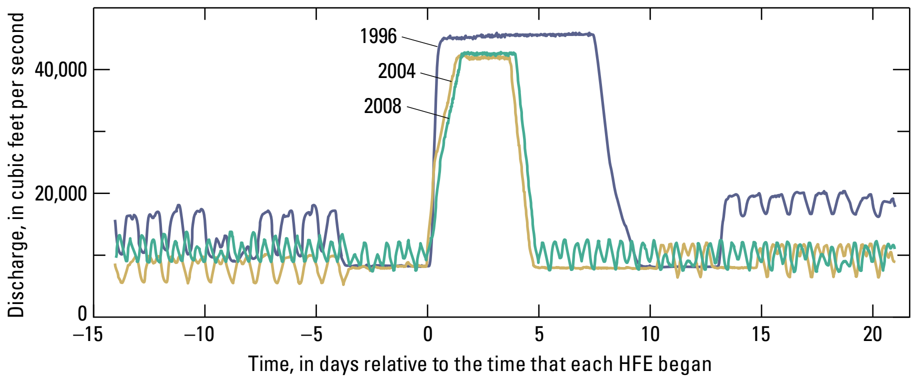


Figure 6. Continuous discharge record for the Colorado River at Lees Ferry for three high-flow experiments (HFEs). The 1996 HFE began at 12:00 a.m. on March 26, 1996; the 2004 HFE began at 12:00 a.m. on November 21, 2004; and the 2008 HFE began at 6:00 p.m. on March 4, 2008.

There was reasonable agreement about the fine-sediment supply rate from the Paria and Little Colorado Rivers. The average annual sand supply from the Paria River was estimated to be between 1.4 and 1.9 million tons, and the supply from the Little Colorado River was estimated to be between 3.3 and 3.4 million tons (table 2). Laursen and others (1976), Howard and Dolan (1981), and Andrews (1991b) documented that the Paria River augmented the amount of pre-dam fine sediment supplied from the upper basin by approximately 4 to 6 percent (table 2). These studies showed that between 77 and 79 percent of the sand and mud transported past the Grand Canyon gage, located 88 miles downstream from Lees Ferry (fig. 1), was supplied by the Colorado River watershed upstream from Lees Ferry. Between 14 and 16 percent of the sand and mud transported past the Grand Canyon gage was supplied by the Paria and Little Colorado Rivers.

Scientists disagreed in their estimates of the amount of fine sediment delivered by the numerous smaller tributaries. Howard and Dolan (1981) estimated that the average annual total sand and mud supply from these tributaries was about 4.4 million tons, but Randle and Pemberton (1987) estimated that this rate was only 700,000 tons, with an unknown percentage of sand (table 2). On the basis of the larger estimate, Howard and Dolan (1981) predicted that sand would accumulate in Marble and Grand Canyons.

Following the 1996 HFE, measurements of the amount of sand delivered by the Paria and Little Colorado Rivers and by the smaller tributaries were resumed. These estimates demonstrate that the supply rate from small tributaries is much less than was assumed by Howard and Dolan (1981) and that the balance between tributary sand supply and main-stem sand-transport capacity, which determines whether sediment evacuation or accumulation is more likely, is very delicate (Webb and others, 2000; Topping and others, 2010).

Fine-Sediment Evacuation or Accumulation?

The management of dam releases for the purpose of maintaining sandbars and related downstream natural resources not only depends on accurate measurements of the amount of sand delivered by the Paria and Little Colorado Rivers and smaller tributaries, but also on the prediction of the rate at which sand is transported by the main current and the prediction of the rate of the transfer of sand and mud between the main current and eddies. The rate and magnitude of eddy-sandbar deposition depends on the magnitude of suspended-sand concentration. Higher suspended-sand concentrations result in higher sand deposition rates and generally larger sandbars.

Predicting the Amount of Suspended-Sand Transport

Scientists have struggled to predict the amount of sand transported by the Colorado River, especially during floods and other high flows. Because the measurement of suspended-sand

Table 2. Estimates of the mean annual suspended-sediment load transported in the Colorado River and its tributaries in the Grand Canyon region.

[ns, not specified; na, not available]

Suspended-sediment load, in tons per year	Period of estimate	Source	Percentage of sand
Colorado River at Lees Ferry gage (pre-dam)			
101,300,000	1929–1957	Iorns and others, 1965	na
65,690,000	1948–1962	Laursen and others, 1976	na
73,019,000	ns	Howard and Dolan, 1981	na
66,100,000	1941–1957	Andrews, 1991b	na
62,800,000	1949–1962	Topping, Rubin, and Vierra, 2000	40
Colorado River at Lees Ferry gage (post-dam)			
8,600,000	1963–1965	Laursen and others, 1976	na
260,000	1966–1970	Topping, Rubin, and Vierra, 2000	na
Paria River near Lees Ferry			
2,655,000	1948–1957	Iorns and others, 1965	na
2,506,000	1949–1957	Laursen and others, 1976	na
3,732,000	1949–1969	Laursen and others, 1976	na
3,214,000	ns	Howard and Dolan, 1981	na
3,020,000	1947–1976	Andrews, 1991b	na
3,300,000	1949–1970	Topping, Rubin, and Vierra, 2000	50
Little Colorado River			
9,836,000	1948–1969	Laursen and others, 1976	na
9,377,000	ns	Howard and Dolan, 1981	na
9,270,000	1941–1957	Andrews, 1991b	na
9,480,000	1949–1970	Topping, Rubin, and Vierra, 2000	30–40
Ungaged tributaries			
4,363,000	ns	Howard and Dolan, 1981	na
700,000	ns	Randle and Pemberton, 1987	na
790,000	ns	Topping, Rubin, and Vierra, 2000; from Griffiths and others, 1996	na
Colorado River at Grand Canyon gage (pre-dam)			
168,000,000	1926–1950	Smith and others, 1960	na
142,000,000	1935–1948	Smith and others, 1960	na
83,610,000	1948–1962	Laursen and others, 1976	na
92,453,000	ns	Howard and Dolan, 1981	na
195,000,000	1925–1940	Andrews, 1991b	na
85,900,000	1941–1957	Andrews, 1991b	na
91,500,000	1948-1962	Topping, Rubin, and Vierra, 2000	35
Colorado River at Grand Canyon gage (post-dam)			
20,490,000	1963–1969	Laursen and others, 1976	na
15,790,000	1966–1969	Laursen and others, 1976	na
11,000,000	1970–1990	Andrews, 1991b, stable rating curve estimation	na
15,430,000	1966–1972	Topping, Rubin, and Vierra, 2000	na

transport is labor intensive and, therefore, costly, scientists usually make occasional measurements and calculate an average relation between river flow and the concentration of sand transported (fig. 7). Typically, scientists assume that scatter in measured data represents statistically random measurement uncertainty and that an average relation may be fit through the center of the cloud of field data. However, early investigations of sediment transport showed that a simple relation was not applicable to the pre-dam Colorado River. For example, Leopold and Maddock (1953) showed that much more suspended sediment was transported during the rising stage of the 1941 spring snowmelt flood than during the receding stage. Scientists refer to such a pattern in which there is a lag or "memory" effect as hysteresis. Because the mechanical forces caused by turbulent streamflow in large rivers are approximately the same at the same discharge, whether during rising or falling stage, scientists explain hysteresis in sediment-transport relations as being the result of changes in the amount of sediment available for transport. The condition is referred to as sediment-supply limitation.

Hysteresis occurred in the pre-dam river, because the months of highest streamflow—spring and early summer—and the months when most sand was supplied to the channel—late summer and fall—were asynchronous. Although sand was brought into Grand Canyon from upstream during the spring snowmelt flood, a large proportion of the sand transported through Grand Canyon during the spring snowmelt flood was locally scoured from the bed and banks during the rising part of the annual flood. This sand had accumulated during the previous late summer and fall when flow in the river was relatively low.

Colby (1964) also described this seasonal pattern of sand accumulation in the summer and fall followed by evacuation during the subsequent spring. He observed that "the quantity and particle size of the available sand generally change with time," and he suggested that the wide range of concentrations measured at the same discharge was caused by changes in the amount of sand on the channel bed and the size of the sand (Colby, 1964, p. D30). Howard and Dolan (1981) analyzed all pre-dam sand-transport data collected between 1948 and 1957 and identified the same seasonal pattern in periods of sand accumulation and evacuation. Burkham (1986) showed similar sand-transport relations in the post-dam river, and Laursen and others (1976) used theoretical transport relations to estimate that the Colorado River could transport more sand than was measured in the years immediately after the dam was closed. Despite these studies, the importance of sand-supply limitation was not explicitly considered by Howard and Dolan (1981), Andrews (1990, 1991b), Smillie and others (1993), or Randle and others (1993), nor was it considered in the analysis of sediment transport in the "Operation of Glen Canyon Dam: Final Environmental Impact Statement" (hereafter referred to as EIS; U.S. Department of the Interior, 1995).

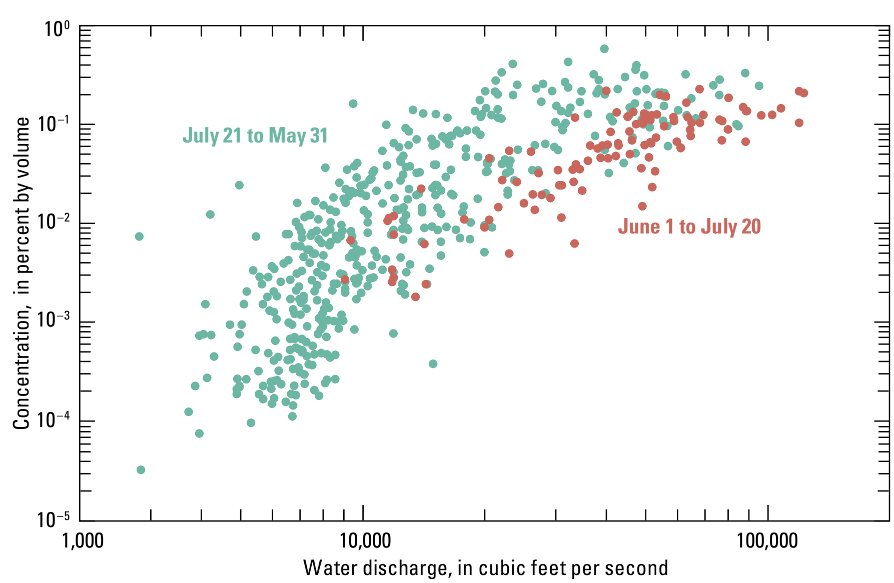


Figure 7. Suspended-sand concentration and discharge of the Colorado River near the Grand Canyon gage at river mile 88 during the pre-dam period (1944–62). Concentrations shown are the average for the measurement section based on depth-integrated samples. The red symbols represent data collected from June 1 to July 20, and the green symbols represent data collected from July 21 to May 31. As described in the text, the systematic nature of the time when measured concentrations were relatively high or low indicates that the scatter is not random and is related to the amount and size of sand available for transport and its distribution on the bed and along the channel margins. Modified from Topping, Rubin, and Vierra (2000, fig. 4b).

The relation between river flow and suspended-sand concentration is further complicated by the existence of downstream variations in sand concentration. Suspended-sand concentration increases downstream when net erosion from the channel bed and from eddy sandbars occurs or when the rate of sand entrainment from the bed is large. Conversely, a downstream decrease in suspended-sand concentration occurs when there is net deposition of sand onto the channel bed or into eddies. Because of these complex interactions, the ability to predict sand transport and concentration at different places in Grand Canyon is essential for anticipating the effects of high flows on sandbars.

Calculations of Post-Dam Sand Mass Balance

The mass balance of sand for any river segment, also referred to as the change in sand storage in a river segment, is the difference between sand input, or sand supply, at the upstream end of the segment and sand output, or sand export, at the downstream end of the segment. In the Colorado River in Grand Canyon, the change in sand storage includes changes in the amount of sand on the channel bed and in the sandbars that are recreational and ecological resources.

Taking into account the characteristic size of the sand delivered by the Paria River, the flow regime of the pre-dam Colorado River, and the anticipated long-term operating rules to generate hydropower at the dam, Laursen and others (1976) predicted that the capacity of the Colorado River to transport sand was relatively high. They also predicted that there would be a decrease in sand storage in the post-dam Colorado River in Marble and Grand Canyons, meaning those river segments would be in sediment deficit; thus, they predicted that sand would be eroded from the river's sandbars and channel bed. Laursen and others (1976, p. 4–86) concluded:

> *the beaches of the Colorado River * * * could be in danger of being washed away since the transport capacity of the regulated river is in excess of the amount of beach-building material being supplied from the tributaries * * * How long they will last cannot as yet be estimated; certainly more than 10 years, probably less than 1,000 years; but how much more or less than 100 years is a matter for continued study.*

In contrast, subsequent investigators assumed that the average amount of sand transported by the Colorado River was much less than the amount assumed by Laursen and others (1976), and these investigators ignored the role of supply limitation. Depending on estimates of the amount of sand supplied by the tributaries entering the Colorado River downstream from Glen Canyon Dam, researchers concluded that (1) the post-dam river was in sediment surplus and had accumulated sand (Howard and Dolan, 1981), (2) the post-dam river was in equilibrium and the rate of sand export was approximately equal to the rate of sand supply (Andrews, 1990, 1991b), or (3) sand was accumulated when dam releases were less than about 31,500 ft^3/s, and sand was evacuated when floods occurred (U.S. Department of the Interior, 1995). It was estimated in the EIS (U.S. Department of the Interior, 1995) that sand had accumulated between 1966 and 1982 (fig. 8) because there were no floods and only one short-duration flow in 1980 (table 1) during that period. This hypothesis led to the assumption that sand could be managed and conserved on the channel bed for decades and that occasional short-duration high flows could mobilize the sediment and redistribute some sand to sandbars while transporting the remainder downstream to Lake Mead. The latter perspective was the working hypothesis of the 1996 HFE and of the beach/habitat building flows proposed in the Record of Decision (U.S. Department of the Interior, 1996).

As described in the next chapter, some of the most important results from the HFEs concern reevaluating the role sand-supply limitation plays in determining how much sediment is transported during each high flow. The central finding of Rubin and others (1998), Rubin and Topping (2001), Topping and others (1999, 2005), Topping, Rubin, and others (2000), and Topping, Rubin, and Vierra (2000) was that the amount of sand stored on the channel bed and in sandbars—now termed sand enrichment—determines the amount of sand transported by subsequent HFEs. These findings indicate that Laursen and others (1976) generally were correct in their assessment of the deficit of sand in the post-dam river. Today, river managers strive to understand the relation among sand supplied from tributaries, short-term sand enrichment in the Colorado River, sand transport during HFEs, sand transport between HFEs during normal operations, and the resultant sand mass balance. Crucial measurements have been made during HFEs and incorporated into numerical models. Collectively, these insights have led to ever-improving predictive tools to anticipate short-term and long-term change in sandbars and associated aquatic and riparian habitats.

Physiography of the Colorado River and Its Valley

Rivers are not uniformly shaped conduits. Instead, natural river channels vary in width, depth, bed material, pattern, and slope—depending on the characteristics of the bedrock and hillslope deposits through which the river has excavated its channel and the geology and relief of the upstream watershed. Variation in channel form is important in determining how a natural river channel responds to conditions of sediment evacuation or accumulation and how the channel responds to floods. Differences in the bedrock exposed on the banks and near the bed of the Colorado River have a substantial effect on channel form and on the downstream distribution of many natural resources, such as the number of campsites or the abundance of archaeological sites. Longitudinal, or downstream, differences in channel form also affect where erosion and deposition occur during HFEs (see text box, Longitudinal Organization of Grand Canyon).

Powell "noted many changes in the dominant 'mood' of Grand Canyon * * * such as the 'oppressive constriction' of the granite gorges" (cited by Howard and Dolan, 1981, p. 273). During the 1980s and 1990s, researchers followed the lead of Howard and Dolan (1981) and characterized the large-scale longitudinal characteristics of Grand Canyon. Schmidt and Graf (1990) divided Grand Canyon into 11 segments (long parts of the channel whose shape is similar) on the basis of rock type at river level and whether the channel was "narrow" or "wide." Schmidt and Graf (1990) showed that the frequency of sandbar campsites and the number and size of sandbars varied by segment (U.S. Department of the Interior, 1988). Griffin (1997) defined 10 "geomorphically similar" segments on the basis of attributes of channel cross-section shape. Brian and Thomas (1984) and Kearsley and others (1994) took a different approach and defined segments on the basis of the frequency of sandbar campsites; "critical" segments were defined as parts of the river with very few campsites.

The longitudinal profile of the Colorado River is a series of long, flat reaches interrupted by short, steep rapids and riffles (see figure in text box, Longitudinal Organization of Grand Canyon). Leopold (1969) reported that 50 percent of the total elevation drop of the river occurred in only 9 percent of the downstream distance, and Magirl and others (2005) found that 66 percent of the total drop, as measured in 2000, occurred in rapids and riffles. The spacing between rapids is determined by the spacing of tributary canyons (Dolan and others, 1978), because debris from each tributary partially blocks the river.

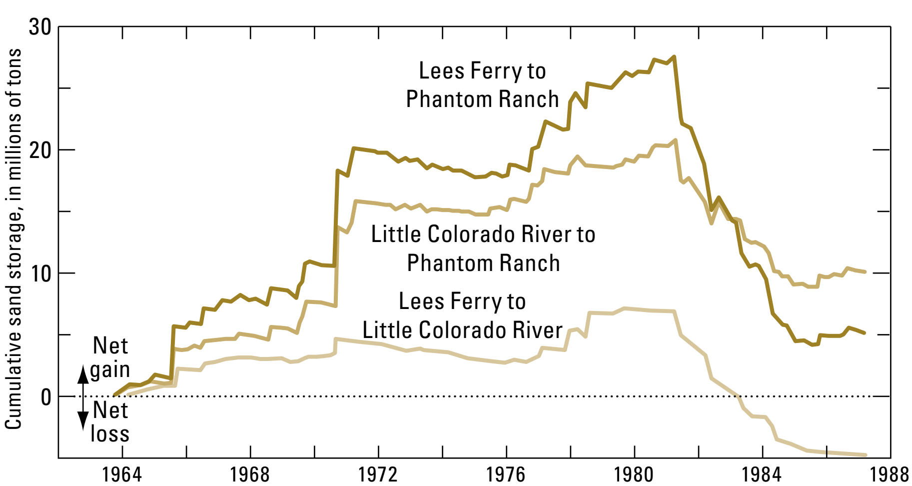
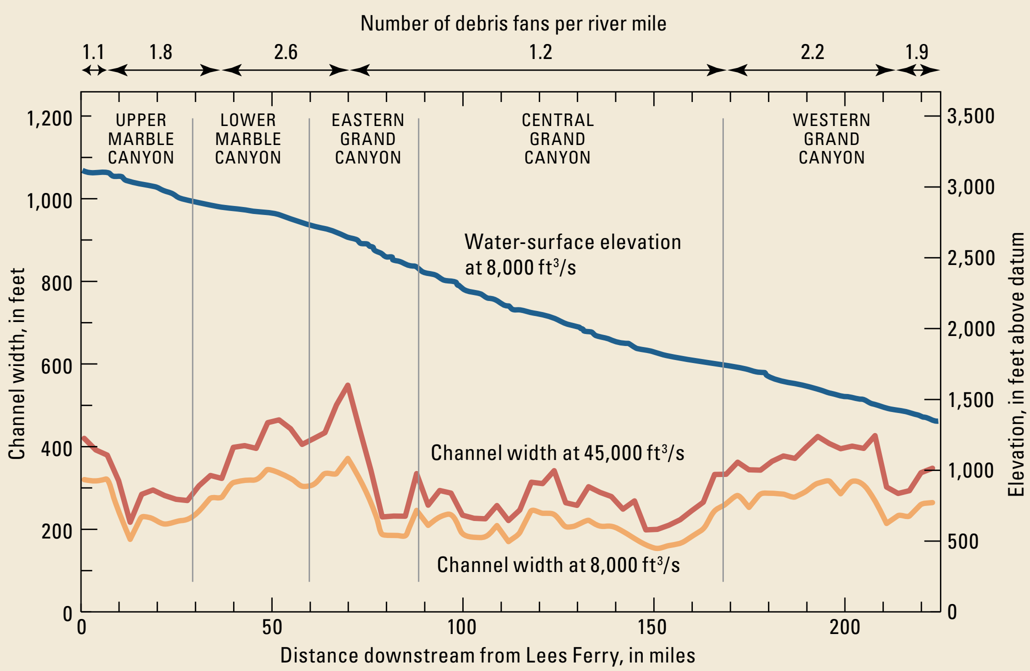


Figure 8. Cumulative sand storage between the Lees Ferry and Grand Canyon gaging stations (river miles 0–88), based on the assumption that the same discharge always transports the same amount of sand. From U.S. Department of the Interior, 1995, fig. III-15.

Longitudinal Organization of Grand Canyon

Grand Canyon researchers and river managers have a wide array of spatially robust and detailed geographic data from which to characterize the longitudinal, or downstream, variation of the Colorado River corridor. These data have been used to estimate the width of the river at different discharges and thereby define river segments as to being narrow or wide and segments that have relatively steep or flat gradients (Magirl and others, 2005, 2008). Other researchers have measured the distribution of eddy sandbars by measuring the debris fans that create fan-eddy complexes (Melis, 1997) or the number of eddy deposition zones (Schmidt and others, 2004). These data provide a picture of the large-scale, longitudinal variation in the physical structure of the Colorado River in Grand Canyon (see figure below) and have resulted in the identification of geomorphic reaches that are based on these characteristics and serve as a basis for stratifying research and monitoring sampling designs (see table 3).

More accommodation space is available for sand deposition in wider reaches than in relatively narrow reaches. The relatively wide reaches include lower Marble Canyon, the upstream part of eastern Grand Canyon, and much of western Grand Canyon. Not only do flood flows inundate much more area relative to low flows in these segments of Grand Canyon, but the frequency of debris fans and of eddy deposition zones is greater than elsewhere. Thus, there is greater area for sand deposition during high-flow experiments in these segments than elsewhere in Grand Canyon. The flattest part of the river's profile is also in lower Marble Canyon where the river-level bedrock is Muav Limestone and Bright Angel Shale (Beus and Morales, 2003) between about river mile (RM) 35 and RM 55. The steepest and narrowest part of the river is upper Granite Gorge in eastern and central Grand Canyon between about RM 75 and RM 115. There is relatively little available space for sand deposition during floods between RM 87 and RM 100, and the fewest number of debris fans in Grand Canyon occur in the same segment. There also is relatively little available space for sand deposition between RM 10 and RM 35.



Downstream variations in channel width and water-surface elevation, and the occurrence of debris fans and eddy deposition zones between Lees Ferry and Diamond Creek. From data described by Magirl and others (2008).

Because debris flows and debris fans exert a strong influence on the Colorado River's longitudinal profile and its cross-sectional form, Melis (1997) measured debris fans and used these data to develop a longitudinal classification that incorporated river width measurements and characteristics of debris fans, such as their number, size, shape, and ability to constrict the channel, into the previous classifications on the basis of changes in river-level bedrock (table 3). Using this approach, Melis (1997) divided Grand Canyon into six segments. Melis's (1997) approach was novel, because he recognized the effects of downstream differences in debris-fan characteristics on the distribution of some river resources that occur near debris fans.

Today, the longitudinal variation in canyon characteristics is the framework within which the impacts of HFEs are described, because it is recognized that different parts of Grand Canyon respond differently to the same HFE. The classification proposed by Schmidt and Graf (1990) primarily is used when describing the longitudinal distribution of natural resources or in aggregating site-scale data (table 3). A different classification is used when describing the fine-sediment mass balance of segments of the river corridor. The latter classification is based on the location of sediment-transport measurement stations (fig. 1), because these stations are used to calculate the mass of fine sediment that has accumulated or been evacuated from different parts of the river corridor. These "sediment-mass-balance segments" are upper Marble Canyon (river mile [RM] 0 to RM 30), lower Marble Canyon (RM 30 to RM 61), eastern Grand Canyon (RM 61 to RM 88), central Grand Canyon (RM 88 to RM 166), and western Grand Canyon (RM 166 to RM 225).

Landforms of the River Corridor

While boating the river or hiking along the channel banks, one observes that sand is intermittently distributed and other parts of the river shoreline are talus (rock debris), bouldery debris-flow deposits, or gravel bars. Specific landforms that have been the focus of most management and scientific interest include eddy sandbars, pre-dam river terraces, eolian (windblown) deposits, and debris-flow deposits.

Eddy Sandbars and Channel-Margin Deposits

Dolan and others (1978) and Howard and Dolan (1981) showed that most sandbars form in eddies that occur immediately downstream from debris fans. Schmidt and Rubin (1995) more precisely described the shorter-scale, or reach-scale, organization of the channel and defined the fan-eddy complex as the fundamental hydraulic and geomorphic feature of Grand Canyon and other debris-fan-affected canyons of the Colorado River watershed. The core of each fan-eddy complex is the debris fan that constricts the channel. A rapid often, but not always, exists here, because velocity is greater in the steeper, narrower, and shallower channel (fig. 10). Upstream from this rapid, streamflow is ponded and is relatively slow. The ponded flow may extend several miles upstream from

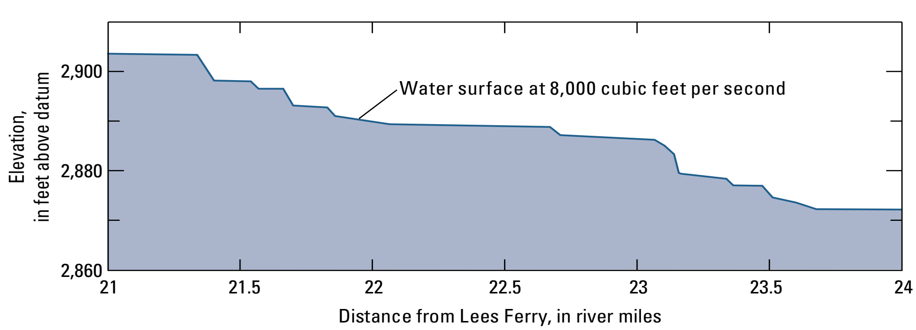


Figure 9. Longitudinal profile of the Colorado River water surface from river mile 21 to 24 in Marble Canyon showing the relatively flat pool segments separated by short and relatively steep rapids. The water-surface profile is based on data collected by light detection and ranging (lidar) in March 2000, when the release from Glen Canyon Dam was steady at 8,000 cubic feet per second (Magirl and others, 2005).

Table 3. Classifications of large-scale organization of the Colorado River on the basis of geomorphic characteristics.

Classifications are those of Schmidt and Graf (1990), Kearsley and others (1994), and Melis (1997). Length of columns is scaled to reflect the river length for each reach. Reach type designation is narrow (N) and wide (W) for Schmidt and Graf (1990) and Melis (1997) and critical (C) and noncritical (NC) for Kearsley and others (1994). River mile designations are rounded to the nearest mile. From Kearsley and others (1999).

Schmidt and Graf (1990)		
Reach number	River mile	Reach type
1	RM 0–11	W
2	RM 11–23	N
3	RM 23–40	N
4	RM 40–62	W
5	RM 62–77	W
6	RM 77–118	N
7	RM 118–126	N
8	RM 126–140	N
9	RM 140–160	N
10	RM 160–214	W
11	RM 214–225	N

Kearsley and others (1994)		
Reach number	River mile	Reach type
1	RM 0–11	NC
2	RM 11–41	C
3	RM 41–76	NC
4	RM 76–116	C
5	RM 116–131	NC
6	RM 131–139	C
7	RM 139–164	C
8	RM 164–225	NC

Melis (1997)		
Reach number	River mile	Reach type
1	RM 0–8	W
2	RM 8–38	N
3	RM 38–77	W
4	RM 77–170	N
Subreach 4A	RM 87–100	Widened narrow
		N
Subreach 4B	RM 116–128	Widened narrow
		N
5	RM 170–213	W
6	RM 213–225	N

a rapid. Kieffer (1985) showed that flow upstream from Crystal Rapids (RM 98), one of the largest rapids in Grand Canyon, is ponded for approximately 1 mile. The banks of the ponded flow sometimes are channel-margin deposits, which are narrow sand deposits that resemble flood plains and sometimes have natural levees on top. Immediately downstream from each rapid, channel width increases in what is termed the expansion (Schmidt, 1990). In the expansion, downstream-directed flow separates from the bank and forms a jet of high-velocity flow in the center of the channel. Recirculating eddies occur between the jet and the channel banks, and sandbars occur in these eddies. The length of the recirculating eddy changes with discharge, and the recirculating zone typically gets longer and narrower as discharge increases (Schmidt, 1990). The channel bed is typically very deep immediately downstream from the rapid, forming a deep scour hole. Downstream from the expansion, the channel width narrows, the bed becomes shallow, and a gravel bar sometimes is formed. If the gravel bar is sufficiently large, a small rapid may occur where the river flows around the bar (Webb and others, 1988).

Recirculating eddies are effective traps of sand and mud that are transported in suspension by the main flow. Observations during the mid-1980s demonstrated that the eddy sandbars have a consistent topography that can be subdivided into separation bars and reattachment bars on the basis of their specific location within each eddy (Schmidt, 1990; Schmidt and Graf, 1990; see text box, The Fan-Eddy Complex). Separation bars mantle the debris fans that form rapids and are deposited in zones of low velocity near where the downstream-directed flow of the rapid separates from the channel bank (Schmidt and Graf, 1990). The reattachment bar forms within the primary cell of recirculating eddy flow, and the highest part of the reattachment bar occurs where downstream-directed flow reattaches to the channel bank. Between the reattachment and separation bar is the primary eddy return-current channel, a deep channel that is maintained by the high-velocity flow of water that exits the primary cell of recirculating eddy flow.

Eddies constitute about 20 percent of the water-surface area (Schmidt and others, 2004), which is a large proportion of the river. There are approximately five eddies per river mile in Marble Canyon, but the frequency of eddies varies between 3.5 and 9.3 per river mile depending on canyon width (Schmidt and others, 2004; Hazel and others, 2006). Measurements of changes in eddy-bar topography suggest that eddies have the potential to accumulate or evacuate very large volumes of sand and mud. Schmidt and others (2004) estimated that about 50 percent of the pre-dam annual accumulation and evacuation of fine sediment occurred by the increase and decrease of eddy-bar size. The volume of fine sediment potentially stored in eddies in Marble and eastern Grand Canyon is 15.8 million tons and 7.4 million tons, respectively (Schmidt and others, 2004). This estimated volume is much larger than the annual pre-dam accumulation and evacuation of fine sediment in Marble and eastern Grand Canyon estimated by Topping, Rubin, and Vierra (2000)—7 million tons. Because the volume of potential deposition in eddies is much larger than the typical amount of fine sediment annually accumulated and evacuated, parts of eddy sandbars must have persisted for many years and have been reworked only by the largest pre-dam floods.

Although the general pattern of flow at the water surface was well understood by the late 1980s, researchers had a poor understanding of the three-dimensional attributes of flow within eddies or the mechanics by which sediment is exchanged between the main current and eddies. Streamflow in rapids is highly turbulent, and the mechanical forces associated with this turbulence suspend sand and mud throughout the water column. Qualitative observations made in the mid-1980s showed that some of the water and associated suspended sediment moves from the main current into the adjacent eddy, and Schmidt and others (1993) simulated this process in a flume. Researchers in the mid-1980s made crude measurements of hydraulics and bathymetry (water depth) in and near eddies. Most observations, however, were qualitative and were based on

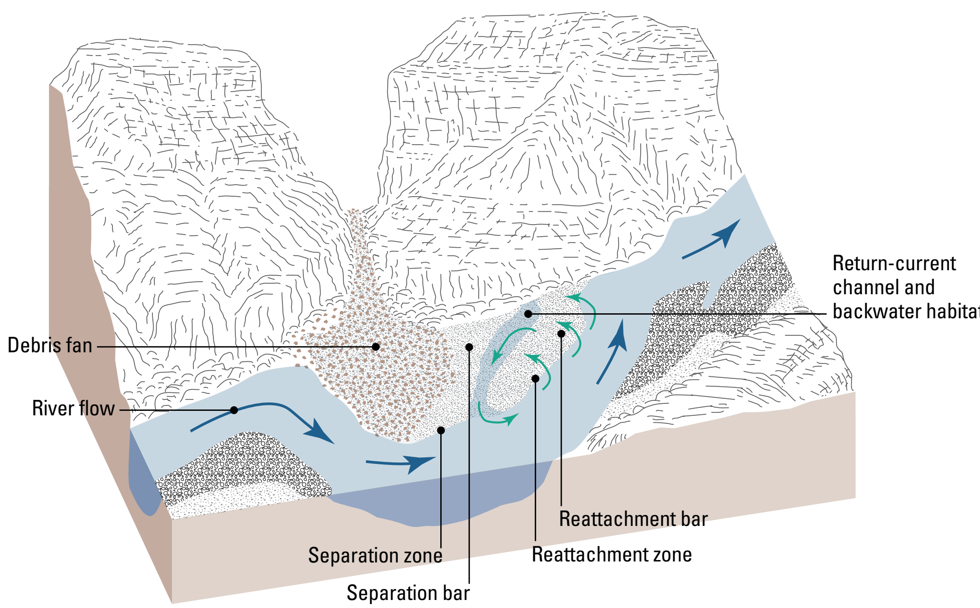


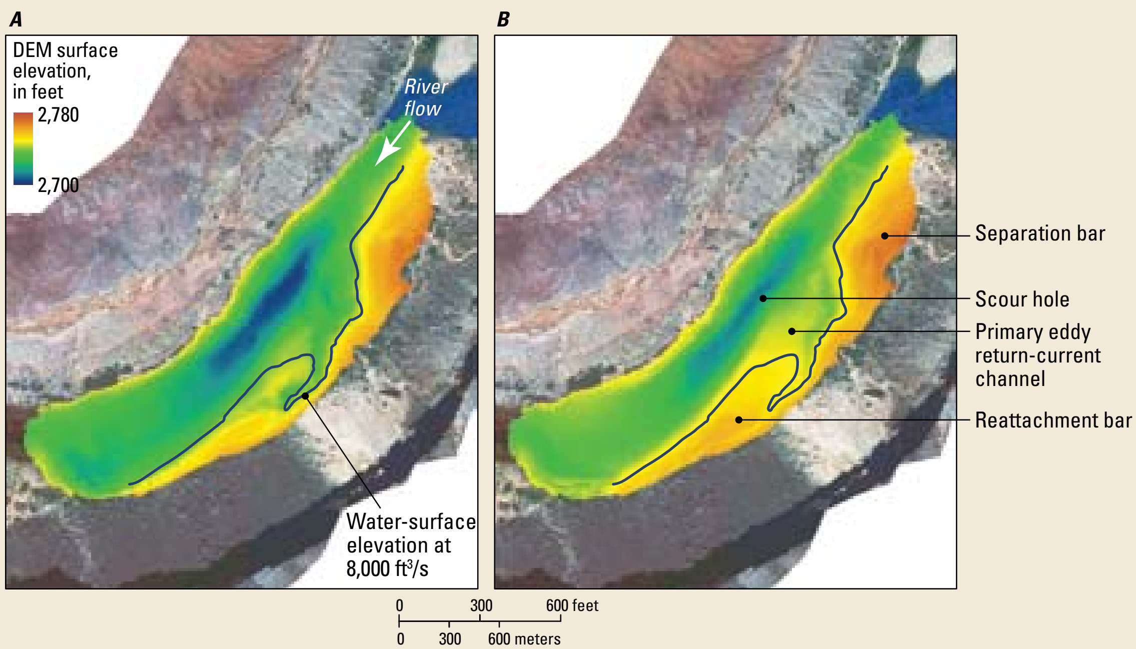
Figure 10. Diagrammatic illustration of a typical fan-eddy complex, including reattachment sandbar, return-current channel, and backwater habitat. Main channel flow is from left to right. The separation zone is the area where downstream flow separates from the bank, and the reattachment zone is the area where downstream flow reattaches to the bank. The small arrows indicate the primary cell of recirculating flow within the eddy at flows during which the sandbar would be submerged. Modified from Schmidt and Graf (1990).

The Fan-Eddy Complex

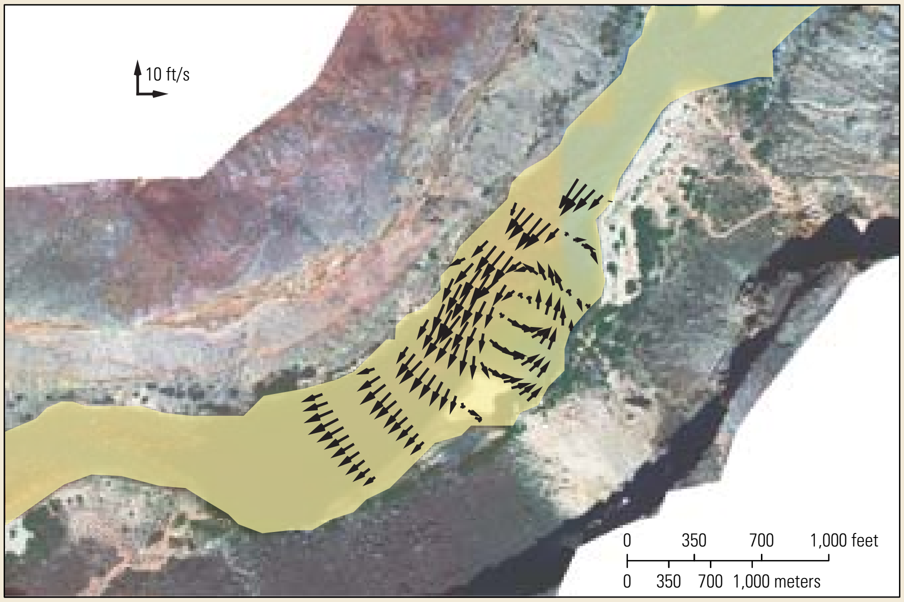
Repeated measurements of the channel bed and eddy sandbars made by using modern topographic and bathymetric (water-depth) mapping techniques (Hazel and others, 2008; Kaplinski and others, 2009) precisely describe the fan-eddy complex. These survey data were combined to develop two maps near Eminence Break camp at river mile 44 in lower Marble Canyon. One such map represents the topography of the lowest elevations surveyed between 1990 and 2008 at each point in the survey area (figure *A* below). A companion map represents the topography of the highest elevations surveyed between 1990 and 2008 at each point in the survey area (figure *B* below).

Debris fans that partly block the channel and eddy sandbars downstream from these debris fans occur in repeating patterns. The difference in topography between the maximum elevations surveyed (figure *B* below) and the minimum elevations surveyed (figure *A* below) are greatest for the reattachment-bar part of the eddy sandbar, indicating that a large amount of sand can be stored or evacuated from these landforms. The primary eddy return-current channel is much smaller when the reattachment bar is large (figure *B* below). The scour hole persists as a topographic feature of the bed even when the bed has a large amount of sediment (figure *B* below).

Flow conditions at this site were measured during the 2008 high-flow experiment (HFE) by Wright and Kaplinski (in press). The recirculating cell of eddy flow is clearly depicted in these measurements, as is the strong upstream flow near the left bank (figure top right). Comparison among figures shows that separation and reattachment bars form in low-velocity conditions in the zones where downstream-directed currents separate and reattach to the left bank.



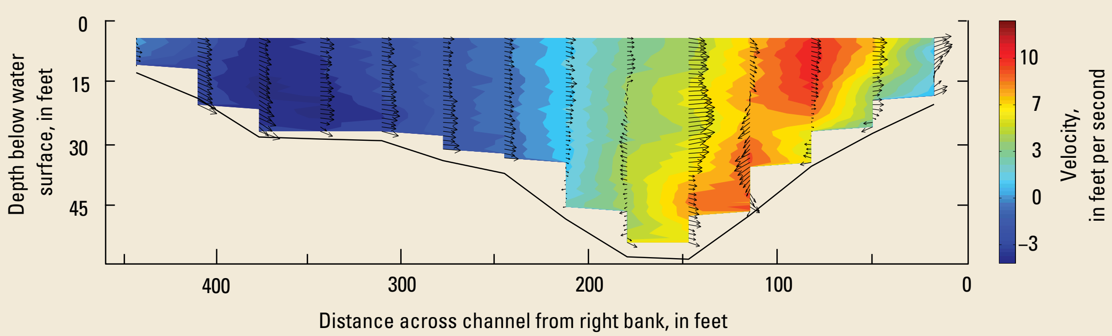
Topography of the bed and of eddy sandbars near Eminence Break camp (RM 44) in lower Marble Canyon. These maps show the typical topography of the channel near tributary debris fans that determine the local hydraulics and shape the channel bed. *A*, This map shows the topography of the lowest elevation of each point in the fan-eddy complex between 1990 and 2008. The three main parts of an eddy sandbar are shown: separation bar, primary eddy return-current channel, and reattachment bar. *B*, This map shows the topography of the highest elevation of each point in the same fan-eddy complex. The difference in topography between the maps in *A* and *B* represents the sediment that was gained, or lost, during this survey period. Note that the distinctive topography of the three main parts of the eddy sandbar can be observed in *A* and *B*. Flow is from top to bottom.



Depth-average horizontal velocities measured at peak flow during the 2008 HFE at the fan-eddy complex shown on the previous page. Scale bars indicate the speed of the flow. Modified from Wright and Kaplinski (in press).

One aspect of the flow in eddies that had not been observed before the measurements made during the March 2008 HFE is that the downstream-directed flow remains confined to a narrow part of the channel near the right bank downstream from the debris fan (figure below), and this narrowing and forcing of the flow to the right bank is caused by the convergence of recirculating eddy flow at the upstream end of the eddy. At the downstream end of the fan-eddy complex, a portion of the flow is oriented into the eddy. Thus, sand in suspension in the main flow first moves onto the reattachment bar.

Collectively, these topographic and flow-velocity measurements demonstrate the close link between the topography of debris fans that cause the Colorado River's rapids, the behavior of streamflow in the lee of debris fans that create large recirculating eddies, and the development of distinct separation and reattachment bars near the upstream and downstream ends of each eddy. The details and channel morphology of each debris fan differ, as do the characteristics of the flow entering each rapid. Because of these challenges, it is impossible to predict the detailed behavior during high flows at every sandbar in Grand Canyon. Thus, scientists strive to generalize results by using the average channel characteristics, average debris fan shape, and average sediment-transport characteristics in different segments of Grand Canyon.



Cross-section view illustrating the three-dimensional characteristics of streamflow during the 2008 HFE. The view is looking downstream and shows the core of high-velocity flow far on the right side of the river. Filled contours are the downstream velocity component; downstream is red and upstream is blue. Arrows show vectors of cross-section and vertical-velocity components. Transect is located at the downstream end of the eddy depicted on the previous page (Wright and Kaplinski, in press).

surface-flow conditions, measurements of bed topography, or interpretation of sedimentary structures of exposed bedforms and bars during periods of low flow (Rubin and others, 1990; Schmidt and Graf, 1990; Andrews, 1991a; Nelson and others, 1994; Rubin and McDonald, 1995).

Research conducted during and since the 1996 HFE provided greater insight about river hydraulics and resultant changes in channel bed and eddy-bar topography, because the technology for making river measurements has greatly improved. Technologies and expanded measurement programs now provide scientists with a better understanding about where sand is distributed on the channel bed and how much of that sand is mobilized and subsequently deposited in eddies during high flows. The identification of fan-eddy complexes as the fundamental building blocks of the river ecosystem led scientists to devise mapping strategies with which to characterize the spatial distribution of these complexes and the distribution of eddy sandbars, campsites, and fish habitat. An ever-improving technology has allowed scientists to understand how fine sediment moves downstream and into eddies. Collectively, these insights provide an unprecedented perspective on how the Colorado River functions mechanistically, and new data contribute to the effort to numerically predict the river's behavior. As described in later chapters, these improvements in understanding have led to better predictions about processes, such as sandbar deposition rates and patterns, which in turn can provide guidance on specific high-flow parameters, such as peak magnitude and duration, for high-flow releases.

Pre-Dam River Terraces and Wind-Blown Deposits

Pre-dam river terraces and wind-blown, or eolian, deposits that occur throughout the river corridor extend to higher elevations than the water surface of the HFEs. Thus, the potential effects of HFEs on these deposits are indirect. Eolian deposits typically occur on or near terraces, and the two units often are interbedded (Hereford and others, 1993). These deposits are host to many of the archeological sites in Grand Canyon (Fairley, 2005). The pre-dam river terraces were originally deposited as eddy sandbars and channel-margin deposits during large pre-dam floods. The terraces are composed primarily of sand and mud, although they may contain layers of coarser tributary and hillslope deposits. The eolian deposits typically are composed of fine sand and silt. These deposits initially were described and mapped in an attempt to understand whether archeological resources were affected by dam operations (Hereford and others, 1993).

In addition to mapping the deposits and categorizing them by age and archeological context, Hereford and others (1993) identified potential mechanisms by which these deposits might be affected by post-dam floods and shorter-duration high flows. One of the most severe outcomes to archeological sites results from the formation and expansion of gullies or rills that form by overland flow across alluvium (sediment deposited by the river) during intense rains (Melis and others, 1995, p. 86; Draut and others, 2004; Pederson and others, 2006; Hazel and others, 2008). Hereford and others (1993) suggested that gully erosion might be arrested or slowed by deposition of sand at gully mouths during HFEs.

Continued research on the pre-dam terraces led to the observation that eolian deposits may play an important role in archeological site preservation. In some cases, the eolian deposits are derived from the pre-dam terraces and are largely inactive. In other cases, the eolian deposits are derived from sandbars close to the river and are active (Draut and Rubin, 2008). Because many of the active dunes are located near archeological sites, this observation led to the hypothesis that increased activity of those dunes might be accomplished by building eddy sandbars, the sand of which might be entrained by canyon winds. In turn, the wind-transported sand might enhance archaeological site preservation by directly burying sites or by filling in small gullies that were eroding into sites (Draut and Rubin, 2008).

Debris-Flow Deposits

Debris fans are maintained by occasional debris flows that emanate from steep, tributary canyons (Graf, 1979). The role of debris flows in creating rapids was first demonstrated by Cooley and others (1977), who described debris flows in December 1966 in Crystal Creek that dramatically changed Crystal Rapids (RM 98) into one of the most difficult rapids of the post-dam river to navigate. Webb and others (1988) described the characteristics of debris flows in Monument Creek (RM 91) in 1984 that changed the configuration of Granite Rapids, and they reexamined the 1966 debris-flow deposits in Crystal and Lava Chuar (RM 65) Creeks (Webb and others, 1989). Researchers in the late 1980s and early 1990s determined that debris flows occurred in all of the nearly 800 steep, ephemeral tributaries in Grand Canyon but that debris flows are more common in some places—upper Marble Canyon and western Grand Canyon—than elsewhere (Griffiths, 1995; Griffiths and others, 1996, 1997; Melis and Webb, 1993; Melis and others, 1995, 1996; Melis, 1997; Webb, Melis, and others, 1999).

Howard and Dolan (1979, 1981) and Graf (1980) predicted that the reduced magnitude of floods following completion of Glen Canyon Dam and other large dams of the Colorado River system might cause accumulation of coarse, bouldery debris in rapids, thereby making rapids more difficult to navigate. Howard and Dolan (1979) further stated that the rapids of Grand Canyon were likely to become increasingly difficult to navigate because of boulder accumulation. Kieffer (1985) estimated that only floods of about 100,000 ft^3/s could transport bouldery debris delivered from tributary flash floods, and a post-dam flood of this magnitude has only occurred once. From measurements made during the 1996 HFE, described in the next chapter, it has been determined that smaller-magnitude floods are capable of transporting recently deposited boulders from debris flows, thus suggesting that boulder accumulation in rapids is not inevitable.

Measurements of Bed-Material Size and Distribution

The bed material of the Colorado River ranges in size from boulders to mud, which reflects the diverse sources of sediment delivered to the river. Bedrock occurs as islands in some places and has been identified on the channel bed by underwater imaging (Anima and others, 1998). Coarse sediments in the river include boulders delivered to the channel bed by debris flows and rockfalls. Wilson (1986) pioneered the use of oceanographic hydroacoustic instruments in Grand Canyon and showed that gravel is widely distributed over much of the channel. He showed that, in fall 1984, between 30 and 81 percent of the channel bed was composed of bedrock or boulders (U.S. Department of the Interior, 1988, table A-2).

Estimates of the proportion of the bed covered by sand vary widely. Because the channel bed and eddies are the only source of sand that creates eddy sandbars during HFEs, scientists have spent much time and effort increasing their understanding of the distribution of sand in the river and how it changes with time. Howard and Dolan (1981) assumed that 75 percent of the bed in Grand Canyon was sand, a value much larger than subsequently estimated by Wilson (1986). Anima and others (1998) used various methods of underwater imaging to show that less than 30 percent of the bed was covered with sand in the early 1990s, and most of this sand was located upstream from rapids and adjacent to eddies near scour holes. Rubin, Anima, and Sanders (1994, p. 6) estimated that the mean thickness of sand in Marble Canyon was “at least a few tens of centimeters and not more than a few meters.” As described in the next chapter, measurements made before and during each HFE now enable scientists to better constrain the amount of sand stored on the bed and the amount available for transport during an HFE. These insights are essential to predicting the outcome of high-flow releases, because river managers seek to transfer new tributary sand inputs from the channel bed to eddies rather than merely moving sand from upstream eddies to those farther downstream.

Adjustment of the Channel Bed at Annual and Decadal Time Scales

If controlled high flows are to be used in the post-dam period to maintain or increase the size of eddy sandbars, it is fundamental to understand the source of sand that is deposited at high elevations during an HFE. Rubin, Anima, and Sanders (1994) provided a conceptual framework that explicitly linked changes in the volume of sandbars with changes in the overall sand mass balance of the river. They argued that two factors control the downstream variations in sandbar erosion: (1) the difference between the amount of sand entering and exiting a given reach and (2) the net rate of sand exchange between the channel bed and eddies. In other words, sandbar erosion (and deposition) depends on how much sand is in the channel and how much of that sand is exchanged with the sand that forms eddy sandbars. The model of Rubin, Anima, and Sanders (1994) is a framework that remains applicable and demonstrates that it is essential to (1) measure large-scale longitudinal changes in sand mass balance, (2) understand the proportion of the total sand supply that is stored in eddies and on the channel bed, and (3) understand the processes by which sand is exchanged between the channel and eddies.

Thus, it is fundamental to understand how the Colorado River adjusts its channel bed at the short time scale of individual floods and also how the river adjusts its form at the multidecadal time scale in response to the large post-dam decrease in sand supply and changes in flow regime. For example, it is not known whether eddy sandbars have been more resistant to change than the sand deposits on the channel bed or whether more sand has been evacuated from the channel bed or eddy sandbars.

Early researchers focused on changes in channel-bed topography, because data were available at the Lees Ferry and Grand Canyon gages (fig. 1). These data (Leopold and Maddock, 1953; Leopold and others, 1964) show that the channel bed had been scoured and filled substantially during the passage of floods and that most of the sand and mud delivered to the Colorado River corridor during the pre-dam period was transported downstream. However, a small, and imprecisely measured, proportion of fine sediment was stored temporarily on the channel bed and banks. These observations were the basis for speculation about whether there were large seasonal or decadal changes in sand accumulation and evacuation. Between the 1950s and the early 1990s, scientists debated whether measured bed changes at the Lees Ferry and Grand Canyon gages were representative of large-scale bed changes throughout Grand Canyon or if those changes were merely local phenomena. Following many years of repeated measurements of bed topography and bed-material size, the current understanding of how the river accumulates and evacuates sand is consistent with the interpretation by Colby (1964). The understanding is that (1) sand is temporarily stored in deep scour holes, other deep parts of the riverbed, and eddies; (2) there are parts of the bed that change little during floods and parts that change greatly; and (3) bed locations that change greatly are an important source of the sand that is entrained by the river and deposited in eddies during HFEs.

In contrast to speculation about changes to the riverbed in Grand Canyon, bed changes in Glen Canyon between the dam and Lees Ferry have been well measured and were well understood at the time of the 1996 HFE. Pemberton (1976) showed that the bed had been substantially scoured in Glen Canyon and that by 1963 the zone of scour had extended about 7 miles downstream from the dam. Grams and others (2007) described in detail the timing and downstream extent of this erosion and bed coarsening that ultimately resulted in the transformation of that reach from a predominantly sand-bedded river to a gravel and cobble-bedded river (see text box, Channel Change in the Glen Canyon Reach).

Adjustment of Sandbars at Annual and Decadal Time Scales

Sandbar erosion in Grand Canyon was observed by river runners and scientists in the early 1970s (Dolan and others, 1974; Laursen and Silverston, 1976). The cause of the erosion was uncertain. Some researchers attributed erosion to the river's tendency to evacuate sand in response to the diminished sand supply. Other researchers focused on the effects of the daily pulses of streamflow caused by the peak production of hydroelectric power because it was assumed that the channel bed was accumulating sand even while the eddy sandbars were eroding. Concerns about erosion prompted the National Park Service (NPS) to establish a sandbar-monitoring program in the mid-1970s. This monitoring program was maintained in the late-1970s and early 1980s by NPS cooperators (see review by Webb, Wegner, and others, 1999). Although Howard (1975) and Howard and Dolan (1976, 1979) initially concluded that sandbar erosion was substantial, these findings were revised by Howard and Dolan (1981, p. 284) who concluded "during the first ten years since the dam, sandy channel banks have suffered only a very slight erosion, with individual cases of both pronounced erosion and marked deposition." Occasional topographic measurements of sandbars were made throughout the early 1980s (Beus and others, 1982, 1984).

Increased funding and scientific attention associated with the initial GCES program coincided with the floods of the mid-1980s (fig. 5). The effects of the summer 1983 flood were not well measured, however, because the flood was underway when the GCES field program began. Channel changes caused by this flood primarily were inferred from observed changes in campsites. Brian and Thomas (1984) reported that some campsites were eroded and others were created by this flood. Most of the campsites that were affected by sand deposition were in western Grand Canyon. The effects of the 1984 flood on sandbars were measured by Beus and others (1985).

The effects of the 1985 flood on sandbars were measured by Schmidt and Graf (1990), who measured sandbar topography during peak flood and flood recession in May and August. They also measured widespread and substantial erosion of flood-formed bars during an experimental period of powerplant fluctuations between October 1985 and mid-January 1986. Occasional topographic measurements of sandbars were made in the late 1980s and as part of the 1990–91 experimental flow periods (Beus and others, 1992).

Schmidt and Graf (1990) and Kearsley and others (1994) evaluated sandbar conditions in the late 1980s within a historical context of topographic changes that had occurred since dam closure by making measurements on aerial photographs taken in 1965, 1973, 1980, 1984, and 1990. Kearsley and others (1994) concluded that approximately one-half of the sandbars used as campsites were smaller in 1990 than in 1965 and only 2 percent were larger (fig. 11). They also concluded that the "benefit" of sandbar rebuilding caused by the 1983 flood had been short lived because of subsequent erosion.

By the mid-1990s, it was generally agreed that large post-dam floods or floods with very large suspended-sand concentrations could rework and rebuild eddy sandbars. Researchers concluded that eddy sandbars had been substantially reworked by the 1983 flood and that large amounts of riparian vegetation had also been removed. Rubin, Schmidt, and others (1994) showed that the smaller floods of 1984 through 1986 had rearranged the 1983 flood deposits and left a relatively thin veneer of reworked sand on platforms of 1983-deposited sand. In January 1993, approximately 4.6 million tons of sand were delivered by flooding in the Little Colorado River, and Wiele and others (1996) showed that the associated high concentrations of sand in the main stem of the river could create large eddy sandbars. The sedimentology of separation bars and reattachment bars formed by the floods of the 1980s was relatively consistent throughout Grand Canyon (Rubin, Schmidt, and others, 1994), providing indication that there may have been some consistency in how eddy sandbars responded to a subsequent HFE.

Progress in monitoring sandbar change has continued during the past 15 years. Today, comprehensive measurements of changes in topography are measured by ground surveys and remote-sensing methods, such as lidar (light detection and ranging; see text box, Modeling the Colorado River Shoreline) and photogrammetry. The spatial and temporal resolution of these measurements is unique among the world's large rivers, yet scientists still struggle to make generalizations about sandbar changes because of the wide range of controlling factors that affect sandbar size and frequency.

Erosion of Eddy Sandbars

By the mid-1990s, the research community realized that sandbar erosion was caused by many processes: (1) nearshore currents, (2) waves generated by rapids (Bauer and Schmidt, 1993), (3) seepage erosion caused when river flows decreased quickly and groundwater in sandbars emerged as springs along the streamward side of the bars (Budhu and Gobin, 1994), (4) wind (Dolan and others, 1974), (5) tributary floods and hillslope runoff (Melis and others 1995; Melis, 1997), (6) mass failures termed rapid failure events (Cluer, 1995), and (7) trampling by hikers and boaters (Valentine and Dolan, 1979). The rapid erosion events observed by Cluer (1995) occurred during fluctuating or steady flows, when a large portion of an eddy sandbar slumped into the main channel and thereby caused a large decrease in sandbar area. Cluer (1995) referred to these events as "rapid failure events" and photographed these events using time-lapse cameras. Rapid-failure events were later measured in detail during HFEs.

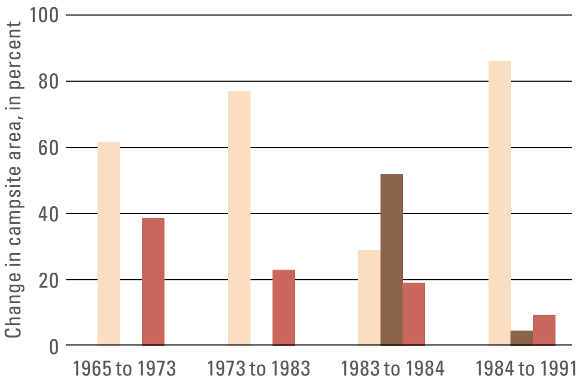


Figure 11. History of changes in campsites in Grand Canyon between 1965 and 1991 based on a composite of results from campsite inventories and aerial photograph interpretation. For each of four time intervals, the percentages of sites are shown that remained approximately the same size (tan), increased in size (brown), or decreased in size (red). Decreases in campsite size occurred in every time interval and the greatest decrease occurred between 1965 and 1973. Some campsites increased in size between 1983 and 1984 and between 1984 and 1991 in response to post-dam floods that occurred between the observations. Modified from Kearsley and others (1994).

Although researchers in the mid-1970s had thought that erosion primarily was caused by large-ranging fluctuations that occurred during days of production of peaking hydroelectric power, researchers in the late 1980s and early 1990s came to realize that eddy sandbar erosion occurred whenever main-stem sand concentrations were low and the flow regime changed. Researchers also realized that the expansion of riparian vegetation led to reduced campsite areas. Although some research has continued concerning the processes and rates of sandbar erosion, the realization that erosion was widespread and inevitable caused researchers to focus more of their attention on how to rebuild sandbars during high releases rather than on how to control the rates of erosion.

Spatial Variability in Patterns of Sandbar Change

Variability in patterns of sandbar change has been observed at both large and small scales. Schmidt and Graf (1990) observed different patterns of sandbar change during the mid-1980s where the channel was narrow and where the channel was relatively wide. Measurements made in the late-1980s and early 1990s showed that different shapes and sizes of debris fans caused eddies and the associated sandbars to respond differently to the same high flow. Recognition of the inherent variability in how sandbars responded to floods subsequently forced researchers to develop robust monitoring programs that would allow recognition of large-scale patterns of sandbar change that would not be overwhelmed by small-scale variability.

Although the study design of the June 1990 through July 1991 test flows sought to explicitly link sandbar erosion with specific flow regimes, Beus and others (1992, p. 59) concluded that "no single test flow alternative affected all sandbars in the same manner." Repeat measurements of 29 sandbars made during the 13-month test period showed that some sandbars were eroded, others had new sand deposition, and others changed little during the entire study period. Study sites did not respond consistently to test flows, and some topographic changes were not expected. Beus and others (1992) found that erosion was widespread and substantial during some steady flows and that deposition of new sand was widespread during some highly fluctuating flows. Such findings were not anticipated by the research and management community, and scientists were inspired to examine the sand-supply conditions during this period. Although the current high-resolution, suspended-sediment monitoring program was not yet in place, Beus and others (1992) speculated that erosion or deposition more likely was determined by the recent occurrence, or lack of occurrence, of tributary sand-supplying floods, than by the flow regimes that were being evaluated.

The Need for High-Flow Experiments

The need to test the potential use of high flows was a significant part of the EIS (U.S. Department of the Interior, 1995) and Record of Decision (U.S. Department of the Interior, 1996), the basis of which was a management objective to maintain or improve, if possible, the condition of sandbars and related resources in Grand Canyon National Park. The studies summarized in this report provided the scientific basis for that objective and identified the gaps in knowledge that high-flow experimentation might fill. Although sandbar erosion was considered the “problem,” these studies recognized that some degree of sandbar erosion was an inevitable natural process, even under restricted flows designed to minimize sand transport and reduce erosion rates. Thus, the idea of using high flows to “replenish” sandbars included the concept that the high flows would need to be repeated with some frequency to compensate for erosion between the events. It was clearly recognized that experimentation was needed. Although the floods of the 1980s and the winter 1993 floods from the Little Colorado River demonstrated that high flows can build sandbars, prescribed high flows require specificity in terms of flow magnitude, duration, hydrograph shape, and the frequency required to meet management objectives. An additional overarching question was whether there was enough sand enrichment to provide the elevated suspended-sediment concentrations needed to build and also maintain sandbars. The following chapter describes and summarizes studies conducted during these high flows that were designed to address these questions and additional studies that were undertaken to monitor the results of the HFEs and evaluate the degree to which they were meeting management objectives.

References

Andrews, E.D., 1986, Downstream effects of Flaming Gorge Dam on the Green River, Colorado and Utah: Geological Society of America Bulletin, v. 97, no. 8, p. 1012–1023.

Andrews, E.D., 1990, The Colorado River—A perspective from Lees Ferry, Arizona, *in* Wolman, M.G., and Riggs, H.C., eds., Surface water hydrology—The geology of North America—Decade of North American geology project, v. 0-1: Boulder, Colo., Geological Society of America, p. 304–314.

Andrews, E.D., 1991a, Deposition rate of sand in lateral separation zones, Colorado River [abs.]: Eos, Transactions, American Geophysical Union, v. 72, no. 44, p. 219.

Andrews, E.D., 1991b, Sediment transport in the Colorado River basin, *in* Proceedings of a Symposium, Colorado River ecology and dam management, May 24–25, 1990, Santa Fe, New Mexico: Washington, D.C., National Academies Press, p. 43–60.

Anima, R.J., Marlow, M.S., Rubin, D.M., and Hogg, D.J., 1998, Comparison of sand distribution between April 1994 and June 1996 along six reaches of the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 98–141, 33 p.

Bauer, B.O., and Schmidt, J.C., 1993, Waves and sandbar erosion in the Grand Canyon—Applying coastal theory to a fluvial system: Annals of the Association of American Geographers, v. 83, no. 3, p. 475–497, doi: 10.1111/j.1467-8306.1993.tb01946.x.

Beus, S.S., Avery, C.C., Stevens, L., Cluer, B., Kaplinski, M., Anderson, P., Bennett, J., Brod, C., Hazel, J., Gonzales, M., Hayes, H., Protiva, F., and Courson, J., 1992, The influence of variable discharge regimes on Colorado River sand bars below Glen Canyon Dam (chap. 6), *in* Beus, S.S., and Avery, C.C., Principal investigators, 1992, The influence of variable discharge regimes on Colorado River sand bars below Glen Canyon Dam—Final report: Bureau of Reclamation, Glen Canyon Environmental Studies, National Park Service cooperative agreement no. CA 8006-8-0002 with Northern Arizona University, 62 p., accessed January 29, 2011, at *http://www.gcmrc.gov/library/reports/physical/Fine_Sed/beus1993.pdf*.

Beus, S.S., Biddle, J.W., Iaquinto, P., Lojko, F.B., and McAfee, B., 1982, Study of beach profiles as a measure of beach erosion on the Colorado River, *in* Beus, S.S., and Carothers, S.W., eds., Colorado River Investigations I—July–August 1982: Northern Arizona University/Museum of Northern Arizona, report submitted to Grand Canyon National Park, p. 16–19, accessed January 29, 2011, at *http://www.gcmrc.gov/library/reports/physical/hydrology/Beus1983.pdf*.

Beus, S.S., Burmaster, B., Byars, B., Dancis, D., Hasenbuhler, P., and Pauls, J., 1984, Changes in beach profiles along the Colorado River in Grand Canyon, 1974-1983, *in* Beus, S.S., and Carothers, S.W., eds., Colorado River Investigations II—July–August 1983: Northern Arizona University/Museum of Northern Arizona, report submitted to Grand Canyon National Park, p. 58–104, accessed January 29, 2011, at *http://www.gcmrc.gov/library/reports/physical/hydrology/Beus1984.pdf*.

Beus, S.S., Carothers, S.W., and Avery, C.C., 1985, Topographic changes in fluvial terrace deposits used as campsite beaches along the Colorado River in Grand Canyon: Journal of the Arizona-Nevada Academy of Science, v. 20, no. 2, p. 111–120.

Beus, S.S., and Morales, Michael, eds., 2003, Grand Canyon geology (2d ed.): New York, Oxford, Oxford University Press, 432 p.

Birdseye, C.H., 1924 (reprinted in 1943), Plan and profile of Colorado River from Lees Ferry, Arizona, to Black Canyon, Arizona–Nevada, and Virgin River, Nevada: U.S. Geological Survey topographic maps, 21 sheets (A–U), scale 1:31,680.

Borland, W.M., and Miller, C.R., 1960, Sediment problems of the lower Colorado River: Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division, v. 86, no. HY4, p. 61–87.

Brandt, S.A., 2000a, Classification of geomorphological effects downstream of dams: Catena, v. 40, no. 4, p. 375–401, accessed January 27, 2011, at *http://dx.doi.org/10.1016/S0341-8162(00)00093-X*.

Brandt, S.A., 2000b, Prediction of downstream geomorphological changes after dam construction—A stream power approach: International Journal of Water Resources Development, v. 16, no. 3, p. 343–367, accessed January 27, 2011, at *http://dx.doi.org/10.1080/713672510*.

Brian, N.J., and Thomas, J.R., 1984, 1983 Colorado River beach campsite inventory: National Park Service, Division of Resource Management, Grand Canyon National Park, 56 p.

Budhu, Muniram, and Gobin, Roger, 1994, Instability of sand bars in Grand Canyon: Journal of Hydraulic Engineering, v. 120, no. 8, p. 919–933.

Burkham, D.E., 1986, Trends in selected hydraulic variables for the Colorado River at Lees Ferry and near Grand Canyon, Arizona—1922–1984: Flagstaff, Arizona, Bureau of Reclamation, Glen Canyon Environmental Studies, 58 p. (Available from National Technical Information Service, PB88-216098/AS.)

Carothers, S.W., and Brown, B.T., 1991, The Colorado River through Grand Canyon—Natural history and human change: Tucson, University of Arizona Press, 235 p.

Clover, E.U., and Jotter, Lois, 1944, Floristic studies in the canyon of the Colorado and tributaries: The American Midland Naturalist, v. 32, no. 3, p. 591–642, accessed December 7, 2009, at *http://www.jstor.org/stable/2421241*.

Cluer, B.L., 1995, Cyclic fluvial processes and bias in environmental monitoring—Colorado River in Grand Canyon: Journal of Geology, v. 103, no. 4, p. 411–421, accessed January 27, 2011, at *http://www.jstor.org/stable/30071162*.

Colby, B.R., 1964, Scour and fill in sand-bed streams: U.S. Geological Survey Professional Paper 462–D, 32 p.

Cooley, M.E., Aldridge, B.N., and Euler, R.C., 1977, Effects of the catastrophic flood of December 1966, North Rim area, eastern Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 980, 43 p.

Cory, H.T., 1913, Irrigation and river control in the Colorado River delta: Transactions of the American Society of Civil Engineers, v. 76, no. 1, p. 1204–1453.

Davis, A.P., 1897, Irrigation near Phoenix, Arizona: U.S. Geological Survey Water-Supply Paper 2, 98 p.

deBuys, W.E., and Myers, Joan, 1999, Salt dreams—Land & water in low-down California: Albuquerque, University of New Mexico Press, 307 p.

Dolan, Robert, Howard, Alan, and Gallenson, Arthur, 1974, Man's impact on the Colorado River in the Grand Canyon: American Scientist, v. 62, no. 4, p. 392–401.

Dolan, Robert, Howard, Alan, and Trimble, David, 1978, Structural control of the rapids and pools of the Colorado River in the Grand Canyon: Science, v. 202, no. 4368, p. 629–631, accessed January 27, 2011, at *http://dx.doi.org/10.1126/science.202.4368.629.*

Draut, A.E., and Rubin, D.M., 2008, The role of eolian sediment in the preservation of archeologic sites along the Colorado River corridor in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1756, 71 p. (Also available at *http://pubs.usgs.gov/pp/1756/*.)

Draut, A.E., Rubin, D.M., Dierker, J.L., Fairley, H.C., Griffiths, R.E., Hazel, J.E., Jr., Hunter, R.E., Kohl, Keith, Leap, L.M., Nials, F.L., Topping, D.J., and Yeatts, Michael, 2004, Sedimentology and stratigraphy of the Palisades, Lower Comanche, and Arroyo Grande areas of the Colorado River corridor, Grand Canyon, Arizona: U.S. Geological Survey Scientific Investigations Report 2005–5072, 74 p. (Also available at *http://pubs.usgs.gov/sir/2005/5072*.)

Evermann, B.W., and Rutter, Cloud, 1895, The fishes of the Colorado Basin: Bulletin of the U.S. Fish Commission, v. 14, p. 473–486, accessed November 5, 2010, at *http://fishbull.noaa.gov/14-1/evermann1.pdf*.

Fairley, H.C., 2005, Cultural resources in the Colorado River corridor, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 11, p. 177–192.

Graf, W.L., 1979, Rapids in canyon rivers: Journal of Geology, v. 87, p. 533–551.

Graf, W.L., 1980, The effect of dam closure on downstream rapids: Water Resources Research, v. 16, no. 1, p. 129–136, accessed January 27, 2011, at *http://dx.doi.org/10.1029/WR016i001p00129.*

Grams, P.E., Schmidt, J.C., and Topping, D.J., 2007, The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956–2000: Geological Society of America Bulletin, v. 119, no. 5–6, p. 556–575, doi:10.1130/B25969.1, accessed February 12, 2010, at *http://gsabulletin.gsapubs.org/content/119/5-6/556.abstract.*

Grant, G.E., Schmidt, J.C., and Lewis, S.L., 2003, A geological framework for interpreting downstream effects of dams on rivers, *in* O'Connor, J.E., and Grant, G.E., eds., A peculiar river—Geology, geomorphology, and hydrology of the Deschutes River, Oregon: Water Science and Application 7, American Geophysical Union, p. 203–219.

Griffin, E.R., 1997, Use of a geographic information system to extract topography for modeling flow in the Colorado River through Marble and Grand Canyons: Boulder, University of Colorado, M.S. thesis, 113 p.

Griffiths, P.G., 1995, Initiation and frequency of debris flows in Grand Canyon, Arizona: Tucson, University of Arizona, M.S. thesis, 56 p.

Griffiths, P.G., Webb, R.H., and Melis, T.S., 1996, Initiation and frequency of debris flows in Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 96–491, 35 p.

Griffiths, P.G., Webb, R.H., and Melis, T.S., 1997, Initiation of debris flows in tributaries of the Colorado River in Grand Canyon, Arizona, *in* Chen, C-l., ed., Debris-flow hazards mitigation—Mechanics, prediction, and assessment, Proceedings of the First International Conference, August 7–9, 1997, San Francisco, California: New York, American Society of Civil Engineers, p. 12–20.

Hazel, J.E., Jr., Grams, P.E., Schmidt, J.C., and Kaplinski, Matt, 2010, Sandbar response in Marble and Grand Canyons, Arizona, following the 2008 high-flow experiment on the Colorado River: U.S. Geological Survey Scientific Investigations Report 2010–5015, 52 p. (Also available at *http://pubs.usgs.gov/sir/2010/5015/*.)

Hazel, J.E., Jr., Kaplinski, Matt, Parnell, R.A., Kohl, Keith, and Schmidt, J.C., 2008, Monitoring fine-grained sediment in the Colorado River ecosystem, Arizona—Control network and conventional survey techniques: U.S. Geological Survey Open-File Report 2008–1276, 15 p. (Also available at *http://pubs.usgs.gov/of/2008/1276/*.)

Hazel, J.E., Jr., Topping, D.J., Schmidt, J.C., and Kaplinski, Matt, 2006, Influence of a dam on fine-sediment storage in a canyon river: Journal of Geophysical Research, v. 111, no. F01025, p. 1–16, doi:10.1029/2004JF000193.

Hereford, Richard, Fairley, H.C., Thompson, K.S., and Balsom, J.R., 1993, Surficial geology, geomorphology, and erosion of archeologic sites along the Colorado River, eastern Grand Canyon, Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 93–517, 46 p.

Howard, A.D., 1975, Establishment of benchmark study sites along the Colorado River in Grand Canyon National Park for monitoring of beach erosion caused by natural forces and human impact: University of Virginia Grand Canyon Study, technical report no. 1, 182 p.

Howard, A.D., and Dolan, Robert, eds., 1976, Alterations of terrace deposits and beaches of the Colorado River in the Grand Canyon caused by Glen Canyon Dam and by camping activities during river float trips—Summary, management implications, and recommendations for future research and monitoring: Colorado River Research Program final report, technical report no. 7, University of Virginia Grand Canyon Study, technical report no. 2, 29 p.

Howard, A.D., and Dolan, Robert, 1979, Changes in the fluvial deposits of the Colorado River in the Grand Canyon caused by Glen Canyon Dam, in Linn, R.M., ed., Proceedings of the First Conference on Scientific Research in the National Parks, November 9–12, 1976, New Orleans, Louisiana: Washington, D.C., National Park Service, p. 845–851.

Howard, Alan, and Dolan Robert, 1981, Geomorphology of the Colorado River in the Grand Canyon: The Journal of Geology, v. 89, no. 3, p. 269–298, doi: 10.1086/628592, accessed February 18, 2010, at *http://www.jstor.org/pss/30078299*.

Iorns, W.V., Hembree, C.H., and Oakland, G.L., 1965, Water resources of the upper Colorado River Basin—Technical report: U.S. Geological Survey Professional Paper 441, 370 p.

Kaplinski, Matt, Hazel, J.E., Jr., Parnell, Rod, Breedlove, Mike, Kohl, Keith, and Gonzales, Mark, 2009, Monitoring fine-sediment volume in the Colorado River ecosystem, Arizona—Bathymetric survey techniques: U.S. Geological Survey Open-File Report 2009–1207, 33 p. (Also available at *http://pubs.usgs.gov/of/2009/1207/*.)

Kearsley, L.H., Quartaroli, R., and Kearsley, M.J.C., 1999, Changes in the number and size of campsites as determined by inventories and measurement, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 147–159.

Kearsley, L.H., Schmidt, J.C., and Warren, K.D., 1994, Effects of Glen Canyon Dam on Colorado River sand deposits used as campsites in Grand Canyon National Park, USA: Regulated Rivers—Research & Management, v. 9, no. 3, p. 137–149, doi:10.1002/rrr.3450090302.

Kieffer, S.W., 1985, The 1983 hydraulic jump in Crystal Rapid—Implications for river-running and geomorphic evolution in the Grand Canyon: The Journal of Geology, v. 93, no. 4, p. 385–406.

Lane, E.W., 1955, The importance of fluvial morphology in hydraulic engineering: Proceedings of the American Society of Civil Engineers, v. 81, paper 745, p. 1–17.

LaRue, E.C., 1916, Colorado River and its utilization: U.S. Geological Survey Water-Supply Paper 395, 231 p.

Laursen, E.M., Ince, Simon, Pollack, Jack, 1976, On sediment transport through the Grand Canyon, *in* Federal Interagency Sedimentation Conference, 3d, Denver, Colorado, March 22–25, 1976, Proceedings: Water Resources Council, Sedimentation Committee, p. 4–76—4–87.

Laursen, E.M., and Silverston, Elliot, 1976, Hydrology and sedimentology of the Colorado River in Grand Canyon, Colorado River Research Program final report: Tucson, University of Arizona, technical report no. 13, Colorado River Research Series contribution no. 41, contract CX821060030 to National Park Service, 26 p.

Leopold, L.B., 1969, The rapids and the pools—Grand Canyon, *in* The Colorado River region and John Wesley Powell: U.S. Geological Survey Professional Paper 669–D, p. 129–145.

Leopold, L.B., and Maddock, Thomas, Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 53 p.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964, Fluvial processes in geomorphology: San Francisco, California, W.H. Freeman, 522 p.

Lippincott, J.B., 1900, Storage of water on Gila River, Arizona: U.S. Geological Survey Water-Supply Paper 33, 98 p.

Magirl, C.S., Breedlove, M.J., Webb, R.H., and Griffiths, P.G., 2008, Modeling water-surface elevations and virtual shorelines for the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Scientific Investigations Report 2008–5075, 32 p. (Also available at *http://pubs.usgs.gov/sir/2008/5075/*.)

Magirl, C.S., Webb, R.H., and Griffiths, P.G., 2005, Changes in the water surface profile of the Colorado River in Grand Canyon, Arizona, between 1923 and 2000: Water Resources Research, v. 41, no. W05021, p. 1–10, accessed January 27, 2011, at *http://dx.doi.org/doi:10.1029/2003WR002519.*

McKee, E.D., 1938, Original structures in Colorado River flood deposits of Grand Canyon: Journal of Sedimentary Petrology, v. 8, no. 3, p. 77–83.

Melis, T.S., 1997, Geomorphology of debris flows and alluvial fans in Grand Canyon National Park and their influence on the Colorado River below Glen Canyon Dam, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 490 p.

Melis, T.S., Phillips, W.M., Webb, R.H., and Bills, D.J., 1996, When the blue-green waters turn red—Historical flooding in Havasu Creek, Arizona: U.S. Geological Survey Water-Resources Investigations Report 96–4059, 136 p. (Also available at *http://pubs.usgs.gov/wri/1996/wri96-4059/*.)

Melis, T.S., and Webb, R.H., 1993, Debris flows in Grand Canyon National Park, Arizona—Magnitude, frequency, and effects on the Colorado River, *in* Shen, H.W., Su, S.T., and Wen, Feng, eds., Hydraulic Engineering 1993—American Society of Civil Engineers Conference, San Francisco, July 25–30, 1993, Proceedings: American Society of Civil Engineers, p. 1290–1295.

Melis, T.S., Webb, R.H., Griffiths, P.G., and Wise, T.W., 1995, Magnitude and frequency data for historic debris flows in Grand Canyon National Park and vicinity, Arizona: U.S. Geological Survey Water-Resources Investigations Report 94–4214, 285 p.

Miller, R.R., Hubbs, C., and Miller, F.H., 1991, Ichthyological exploration of the American West—The Hubbs-Miller era, 1915–1950, *in* Minckley, W.L., and Deacon, J.E., eds., Battle against extinction—Native fish management in the American west: Tucson, The University of Arizona Press, p. 19–40.

Mueller, G.A., and Marsh, P.C., 2002, Lost, a desert river and its native fishes—A historical perspective of the lower Colorado River: U.S. Geological Survey Information and Technology Report USGS/BRD/ITR—2002–0010, 69 p.

Nelson, J.M., McDonald, R.R., and Rubin, D.M., 1994, Computational prediction of flow and sediment transport patterns in lateral separation eddies [abs.]: Eos, Transactions, American Geophysical Union, v. 75, no. 44, p. 268.

Pederson, J.L., Petersen, P.A., and Dierker, J.L., 2006, Gullying and erosion control at archaeological sites in Grand Canyon, Arizona: Earth Surface Processes and Landforms, v. 31, p. 507–525, doi:10.1002/esp.1286, accessed March 12, 2010, at *http://www.usu.edu/geo/pederson/pederson%20et%20al.%202006%20espl.pdf*.

Pemberton, E.L., 1976, Channel changes in the Colorado River below Glen Canyon Dam, *in* Federal Interagency Sedimentation Conference, 3d, March 22–25, 1976, Denver, Colorado, Proceedings: Water Resources Council, Sedimentation Committee, p. 5–61—5–73.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C., 1997, The natural flow regime—A paradigm for river conservation and restoration: Bioscience, v. 47, no. 11, p. 769–784.

Powell, J.W., 1875, Exploration of the Colorado River of the West and its tributaries explored in 1869, 1870, 1871, and 1872, under the direction of the Secretary of the Smithsonian Institution: Washington, D.C., U.S. Government Printing Office, Smithsonian Institute Publication, 291 p.

Powell, J.W., 1895, Canyons of the Colorado: Meadville, Pennsylvania, Flood and Vincent, The Chautauqua-Century Press, 400 p.

Randle, T.J., and Pemberton, E.L., 1987, Results and analysis of STARS (Sediment Transport and River Simulation model) modeling efforts of the Colorado River in Grand Canyon—Final report: Salt Lake City, Utah, submitted to Bureau of Reclamation, Glen Canyon Environmental Studies, 182 p. (Available from National Technical Information Service, PB88-183421.)

Randle, T.J., Strand, R.I., and Streifel, A., 1993, Engineering and environmental considerations of Grand Canyon sediment management, *in* Engineering Solutions to Environmental Challenges—Annual Lecture Series, 13th, Proceedings, Chattanooga, Tennessee: U.S. Committee on Large Dams, p. 1–13.

Rubin, D.M., Anima, R.A., and Sanders, Rex, 1994, Measurements of sand thicknesses in Grand Canyon, Arizona, and a conceptual model for characterizing changes in sand-bar volume through time and space: U.S. Geological Survey Open-File Report 94–597, 9 p.

Rubin, D.M., and McDonald, R.R., 1995, Nonperiodic eddy pulsations: Water Resources Research, v. 31, no. 6, p. 1595–1605.

Rubin, D.M., Nelson, J.M., and Topping, D.J., 1998, Relation of inversely graded deposits to suspended-sediment grain-size evolution during the 1996 flood experiment in Grand Canyon: Geology, v. 26, no. 2, p. 99–102, accessed December 29, 2009, at *http://geology.gsapubs.org/content/26/2/99*.

Rubin, D.M., Schmidt, J.C., Anima, R.A., Brown, K.M., Hunter, R.E., Ikeda, Hiroshi, Jaffe, B.E., McDonald, R.R., Nelson, J.M., Reiss, T.E., Sanders, Rex, and Stanley, R.G., 1994, Internal structure of bars in Grand Canyon, Arizona, and evaluation of proposed flow alternatives for Glen Canyon Dam: U.S. Geological Survey Open-File Report 94–594, 56 p., accessed March 15, 2010, at *http://pubs.er.usgs.gov/usgspubs/ofr/ofr94594*.

Rubin, D.M., Schmidt, J.C., and Moore, J.N., 1990, Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona: Journal of Sedimentary Petrology, v. 60, no. 6, p. 982–991.

Rubin, D.M., and Topping, D.J., 2001, Quantifying the relative importance of flow regulation and grain size regulation of suspended-sediment transport α and tracking changes in grain size of bed sediment β: Water Resources Research, v. 37, no. 1, p. 133–146.

Schmidt, J.C., 1990, Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona: The Journal of Geology, v. 98, no. 5, p. 709–724.

Schmidt, J.C., Andrews, E.D., Wegner, D.L., Patten, D.T., Marzolf, G.R., and Moody, T.O., 1999, Origins of the 1996 controlled flood in Grand Canyon, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 23–36.

Schmidt, J.C., and Graf, J.B., 1990, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1493, 74 p., accessed March 17, 2010, at *http://pubs.er.usgs.gov/usgspubs/citfor/pp/pp1493*.

Schmidt, J.C., and Rubin, D.M., 1995, Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans, *in* Costa, J.E., Miller, A.J., Potter, K.W., and Wilcock, P.R., eds., Natural and anthropogenic influences in fluvial geomorphology: American Geophysical Union, Geophysical Monograph Series, v. 89, p. 177–195.

Schmidt, J.C., Rubin, D.M., and Ikeda, Hiroshi, 1993, Flume simulation of recirculating flow and sedimentation: Water Resources Research, v. 29, no. 8, p. 2925–2939, doi:10.1029/93WR00770, accessed August 17, 2010, at *http://www.agu.org/pubs/crossref/1993/93WR00770.shtml*.

Schmidt, J.C., Topping, D.J., Grams, P.E., and Hazel, J.E., 2004, System-wide changes in the distribution of fine sediment in the Colorado River corridor between Glen Canyon Dam and Bright Angel Creek, Arizona—Final report: Logan, Utah, Utah State University, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, cooperative agreement no. 1425-98-FC-40-22640, 107 p., accessed January 29, 2011, at *http://www.gcmrc.gov/library/reports/Physical/Fine_Sed/Schmidt2004.pdf*.

Schmidt, J.C., and Wilcock, P.R., 2008, Metrics for assessing the downstream effects of dams: Water Resources Research, v. 44, no. W04404, p. 1–19, doi:10.1029/2006WR005092, accessed November 9, 2010, at *http://www.agu.org/journals/wr/wr0804/2006WR005092/*.

Smillie, G.M., Jackson, W.L., and Tucker, Dean, 1993, Colorado River sand budget—Lees Ferry to Little Colorado River: Washington, D.C., U.S. Department of the Interior, National Park Service, technical report NPS/NRWRD/NRTR-92/12, 11 p.

Smith, D.L., and Crampton, C.G., 1987, The Colorado River survey—Robert B. Stanton and the Denver, Colorado Canyon and Pacific railroad: Salt Lake City, Howe Brothers, 305 p.

Smith, W.O., Vetter, C.P., and Cummings, G.B., 1960, Comprehensive survey of sedimentation in Lake Mead, 1948–49: U.S. Geological Survey Professional Paper 295, 254 p., accessed January 5, 2011, at *http://pubs.er.usgs.gov/usgspubs/pp/pp295*.

Stanley, J.W., 1951, Retrogression on the lower Colorado River after 1935: American Society of Civil Engineers Transactions, v. 116, p. 943–957.

Stephens, H.G., and Shoemaker, E.M., 1987, In the footsteps of John Wesley Powell—An album of comparative photographs of the Green and Colorado Rivers, 1871–72 and 1968: Boulder, Colorado, Johnson Books, 286 p.

Stevens, J.C., 1938, The effect of silt-removal and flow-regulation on the regimen of Rio Grande and Colorado Rivers: Transactions of the American Geophysical Union, v. 19, p. 653–659.

Thomas, H.E., 1960, Drainage basin tributary to Lake Mead, *in* Smith, W.O., Vetter, C.P., Cummings, G.B., eds., Comprehensive survey of sedimentation in Lake Mead, 1948–49: U.S. Geological Survey Professional Paper 295, p. 21–30.

Topping, D.J., Rubin, D.M., Grams, P.E., Griffiths, R.E., Sabol, T.A., Voichick, Nicholas, Tusso, R.B., Vanaman, K.M., and McDonald, R.R., 2010, Sediment transport during three controlled-flood experiments on the Colorado River downstream from Glen Canyon Dam, with implications for eddy-sandbar deposition in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010–1128, 111 p. (Also available at *http://pubs.usgs.gov/of/2010/1128/*.)

Topping, D.J., Rubin, D.M., Nelson, J.M., Kinzel, P.J., III, and Bennett, J.P., 1999, Linkage between grain-size evolution and sediment depletion during Colorado River floods, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 71–98.

Topping, D.J., Rubin, D.M., Nelson, J.M., Kinzel, P.J., III, and Corson, I.C., 2000, Colorado River sediment transport, 2. Systematic bed-elevation and grain-size effects of sand supply limitation: Water Resources Research, v. 36, no. 2, p. 543–570, accessed January 14, 2011, at *http://dx.doi.org/10.1029/1999WR900286*.

Topping, D.J., Rubin, D.M., and Schmidt, J.C., 2005, Regulation of sand transport in the Colorado River by changes in the surface grain size of eddy sandbars over multi-year timescales: Sedimentology, v. 52, no. 5, p. 1133–1153, doi:10.1111/j.1365-3091.2005.00738.x.

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport, 1. Natural sediment supply limitation and the influence of Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515–542, doi: 10.1029/1999WR900285.

Topping, D.J., Schmidt, J.C., and Vierra, L.E., Jr., 2003, Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000: U.S. Geological Survey Professional Paper 1677, 118 p. (Also available at *http://pubs.usgs.gov/pp/pp1677/*.)

Turner, R.M., and Karpiscak, M.M., 1980, Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona: U.S. Geological Survey Professional Paper 1132, 125 p.

U.S. Department of the Interior, 1988, Glen Canyon Environmental Studies Executive Review Committee, Final report: Bureau of Reclamation, Glen Canyon Environmental Studies, 84 p. + apps. (Available from National Technical Information Service, PB88-183348/AS.)

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam—Final Environmental Impact Statement, Colorado River Storage Project, Coconino County, Arizona: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Regional Office, 337 p., accessed November 18, 2010, at *http://www.usbr.gov/uc/library/envdocs/eis/gc/pdfs/Cov-con/cov-con.pdf*.

U.S. Department of the Interior, 1996, Record of decision, Operation of Glen Canyon Dam—Final Environmental Impact Statement: Washington, D.C., Office of the Secretary of the Interior, Bureau of Reclamation, 15 p., accessed May 26, 2010, at *http://www.usbr.gov/uc/rm/amp/pdfs/sp_appndxG_ROD.pdf*.

Valentine, Susan, and Dolan, Robert, 1979, Footstep-induced sediment displacement in the Grand Canyon: Environmental Management, v. 3, no. 6, p. 531–533, doi:10.1007/BF01866322.

Webb, R.H., 1996, Grand Canyon—A century of change—Rephotography of the 1889–1890 Stanton expedition: Tucson, The University of Arizona Press, 290 p.

Webb, R.H., Griffiths, P.G., Melis, T.S., and Hartley, D.R., 2000, Sediment delivery by ungaged tributaries of the Colorado River in Grand Canyon: U.S. Geological Survey Water-Resources Investigations Report 00–4055, 67 p.

Webb, R.H., Melis, T.S., Griffiths, P.G., Elliott, J.G., Cerling, T.E., Poreda, R.J., Wise, T.W., and Pizzuto, J.E., 1999, Lava Falls rapid in Grand Canyon—Effects of late Holocene debris flows on the Colorado River: U.S. Geological Survey Professional Paper 1591, 90 p.

Webb, R.H., Pringle, P.T., Reneau, S.L., and Rink, G.R., 1988, Monument Creek debris flow, 1984—Implications for formation of rapids on the Colorado River in Grand Canyon National Park: Geology, v. 16, no. 1, p. 50–54, doi: 10.1130/0091-7613(1988)016<0050:MCDFIF>2.3.CO;2, accessed December 29, 2009, at *http://geology.gsapubs.org/content/16/1/50.*

Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.

Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., 1999, The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, 367 p.

Webb, R.H., Wegner, D.L., Andrews, E.D., Valdez, R.A., and Patten, D.T., 1999, Downstream effects of Glen Canyon Dam on the Colorado River in Grand Canyon—A review, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 1–21.

Wiele, S.M., Graf, J.B., and Smith, J.D., 1996, Sand deposition in the Colorado River in the Grand Canyon from flooding of the Little Colorado River: Water Resources Research, v. 32, no. 12, p. 3579–3596, doi: 10.1029/96WR02842, accessed January 13, 2010, at *http://www.agu.org/journals/wr/v032/i012/96WR02842/.*

Wiele, S.M., and Griffin, E.R., 1997, Modifications to a one-dimensional model of unsteady flow in the Colorado River through Grand Canyon, Arizona: U.S. Geological Survey Water-Resources Investigations Report 97–4046, 17 p.

Wiele, S.M., and Smith, J.D., 1996, A reach-averaged model of diurnal discharge wave propagation down the Colorado River through the Grand Canyon: Water Resources Research, v. 32, no. 5, p. 1375–1386, doi:10.1029/96WR00199.

Williams, G.P., and Wolman, M.G., 1984, Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, 83 p., accessed September 9, 2010, at *http://pubs.er.usgs.gov/usgspubs/pp/pp1286*.

Wilson, R.P., 1986, Sonar patterns of Colorado River bed, Grand Canyon, *in* Federal Interagency Sedimentation Conference, 4th, March 24–27, 1986, Las Vegas, Nevada, Proceedings: U.S. Geological Survey Subcommittee on Sedimentation—Interagency Advisory Committee on Water Data, v. 2, p. 5–133—5–142.

Wright, S.A., and Kaplinski, M., in press, Flow structures and sandbar dynamics in a canyon river during a controlled flood, Colorado River, Arizona: Journal of Geophysical Research.

Paul Grams, U.S. Geological Survey

CHAPTER 3

The High Flows—Physical Science Results

By John C. Schmidt[1] and Paul E. Grams[2]

As described in chapters 1 and 2, both the existence of Glen Canyon Dam as a physical barrier and the regulation of streamflow and water temperature by operation of the dam caused changes to the downstream environment of the Colorado River (fig. 1). The undesirable effects from the existence of the dam and Lake Powell, the reservoir formed by the dam, could be mitigated only by costly alterations or construction of new facilities. Those effects that result completely from the operation of the dam, however, could possibly be mitigated by changes in the schedule of dam releases that generate hydroelectricity and by the release of additional flow using tubes that bypass the powerplant's turbines. Some changes to the Colorado River result from both the existence and operation of the dam, such as the temperature of waters released downstream, and these effects could be partially mitigated by changes in the elevations at which water is extracted from Lake Powell.

Many changes have occurred in the physical structure and geomorphic processes of the Colorado River downstream from the dam since it was completed in 1963. The reduced magnitude and frequency of floods have caused accumulation of gravel, cobbles, and boulders in bars and in rapids. The greatly reduced supply of sand and mud once delivered from the upstream watershed led to bed incision and removal of most of the sand that once covered the Colorado River in the 16 miles between the dam and Lees Ferry (fig. 1). Downstream from Lees Ferry, the greatly reduced sand and mud supply has led to a decrease in the number and size of sandbars.

High-flow experiments (HFEs) have been implemented in order to make critical measurements of physical processes of the post-dam river, especially regarding how the Colorado River transports and reworks the remaining small supply of sand and mud, primarily contributed by the Paria and Little Colorado Rivers. Additionally, HFEs have been implemented as management actions in order to evaluate if short-duration high flows could significantly restructure some of the valued natural resources of the Colorado River ecosystem. In this chapter, the scientific findings and insights gained from the three HFEs conducted in 1996, 2004, and 2008 are summarized as they pertain to important physical processes and related natural resources. This chapter primarily focuses on processes and attributes related to sand, because that is the physical attribute of the system most closely associated with target natural and cultural resources. The movement of gravel and boulders is briefly summarized as are the changes in associated natural resources, such as characteristics of rapids.

The decision to implement the first HFE in 1996 followed extensive consideration of the effects of post-dam floods and short-duration high flows. As described in chapter 2, post-dam floods, as defined by the Bureau of Reclamation, are those dam releases that exceed the capacity of the hydroelectric powerplant and last longer than a month; these floods occurred in 1965,

[1] Intermountain Center for River Rehabilitation and Restoration, Department of Watershed Sciences, Utah State University, Logan, UT 84322–5210.

[2] U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, 2255 N. Gemini Drive, Flagstaff, AZ 86001.

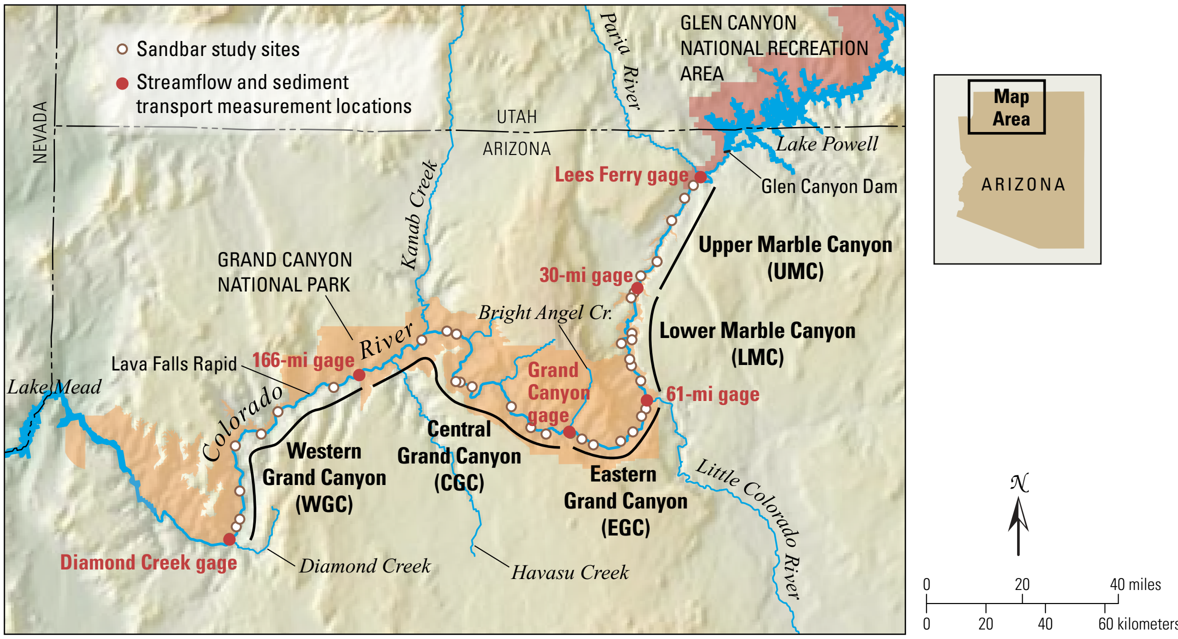


Figure 1. The Grand Canyon region, showing locations of gaging stations and data-collection sites for sandbar topography and channel bathymetry. The Lees Ferry gage (U.S. Geological Survey station 093820000) continuously measures stage and streamflow; supplemental sediment transport measurements have been made during some post-dam floods and all high-flow experiments (HFEs). The 30-mile, 61-mile, Grand Canyon (U.S. Geological Survey station 09402500), 166-mile, and Diamond Creek (U.S. Geological Survey station 09404200) gages continuously measure stage, streamflow, and suspended-sand concentration. During the 1996 HFE, data were collected at the Lees Ferry, 61-mile, Grand Canyon, and 166-mile gages. During the 2004 HFE, data were collected at the Lees Ferry, 30-mile, 61-mile, Grand Canyon, and Diamond Creek gages. Data were collected at all six gages during the 2008 HFE. See Topping and others (2010) for detailed information on the data collected at each gage. The reaches for sand mass-balance calculations between the gages are also identified. Modified from Hazel and others (2010).

1983, 1984, 1985, and 1986. Short-duration high flows also exceed powerplant capacity but last only a few days. Before 1996, short-duration high flows occurred in June and July 1980 and August 1984. These high flows were engineering tests conducted to evaluate the dam's spillway.

Measurements and observations made during and after the post-dam floods of the mid-1980s convinced the research and resource management communities that long-duration floods eroded sandbars and caused damage to other resources (U.S. Department of the Interior, 1988). Other studies, however, indicated that the physical and ecological responses to short-duration high flows were potentially beneficial. Thus, the National Research Council (1996) encouraged the use of short-duration high flows as a tool in rehabilitating desired attributes of the riverine ecosystem (Schmidt, Andrews, and others, 1999).

Streamflow Characteristics of Three High-Flow Experiments

The first HFE occurred between March 26 and April 7, 1996, and was a 7-day steady release of 45,000 cubic feet per second (ft^3/s) that was preceded and followed by low, steady flows of 8,000 ft^3/s for 4 days (chapter 2, fig. 6, this volume). The second HFE occurred between

November 22 and 24, 2004, and was a 60-hour steady release of about 41,700 ft^3/s. The third HFE occurred between March 6 and 8, 2008, and was a 60-hour release of about 42,800 ft^3/s. The 2004 and 2008 high flows rose over 30-hour periods, a 50-percent slower rate of rise than for the 1996 high flow.

The magnitude of floods on wide rivers decreases downstream if a substantial amount of the floodwaters temporarily occupies the flood plain. However, the magnitude of a flood can increase downstream if there are large inflows from tributaries. In narrow-bottomed canyons, such as Grand Canyon, flood attenuation caused by overbank flooding is small, and the primary downstream changes in flood magnitude occur when a high flow coincides with tributary inflows.

During the 1996 HFE, tributary inflow was minimal, and flow of the Colorado River at Diamond Creek (fig. 1), 241 miles downstream from the dam, exceeded the release at the dam by about 500 ft^3/s, which was only a 1-percent increase in flood magnitude. In contrast, substantially more tributary inflow was measured in 2004 and in 2008, and discharge at Diamond Creek exceeded the magnitude of the dam release by about 5 percent.

Purposes and Design of the High-Flow Experiments

The HFEs had two purposes, one related to management of riverine resources and another related to improving scientific understanding of physical and biological processes in the river (Marzolf and others, 1999; Schmidt, Andrews, and others, 1999; Patten and others, 2001). Thus, each HFE was a management action with natural resource responses that were predicted and evaluated through environmental assessments (U.S. Department of the Interior, 2002, 2004). Each HFE was also a scientific experiment during which critical measurements were made and scientific hypotheses were tested. The dual purposes of the HFEs were closely linked, because each prediction about a resource response was itself a hypothesis that could be tested.

As management actions, the goals of the HFEs were to improve those river resources that are well adapted to floods, control undesirable physical and biological attributes of the river ecosystem, and not damage desirable natural resources less well adapted to floods. Four of the primary objectives of the 1996 HFE focused on anticipated positive responses of resources well adapted to floods (Schmidt, Andrews, and others, 1999; Patten and others, 2001):

- rejuvenate low-velocity habitats for native fishes
- enlarge sand deposits
- preserve and restore sandbars used as campsites
- provide water to vegetation in the upper riparian zone

Two other objectives of the 1996 HFE—reduce nearshore vegetation and remove nonnative fish downstream from Lees Ferry—sought to control undesirable species believed to be less well adapted to floods. In addition, it was predicted that desirable resources less well adapted to floods, such as nonnative rainbow trout (*Oncorhynchus mykiss*) that live in the Colorado River immediately downstream from Glen Canyon Dam, would not be adversely affected.

Although any HFE might be perceived as "failing" if specific desired resource responses are not achieved, the success of an HFE may also be judged by the scientific understanding gained from the experiment and comparisons with other HFEs. Marzolf and others (1999, p. 367) observed

> [The 1996 HFE] *was conducted to demonstrate management utility. At the same time, the flood was* [an] * * * *experiment to test specific ideas about what had been learned about the physics of flow, sediment transport, and sediment deposition. As a management demonstration, the flood might have resulted in failure: that is, the expected beneficial effects might not have been realized. As* [an] * * * *experiment, the flood could*

not fail, because no matter what happened new knowledge would have been gained as long as appropriate observations were made. Ideas would have been either reinforced and understood more certainly because the result was as expected and the causes and effects more clearly documented, or concepts would be rejected, and knowledge would have changed because the results were not as expected. In fact, science proceeds most certainly when incorrect ideas are rejected.

Between 1996 and 2008, scientific hypotheses for each HFE evolved as learning progressed. In 1996, predictions about sediment transport were very explicit. It was predicted that 840,000 tons of sand would be transported past the 61-mile gage (fig. 1) during the 7-day HFE. New deposition on sandbars was predicted to be 1 to 3 feet thick (Schmidt, Andrews, and others, 1999). The 2004 HFE was predicted "to create sandbars more efficiently and with a more diverse grain size distribution * * * and * * * to transport a smaller percentage of sediment downstream" (U.S. Department of the Interior, 2002, p. 43). It was also hypothesized that the 2004 HFE would result in sandbars with larger proportions of mud and very fine sand than sandbars formed in 1996. It was predicted that these sandbars "would likely be more resistant to erosion and retain more nutrients than coarser grained sandbars" because clay and silt add strength to sand deposits (U.S. Department of the Interior, 2002, p. 43).

The duration and timing of the 2004 and 2008 HFEs were partly designed to clarify findings gained from the previous HFEs. The magnitude of each HFE was similar because of constraints inherent in the design of the dam (when the reservoir is full, no more than about 31,500 ft^3/s may be released through the powerplant and an additional 15,000 ft^3/s may be released through tubes that bypass the powerplant). The similarity of flood magnitude among the HFEs allowed scientists to replicate some of their measurements (U.S. Department of the Interior, 2002). The duration of the HFEs was adjusted, however, because results from the 1996 experiment demonstrated that high concentrations of suspended sand in the river could be sustained for only a few days. The timing of the 2004 HFE was adjusted to evaluate the benefit of scheduling a high flow in the fall to more closely coincide with the tributary floods that had delivered large amounts of fine sediment to the Colorado River. The 2008 HFE occurred after 2 consecutive years of unusually large tributary inputs of fine sediment and before most of the new sand was exported downstream to Lake Mead by typical dam releases.

Research and evaluation efforts conducted during HFEs can be categorized into two groups (Marzolf and others, 1999). Process/response studies monitor resource response and are designed to encourage learning about the mechanisms and processes by which high flows affect resources. In contrast, negative-impact studies simply monitor the target resource and have limited ability to explain the processes and links that caused the response. Negative-impact studies typically are undertaken when it is believed that there will not be a substantial resource response, when there is insufficient understanding to design a process/response study, or if there is insufficient funding to implement such a study. In 1996, process/response studies focused on measuring the downstream passage of the flood wave, the amount of sediment transported by the river, changes in the amount of sediment on the channel bed, scour of tributary debris-flow deposits near debris fans that form rapids, sandbar erosion and deposition, organic-matter transport, changes in riparian vegetation, and water quality.

Negative-impact studies in 1996 included studies of the aquatic food web, native and non-native fish populations, Kanab ambersnails (*Oxyloma haydeni kanabensis*), and changes in marshes (see chapter 4, this volume). Studies of these biological resources were "primarily to document resource losses or changes" (Marzolf and others, 1999, p. 365) and did not attempt to measure physical or biological ecosystem processes. Over time, biologically oriented process/response studies evolved. Food-web monitoring, for example, shifted from negative-impact studies to process/response studies. Fish studies were increasingly tied to questions associated with the effects of specific dam operations and specific life-history stages.

Evaluation of Physical Effects of the High-Flow Experiments: Key Measurements and Analyses

Most sandbars in Grand Canyon are present in eddies downstream from obstructions that partially block the channel. These obstructions are primarily caused by accumulations of boulders, cobbles, and gravel at the mouths of steep, ephemeral tributaries that partly block the Colorado River and form its rapids. Large, recirculating eddies are present downstream from virtually every rapid, and these eddies are effective traps for the fine sediment carried in suspension by the Colorado River. Eddy sandbars form when the flooding river carries suspended sediment into eddies at a higher rate than the sand and mud can be circulated within the eddy or be returned to the main flow. Large eddy sandbars form when suspended-sediment loads are transported in high concentrations by the main flow. High sandbars are constructed by large magnitude floods that rise to relatively high elevations.

Observations made during the HFEs determined that the concentration and amount of sand transported by high flows is a function of the volume and areal distribution of sand on the channel bed immediately before each high flow. If the areal extent of sand is the same, higher concentrations of suspended sand occur if the sand is finer. Thus, the highest suspended-sand concentrations occur when there is a large amount of fine sand covering a large area of the channel bed. The lowest suspended-sand concentrations occur when there is a small volume of medium or coarse sand spread over a small area of the channel bed. In order to compare the conditions during HFEs, the amount of suspended-sand concentrations and loads and how these amounts changed throughout Grand Canyon must be determined. In turn, such a comparison necessitates evaluation of the amount of sand on the channel bed and in eddies before each HFE and the characteristic size of that sand.

As scientific insight and understanding evolved after the 1996 HFE, scientists changed the measurement strategies and techniques used to characterize river conditions prior to each experiment as well as the techniques used to measure river hydraulics and sediment transport during high flows. New analytical approaches also allowed retrospective analyses; thus, inferences about conditions that existed immediately before the 1996 HFE have been made even though there were few direct measurements made immediately before that high flow (see text box, Monitoring Fine Sediment in Grand Canyon).

Description of River Segments

Nearly all of the sandbar and sediment-transport data collected during the three high flows were collected at monitoring sites located between Lees Ferry and Diamond Creek (fig. 1). This 225-mile river corridor is subdivided into segments. As explained in chapter 2, these subdivisions vary depending on the purpose of the classification. For sediment budgeting, the primary distinction is between Marble Canyon and Grand Canyon. Marble Canyon begins at Lees Ferry and extends downstream to the Colorado River's confluence with the Little Colorado River. Grand Canyon extends from the mouth of the Little Colorado River downstream to the confluence with Diamond Creek, although physiographically, Grand Canyon extends to the Grand Wash Cliffs at river mile[3] (RM) 277. Diamond Creek, however, is used for sediment budgeting purposes, because Lake Mead reservoir inundates much of the Colorado River farther downstream. Marble Canyon is subdivided into upper and lower Marble Canyon at RM 30, which is the location of the 30-mile gage (fig. 1). Eastern Grand Canyon extends from the confluence with the Little Colorado River (RM 61) downstream to the Grand Canyon gage (RM 88; fig. 1). The two largest tributaries downstream from the Little Colorado River—Kanab Creek and Havasu Creek—join the Colorado River in central Grand Canyon. The downstream end of central Grand Canyon is designated at RM 166, the location of the 166-mile gage. Western Grand Canyon extends from this point downstream to the Grand Wash

[3] Locations along the Colorado River in Grand Canyon are referenced by the convention of river mile, which is the distance downstream from Lees Ferry, Arizona, along the channel centerline.

Monitoring Fine Sediment in Grand Canyon

The ability to use high-flow experiments (HFEs) to build sandbars in Grand Canyon depends on the delicate balance between the amount of sand that is supplied to the river by tributaries downstream from Glen Canyon Dam and the amount that is transported downstream to Lake Mead. The difference between these quantities is called a sediment budget and, if positive, is the amount of sand "surplus" that may be redistributed from the river's channel bed to sandbars by high flows. If negative, that difference is the amount of sand that is being eroded from the channel bed and banks. HFEs conducted while maintaining a positive sand budget should continue to cause increases in sandbar size. HFEs conducted in the context of a negative sand budget may result in erosion of sand from the channel bed with temporary increases in sandbar size at the expense of sand stored on the channel bed. Overall, HFEs conducted during such sand "deficit" conditions would eventually eliminate the antecedent conditions that presently cause the river to build sandbars during high flows in the future.

David J. Topping, U.S. Geological Survey

Scientists monitor the sand budget, also known as a sand "mass balance," by measuring the amount of sand and mud that is transported past monitoring stations on the Colorado River and some of the tributaries. Although some sand is transported by rolling or bouncing on the channel bed, more than 90 percent of the sand and all of the mud is carried in suspension above the bed. The standard method for measuring suspended-sediment transport in rivers has been essentially the same since the time the first samples were collected in the Colorado River in the 1920s. This method involves collecting a sample of water and analyzing the sample to determine the concentration and grain size of sand and mud. Samples may be collected by a wide array of sampler types, which have improved over time resulting in more accurate and more consistent measurements. One drawback with these "conventional" samples is that even the most robust sampling schemes that collect samples at multiple locations and depths across the channel actually sample a relatively small fraction of the water passing by any given point. Conventional samples also require the presence of a field crew and use of either a fixed cableway (bottom photograph) or a motor boat (top photograph), which greatly limits how often samples can be collected. While use of an automated pump sampler may allow a somewhat greater frequency of sampling, these samplers also have strict limitations in the number and size of samples that may be collected. Because suspended-sediment concentrations can change rapidly and dramatically and these changes do not necessarily correspond to changes in streamflow, accurate estimates of sand loads require a more robust sampling program than is possible with any of these conventional sampling methods.

Nancy Hornewer, U.S. Geological Survey

Beginning in 2002, sediment researchers initiated a program to overcome some of these obstacles by the use of "surrogate" technologies for measuring suspended-sediment concentrations in water. This effort evolved into the current monitoring program, which relies heavily on the use of a combination of acoustic and optical instruments that measure suspended-sediment concentrations and grain size at 15-minute intervals at five locations along the Colorado River in Marble and Grand Canyons (fig. 1). While these instruments provide the frequency of sampling that is needed, they still require periodic maintenance and calibration with conventional samples. All of these surrogate samplers are connected to field computers, many of which are integrated into a two-way, broadband, satellite-communication system. This allows access to the data from the office and remote instrument observation and maintenance. In its current form, the monitoring network provides the ability, in virtually real-time, to monitor suspended-sediment concentrations and determine the status of the sand budget. This information on sand-enrichment levels can then be made available to scientists and managers for planning potential future high flows.

Cliffs (RM 277), but Diamond Creek is the last point where streamflow and sediment measurements are made.

The river is subdivided differently for the purposes of evaluating the response of sandbars and campsites to HFEs. In some reaches, sandbars and associated camping areas are common relative to demand for recreational campsites while in other reaches demand for campsites frequently exceeds the available supply. Kearsley and others (1994), therefore, divided the river into critical reaches, where campsites are relatively scarce, and noncritical reaches, where campsites are relatively abundant (see chapter 2, table 3, this volume).

Sand Enrichment

Colorado River scientists and managers define the supply of sand delivered by tributaries prior to an HFE as the antecedent sand enrichment (Topping and others, 2010). Antecedent sand enrichment is calculated as the difference between the amount of sand entering and leaving a river segment for a specified time period (see chapter 2, this volume). The objective of each HFE was to redistribute this antecedent sand supply, because that sand primarily is present as submerged eddy sandbars or covers other submerged parts of the channel bed. The goal of the HFEs was to mobilize this sand and build larger eddy sandbars that extend to higher elevations, while minimizing the associated transport of sand downstream toward Lake Mead reservoir. Antecedent sand enrichment is a powerful tool that was used in planning the 2004 and 2008 HFEs and can be used in planning future high flows. Antecedent mud enrichment is not typically calculated and is of less interest in evaluating the effects of high flows on rebuilding eddy sandbars.

One possible long-term experiment Colorado River managers could conduct is to schedule as many high flows in Grand Canyon as can be sustained by the supply of sand delivered from the tributaries. As described below, scientists have learned that each HFE mobilized all, or nearly all, of the antecedent sand enrichment. Thus, to avoid long-term sand depletion, the duration of future high flows can only be for the time it takes to deplete this antecedent supply. Also as explained below, scientists have learned that flood-constructed sandbars erode during the periods between high flows. Thus, a desired outcome of the HFE experimental program is to quantify the balance among the rate of supply of sand from tributaries that increases the antecedent sand enrichment, the quantity of sand mobilized by high flows of different magnitude and duration, and the rate at which sandbars erode during the periods between high flows.

However, not all of the fine sediment on the channel bed and in eddies immediately before an HFE is antecedent sand enrichment. Additionally, there is sand that was in the river channel before Glen Canyon Dam was completed in 1963. The amount of this nonrenewable supply of sand that was in the river at the time of dam completion is unknown. Because monitoring was sparse, the change in the nonrenewable supply that occurred between 1963 and the beginning of the HFEs in 1996 is also unknown, but Topping and others (2000) concluded that an increase in sand storage during this period was unlikely (see chapter 2, this volume). Evolving technology since the late 1990s, however, has provided increasingly precise ways to measure the recent deliveries of sand by tributaries, primarily from the Paria and Little Colorado Rivers. Scientists also are able to more accurately and precisely measure the rate at which that sediment is transported downstream after entering the Colorado River. Because the antecedent sand enrichment is determined by the recent delivery of tributary sand minus the export of that sand farther downstream toward Lake Mead prior to the HFE, improved measurement of main-stem sand transport is a critical component of the calculation of the sand enrichment of each part of Marble and Grand Canyons.

In upper Marble Canyon (fig. 1), the antecedent sand enrichment is calculated as the sum of all sand inputs that enter the Colorado River between Lees Ferry and the 30-mile gage, minus the measured export of sand past the 30-mile gage. Sand inputs from the Paria River are estimated on the basis of measurements of discharge and sand concentrations, and the same procedure is used to estimate sand inflow from the Little Colorado River (Topping and others, 2010). For smaller tributaries, including Kanab and Havasu Creeks, inputs are estimated on the basis of regional relations (Webb and others, 2000; Topping and others, 2010).

Antecedent sand enrichment can be calculated for any time period for which measurements are available. Topping and others (2010) used different time periods to calculate enrichment before the 2004 and 2008 HFEs. They justified using different time periods because each HFE had a different experimental design and planning period.

Field Measurements of Suspended Sediment

Suspended-sediment data were collected at four gages during the 1996 HFE, and findings from that HFE prompted expansion of sediment-monitoring efforts in tributaries and the Colorado River (see text box, Monitoring Fine Sediment in Grand Canyon). Five gages measured suspended sediment in the main stem during the 2004 HFE, and six gages were in operation during the 2008 HFE. These data, combined with data collected in the tributaries, allowed direct calculation of antecedent sand enrichment in 2004 and 2008. The monitoring program is described in detail by Topping and others (2010).

Longitudinal, or downstream, patterns in sand transport during the HFEs were measured in two ways. First, scientists compared the concentrations of suspended sand at the different gages in 1996, 2004, and 2008. Second, scientists made measurements of sand concentration at approximately 0.5-mile intervals between the gages on downstream sampling trips in 2004 and 2008.

The objective of the latter sampling scheme was to examine how suspended-sand concentration changed within one parcel of the HFE's water as it passed downstream from Lees Ferry through Marble and Grand Canyons. This type of sampling is informative, because it can be used to identify which parts of the river contributed relatively more or less sand to the river's transported load during the HFE. Because no sand is released with the water at the dam and tributary sand input during the HFEs has been negligible, all of the sand in transport downstream comes from the channel bed and from eddy sandbars. The suspended-sediment concentration increases rapidly as sand and mud that had been deposited on the bed and in eddies is entrained, or picked up, by the high flow. At some distance downstream, however, the quantity of fine sediment entrained by the flow from some parts of the channel is approximately balanced by the quantity deposited in other locations, and beyond this point, there are reaches where there are only localized imbalances between erosion and deposition. Downstream increases in suspended-sand concentration reflect net erosion of sand from the channel bed and eddy sandbars; conversely, downstream decreases in suspended-sand concentration reflect net deposition.

During the 2004 HFE, scientists collected samples between the Lees Ferry and Grand Canyon gages (fig. 1) while boating downstream. During the 2008 HFE, two groups of scientists collected samples between Lees Ferry and the Grand Canyon gage and between the Grand Canyon and Diamond Creek gages (Topping and others, 2010).

The advantage of the downstream sampling trips was that direct measurements of suspended-sand conditions were made along the entire river course. The disadvantage, however, was that the sampled conditions only represented the characteristics of the flow at the beginning of each HFE when the sampling was conducted. In contrast, the continuous sampling at the gages described the ever-changing suspended-sand concentration but only at a few locations.

Sandbar Monitoring

Since the mid-1990s, the sandbar-monitoring effort has been led by the Northern Arizona University Sandbar Studies Group (see text box, Measuring Colorado River Sandbars). This program was initiated during the experimental flow program of 1990 and 1991 (Beus and others, 1992) when sandbar-surveying protocols were first established and measurement sites were identified. Since that time, the number of measurement sites has expanded, and methods have evolved (Hazel, Kaplinski, Parnell, Kohl, and Schmidt, 2008; Kaplinski and others, 2009).

Figure 2. Data collection at the sandbar study site near river mile 175 following the 2008 high-flow experiment (HFE). View is downstream from the shoreline on the right bank of the river. Photograph courtesy of Grand Canyon Youth.

Because the number of sandbar monitoring sites has increased over time and the 2004 HFE included monitoring only in Marble Canyon and eastern Grand Canyon, there are generally fewer data from which to make comparisons among the HFEs than there are data to analyze individual HFEs. Detailed measurements of sandbars and the adjacent channel were made before and after the HFE at 32 sites in 1996, 12 sites in 2004, and 40 sites in 2008 (Hazel and others, 1999; Hazel and others, 2010). Of these sites, seven in Marble Canyon were monitored before and after each of the three HFEs, and 15 in Grand Canyon were monitored before and after the 1996 and 2008 HFEs (Grams, Hazel, and others, 2010).

These monitoring sites represent a small subset of the total number of all eddy sandbars in Grand Canyon. Schmidt and others (2004) estimated that there are approximately 300 large eddies, each greater than about 11,000 square feet (ft^2) in area, with eddy sandbars in upper and lower Marble Canyon. Extrapolation of measurements from the relatively few monitoring sites to the rest of Marble and Grand Canyons has been a longstanding challenge. For example, no more than about 8 percent of all sandbars in upper or lower Marble Canyon have been measured annually. The number of measured sandbars is an even smaller percentage of the total number of sandbars in eastern, central, and western Grand Canyon.

Collecting detailed topographic information about a significantly greater number of the sandbars on an annual basis has never been feasible, because such sampling would require a great many resources. Although monitoring by aerial photographs has been used to measure additional sandbars (Schmidt, Grams, and Leschin, 1999), this method yields less precise measurements and has not been repeated during every HFE. Nevertheless, one of the strengths of the existing sandbar-monitoring program in Grand Canyon is its longevity; there are few rivers in the world where such precise annual measurements of channel morphology have been made over a 20-year period.

The amount of sand that can accumulate in an eddy during any high flow is at least partly controlled by the antecedent sandbar volume. Beus and others (1992) found that if eddy sandbars are relatively large just before a high flow, less new sand is deposited, presumably because there is less accommodation space where new sand deposition can occur (Hazel and others, 1999).

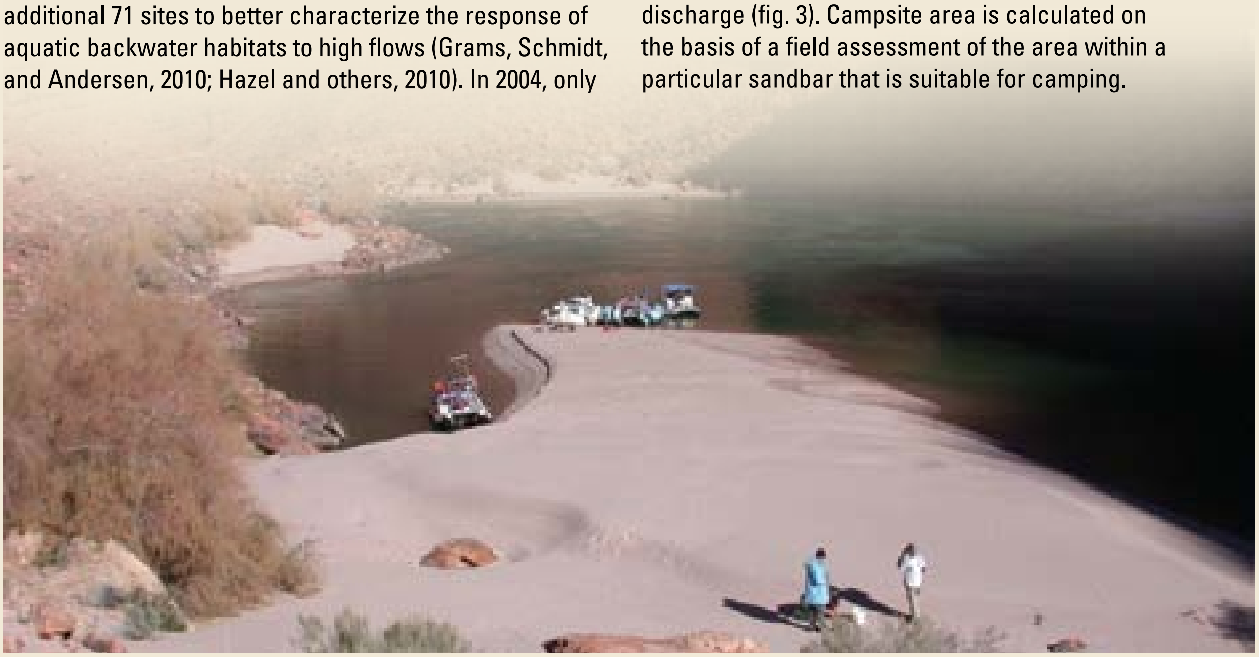
The topography of sandbars was measured immediately before each HFE. Soon after each HFE (fig. 2), the topography was measured again to determine the amount of sand deposited or eroded during each experiment (see text box, Measuring Colorado River Sandbars). Sandbar volume is computed above a “minimum surface.” This minimum surface is computed from all available survey data for each monitoring site and reflects the topography of the lowest elevation

Measuring Colorado River Sandbars

Field-based monitoring of sandbars in Grand Canyon dates back to the early 1970s, about a decade after Glen Canyon Dam was completed, when it was first recognized that sandbars were at risk of erosion. The monitoring methods have evolved from simple topographic profiles, to complete topographic mapping of exposed sandbars, and finally to comprehensive topographic-bathymetric (water-depth) mapping of both the exposed and submerged portions of sandbars (fig. 3). The primary challenge of sandbar monitoring has always been in satisfying the need for precise, or closely spaced, measurements at each monitoring site, while at the same time monitoring a large and representative number of sandbars. Precise measurements are required to adequately characterize the topography of each site, and a large sample size is required because sandbars can independently change in shape and size. It was found that imprecise, widely spaced measurements could erroneously indicate a change in sandbar size when in fact sand was just redistributed within the same site. The topographic surveys collected as part of the current monitoring protocol can be used to detect both changes in sandbar shape and size. These measurements are made by scientists using conventional ground-based survey methods (Hazel and others, 2010). The number of study sites has increased gradually since 1990, with detailed measurements made before and after the HFEs at 32 sites in 1996 and 40 sites in 2008. In 2008, topographic surveys were collected at an additional 71 sites to better characterize the response of aquatic backwater habitats to high flows (Grams, Schmidt, and Andersen, 2010; Hazel and others, 2010). In 2004, only 12 of the sites in Marble Canyon and eastern Grand Canyon that were surveyed in 1996 and 2008 were surveyed before and after the HFE. The more comprehensive surveys that include bathymetry are typically conducted near the time of high flows and not as part of the annual sandbar monitoring. While these surveys provide much more information than the topographic surveys alone, they require a much more extensive data-collection effort and substantially more post processing (Kaplinski and others, 2009).

The elevation data collected as part of the sandbar monitoring may be used in several different ways, depending on the specific science or resource-management question. Typically, the sandbar data are analyzed to determine sandbar area and volume within three elevation zones. It is important to track the sandbars by elevation zone because, for example, a large volume of sand that is low in the channel may not contribute to a large campsite but it may create a large backwater habitat. The elevation zones are separated at the river stage represented by a discharge of 8,000 cubic feet per second, also called the reference stage (fig. 3).

Analyses may be conducted to determine how changes in sandbars affect specific resources, such as backwater habitat abundance and campsite area. Changes in backwater habitat are determined by calculating the area and volume of backwater habitat for each sandbar survey that would exist at a particular river discharge (fig. 3). Campsite area is calculated on the basis of a field assessment of the area within a particular sandbar that is suitable for camping.



David J. Topping, U.S. Geological Survey

River mile 22, December 2004

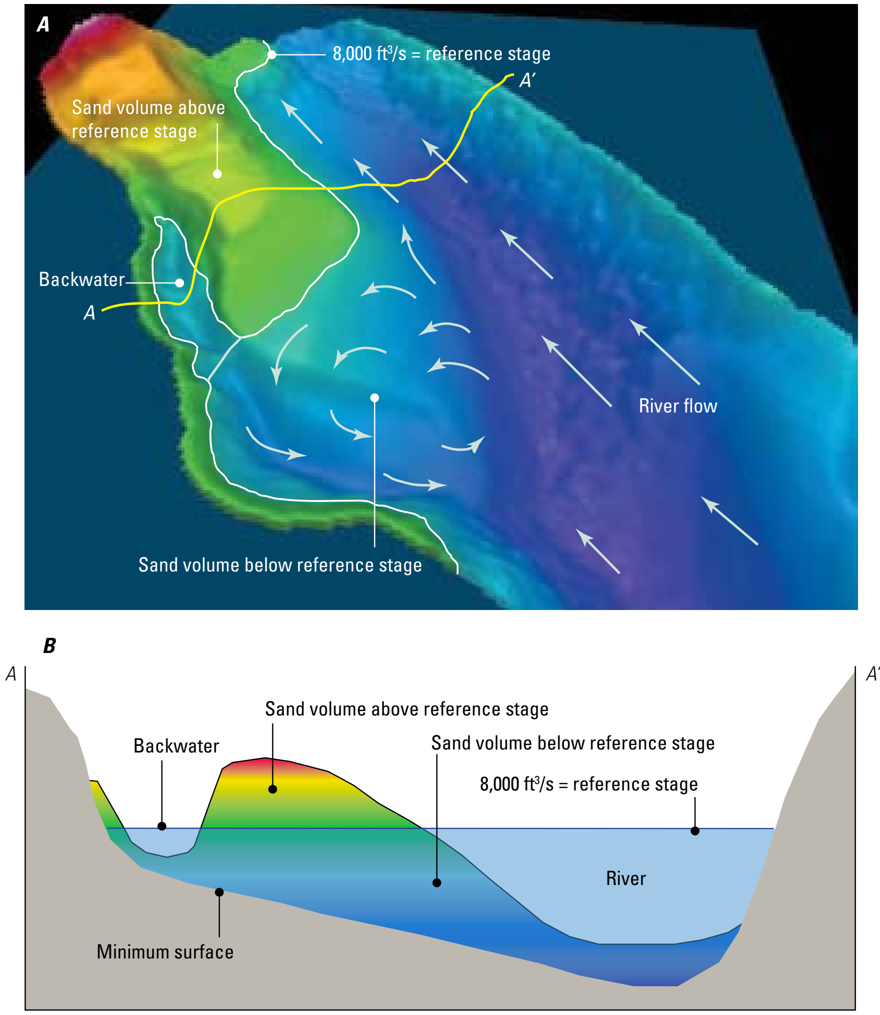


Figure 3. *A*, Perspective view based on 3-foot resolution digital elevation model of a typical eddy sandbar and the adjacent channel showing pattern of recirculating flow, the reference stage of 8,000 ft³/s in white, and a typical backwater as defined by aquatic ecologists. The portions of the sandbar above the reference stage and below the reference stage are distinguished. Main-stem flow is from bottom right to top left. *B*, Cross-section view of an eddy sandbar and channel illustrating the region for sand above the reference stage and total sand (sand above the reference stage plus sand below the reference stage). Modified from Grams, Hazel, and others (2010).

surveyed for each part of the sandbar (fig. 3). The volumes of sand contained in the sandbars typically are reported in two categories that distinguish between sand that is usually submerged below the water surface and sand that is usually exposed above the water surface. The elevation at which this distinction is made is called “the reference stage,” defined as the elevation of the water surface at a river discharge of 8,000 ft^3/s. This discharge was chosen because sand below the corresponding river stage is almost always submerged; flows of 8,000 ft^3/s or greater have occurred 75 percent of the time in the Colorado River since 1963 (Topping and others, 2003). Sand above the reference stage is either always exposed above the water surface or is intermittently exposed during periods of diurnally fluctuating dam releases and during HFEs.

River Conditions Prior to Each High-Flow Experiment

River conditions prior to each of the three HFEs can be compared on the basis of the antecedent sand enrichment and by comparing estimates of how that enrichment was distributed over the channel bed and estimates of the grain size of that sand (Topping and others, 2010). The latter two factors were estimated from the concentration and grain size of suspended sand transported on the first day of each HFE using techniques developed by Rubin and Topping (2001) and Topping and others (2010), but can only be applied to the channel near each gage.

Antecedent Sand Enrichment: Volume, Distribution, and Grain Size

The sediment-transport measurement program in place in the early 1990s precludes estimation of the antecedent sand enrichment immediately before the 1996 HFE, but enrichment in Marble Canyon was probably less than before the 2004 and 2008 HFEs. Tributary inputs of sand had been relatively small and average dam releases relatively large in the year preceding the 1996 HFE (table 1). In contrast, tributary inputs to Marble Canyon were larger, had occurred more recently, and were of a finer grain size before the 2004 and 2008 HFEs.

Interpretation of the conditions in eastern Grand Canyon before the 1996 HFE are also complicated by the lingering effect of Little Colorado River floods that had occurred in the winter of 1993.

Table 1. Conditions affecting sand enrichment for high-flow experiments (HFEs) conducted in 1996, 2004, and 2008. Modified from Topping and others (2010).

[ft^3/s, cubic feet per second; nd, no data]

	1996	2004	2008
Conditions of streamflow and tributary sand supply			
Median dam release for year preceding HFE (ft^3/s)	15,400[a]	10,500[b]	11,300
Paria River sand supply for year preceding HFE (million tons)	0.42	0.69	1.01
Little Colorado River sand supply for year preceding HFE (million tons)	0.04	0.21	1.23
Sand enrichment for accounting period[c] (million tons)			
Upper Marble Canyon	nd	0.42 ± 0.12	1.32 ± 0.69
Lower Marble Canyon	nd	0.13 ± 0.05	0.59 ± 0.30
Eastern Grand Canyon	nd	0.02 ± 0.05	0.92 ± 0.73
Central and western Grand Canyon	nd	0.17 ± 0.11	1.01 ± 0.44
Bed sand area (ranking 1 = greatest relative bed sand area)			
Upper Marble Canyon	nd	2	1
Lower Marble Canyon	1[d]	3	1
Eastern Grand Canyon	1	3	2
Central Grand Canyon	1	nd	2
Western Grand Canyon	nd	2	1
Bed sand grain size (ranking 1 = finest relative grain size)			
Upper Marble Canyon	nd	1	2
Lower Marble Canyon	3	2	1
Eastern Grand Canyon	3	2	1
Central Grand Canyon	2	nd	1
Western Grand Canyon	nd	2	1

[a] This discharge would result in either no accumulation of the tributary-supplied sand or net scour of sand already stored in the Colorado River during the year prior to the CFE (from Topping and others, 2000).

[b] This discharge is low enough to be within the range in Topping and others (2000) under which net sand accumulation is most likely to occur.

[c] Accounting period for 2004 HFE extends from July 1, 2004, to rising limb of 2004 HFE. Accounting period for the 2008 HFE extends from recession of the 2004 HFE to the rising limb of the 2008 HFE.

[d] The bed sand area for lower Marble Canyon was approximately the same in 1996 and 2008.

Topping and others (2010) estimated that a similar or larger amount of sand probably was on the channel bed in eastern Grand Canyon in 1996 than in 2004 or 2008, but this sand was of coarser size than sand on the bed prior to the 2004 and 2008 HFEs (table 1).

Antecedent sand enrichment can be calculated for the 2004 and 2008 HFEs, and these calculations indicate that there was more sand available for transport in 2008 except in upper Marble Canyon. Additionally, before the 2008 HFE, the sand was of a finer size except in upper Marble Canyon (table 1). Upper Marble Canyon had between 630,000 and 2,010,000 tons of sand immediately before the 2008 HFE, primarily resulting from floods in the Paria River that had delivered between 3,300,000 and 4,100,000 tons during the preceding 3½ years (Topping and others, 2010). In October 2006, two floods in the Paria River with a recurrence interval of 7 years occurred in 1 week and supplied about 1,400,000 tons of sand.

Sand enrichment in upper Marble Canyon in 2004 was about 70 percent less than in 2008, because the Paria River only delivered between 610,000 and 750,000 tons of sand during the 4½ months immediately before that experiment. There is no evidence that the Colorado River had been accumulating significant amounts of sand prior to the summer of 2004. The enriched sand in upper Marble Canyon was much finer in 2004, because the 2004 HFE was conducted soon after floods occurred in the Paria River.

Antecedent Sandbar Volume

The amount of new sandbar deposition depends not only on the antecedent sand enrichment but also on the antecedent sandbar volume, because less deposition can occur if the eddy sandbars are relatively large when a high flow occurs (Hazel and others, 1999). There was less room for new sandbar deposition in upper Marble Canyon in 2008, because eddy sandbars were larger than before the previous HFEs (Grams, Hazel, and others, 2010). Eddy sandbars in lower Marble Canyon, in eastern Grand Canyon, and farther downstream were all approximately the same size before each experiment.

Insights About River Processes

Sediment Concentration, Load, and Grain Size

Measurements made during the 1996 HFE confirmed that only a limited amount of sand is available to be transported by the post-dam Colorado River. Documentation of this phenomenon, called sediment supply limitation, is one of the most important findings of the HFE physical-science research program (Schmidt, 1999). Measurements in 1996 showed that the 7-day high flow quickly depleted the antecedent sand enrichment (fig. 4*A*). The concentration of suspended sand and mud was greatest on the first day of the HFE and quickly decreased thereafter (Rubin and others, 1998; Topping and others, 1999, 2000; Rubin and Topping, 2001). These findings, coupled with modeling that showed that the highest rates of sandbar deposition occurred during the first days of the high flow (Wiele and Torizzo, 2005), led to the decision to reduce the duration of the 2004 and 2008 HFEs to less than one-half the duration of the 1996 HFE. The last days of the 1996 HFE transported much less fine sediment and did not substantially increase deposition of eddy sandbars (Schmidt, 1999).

The observations made during the 1996 HFE inspired Topping and others (2000) to comprehensively reanalyze the pre-dam sediment-transport data, which led to confirmation of the early observations of Leopold and Maddock (1953) and Colby (1964). This reanalysis demonstrated that sand-supply limitation had also occurred in the pre-dam river. Sand had accumulated during the pre-dam period between Lees Ferry and the Grand Canyon gage (fig. 1) only when flows were less than about 9,000 ft^3/s (Topping and others, 2000). The management implication of this finding was that sand contributed by tributaries can only be stored in the river channel when flows are less

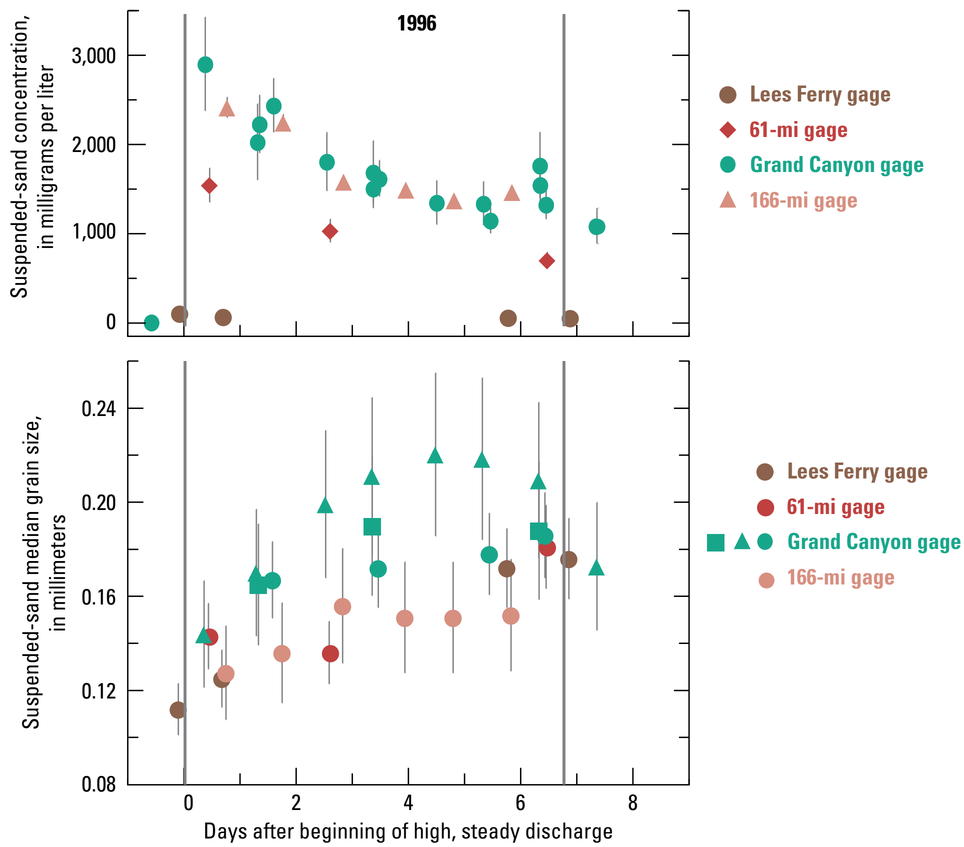


Figure 4*A*. Suspended-sand data collected during the 1996 high-flow experiment (HFE) at all study sites. The upper graph shows suspended-sand concentration; the lower graph shows suspended-sand median grain size. Data were shifted in time such that zero time (indicated by the leftmost vertical gray line) is the beginning of high, steady discharge during the HFE. The right vertical gray line indicates the end of the high, steady discharge part of the HFE. The symbols represent discrete samples. Error bars indicate the 95-percent confidence interval associated with these measurements. Modified from Topping and others (2010). Gage locations are shown in figure 1.

than about 9,000 ft^3/s. This finding was tested as a management approach and demonstrated to be effective in 2000 during the low summer steady flow (LSSF) experiment when dam releases were about 8,000 ft^3/s for 3 summer months (Schmidt and others, 2007). Sand does not accumulate in the channel over multiyear periods in the post-dam period, because post-dam flows usually are greater than 9,000 ft^3/s (Topping and others, 2003).

Scientists also learned that there is good correlation between the magnitude of antecedent sand enrichment and of suspended-sediment concentration (Topping and others, 2010). Antecedent sand enrichment and suspended-sand concentration were greatest in 2008 (Topping and others, 2010). Average suspended-sand concentration was lowest in Marble Canyon and in western Grand Canyon in 1996 when enrichment was less than before the other HFEs.

Scientists also learned that the antecedent conditions of bed-sand area and bed-sand grain size may compensate for each other. In 2008 in upper Marble Canyon, high suspended-sand concentration was promoted by a large area of the channel bed covered by sand (table 1). In 2004, high suspended-sand concentration was promoted by a smaller proportion of the channel bed covered by finer sand. In lower Marble Canyon, the channel bed was less extensively covered, and the grain sizes were slightly coarser in 2004 than in 2008, thereby causing lower concentrations of suspended sand. Sand concentrations in eastern Grand Canon were lower in 1996 than in 2008, because the sand on the channel bed was very coarse.

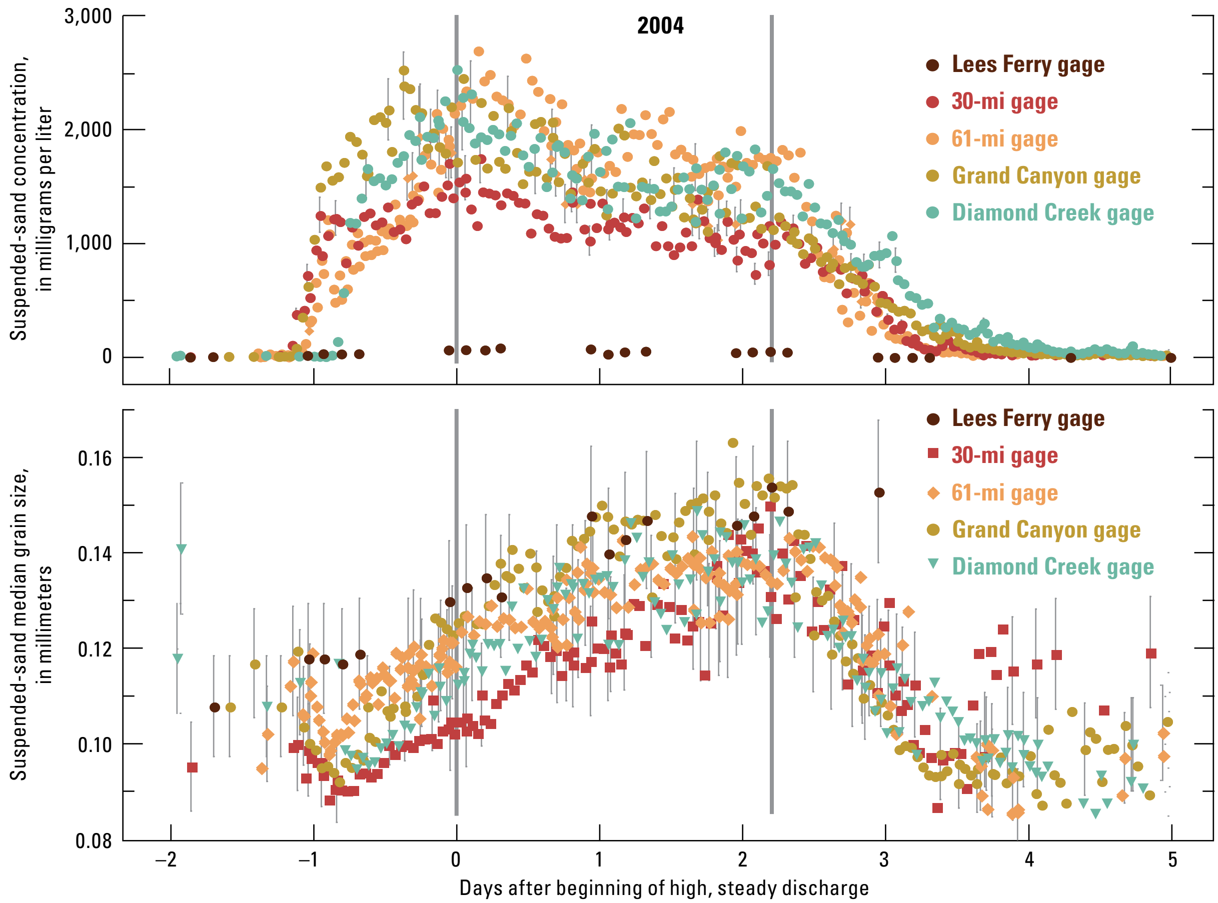


Figure 4*B*. Suspended-sand data collected during the 2004 high-flow experiment (HFE) at all study sites. The upper graph shows suspended-sand concentration; the lower graph shows suspended-sand median grain size. Data were shifted in time such that zero time (indicated by the leftmost vertical gray line) is the beginning of high, steady discharge during the HFE. The right vertical gray line indicates the end of the high, steady discharge part of the HFE. The symbols represent discrete samples. Error bars indicate the 95-percent confidence interval associated with these measurements. Modified from Topping and others (2010). Gage locations are shown in figure 1.

Longitudinal (Downstream) Patterns in Sediment Transport

Downstream trends in the concentration and size of suspended sand measured during the 2004 and 2008 HFEs indicate that neither the antecedent sand enrichment nor the grain size of that sand was uniformly distributed on the channel bed immediately before the HFEs. Because most of the sand delivered to the Colorado River enters at two discrete locations—the Paria and Little Colorado Rivers—the distribution and characteristics of the antecedent sand enrichment is primarily determined by three factors. The first factor is the amount and sizes of the sand that enters from these tributaries. The second factor is the Colorado River's flow regime during the period preceding each HFE, because dam releases control how much and how far sand delivered from each tributary is transported downstream. Dam releases also affect the amount of sand that resides in eddies as compared to the amount in the main channel. The third factor is the geomorphic organization of the canyon into narrow and wide segments, because sand has a tendency to accumulate in the wide parts of Marble and Grand Canyons where there are more eddies and the channel gradient is relatively flat.

Topping and others (2010) used the longitudinal data to show that much more of the channel bed between RMs 15 and 35 and between RMs 51 and 85 was covered by sand before the 2008 HFE than before the 2004 HFE. Upstream from RM 15, the antecedent sand enrichment was finer in 2004 than in 2008.

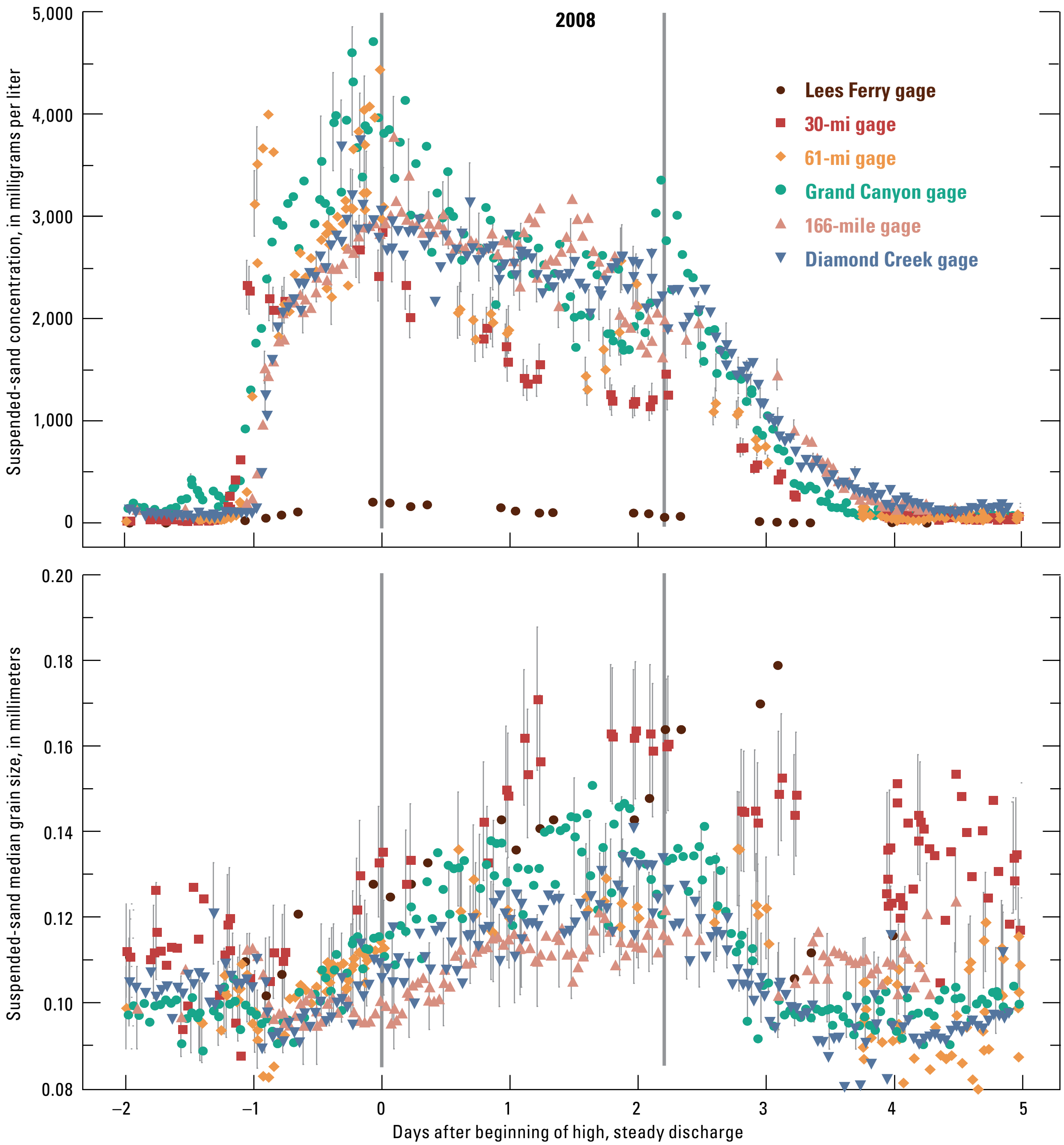


Figure 4*C*. Suspended-sand data collected during the 2008 high-flow experiment (HFE) at all study sites. The upper graph shows suspended-sand concentration; the lower graph shows suspended-sand median grain size. Data were shifted in time such that zero time (indicated by the leftmost vertical gray line) is the beginning of high, steady discharge during the HFE. The right vertical gray line indicates the end of the high, steady discharge part of the HFE. The symbols represent discrete samples. Error bars indicate the 95-percent confidence interval associated with these measurements. Modified from Topping and others (2010). Gage locations are shown in figure 1.

These measurements also show that the geomorphic organization of Marble and Grand Canyons plays a large role in determining the distribution of where erosion or deposition occurs during each HFE. Despite different proportions of the channel bed covered by sand of different grain sizes in 2004 and 2008, the spatial patterns of erosion and deposition were similar early in each event when the downstream sampling was conducted. In 2004 and 2008, net erosion of sand was measured at the beginning of the HFE in upper Marble Canyon between RMs 0 and 24 (fig. 5). Farther downstream to approximately RM 50 in lower Marble Canyon, net deposition was measured in 2004 and 2008. Net erosion was measured in 2004 between RMs 50 and 85, where measurements ceased. In 2008, net erosion was measured between RMs 50 and 105, and net deposition was measured between RMs 105 and 179. Farther downstream, erosion and deposition were in balance.

These measurements only describe conditions of the initial stages of each high flow and cannot be used to determine net sediment budgets for the HFEs. Nevertheless, the findings demonstrate that the downstream effects of high flows vary and evolve over space as well as time. Thus, the physical processes that drive eddy-sandbar deposition or erosion evolve during high flows and differ in various parts of the canyons. Different parts of Marble and Grand Canyons respond to the same HFE differently.

The Relation Between Main-Stem Sediment Transport and Eddy-Sandbar Characteristics

Designing high flows to build sandbars requires understanding how the characteristics of the sandbars that are being deposited evolve with the characteristics of the sediment transported by the river. Rubin and others (1998) and Topping and others (1999) described how the grain-size distribution of the suspended sediment, the grain-size distribution of the fine sediment on the channel bed, and the grain-size distribution of the flood deposits that make up eddy sandbars co-evolved during the 1996 HFE. Rubin and others (1998) also showed that the concentration of suspended sand in one eddy evolved over time with the progressively declining main-channel

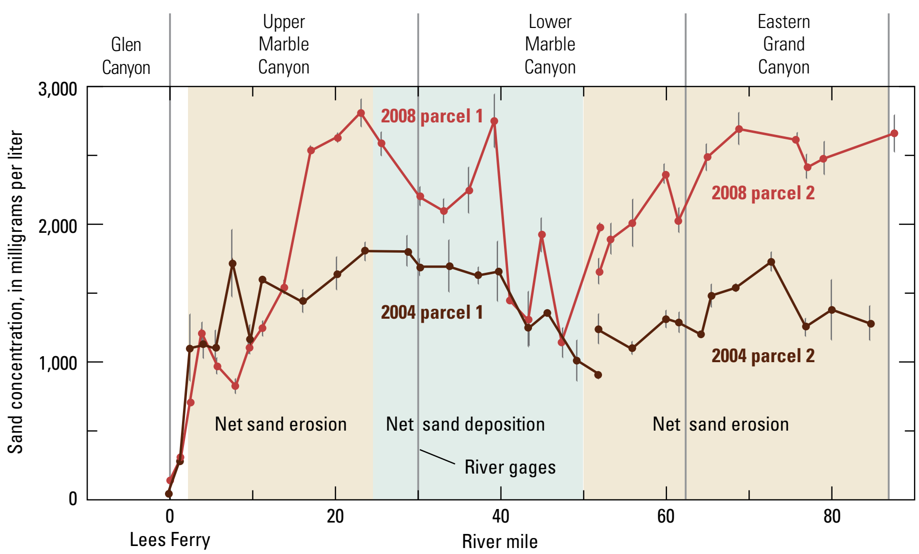


Figure 5. Downstream changes in suspended-sand concentration measured during high-flow experiments in 2004 and 2008. Tan shading indicates reaches of net sand erosion, and blue shading indicates reaches of net sand deposition. “Parcel 1” indicates sampling on the first day of the steady high flow, and “parcel 2” indicates sampling on the second day of the steady high flow. Vertical lines indicate locations of the Lees Ferry, 30-mile, 61-mile, and Grand Canyon gages. Modified from Topping and others (2010). Gage locations are shown in figure 1.

suspended-sand concentration. They compared measurements at an eddy at RM 122 and at the Grand Canyon gage (RM 88; fig. 1) and found that the concentrations of suspended sand in the eddy and in the main channel during the HFE both decreased by a factor of two. The concentration of mud in suspension decreased by a factor of five, and the size of the silt and clay particles that constitute the mud also increased.

Mud travels downstream faster than sand; thus, mud is the first sediment deposited into eddies. As a result, the newly formed eddy deposit is muddiest at its base, and this mud subsequently is buried by coarser sand (Rubin and others, 1998). In 1996, flood deposits coarsened upward by a factor of two (fig. 6). Similar sedimentological patterns of upward coarsening of sandbar deposits were observed after the 2004 HFE (Topping and others, 2006) and the 2008 HFE (Draut, Topping, and others, 2010). One implication of these observations is that manipulating high flows for the purpose of increasing the content of mud in newly formed sandbars, as hypothesized before the 2004 HFE, is difficult because mud is quickly transported downstream, and muddy sand is subsequently buried by coarser sand deposited in the last days of each high flow.

The studies demonstrating the links between main-stem suspended-sediment concentration and eddy-sandbar characteristics showed that, "For identical flows, an eddy deposit can either aggrade or erode, depending on the concentration of sediment in the main-channel flow" (Rubin and others, 1998, p. 99). Field measurements made in 1996 and computer models that simulated the hydraulics and sediment transport in eddies (Wiele and others, 1999) showed that the magnitude of suspended-sand concentration determines the sand deposition rate. Larger sandbars are formed by high flows that have high suspended-sand concentrations.

Sandbar Response to High-Flow Experiments

Scientists have struggled to generalize about the patterns of sandbar change caused by high flows. As described in chapter 2, this volume, there is large variability in how specific eddy sandbars respond to a discrete high flow. Observations made in 1996 demonstrated that not all eddy sandbars in the same river segment responded in the same way, despite the fact that the discharge and main-stem suspended-sand concentration were similar (Rubin and others, 1998; Schmidt, Grams, and Leschin, 1999; Topping and others, 1999).

Daily measurements of sandbar building in 1996 and 2008 indicate that most eddy-sandbar deposition occurred during the first few days of each high flow. Measurements of daily

Figure 6. Cross-sectional view of a sand deposit formed by the 1996 high-flow experiment. The image was taken following the high flow and shows the upper 4.5 feet of a 15-foot-thick deposit. The deposit consists of fine-grained sand in the lower left and coarser cross-bedded layers in the upper 1.5 feet of the deposit. Photograph taken by David M. Rubin, U.S. Geological Survey.

topographic change were made at five sites in 1996 and two sites in 2008. In 1996, most deposition occurred during the first 3 days of the experiment, and erosion tended to dominate thereafter (Andrews and others, 1999; Schmidt, 1999). Wright and Kaplinski (in press) showed that deposition rates above reference stage were high for the entire 60 hours of the 2008 HFE. Scientists have concluded that efficient sandbar building during a high-flow event can occur in 1 to 3 days, but longer high flows have the potential to cause sustained sandbar deposition if the antecedent sand enrichment is unusually large.

Measurements made during the 1996 HFE were also used to examine the elevation of sandbars. Andrews and others (1999) reported that sandbars accumulated sand to within about 1 foot of the water surface at the peak flow, but did not aggrade much more than this. During the subsequent HFEs, sandbar elevations increased similarly because the magnitude of those HFEs was similar to that in 1996 (table 2). Hazel and others (2006) reported that less sand was deposited by smaller floods; a 31,000 ft^3/s dam release in 2000 caused increases in sandbar volume above the 8,000 ft^3/s reference stage that were about 80 percent less than the sandbar changes caused by the 1996 HFE.

As described in chapter 2, previous analyses of sandbar change had detected few common patterns of topographic change caused by post-dam floods or short-duration high flows. Hazel and others (2010) distinguished four styles of sandbar change (table 3) on the basis of whether or not the net topographic change of the eddy sandbar and adjacent channel was erosion or deposition above the reference stage and below the reference stage. The four styles represent the four possible combinations: net deposition above and below the reference stage (style 1; figs. 7, 8), net erosion below the reference stage and net deposition above (style 2; figs. 9, 10), net erosion above and below the reference stage (style 3; figs. 11, 12), and net deposition below the reference stage and net erosion above (style 4).

Table 2. Summary of changes in sandbar and channel elevation for three high-flow experiments (HFEs). Values are average elevation change for indicated storage component, in feet.

Storage component	1996 HFE	2004 HFE	2008 HFE
Eddy sandbars above reference stage	0.59 ± 0.16	0.52 ± 0.13	0.49 ± 0.13
Eddy sandbars below reference stage	–1.84 ± 0.59	–1.57 ± 0.46	–1.35 ± 0.56
Channel-margin sandbars above reference stage[a]	0.98 ± 0.33	0.98 ± 0.33	0.98 ± 0.33
Main channel below reference stage	–1.61 ± 0.43	–1.74 ± 0.95	0.72 ± 0.72

[a] Although thickness changes in channel margin deposits are large, these deposits occupy much less area than eddy sandbars and contribute much less to the change in sand storage (Hazel and others, 2006). These changes were measured separately from eddy sandbars only in 1996 (Hazel and others, 2006), and the same change in elevation was assumed for 2004 and 2008.

Styles 1 and 2—where net deposition occurred above the reference stage—are the predominant style of eddy sandbar change caused by HFEs. The relative proportion of eddy sandbars in style 1 or style 2 varied among the HFEs. The 2008 HFE had the highest measured suspended-sediment concentrations and the greatest proportion of measured sandbars with a style 1 response. Forty-five percent of surveyed sandbars in Marble and Grand Canyons had a style 1 response, and 37 percent had a style 2 response (fig. 13*C*). Somewhat lower suspended-sand concentrations during the 2004 HFE caused only 26 percent of measured sandbars to follow style 1 (fig. 13*B*). Even lower suspended-sand concentrations during the 1996 HFE caused only 9 percent of the measured sandbars to

Table 3. Styles of sandbar response (from Hazel and others, 2010).

Response style	Sandbar response above reference stage	Sandbar response below reference stage
1	Deposition	Deposition
2	Deposition	Erosion
3	Erosion	Erosion
4	Erosion	Deposition

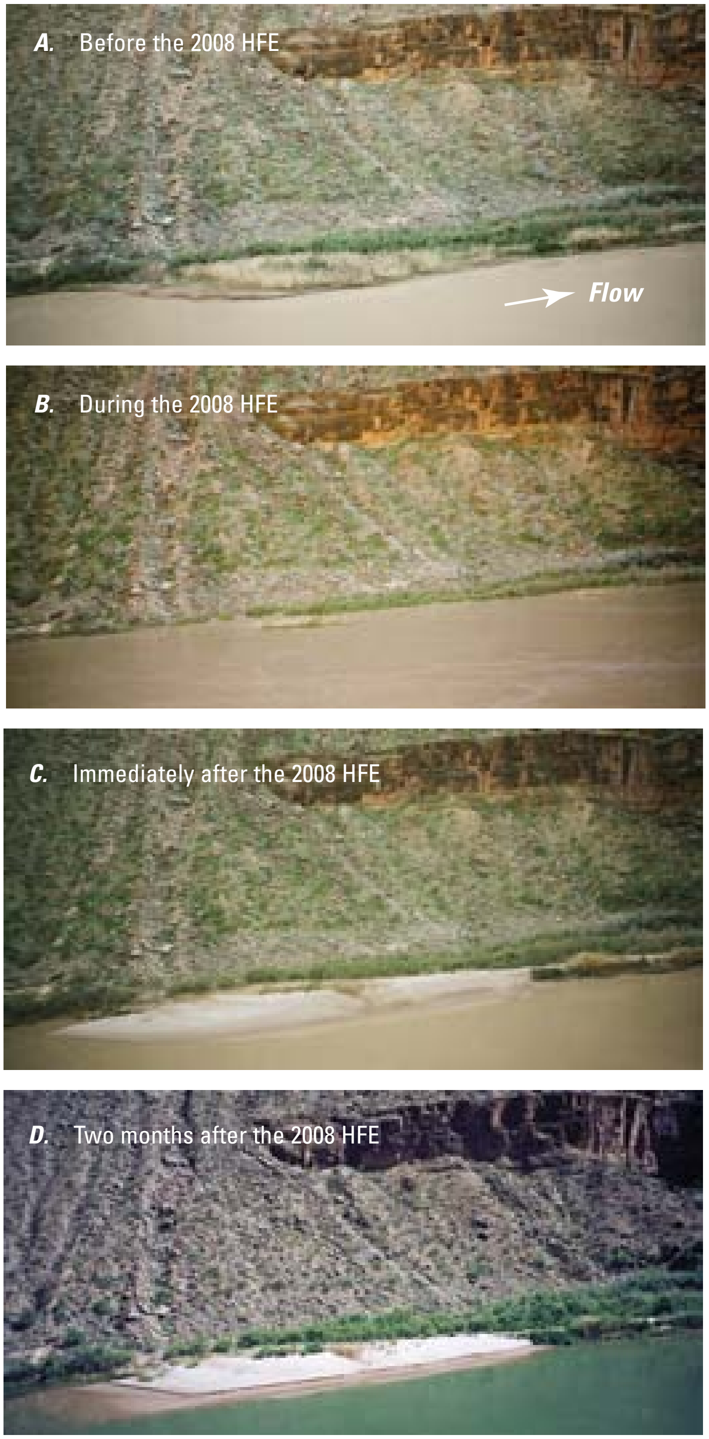


Figure 7. Matched photographs of river mile 172 where style 1 net depositional response occurred. View is from the right bank of the river and shows the eddy sandbar (*A*) before, (*B*) during, (*C*) immediately after, and (*D*) 2 months after the 2008 high-flow experiment. Streamflow is from left to right. From Hazel and others (2010).

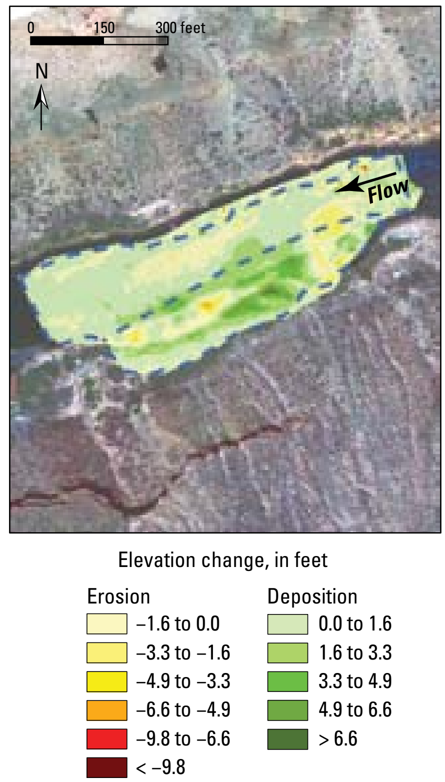


Figure 8. Style 1 net depositional response to the 2008 high-flow experiment at river mile 172. The dashed lines show the study site boundary and the approximate location of the boundary between the main channel and the eddy. Streamflow is from right to left. Modified from Hazel and others (2010).

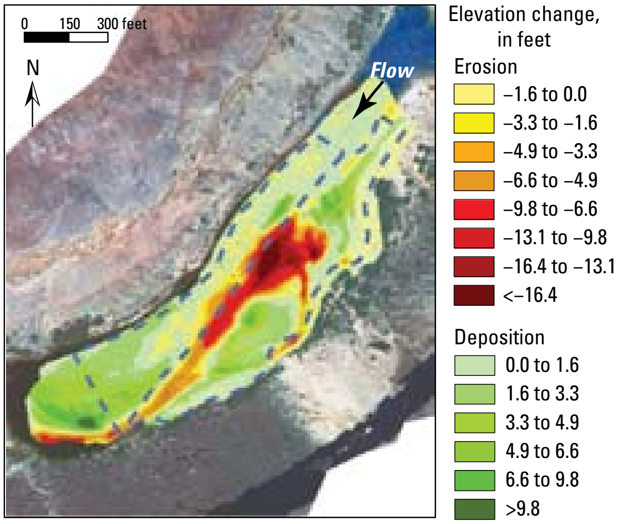


Figure 9. Style 2 deposition and erosion during 2008 high-flow experiment at river mile 44. The dashed lines show the study site boundary and the approximate location of the boundary between the main channel and the eddy. Streamflow is from top to bottom. Modified from Hazel and others (2010).

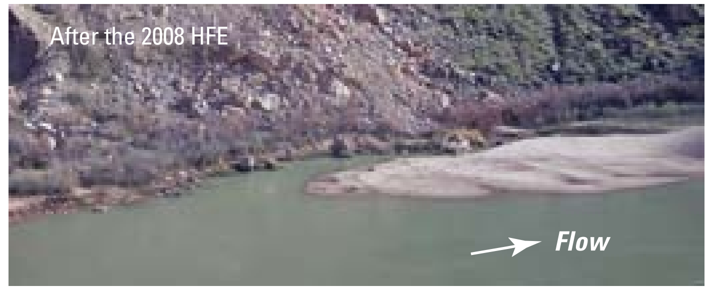


Figure 10. The large reattachment bar that existed after the high flow on March 10, 2008, at river mile 44. View of the sandbar is from across the river, and streamflow is from left to right. Modified from Hazel and others (2010).

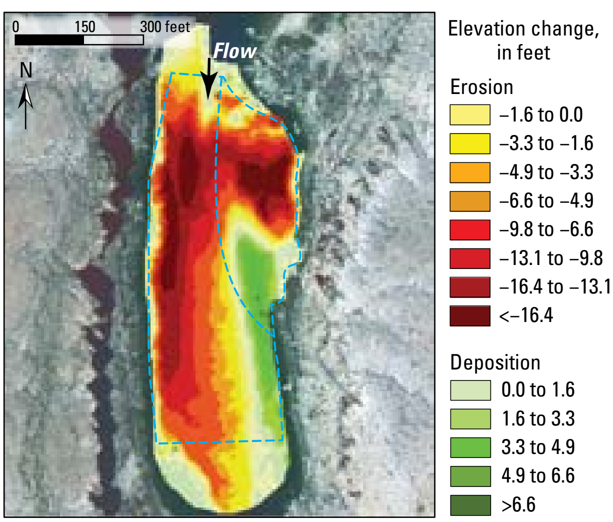


Figure 11. Erosion and deposition illustrating style 3 sandbar response at river mile 3. The dashed lines show the study site boundary and the approximate location of the boundary between the main channel and the eddy. Streamflow is from top to bottom. Modified from Hazel and others (2010).

Figure 12. Matched photographs of river mile 3 showing style 3 response of the eddy sandbar. *A*, Before the 2008 high-flow experiment (HFE). *B*, Immediately after the 2008 HFE. Streamflow is from left to right. Modified from Hazel and others (2010).

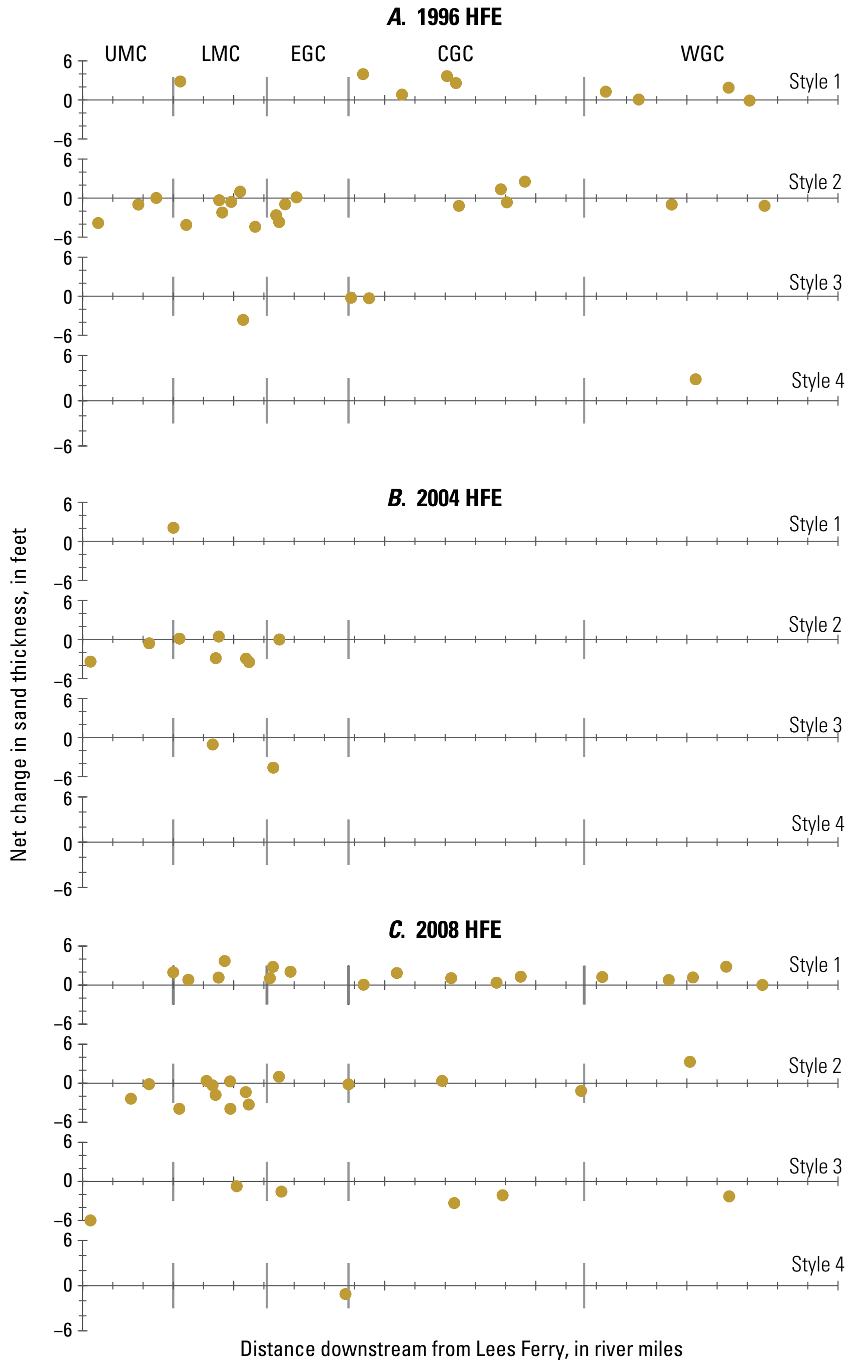


Figure 13. Downstream variations in response style at study sites for the 1996, 2004, and 2008 high-flow experiments (HFEs). Upper Marble Canyon (UMC), lower Marble Canyon (LMC), eastern Grand Canyon (EGC), central Grand Canyon (CGC), and western Grand Canyon (WGC) segments are shown. *A*, The distribution of total-eddy net change in thickness of sand for each response style with distance downstream for the 1996 HFE. *B*, The distribution of total-eddy net change in thickness of sand for each response style with distance downstream for the 2004 HFE. Data were not collected in central Grand Canyon or western Grand Canyon. *C*, The distribution of total-eddy net change in thickness of sand for each response style with distance downstream for the 2008 HFE. Modified from Hazel and others (2010).

be classified as style 1 (fig. 13*A*). In 2004 and 1996, the predominant style of sandbar response in Grand Canyon was style 2. In each of the three HFEs, between 14 and 18 percent of the monitoring sites exhibited net erosion—a style 3 response. Style 4 response represents sand accumulation below the reference stage and is uncommon during HFEs.

Despite the insight gained by describing styles of topographic change in sandbars during the HFEs, the large variability inherent in how river processes create sandbars continues to make it difficult to predict how individual sandbars respond to high flows. For example, while style 1 and style 2 responses were most common in each reach for each HFE, there were nearly always at least one or two sites that exhibited a style 3 response (fig. 13). Thus, at the same time that most sandbars build during an HFE, it is always possible that a nearby sandbar may erode.

Redistribution of River-Deposited Sand to Higher Elevations by Wind

Although wind and blowing sand are common phenomena in Grand Canyon, the connection between sandbar deposition caused by HFEs, eolian (windblown) sand transport, and deposition of windblown sand at archeological sites is complex and difficult to predict and monitor. It is even more difficult to predict if the deposition of windblown sand near archaeological sites effectively protects those sites from erosion. Links among these processes were not investigated until the 2004 HFE (Draut and Rubin, 2008). This study and continued investigation during the 2008 HFE (Draut, Hazel, and others, 2010) documented that, in at least some cases, newly deposited sandbars exposed to the wind caused elevated wind-blown sand transport rates and that wind-deposited sand dunes were rejuvenated (fig. 14). Some of these newly formed dunes subsequently covered archaeological sites or filled small gullies that threatened to erode archaeological resources (Draut and Rubin, 2008; Draut, Hazel, and others, 2010). No data, however, are available with which to demonstrate if the occurrence of these processes was widespread or isolated to a few locations.

Sand Deposition in Tributary Gullies

Archaeological sites adjacent to gullies and small ephemeral streams are potentially threatened by bank erosion. In some locations, incision of deep gullies that traverse through archaeological sites cause soil erosion and loss of cultural artifacts. Hereford and others (1996) speculated that deposition of sand in the mouths of these gullies during high flows and floods might arrest continued gully erosion and thereby protect archaeological sites.

These gullies have been present for many years, and pre-dam rates of gully erosion are unknown. Additionally, it is not known if the changes in flood regime and sediment supply caused by Glen Canyon Dam have significantly changed the magnitude of deposition of flood sands in

Figure 14. Eolian dune crest that formed on a high-flow-experiment-deposited sandbar taken on July 29, 2008. From Draut, Hazel, and others (2010).

the mouths of gullies. Monitoring of a few of these gullies before and after the HFEs showed that sand deposition occurs in the mouths of some gullies (Hazel, Kaplinski, Parnell, and Fairley, 2008). Those sand deposits, however, do not usually persist, because they are eroded whenever flow occurs in the gullies and ephemeral streams. Thus, it is unlikely that deposition of flood sands in the mouths of gullies can stem gully erosion and contribute to archaeological site protection.

Mobilization of Debris-Flow Deposits at Debris Fans

Debris fans are accumulations of deposits formed by debris flows and flash floods emanating from steep tributary canyons (Webb and others, 1989). These deposits include very large boulders that constrict the flow of the river and create the rapids of Marble and Grand Canyons (Howard and Dolan, 1981). Measurements made during the 1996 HFE showed that recent debris-flow deposits can be mobilized by short-duration, high-flow releases. Pizzuto and others (1999) measured movement of boulders from a new debris-flow deposit at the Prospect Creek debris fan that forms Lava Falls rapid. Webb and others (1999) measured debris-fan reworking caused by the same HFE at other sites. These studies confirmed Kieffer's (1985) speculation that large flows are needed to prevent debris-flow aggradation at rapids. However, the HFE studies show that boulder-mobilizing flows can be much less than those estimated by Kieffer (1985) if the high flows occur within a few months of a substantial debris flow.

The Cumulative Effect of the High-Flow Experiments on Sandbars and Related Resources

Clearly, HFEs have allowed vast improvements in understanding the physical processes of the Colorado River in Grand Canyon. At the same time, each of these high flows has affected the natural resources of the river corridor, especially those resources formed by sand. In this section, the long-term, cumulative changes in three resources are described: (1) eddy sandbars, because these sandbars are a distinctive attribute of the pre-dam river landscape, (2) campsites on eddy sandbars, because campsites are a recreational resource, and (3) backwaters or embayments of stagnant or slow-moving water that occur at the edges of sandbars, because these backwaters provide aquatic habitat for some valued fish species.

The removal of fine sediment caused by sediment-deficit conditions in the post-dam river caused at least a 25-percent decrease in the average size of eddy sandbars in Grand Canyon between completion of Glen Canyon Dam in 1963 and the early 1990s (Schmidt and others, 2004). This decrease altered the river landscape, decreased the number and size of campsites, and changed the distribution and characteristics of aquatic habitat. Restoring, or enlarging, sandbars has been suggested as a goal of the Glen Canyon Dam Adaptive Management Program (National Research Council, 1999), although there are other potential restoration targets for the Colorado River in Marble and Grand Canyons (Schmidt and others, 1998; Schmidt, 2010).

The cumulative effect of the three HFEs cannot be uniquely isolated to the deposition caused by each high flow. Although eddy sandbars are constructed during high flows, they are eroded by the intervening flows. Over the long-term, average sandbar size either increases or decreases depending on (1) the magnitude of deposition during each high flow, (2) the frequency of those high flows, and (3) the rate of sandbar erosion that occurs between the high flows (fig. 15).

A sustainable river-management program that rebuilds eddy sandbars should seek to reverse the long-term erosional trend that began in 1963 through the redistribution of the tributary-derived sand supply—the only renewable supply of sand to the post-dam Colorado River. An alternative sustainable river-management program would be to augment the sand supply at Lees Ferry using sand accumulated in Lake Powell (Rubin and others, 2002; Randle and others, 2007). An example of an unsustainable management strategy would be to use high-flow releases to progressively mobilize and export the nonrenewable supply of sand that had been delivered to Marble and

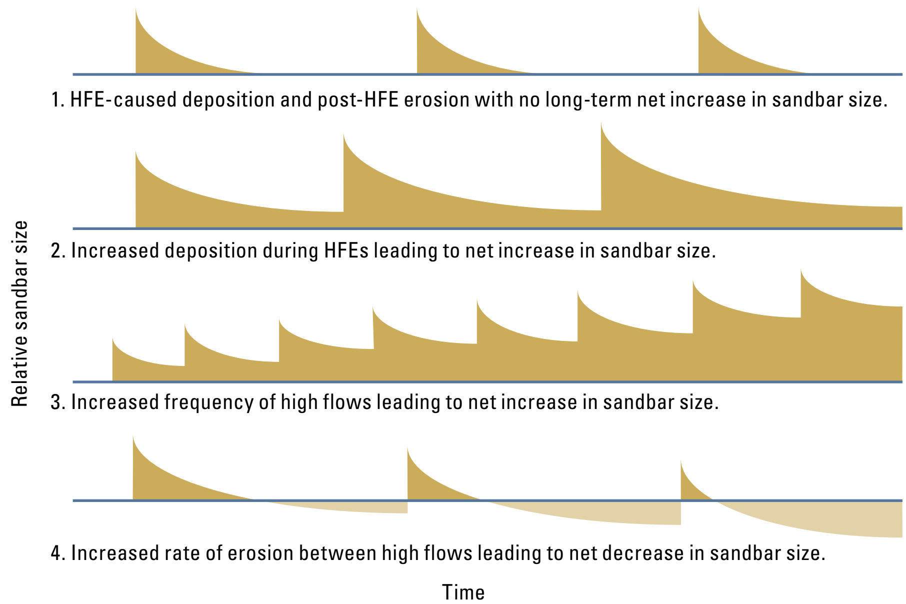


Figure 15. Conceptual diagram illustrating the dependency of net sandbar size on potential variations in the amount of deposition that occurs during a high-flow experiment (HFE), the frequency of HFEs, and the rate of post-HFE erosion. The case shown at the top shows a hypothetical amount of HFE deposition followed by an equal amount of erosion. Cases two and three result in net increases in sandbar size by increasing the amount of deposition during HFEs and increasing the frequency of HFEs, respectively. Such responses would require sufficiently great antecedent sand enrichment to support either larger or more frequent HFEs. In the final example, the rate of erosion following HFEs is increased, resulting in net decreases in sandbar size.

Grand Canyons before the dam was constructed. The success of such a program would be unsustainable, because eventually the nonrenewable sand supply would be exhausted.

Thus, the three HFEs are also evaluated in terms of the degree to which each experiment represents “sustainable” river management. The amount and distribution of eddy-sandbar deposition in different river segments during different HFEs are also compared in relation to the amount of sand transported to Lake Mead and the sources of the sand entrained by each high flow.

Sandbar Size

Assessment of the cumulative effects of the three HFEs on eddy sandbars involves segment-scale evaluation of the long-term changes of eddy sandbars. Thus, this assessment involves averaging the topographic changes measured at specific sites in order to make segment-scale generalizations.

Average Sandbar Changes Above Reference Stage During and After Each High-Flow Experiment

More than 80 percent of the post-dam fine sediment is stored in eddies below the reference stage (8,000 ft^3/s; Hazel and others, 2006). Nevertheless, deposition above the reference stage determines the amount of sand that can be seen by visitors to Grand Canyon National Park and how much sand is potentially available as campsites. Every HFE caused widespread new sandbar deposition above the reference stage. Deposition occurred at most eddy sandbars, and most sandbars changed consistent with styles 1 or 2 of sand deposition.

Eddy-sandbar deposition above the reference stage was greater in parts of Marble and Grand Canyons where the suspended-sand concentration was greatest. In upper Marble Canyon, the 2008 HFE had the highest suspended-sand concentration and created the largest eddy sandbars (fig. 16). The other HFEs had lower suspended-sand concentrations and deposited smaller sandbars. These patterns are illustrated by the ranking of the post-HFE to pre-HFE ratios of sandbar volume (table 4); four of the five greatest proportional increases in sandbar volume occurred in or immediately downstream from Marble Canyon during either the 2004 or 2008 HFEs.

Sandbar erosion rates were high immediately following each of the three high flows. Higher erosion rates occurred when the average dam releases were high or when there was little or no fine sediment input from tributaries. Thus, erosion rates were highest after the 1996 HFE (Grams, Hazel, and others, 2010) when tributary sediment inputs were low and average release volumes were high (fig. 17). Erosion rates were lowest following the 2004 HFE when tributary sediment inputs were high and average release volumes were relatively low. The 2008 HFE had intermediate conditions with intermediate erosion rates. Following the 1996 and 2008 HFEs, high erosion rates occurred during the summer season when the average volume of dam releases was higher than in 2004. Erosion rates were lower during the 6-month period after the 2004 HFE (Grams, Hazel, and others, 2010).

Table 4. The ten largest changes in sandbar volume between pre-high-flow experiment (HFE) and post-HFE conditions among 34 sites monitored before and after the 1996 and 2008 HFEs and 9 sites monitored before and after the 2004 HFE.

Ranking	Ratio of post-HFE to pre-HFE sandbar volume	Site	HFE year
1	4.42	RM 65R	2004
2	4.21	RM 65R	2008
3	2.89	RM 63R	2008
4	2.51	RM 30R	2004
5	2.33	RM 63R	1996
6	2.20	RM 139R	1996
7	2.18	RM 119R	1996
8	1.89	RM 30R	2008
9	1.84	RM 30R	1996
10	1.80	RM 47R	2008

Long-Term, Cumulative Changes in Sandbar Topography

Long-term rehabilitation of eddy sandbars can occur only if the increases in sand volume caused by high flows exceed the erosion that occurs during the intervening periods (fig. 15). Alternatively, if there are only small amounts of deposition during high flows and large volumes of erosion during intervening periods, a long-term decrease in sandbar size will result.

On average, the net effect, over the long term, of the HFE program has been to rebuild eddy-sandbar study sites above the reference stage in the downstream part of Marble Canyon and in most of Grand Canyon. Eighty-three percent of the long-term monitoring sites in lower Marble Canyon were larger in October 2008 than in March 1996. All of the 16 long-term monitoring sites in central and western Grand Canyon were larger in October 2008. However, in upper Marble Canyon and in eastern Grand Canyon, only one-third of the long-term monitoring sites were larger in October 2008 than they were in February 1996 prior to implementation of the first HFE in March 1996 (table 5). Two-thirds of the sites were smaller.

The temporal pattern leading to cumulative increase in sandbar size is illustrated by the changes that have occurred near RM 22 (fig. 18). Here, erosion that occurred during the periods between the HFEs removed only a small proportion of the high-flow deposits, and new deposition during each HFE exceeded the erosion that occurred during the previous period. Thus, the volume of sand at the eddy sandbar near RM 22 was much greater in 2010 than in 1996 (fig. 19). Long-term decrease in sandbar volume occurred where erosion during the intervening periods was large and deposition during high flows was small and limited to a small area. For example, the sandbar at RM 68 was progressively eroded, and the long-term changes at RM 16 and RM 47 have been relatively small.

Table 5. Summary of changes in sandbar size between February 1996 and October 2008.

Reach	Number of sites	Number of sites that are larger than February 1996 measurements	
		April 2008	October 2008
Upper Marble Canyon	6	4	2
Lower Marble Canyon	6	6	5
Eastern Grand Canyon	6	5	2
Central and western Grand Canyon	16	16	16
Entire study area	34	31	25

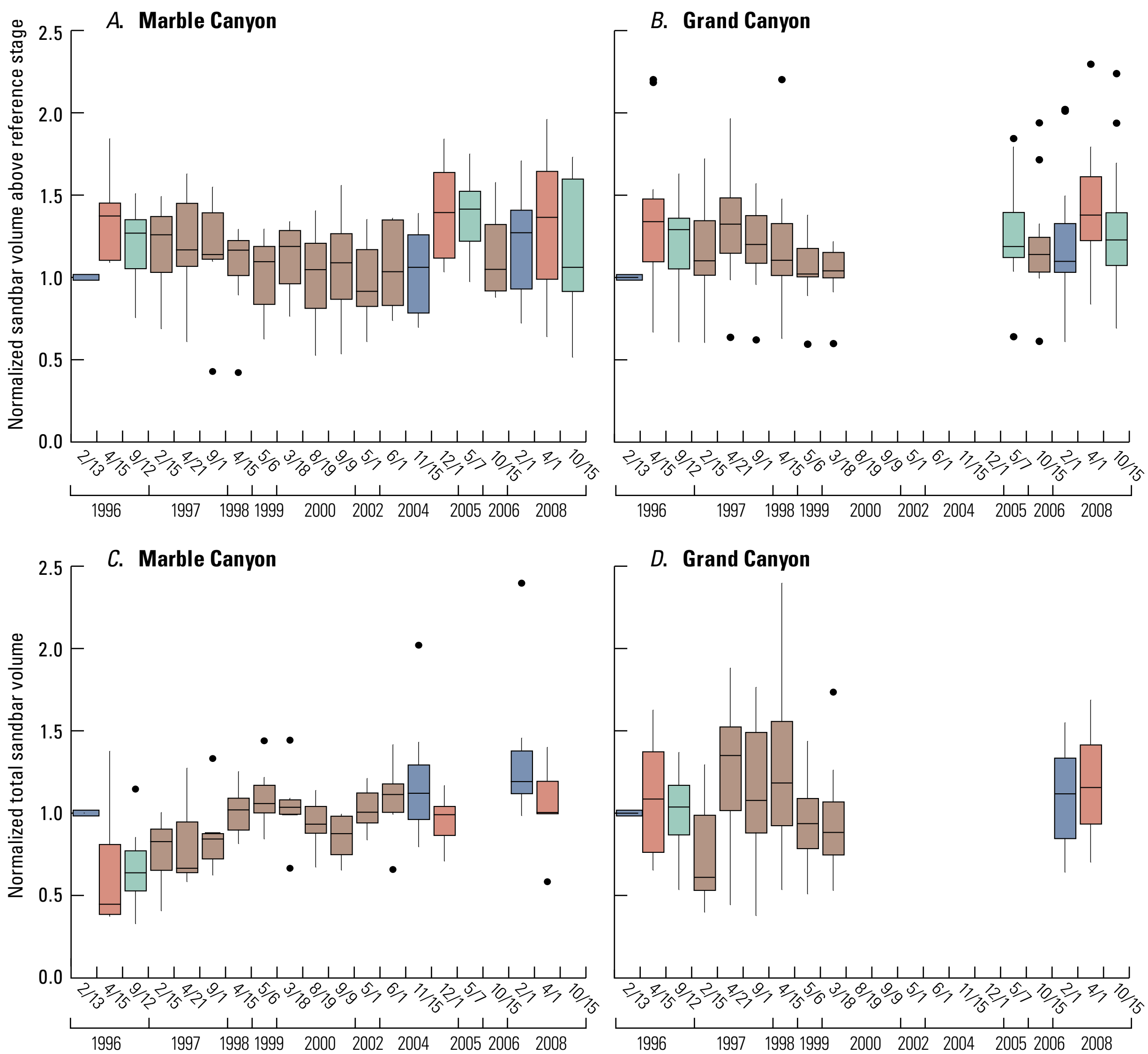


Figure 16. Sandbar volume that is normalized by dividing the volume for each indicated date by the volume measured in February 1996, before the 1996 high-flow experiment. Thus, the initial data point for each plot is equal to one, because it is the initial survey divided by itself (thick blue line). Where values are greater than one, sandbar size is larger than February 1996; where values are less than one, sandbar size is smaller than February 1996. *A*, Normalized sandbar volume above reference stage (8,000 cubic feet per second) in Marble Canyon. *B*, Normalized sandbar volume above reference stage in Grand Canyon. *C*, Normalized total sandbar volume in Marble Canyon. *D*, Normalized total sandbar volume in Grand Canyon. In each plot, the shaded region shows the upper and lower quartiles, the line shows the median value, the whiskers show the range of all data within 1.5 times the distance between the bounds of the upper and lower quartiles. Outliers outside this range are shown with unique symbols. Pre-flood measurements are shown in blue, post-flood measurements are shown in red, 6-month post-flood measurements are shown in green, and measurements made between controlled floods are shown in brown. Modified from Grams, Hazel, and others (2010).

Sediment Mass Balance

One of the key management issues regarding the use of high flows as a tool in redistributing sand from the channel bed to eddy sandbars is minimizing the amount of sand transported to western Grand Canyon and Lake Mead and maximizing the amount of sand deposited in sandbars. A comparison of the sediment mass balance of each HFE allows for the evaluation of this ratio.

The quantity of sand transported into and out of each segment of Grand Canyon has been well measured since about 2000. However, measurements of changes in the distribution and size of eddy sandbars and of sand on the channel bed are not nearly as numerous, because few places have been repeatedly measured. The few measurements of sandbar deposition or erosion were averaged for each segment, and uncertainty was assigned on the basis of the variability and number of sites measured in each segment. Average changes in topography were multiplied by the estimated total area of eddies and of the channel in order to estimate the volume of sand deposited or eroded from each part of Grand Canyon (table 2) using methods developed by Schmidt (1999) and Hazel and others (2006). The sand budget calculations are reported with the appropriate degree of uncertainty.

Upper and Lower Marble Canyon

New deposition of eddy sandbars and channel-margin deposits above the reference stage in Marble Canyon was between 490,000 and 870,000 tons in 1996, between 450,000 and 770,000 tons in 2004, and between 420,000 and 740,000 tons in 2008 (table 6). Where did this sand come from? How much was transported downstream in relation to the amount that created these new deposits?

Topping and others (2010) showed that, in 2008, the total amount of new deposits in Marble Canyon and sand exported farther downstream was probably less than the antecedent sand enrichment. Thus, the 2008 HFE probably mobilized most, or all, of the antecedent sand enrichment in Marble Canyon, and it is unlikely that the 2008 HFE mobilized any of the sand supply that had entered the river corridor before 2004. New deposits in upper and lower Marble Canyon in 2008 (table 6) were between 14 and 76 percent of the antecedent sand enrichment (table 1). Export of sand to eastern Grand Canyon was between 920,000 and 1,020,000 tons, which was between 32 and 111 percent of the antecedent sand enrichment. The wide range of estimates of each part of the mass balance—the antecedent sand enrichment, the volume of new deposits, and the amount of sand exported farther downstream—yields large uncertainty in these estimates.

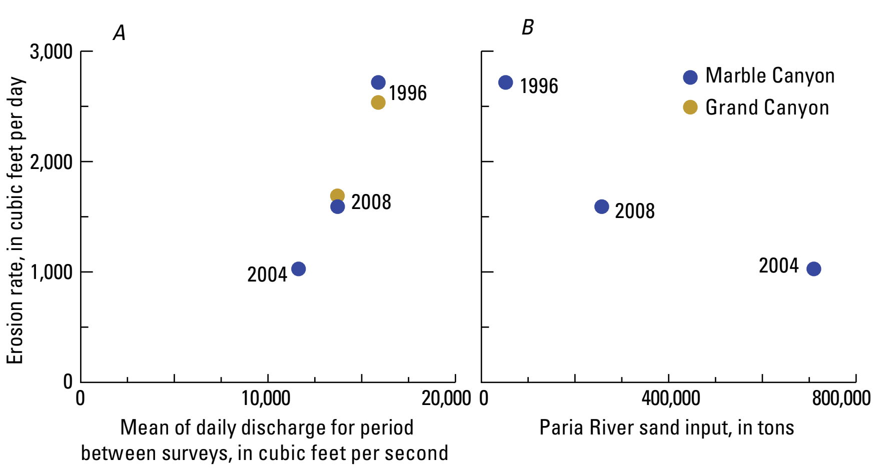


Figure 17. Rate of sandbar erosion following the 1996, 2004, and 2008 high-flow experiments (HFEs). *A*, The relation between sandbar erosion and the average of mean daily discharge for the period between surveys conducted immediately after HFEs and 6 months after HFEs for sites in Marble Canyon, eastern Grand Canyon, and combined central and western Grand Canyon. *B*, The relation between sandbar erosion and the total magnitude of Paria River sand inputs for the same time period and sites shown in *A*. From Grams, Hazel, and others (2010).

Figure 18. Matched views looking across the Colorado River at the study site near river mile 22 showing conditions before and after each high-flow experiment (HFE). *A*, Before the 1996 HFE. *B*, After the 1996 HFE. *C*, Before the 2004 HFE. *D*, After the 2004 HFE. *E*, Before the 2008 HFE. *F*, After the 2008 HFE. The images show deposition by each HFE, and a sandbar that is progressively larger following each HFE. Photographs by Joseph Hazel and Matt Kaplinski, Northern Arizona University.

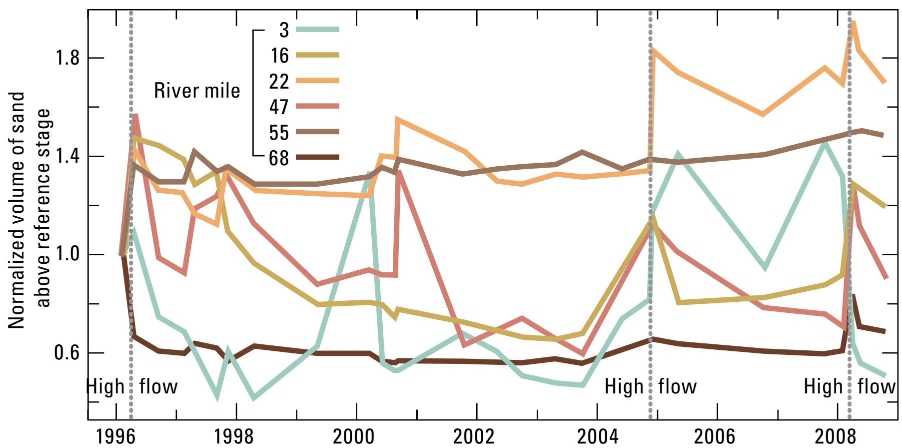


Figure 19. Normalized sandbar volume above the reference stage at selected sites for February 1996 to October 2009. Normalized means that the values shown are relative values; they are shown as the ratio of sandbar volume measured on the indicated date to sandbar volume measured in February 1996, before the 1996 high-flow experiment. Each high flow is shown by a vertical dotted gray line.

In contrast, the 2004 HFE probably mobilized all of the antecedent sand enrichment in Marble Canyon and probably also mobilized older, remnant sand deposits. New deposits in Marble Canyon were between 450,000 and 770,000 tons—between 63 and 200 percent of the antecedent sand enrichment. The total amount of sand exported from Marble Canyon—between 690,000 and 760,000 tons—was large in relation to the antecedent sand enrichment—between 96 and 205 percent of the antecedent supply—because the enrichment was only between 380,000 and 720,000 tons. Thus, the 2004 HFE probably mobilized more sand than just the amount that had entered upper and lower Marble Canyon in the 4½ months immediately before that HFE.

In 1996, the total amount of sand transported from lower Marble Canyon to eastern Grand Canyon was large, but there are no data about the antecedent sand enrichment to compare with transport data. The sum of the total amount of sand transported downstream plus the amount of sand that formed new sand deposits in upper and lower Marble Canyons probably exceeded the antecedent sand supply, because little sand was contributed by the Paria River in the year before that first HFE.

Eastern, Central, and Western Grand Canyon

Comparison of antecedent sand enrichment and the volume of sand entering and exiting eastern, central, and western Grand Canyon in 2004 and 2008 indicates that the 2004 HFE mobilized a higher proportion of the antecedent supply than did the 2008 HFE. Neither HFE, however, is likely to have mobilized older sand deposits.

General Conclusions

The sediment mass balance calculations show that each HFE mobilized most, or all, of the antecedent sand enrichment in Marble Canyon. Some of this mobilized sand was deposited in eddies to form larger sandbars; the remainder of the sand was exported farther downstream. In other words, the "checking account" of accumulated sand enrichment in Marble Canyon was "re-zeroed" by each HFE. This conceptual model of accumulation, mobilization, redistribution, and re-zeroing was previously envisioned by the U.S. Department of the Interior (1995). The difference between the conceptual model proposed in the mid-1990s and the model based on insights gained from the three HFEs is that scientists now know that the interval over which new tributary sand accumulates is relatively short; new sand is generally exported downstream within a year. Accumulation only occurs when tributary delivery of sand is relatively large and dam releases are relatively low volume (Rubin and others, 2002; Topping and others, 2010).

Table 6. Estimated total sediment deposition in Marble Canyon (all values in millions of tons).

Storage location	1996 HFE	2004 HFE	2008 HFE
Eddy above reference stage	0.58 ± 0.16	0.51 ± 0.13	0.48 ± 0.13
Channel-margin above reference stage	0.10 ± 0.03	0.10 ± 0.03	0.10 ± 0.03
Sum of deposits above reference stage	0.68 ± 0.19	0.61 ± 0.16	0.58 ± 0.16

Campsites

While campsites in Grand Canyon are not officially designated, a large number of eddy sandbars are frequently used for camping, such that river runners expect the sandbars to be available for use by boating parties. Many of these sites are marked on river running guide maps (Stevens, 1990; Belknap and Belknap Evans, 2001). Thus, these sandbars constitute a population of informally designated campsites, and a large number of these campsites are partially or completely affected by high flows. For monitoring purposes, campsites are defined as relatively flat areas that are bare or sparsely vegetated (Kearsley and others, 1999).

Since most eddy sandbars increased in area and volume after each HFE, it is not surprising that the areas of most campsites increased similarly. Kearsley and others (1999) reported that the 1996 HFE caused a 37-percent increase in the total number of campsites in Grand Canyon. They also reported that the campsite area of 50 randomly selected sites increased by nearly 50 percent (Kearsley and others, 1999). Hazel and others (2010) reported that the 2008 HFE caused a 100-percent increase in the campsite area of 37 sites.

The proportional changes in campsite area caused by the HFEs differ from the proportional changes in sandbars, however. The relation between geomorphic changes in eddy sandbars and campsites is confounded by two factors. One factor solely concerns geomorphology; changes in sandbar volume do not necessarily cause commensurate changes in sandbar area (fig. 20). For example, increases in sandbar thickness may increase the elevation of the sandbar, but the area that is useful as a campsite may not change substantially (Kearsley and others, 1999). A second confounding factor is that sand deposition amongst vegetation often does not increase campsite area, because river runners often avoid densely vegetated areas (fig. 21).

Although each HFE caused short-term increases in campsite area, erosion and vegetation invasion led to decreased campsite area during the intervening periods (fig. 22; Hazel and others, 2010; Kaplinski and others, 2010). Kearsley and others (1999) reported that 44 percent of the campsites created by the 1996 HFE were not usable 6 months later. Hazel and others (2010) reported substantial erosion and campsite area decline in the 6-month period following the 2008 HFE. Between HFEs, campsite area declined more in noncritical areas than in critical areas (fig. 22), owing to more extensive expansion of riparian vegetation (see chapter 4, this volume).

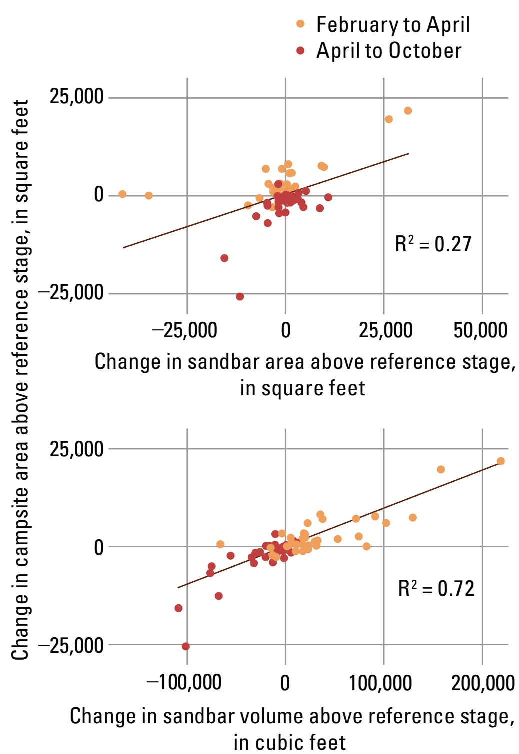


Figure 20. Relation between change in campsite area and change in sandbar area and volume for two time intervals in 2008, pre- to post-flood (February–April) and the following 6 months (April–October). A linear-regression (straight-line) fit for both time intervals combined is shown. Modified from Hazel and others (2010).

Implications to Aquatic Habitat: Response of Sandbar-Created Backwaters to High-Flow Experiments

The redistribution of sand during high flows not only leads to eddy-sandbar deposition but also causes changes in sandbar topography that substantially increases the number and size of backwaters. These areas of low or stagnant flow are nursery rearing habitat for humpback chub (*Gila cypha*). These desirable topographic changes primarily occur where there is substantial deposition of the reattachment bar within an eddy. Reattachment bars are the part of an eddy sandbar that underlies most of the recirculating flow (Rubin and others, 1990). Grams, Schmidt, and Andersen (2010) documented changes in sandbar topography at 78 reattachment bars and reported that deposition on the bar and erosion in the adjacent eddy return-current channel occurred at one-half of these sites during the 2008 HFE. These changes accentuated bar relief (see chapter 2 text box, The Fan-Eddy Complex) and led to increases in the area and volume of backwater habitat. These changes in sandbar morphology were summarized by Grams, Schmidt, and Andersen (2010) in plots that show backwater area as a function of discharge (fig. 23). The March 2008 HFE resulted in increases in the area of backwater habitat that would be present at all discharges between 8,000 and 20,000 ft^3/s. The increase persisted for at least 2 months, but returned to conditions similar to those before the HFE by about 6 months after the HFE.

Conclusions

Over the long term, eddy-sandbar size can only be increased if (1) high flows cause substantial deposition, (2) high flows occur frequently, and (3) erosion that occurs between high flows is less than the deposition. Thus, the net effect of high flows in building eddy sandbars results from the

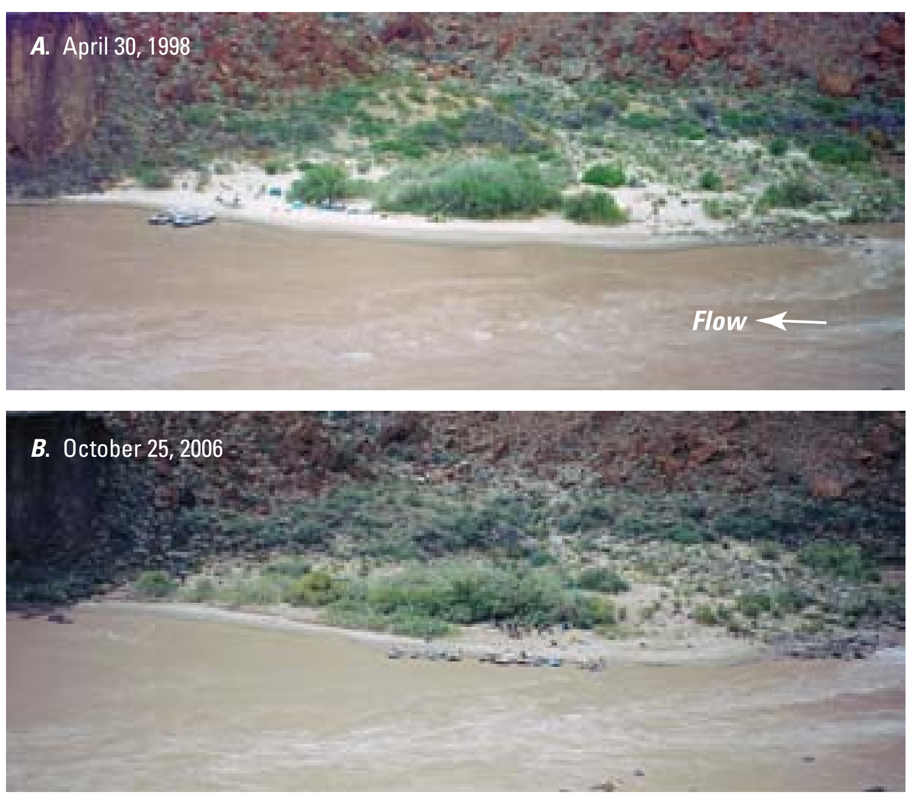


Figure 21. Repeat views looking across the Colorado River from the left bank at the sandbar and campsite located at river mile 202.3. Flow in main channel is from right to left. Between 1998 and 2006, woody vegetation, primarily arrowweed (*Pluchea sericea*), had expanded to cover large areas of the formerly sandy, unvegetated sandbar. *A*, Photograph taken April 30, 1998, at a river discharge of about 14,000 ft^3/s. *B*, Photograph taken October 25, 2006, at a river discharge of about 11,700 ft^3/s.

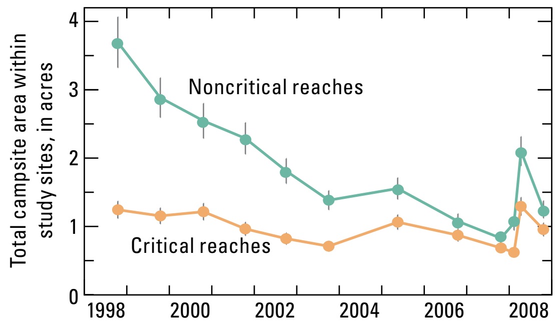


Figure 22. High-elevation campsite area in critical and noncritical reaches between 1998 and 2008. The error bars show plus and minus 10 percent uncertainty. Critical reaches are reaches where campsites are in scarce supply, and noncritical reaches have more abundant campsites. Modified from Kaplinski and others (2010).

magnitude *and* the frequency of high flows and the deposition they cause. Erosion ensues rapidly after each high flow, and the rate of erosion declines thereafter but persists. The longer the time period between HFEs, the more erosion occurs.

The HFE research program demonstrated that eddy sandbars are quickly constructed by high flows if those flows have high suspended-sand concentrations. In turn, high suspended-sand concentrations are caused by large antecedent sand-enrichment conditions or by smaller antecedent sand enrichment with very fine grain sizes. Thus, every time that enrichment is large in quantity or fine in grain size, an opportunity exists to build sandbars and to reverse erosional trends (see chapter 5, this volume).

Although there has been no experimentation with substantially larger HFE magnitudes, it is likely that high flows larger in magnitude than the three HFEs conducted to date would produce larger sandbars than those measured between 1996 and 2008, provided that the antecedent sand enrichment is sufficiently large to sustain high concentrations of suspended sand for 1 to 3 days. Larger sandbars would be expected to form, because a larger area would be inundated, and the water-surface elevation would be higher. Available data are consistent with the perception that the high-flow deposits would be thicker when high flows are larger in magnitude.

The duration of high flows should typically be only a few days if the sole objective is to increase eddy sandbar size. The duration of the 1996 HFE was too long, because the supply of sand was exhausted before the end of the 7-day event (Topping and others, 1999). In contrast, elevated sand concentrations were maintained throughout the 2008 HFE (Topping and others, 2010). Moreover, daily measurements made during the 2008 HFE indicated that sandbars above the reference stage were still getting larger up to the end of the high flow (Wright and Kaplinski, in press). This indicates that there may be sand-enriched conditions in which peak-flow durations longer than 60 hours could result in a greater sandbar-building response than has yet been observed. This

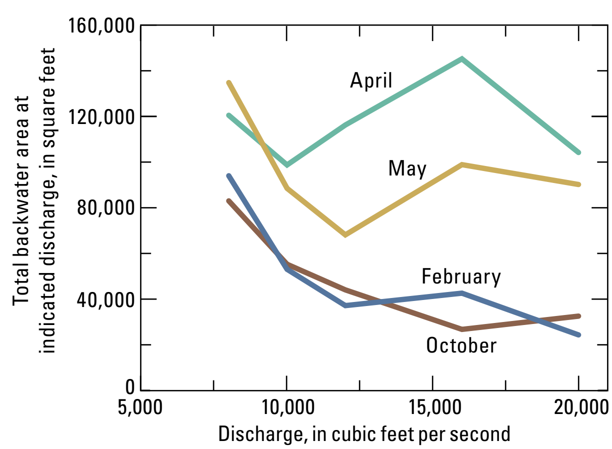


Figure 23. The relation between total backwater habitat area and discharge for the sandbar and backwater monitoring sites in 2008. Modified from Grams, Schmidt, and Andersen (2010).

potential benefit of longer-duration flows must be balanced against the greater net sand export from Grand Canyon that would also occur.

The HFE research program also showed that high flows that are released when antecedent sand enrichment is low have the potential to remove more sand from the channel bed than just the antecedent enrichment. Thus, high flows have the potential to remove some of the nonrenewable sand resource if the high flows are not properly scheduled. This scenario probably happened in 1996 and may have happened in 2004. Thus, a sustainable program of HFEs must be based on accurate accounting of the antecedent enrichment and of the grain sizes of that enrichment. Simply scheduling high flows on a regular basis and ignoring the magnitude of the antecedent supply risks accelerating long-term erosion of eddy sandbars. See chapter 5, this volume, for possible future HFE options.

The evidence that supports this conclusion is the comparison of antecedent sand enrichment and sand budgets for the three HFEs. The sand enrichment prior to the 2008 HFE was more than sufficient to cause widespread increases in sandbar sizes. The sand enrichment prior to the 1996 HFE was too small to support the high-elevation deposition that was measured; some of the new sand deposited at high elevation by this flood was eroded from low-elevation parts of eddy sandbars and from the main channel and was remnant sand delivered to the Colorado River a few years to a decade before March 1996. Sand enrichment before the 2004 HFE was sufficiently large and was probably the source for all of the new high-elevation sandbars in upper Marble Canyon, but remnant sand that was not part of the antecedent sand enrichment was deposited in high-elevation sandbars farther downstream. These differences in antecedent sand conditions in different parts of Marble and Grand Canyons present another challenge for sustainable river management—the need to make assessments of antecedent conditions in different segments of the river corridor before scheduling HFEs. Additionally, resource-management goals for future high flows could potentially differ in various parts of Marble and Grand Canyons if sand enrichment is not uniformly widespread.

Rubin and others (2002) described the management alternatives faced at those times when tributaries supply large amounts of sand to the Colorado River. Dam releases of less than 9,000 ft^3/s are needed to retain sand so that it is not exported to western Grand Canyon and Lake Mead. This low-flow regime would have to be maintained as the primary flow regime until the next high flow was scheduled in order to retain that sand in upstream parts of Marble and Grand Canyons, thereby ensuring the largest possible antecedent sand enrichment.

Measurements also demonstrate that there is substantial site-to-site variability in the magnitude and distribution of sandbar deposition caused by any high flow. The topographic response of specific sandbars to specific high flows cannot be predicted with precision. Thus, the predicted response of sandbars to specific future high flows must to be characterized by average, large-scale river segment behavior.

Some physical processes measured during the HFEs are well understood but not easily generalized to all of Marble and Grand Canyons. Scientists understand that discharges of about 45,000 ft^3/s can mobilize recently deposited debris flows and that canyon winds may redistribute sand from sandbars to higher elevations and sometimes bury archaeological sites. Unfortunately, neither process is easily generalized nor are there quantitative estimates of the river-segment-scale importance of these processes.

Thus, there is no question that high flows similar in magnitude to those that occurred during the HFEs of 1996, 2004, and 2008 effectively mobilize accumulated fine sand delivered by tributaries downstream from Glen Canyon Dam and rebuild eddy sandbars in Marble and Grand Canyons. Short-duration dam releases mobilize this sand and either redistribute it to eddy sandbars or to western Grand Canyon and Lake Mead. Sand-enrichment conditions similar to those prior to the 2008 HFE afford great potential to build sandbars with relatively small volumes of water.

Limited research has been conducted on the magnitude of sandbar erosion that occurs during periods between HFEs. Grams, Schmidt, and Andersen (2010) reported that more erosion occurs when total flow is large. Therefore, large dam releases that are entirely within powerplant capacity and that occur between HFEs are likely to undo the positive effects of sandbar building, backwater creation, and campsite expansion caused by HFEs. Even though high flows are an important part of an adaptive management program to rebuild sandbars, they remain only one part of a complex strategy.

References

Andrews, E.D., Johnston, C.E., Schmidt, J.C., and Gonzales, Mark, 1999, Topographic evolution of sandbars, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union: Geophysical Monograph Series, v. 110, p. 117–130.

Belknap, Buzz, and Belknap Evans, Lorie, 2001, Grand Canyon river guide: Evergreen, Colorado, Westwater Books, 112 p.

Beus, S.S., Avery, C.C., Stevens, L., Cluer, B., Kaplinski, M., Anderson, P., Bennett, J., Brod, C., Hazel, J., Gonzales, M., Hayes, H., Protiva, F., and Courson, J., 1992, The influence of variable discharge regimes on Colorado River sand bars below Glen Canyon Dam (chap. 6), *in* Beus, S.S., and Avery, C.C., Principal investigators, 1992, The influence of variable discharge regimes on Colorado River sand bars below Glen Canyon Dam—Final report: Bureau of Reclamation, Glen Canyon Environmental Studies, National Park Service cooperative agreement no. CA 8006-8-0002 with Northern Arizona University, 62 p., accessed January 29, 2011, at *http://www.gcmrc.gov/library/reports/physical/Fine_Sed/beus1993.pdf*.

Colby, B.R., 1964, Scour and fill in sand-bed streams: U.S. Geological Survey Professional Paper 462–D, 32 p.

Draut, A.E., Hazel, J.E., Jr., Fairley, H.C., and Brown, C.R., 2010, Aeolian reworking of sandbars from the March 2008 Glen Canyon Dam high-flow experiment in Grand Canyon, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 325–331. (Also available at *http://pubs.usgs.gov/sir/2010/5135/*.)

Draut, A.E., and Rubin, D.M., 2008, The role of eolian sediment in the preservation of archeologic sites along the Colorado River corridor in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1756, 71 p. (Also available at *http://pubs.usgs.gov/pp/1756/*.)

Draut, A.E., Topping, D.J., Rubin, D.M., Wright, S.A., and Schmidt, J.C., 2010, Grain-size evolution in suspended sediment and deposits from the 2004 and 2008 controlled-flood experiments in Marble and Grand Canyons, Arizona, *in* Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, 2010, June 27–July 1, 2010, Las Vegas, Nevada, Proceedings: Advisory Committee on Water Information, CD-ROM.

Grams, P.E., Hazel, J.E., Schmidt, J.C., Kaplinski, Matt, Wright, S.A., Topping, D.J., and Melis, T.S., 2010, Geomorphic response of sandbars to the March 2008 high-flow experiment on the Colorado River downstream from Glen Canyon Dam, *in* Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, 2010, June 27–July 1, 2010, Las Vegas, Nevada, Proceedings: Advisory Committee on Water Information, CD-ROM.

Grams, P.E., Schmidt, J.C., and Andersen, M.E., 2010, 2008 high-flow experiment at Glen Canyon Dam—Morphologic response of eddy-deposited sandbars and associated aquatic backwater habitats along the Colorado River in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010–1032, 73 p. (Also available at *http://pubs.usgs.gov/of/2010/1032/*.)

Hazel, J.E., Jr., Grams, P.E., Schmidt, J.C., and Kaplinski, Matt, 2010, Sandbar response in Marble and Grand Canyons, Arizona, following the 2008 high-flow experiment on the Colorado River: U.S. Geological Survey Scientific Investigations Report 2010–5015, 52 p. (Also available at *http://pubs.usgs.gov/sir/2010/5015/*.)

Hazel, J.E., Jr., Kaplinski, Matt, Parnell, R.A., and Fairley, H.C., 2008, Aggradation and degradation of the Palisades gully network, 1996 to 2005, with emphasis on the November 2004 high-flow experiment, Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 2008–1264, 14 p.

Hazel, J.E., Jr., Kaplinski, Matt, Parnell, R.A., Kohl, Keith, and Schmidt, J.C., 2008, Monitoring fine-grained sediment in the Colorado River ecosystem, Arizona—Control network and conventional survey techniques: U.S. Geological Survey Open-File Report 2008–1276, 15 p. (Also available at *http://pubs.usgs.gov/of/2008/1276/*.)

Hazel, J.E., Jr., Kaplinski, M., Parnell, R., Manone, M., and Dale, A., 1999, Topographic and bathymetric changes at thirty-three long-term study sites, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 161–183.

Hazel, J.E., Jr., Topping, D.J., Schmidt, J.C., and Kaplinski, Matt, 2006, Influence of a dam on fine-sediment storage in a canyon river: Journal of Geophysical Research, v. 111, no. F01025, p. 1–16, doi:10.1029/2004JF000193.

Hereford, Richard, Thompson, K.S., Burke, K.J., and Fairley, H.C., 1996, Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona: Geological Society of America Bulletin, v. 108, p. 3–19.

Howard, Alan, and Dolan, Robert, 1981, Geomorphology of the Colorado River in the Grand Canyon: The Journal of Geology, v. 89, no. 3, p. 269–298, doi: 10.1086/628592, accessed February 18, 2010, at *http://www.jstor.org/pss/30078299*.

Kaplinski, Matt, Hazel, J.E., Jr., and Parnell, Rod, 2010, Colorado River campsite monitoring, 1998–2006, Grand Canyon National Park, Arizona, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 275–284. (Also availaable at *http://pubs.usgs.gov/sir/2010/5135/*.)

Kaplinski, Matt, Hazel, J.E., Jr., Parnell, Rod, Breedlove, Mike, Kohl, Keith, and Gonzales, Mark, 2009, Monitoring fine-sediment volume in the Colorado River ecosystem, Arizona—Bathymetric survey techniques: U.S. Geological Survey Open-File Report 2009–1207, 33 p. (Also available at *http://pubs.usgs.gov/of/2009/1207/*.)

Kearsley, L.H., Quartaroli, R.D., and Kearsley, M.J.C., 1999, Changes in the number and size of campsites as determined by inventories and measurement, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 147–159.

Kearsley, L.H., Schmidt, J.C., and Warren, K.D., 1994, Effects of Glen Canyon Dam on Colorado River sand deposits used as campsites in Grand Canyon National Park, USA: Regulated Rivers—Research & Management, v. 9, no. 3, p. 137–149, accessed December 30, 2009, at *http://www3.interscience.wiley.com/cgi-bin/fulltext/113512382/PDFSTART*.

Kieffer, S.W., 1985, The 1983 hydraulic jump in Crystal Rapid—Implications for river-running and geomorphic evolution in the Grand Canyon: The Journal of Geology, v. 93, no. 4, p. 385–406, doi:10.1086/628962, accessed December 28, 2009, at *http://www.journals.uchicago.edu/doi/abs/10.1086/628962*.

Leopold, L.B., and Maddock, Thomas, Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 53 p.

Marzolf, G.R., Jackson, W.L., and Randle, T.J., 1999, Flood releases from dams as management tools—Interactions between science and management, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 359–367.

National Research Council, 1996, River resource management in Grand Canyon: Washington, D.C., National Academies Press, Committee to Review the Glen Canyon Environmental Studies, 226 p.

National Research Council, 1999, Adaptive management for water resources project planning: Washington, D.C., National Academies Press, Panel on Adaptive Management for Resource Stewardship, Committee to Assess the U.S. Army Corps of Engineers Methods of Analysis and Peer Review for Water Resources Project Planning, 138 p.

Patten, D.T., Harpman, D.A., Voita, M.I., and Randle, T.J., 2001, A managed flood on the Colorado River—Background, objectives, design, and implementation: Ecological Applications, v. 11, no. 3, p. 635–643.

Pizzuto, J.E., Webb, R.H., Griffiths, P.G., Elliott, J.G., and Melis, T.S., 1999, Entrainment and transport of cobbles and boulders from debris fans, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 53–70.

Randle, T.J., Lyons, J.K., Christensen, R.J., and Stephen, R.D., 2007, Colorado River ecosystem sediment augmentation appraisal engineering report: Denver, Colorado, U.S. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, 71 p., accessed on November 12, 2010, at *http://www.gcmrc.gov/library/reports/physical/Fine_Sed/Randle2007.pdf*.

Rubin, D.M., Nelson, J.M., and Topping, D.J., 1998, Relation of inversely graded deposits to suspended-sediment grain-size evolution during the 1996 flood experiment in Grand Canyon: Geology, v. 26, no. 2, p. 99–102, accessed December 29, 2009, at *http://geology.gsapubs.org/content/26/2/99*.

Rubin, D.M., Schmidt, J.C., and Moore, J.N., 1990, Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona: Journal of Sedimentary Petrology, v. 60, no. 6, p. 982–991.

Rubin, D.M., and Topping, D.J., 2001, Quantifying the relative importance of flow regulation and grain size regulation of suspended-sediment transport α and tracking changes in grain size of bed sediment β: Water Resources Research, v. 37, no. 1, p. 133–146.

Rubin, D.M., Topping, D.J., Schmidt, J.C., Hazel, J., Kaplinski, M., and Melis, T.S., 2002, Recent sediment studies refute Glen Canyon Dam hypothesis: Eos, Transactions, American Geophysical Union, v. 83, no. 25, p. 273, 277–278.

Schmidt, J.C., 1999, Summary and synthesis of geomorphic studies conducted during the 1996 controlled flood in Grand Canyon, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 329–341.

Schmidt, J.C., 2010, A watershed perspective of changes in streamflow, sediment supply, and geomorphology of the Colorado River, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 51–76. (Also available at *http://pubs.usgs.gov/sir/2010/5135/*.)

Schmidt, J.C., Andrews, E.D., Wegner, D.L., Patten, D.T., Marzolf, G.R., and Moody, T.O., 1999, Origins of the 1996 controlled flood in Grand Canyon, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 23–36.

Schmidt, J.C., Grams, P.E., and Leschin, M.F., 1999, Variation in the magnitude and style of deposition and erosion in three long (8–12 km) reaches as determined by photographic analyses, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 185–203.

Schmidt, J.C., Topping, D.J., Grams, P.E., and Hazel, J.E., 2004, System-wide changes in the distribution of fine sediment in the Colorado River corridor between Glen Canyon Dam and Bright Angel Creek, Arizona—Final report: Logan, Utah, Utah State University, submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, cooperative agreement no. 1425-98-FC-40-22640, 107 p., accessed January 31, 2011, at *http://www.gcmrc.gov/library/reports/Physical/Fine_Sed/Schmidt2004.pdf*.

Schmidt, J.C., Topping, D.J., Rubin, D.M., Hazel, J.E., Jr., Kaplinski, Matt, Wiele, S.M., and Goeking, S.A., 2007, Streamflow and sediment data collected to determine the effects of low summer steady flows and habitat maintenance flows in 2000 on the Colorado River between Lees Ferry and Bright Angel Creek, Arizona: U.S. Geological Survey Open-File Report 2007–1268, 79 p. (Also available at *http://pubs.usgs.gov/of/2007/1268/*.)

Schmidt, J.C., Webb, R.H., Valdez, R.A., Marzolf, G.R., and Stevens, L.E., 1998, Science and values in river restoration in the Grand Canyon: BioScience, v. 48, no. 9, p. 735–747, accessed August 17, 2010, at *http://www.jstor.org/stable/1313336*.

Stevens, Larry, 1990, The Colorado River in Grand Canyon—A comprehensive guide to its natural and human history (3d ed.): Flagstaff, Arizona, Red Lake Books, 115 p.

Topping, D.J., Rubin, D.M., Grams, P.E., Griffiths, R.E., Sabol, T.A., Voichick, Nicholas, Tusso, R.B., Vanaman, K.M., and McDonald, R.R., 2010, Sediment transport during three controlled-flood experiments on the Colorado River downstream from Glen Canyon Dam, with implications for eddy-sandbar deposition in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010–1128, 111 p. (Also available at *http://pubs.usgs.gov/of/2010/1128/*.)

Topping, D.J., Rubin, D.M., Nelson, J.M., Kinzel, P.J., III, and Bennett, J.P., 1999, Linkage between grain-size evolution and sediment depletion during Colorado River floods, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 71–98.

Topping, D.J., Rubin, D.M., Schmidt, J.C., Hazel, J.E., Melis, T.S., Wright, S.A., Kaplinski, Matt, Draut, A.E., and Breedlove, M.J., 2006, Comparison of sediment-transport and bar-response results from the 1996 and 2004 controlled-flood experiments on the Colorado River in Grand Canyon, *in* Proceedings of the Eighth Federal Interagency Sedimentation Conference, April 2–6, 2006, Reno, Nevada: Advisory Committee on Water Information, p. 171–179 (available on CD-ROM).

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport, 1. Natural sediment supply limitation and the influence of the Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515–542, doi: 10.1029/1999WR900285.

Topping, D.J., Schmidt, J.C., and Vierra, L.E., Jr., 2003, Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000: U.S. Geological Survey Professional Paper 1677, 118 p. (Also available at *http://pubs.usgs.gov/pp/pp1677/*.)

U.S. Department of the Interior, 1988, Glen Canyon Environmental Studies Executive Review Committee, Final report: Bureau of Reclamation, Glen Canyon Environmental Studies, 84 p. + apps. (Available from National Technical Information Serivce, PB88-183348/AS.)

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam—Final Environmental Impact Statement, Colorado River Storage Project, Coconino County, Arizona: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Regional Office, 337 p., accessed November 18, 2010, at *http://www.usbr.gov/uc/library/envdocs/eis/gc/pdfs/Cov-con/cov-con.pdf*.

U.S. Department of the Interior, 2002, Proposed experimental releases from Glen Canyon Dam and removal of non-native fish—Environmental assessment: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Regional Office, 112 p., accessed January 31, 2011, at *http://www.usbr.gov/uc/envdocs/ea/gc/PropExpReleasesEA-09-2002.pdf*.

U.S. Department of the Interior, 2004, Proposed experimental actions for water years 2005–2006 Colorado River, Arizona, in Glen Canyon National Recreation Area and Grand Canyon National Park—Draft supplemental environmental assessment: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Regional Office, 26 p., accessed March 25, 2010, at *http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1419&context=govdocs*.

Webb, R.H., Griffiths, P.G., Melis, T.S., and Hartley, D.R., 2000, Sediment delivery by ungaged tributaries of the Colorado River in Grand Canyon: U.S. Geological Survey Water-Resources Investigations Report 00–4055, 67 p.

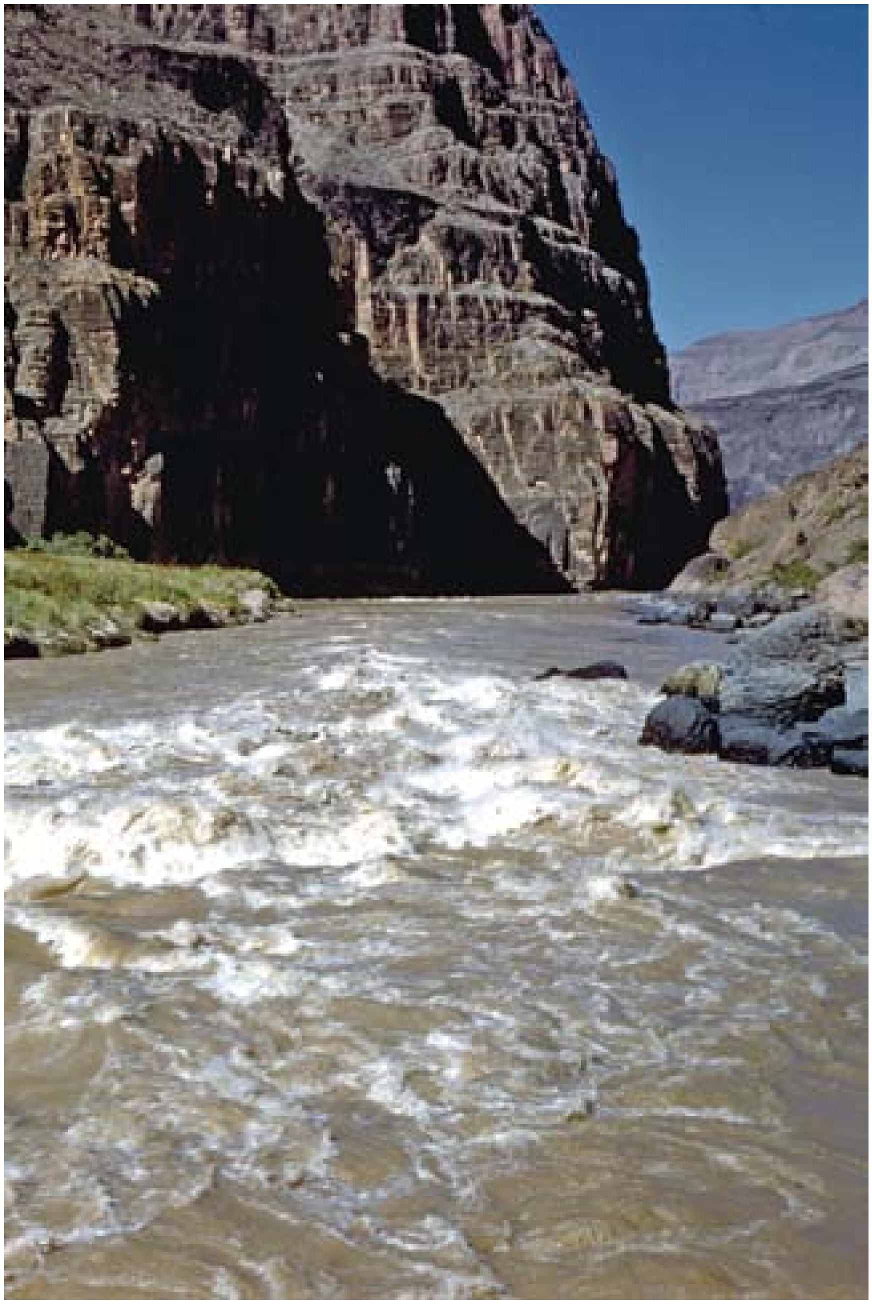
Webb, R.H., Melis, T.S., Griffiths, P.G., and Elliott, J.G., 1999, Reworking of aggraded debris fans, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 37–51.

Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.

Wiele, S., and Torizzo, M., 2005, Modelling of sand deposition in archaeologically significant reaches of the Colorado River in Grand Canyon, USA, *in* Bates, P.D., Lane, S.N., and Ferguson, R.I., eds., Computational fluid dynamics—Applications in environmental hydraulics: Hoboken, New Jersey, John Wiley & Sons, chap. 14, p. 357–394, accessed November 29, 2010, at *http://onlinelibrary.wiley.com/doi/10.1002/0470015195.ch14/summary*.

Wiele, S.M., Andrews, E.D., and Griffin, E.R., 1999, The effect of sand concentration on depositional rate, magnitude, and location in the Colorado River below the Little Colorado River, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 131–145.

Wright, S.A., and Kaplinski, M., in press, Flow structures and sandbar dynamics in a canyon river during a controlled flood, Colorado River, Arizona: Journal of Geophysical Research.



National Park Service

CHAPTER 4

Biological Responses to High-Flow Experiments at Glen Canyon Dam

By Theodore A. Kennedy[1,2] and Barbara E. Ralston[1,2]

Sandbars are a prominent geomorphic feature of the Colorado River (see chapters 2 and 3, this volume, for description). Closure of Glen Canyon Dam in 1963 (fig. 1) and subsequent operations have eroded these features. The Glen Canyon Dam Adaptive Management Program (GCDAMP) has released artificial floods (termed high-flow experiments (HFE)) to reestablish sandbar building processes in the hopes of benefitting a variety of biological, physical, and cultural resources that are dependent on floods or the sandbars and associated geomorphic features that are created by the floods (see chapters 2 and 3, this volume). High-flow experiments were conducted in March 1996, November 2004, and March 2008. The purpose of this chapter is to synthesize the biological resource responses to these three HFEs to assess whether this policy option is having a measurable effect on biological resources.

This chapter focuses on five biological resources that are of importance to the GCDAMP: (1) riparian vegetation, (2) Kanab ambersnail (*Oxyloma haydeni kanabensis*), (3) rainbow trout (*Oncorhynchus mykiss*), (4) endangered humpback chub (*Gila cypha*), and (5) other native fish populations (flannelmouth sucker (*Catostomus latipinnus*), bluehead sucker (*Catostomus discobolus*), and speckled dace (*Rhinichthys osculus*); see text box, Descriptions of Selected Fish Species in Grand Canyon. Riparian vegetation is valued because it provides high-quality habitat for terrestrial wildlife. Kanab ambersnails are federally listed as endangered, and portions of their habitats may be destroyed during HFEs. Rainbow trout were introduced to the tailwater below Glen Canyon Dam shortly after the dam was closed, and maintaining a sport fishery in the tailwater is an important GCDAMP goal (Gloss and Coggins, 2005). Humpback chub are native to the Colorado River Basin, and the Little Colorado River population in Grand Canyon is the largest anywhere (Coggins and Walters, 2009). Because many GCDAMP policies, including HFEs, are intended specifically to benefit humpback chub, much of this chapter focuses on describing links between HFEs and this imperiled species. The response of the three other native fish species still present in Grand Canyon is evaluated separately from humpback chub (four other species of fish native to the Colorado River have become extirpated since closure of Glen Canyon Dam; Gloss and Coggins, 2005). In addition to rainbow trout, other nonnative species are present in the Colorado River (for example, common carp *Cyprinus carpio*; see text box, Descriptions of Selected Fish Species in Grand Canyon), but these species are not discussed in this chapter because a GCDAMP goal for these species has not been established, the link between these nonnative species and HFEs is highly uncertain, and the effects of these nonnative species on native species are relatively unknown (see Yard and others, in press, for analysis of

[1] U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, 2255 N. Gemini Drive, Flagstaff, AZ 86001.

[2] Both authors contributed equally to the development of this chapter.

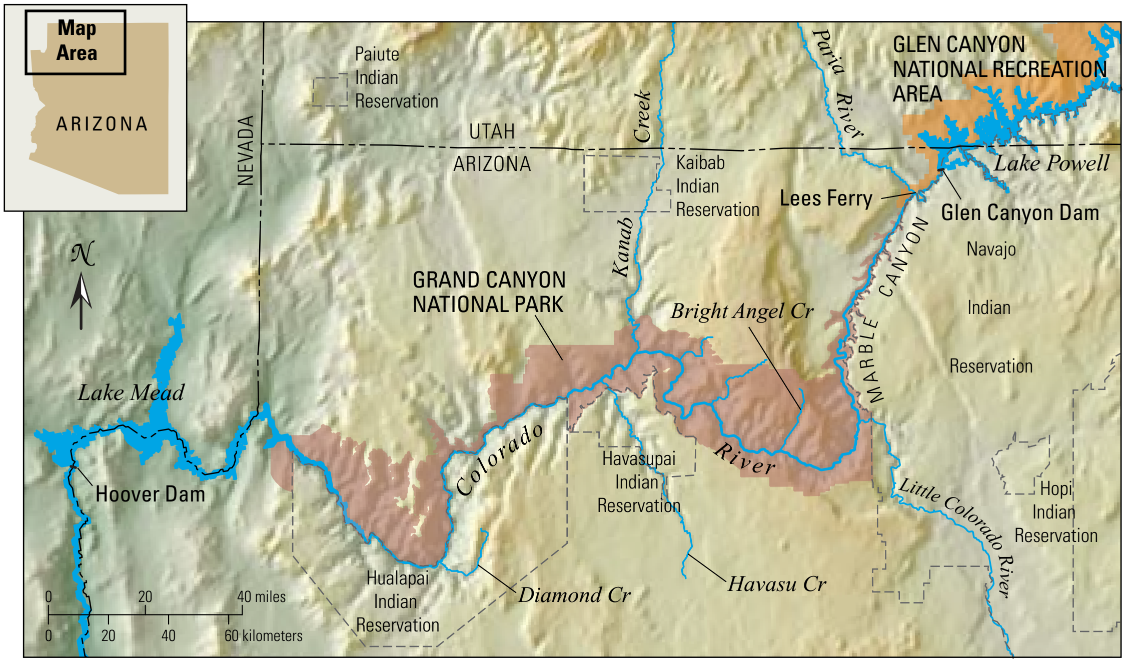


Figure 1. The Colorado River below Glen Canyon Dam, Arizona.

the effects of brown trout (*Salmo trutta*) on humpback chub). Although a GCDAMP goal has been established for the aquatic food base (algae and invertebrates), food-base data are only discussed in this chapter in the context of the fish population responses. This approach is consistent with the GCDAMP goal for food base, which is simply to maintain an adequate food supply for fish. For simplicity, the terrestrial ecosystem is considered separately from the aquatic ecosystem throughout this chapter.

Terrestrial Ecosystem

Background

Riparian vegetation along shoreline slopes below Glen Canyon Dam reflects the progressive reduction in annual flood peaks that occurred with regulation of the Colorado River (Carothers and Brown, 1991; Topping and others, 2003; Kennedy and Ralston, 2010). Vegetation cover increased substantially following the reduction in annual flood peaks associated with the closure of Glen Canyon Dam (Turner and Karpiscak, 1980; Kennedy and Ralston, 2010). Numbers of nonnative tamarisk (*Tamarix* spp.) expanded dramatically in Grand Canyon following river regulation, although the species was present in the river as early as 1938 (Clover and Jotter, 1944). Four distinct vegetation zones currently exist and reflect the frequency of inundation and disturbance, which is dependent on elevation above river level (fig. 2). Plants closest to the shore and up to about the 20,000 cubic feet per second (ft^3/s) stage elevation experience daily inundation for at least some periods of the year. Wetland species common in this zone include sedges (*Carex* spp.), cattail (*Typha latifolia*), horsetail (*Equisetum* spp.), and common reed (*Phragmites australis*). The lower riparian zone (between 20,000 and 31,000 ft^3/s stage elevations) has not been regularly inundated since 2000 because of a long-term drought in the upper Colorado River Basin. Vegetation in this zone includes woody riparian species, such as tamarisk, seep willow (*Baccharis* spp.), coyote willow (*Salix exigua*), and arrowweed (*Pluchea sericea*). The middle riparian zone is inundated during HFEs when discharge is between 31,000 and 45,000 ft^3/s. Plants found in this zone are similar to those in the lower riparian zone, but also include bunch grasses (sand dropseed, *Sporobolus cryptandrus*) and perennial shrubs (spiny aster, *Chloracantha spinosa*). The upper riparian zone includes the pre-dam riparian faculative vegetation, those species found in both riparian and upland habitats, and desert species associated with the Colorado Plateau, Great Basin, and Sonoran Desert floristic areas (McLaughlin, 1989). Honey mesquite (*Prosopis glandulosa*), catclaw acacia (*Acacia greggii*), mountain pepperweed (*Lepidium montanum*), Mormon tea (*Ephedra nevadensis*), prickly pear cactus (*Opuntia* spp.), creosote (*Larrea tridentata*), ocotillo (*Fouquieria splendens*), and brittlebush (*Encelia farinosa)* are common in this zone (Carothers and Brown, 1991). The cover of riparian vegetation is highest in wide, alluvial reaches and lowest in narrow, bedrock-confined reaches (Ralston and others, 2008).

Freshwater springs are present along the river channel, and their locations are tied to fractures in the underlying geology that allow groundwater discharge (Huntoon, 1981). Springs support a high diversity of riparian and wetland plant species. Vaseys Paradise is a spring located 32 miles downstream from Lees Ferry (fig. 1), the source of which is groundwater that is discharged about 125 feet above the Colorado River from a cave in the Redwall Limestone (fig. 3; Huntoon, 1981). Plant species that are common in this spring include nonnative watercress (*Rorippa nasturtium-aquaticum*), native cardinal monkey flower (*Mimulus cardinalis*), and water sedge (*Carex* sp.). The amount of discharge in the spring affects the lateral extent of vegetation growth along the canyon wall, and peak discharges in the Colorado River determine the lower extent that vegetation occupies (Ralston, 2005).

Vaseys Paradise is designated as a critical habitat for the endangered Kanab ambersnail (England, 1992). This species was listed as endangered in 1992 (England, 1992); however, uncertainties regarding the taxonomy (it may not be a unique species) may eventually affect its status as an endangered species (Meretsky and others, 2002). At Vaseys Paradise, the snail occupies habitats from well above historic flood elevations down to the river shoreline (Ralston, 2005).

High-Flow Experiments

The geomorphic features that are reworked and rebuilt during HFEs—sandbars, rocky slopes, debris fans, and return-current channels—are the substrate for growth of riparian vegetation. Thus, HFEs can affect vegetation through changes in habitat and also through burial and removal during the HFE itself. The vegetation response to HFEs affects terrestrial wildlife, through changes in habitat, and sociocultural resources, through changes in campsite area. The structural complexity of riparian vegetation is particularly important for nesting birds (Sogge and others, 1998). Plant-dwelling arthropods are food resources for some riparian bird species (Yard and others, 2004). The quantity and type of vegetation that colonizes sandbars affect campsite area in Grand Canyon (Kearsley and others, 1994). Increasing campsite area through sandbar building is one

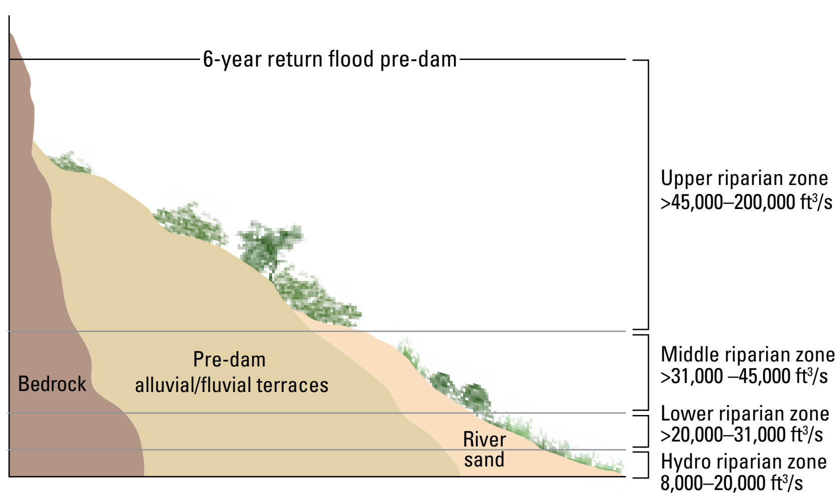


Figure 2. Vegetation zones according to inundation frequency and flow magnitude. In the post-dam period since 1991, when restrictions constrained dam operations, flows actively influence riparian vegetation up to the 45,000 cubic feet per second (ft^3/s) water-surface elevation. The higher elevation benches above this elevation are subject to floods up to the 6-year return flood frequency (200,000 ft^3/s). Vegetation follows a moisture gradient from water-tolerant plants located near the shoreline to species that tolerate drier upslope conditions (Ralston, 2010).

Figure 3. *A*, Kanab ambersnail (*Oxyloma haydeni kanabensis*), with a dime for perspective. *B*, The spring at Vaseys Paradise, one of three locations where the snails are found, showing the high discharge released from the caves high above the Colorado River. A scour line from the 1996 HFE is present in the photograph, with vegetation re-growing below the line in places. *C*, Watercress (*Rorippa nasturtium-aquaticum*). *D*, Cardinal monkeyflower (*Mimulus cardinalis*), the primary plant species associated with Kanab ambersnail. (Ambersnail photograph by Roy Averill-Murray, Arizona Game and Fish Department; other photographs by Jeff Sorensen, Arizona Game and Fish Department.)

of the primary motivations for conducting HFEs. Vegetation also affects the rate of sediment erosion and deposition during floods in general (Malanson, 1993; Simon and others, 2004). In this section, two aspects of riparian vegetation response are evaluated: (1) whether HFEs affect vegetation cover, which has implications for both wildlife and campsite area, and (2) whether HFEs differentially affect the cover of native as opposed to nonnative vegetation. No published studies are available regarding the 2004 HFE, so the 1996 and 2008 spring-timed HFEs are the focus of this review.

Riparian Vegetation

The magnitude and duration of both the 1996 and 2008 HFEs were insufficient to remove woody riparian plants, but some wetland plants close to the shoreline were removed (Kearsley and Ayers, 1999; Stevens and others, 2001; Ralston, 2010). Sediment deposition completely or partially buried plants, including coyote willow, seepwillow (*Baccharis* spp.), tamarisk, and some low-lying grasses and forbs. The 1996 HFE caused a 20-percent reduction in the total areal cover of woody and herbaceous plants on sandbars but this reduction was short lived, lasting less than 12 months (Kearsley and Ayers, 1999; Stevens and others, 2001). Herbaceous plant cover on sandbars doubled within 6 months of the 2008 HFE (Ralston, 2010).

Burial of vegetation during HFEs may affect riparian community structure by favoring plants adapted to burial and growth through vegetative reproduction. Plants that recovered quickly following the 2008 HFE were ones that are well adapted to burial, such as coyote willow (Ralston, 2010). Clonal wetland plants, such as common reed, also quickly occupied bare sandbars and shorelines following both the 1996 and 2008 HFEs (Kearsley and Ayers, 1999; Ralston 2010). Seed banks were immediately depleted during the 1996 HFE, which resulted in a localized reduction in sources of seeds for germination (Kearsley and Ayers, 1999). Nutrients derived from decomposing vegetation buried in sandbars during HFEs may also facilitate colonization of sandbars by vegetation (Parnell and others, 1999).

The timing of an HFE can affect the success of plants that are propagated with seeds. One of the primary concerns regarding HFE timing is the risk of distributing seeds of invasive species, especially tamarisk. The 1996 and 2008 HFEs occurred during the time of year before tamarisk begins producing seeds—seed production generally occurs between April and September. As such, the establishment of tamarisk seedlings was low (less than 2 percent) in 1996 and 2008 (Kearsley and Ayers, 1999; Stevens and others, 2001; Ralston, 2010). Tamarisk is a poor competitor in dense vegetation (Sher and others, 2000). Following the 2008 HFE, tamarisk seedlings were most commonly found in the lower riparian zone where vegetative cover was less than 15 percent (Ralston, 2010). The combination of sparse vegetation and consistent water availability throughout the growing season should have created ideal conditions for tamarisk seedling establishment, yet establishment was still low (Ralston, 2010). High-flow experiments that are coincident with tamarisk seed production could favor seedling establishment by tamarisk, but native species such as willows are also producing seeds at this time of year, so tamarisk would not be the only species poised to take advantage of favorable germination conditions following HFEs.

Kanab Ambersnail

The 1996 HFE resulted in the loss of 16 percent of the habitat used by Kanab ambersnail at Vaseys Paradise (Stevens and others, 2001). Conservation measures associated with HFEs in 2004 and 2008 included temporary removal of snails and their habitat prior to the HFE. Snails were released above the inundation zone, while mats of vegetation were temporarily held above the zone of inundation until the HFE was over and then returned to their original location. Vegetation recovery occurred within 6 months (U.S. Department of the Interior, 2008a). A snail census following the 2004 HFE documented no substantial decline in abundance, perhaps due to these mitigation measures (Sorensen, 2005, 2009).

Synthesis

High-flow experiments conducted in early spring appear to be a useful tool for meeting GCDAMP objectives for riparian vegetation, including maintaining native marsh and riparian communities and reducing nonnative species. However, reductions in campsite area due to vegetation recovery and expansion following HFEs might offset the temporary increases in campsite area that have previously occurred because of sandbar building during HFEs (Kaplinski and others, 2005). Vegetation may also influence sandbar building because the presence of vegetation along shorelines reduces water velocities and decreases the capacity of the river to rework and redistribute sediment (Simon and others, 2004). The effect that increased post-dam vegetation has on sediment deposition and erosion dynamics in the Colorado River is largely unknown. Future sediment studies might consider incorporating mechanical vegetation removal from shorelines to better understand the effects of vegetation on sediment deposition and sandbar building. Lastly, the effects of HFE timing on riparian vegetation is highly uncertain because no data were collected during the fall-timed 2004 HFE.

High-flow experiments lead to temporary reductions of Kanab ambersnail habitat, which in the absence of mitigation measures lead to direct reductions in the number of snails. Conservation measures associated with recent HFEs apparently limited the loss of snail habitat and snail mortality. However, Kanab ambersnails are distributed well above the stage elevation of HFEs, so these short-duration disturbances only affect a relatively small proportion of the overall habitat and population (about 15 percent). Furthermore, this species clearly survived and persisted despite natural pre-dam floods that were much larger in magnitude and duration than HFEs. Thus HFEs may not represent a substantial threat to the persistence of Kanab ambersnail populations at Vaseys Paradise.

Aquatic Ecosystem

Background

The serial discontinuity concept (Ward and Stanford, 1983) is a useful framework for describing the aquatic ecosystem downstream from Glen Canyon Dam (fig. 1). Dams such as Glen Canyon affect fish populations because of changes in the physical template, creating a "discontinuity" in the whole ecosystem. For the purposes of this report, the physical template of the Colorado River is defined as the physical habitat (backwaters and other channel features; Schmidt and Graf, 1990) and parameters such as water temperature, suspended sediment, and flow regime. The physical template of the Colorado River changes with distance downstream as climate and the cumulative influence of tributaries gradually cause the physical aspects of the ecosystem to shift to those more typical of unimpounded segments (Carothers and Brown, 1991). Water temperature and water clarity are two aspects of this changing physical template that appear to have a pronounced effect on fish assemblages below Glen Canyon Dam (Carothers and Brown, 1991; Gloss and Coggins, 2005).

Glen Canyon Dam has an overriding influence on native fish populations because of its effects on water temperatures. Water released from Glen Canyon Dam is cold (table 1) because it is drawn from deep within Lake Powell, the reservoir formed by the dam. These low water temperatures are often too low for successful native fish reproduction in the main stem (Minckley and Deacon, 1991; Valdez and Ryel, 1995; Voichick and Wright, 2007) and effectively restrict native fish spawning to warm-water tributaries. For example, water temperatures must be at least 61 degrees Fahrenheit (°F) for humpback chub to initiate spawning (Hamman, 1982). Cold water temperatures also limit growth rates for native fish that are rearing in the main stem (Clarkson and Childs, 2000); growth is a strong predictor of survival for animal populations (Krebs, 2008). Water temperatures gradually warm with distance downstream (table 1).

Glen Canyon Dam also has an overriding influence on fish populations because of its influence on water clarity (table 1; fig. 4). Suspended sediment settles in Lake Powell, so water released from the dam is much clearer than water that flowed through Glen Canyon during pre-impoundment conditions (Topping and others, 2000). Tributaries periodically flood, contributing vast quantities of sediment (from boulders to fine clay) to the river (Topping, 1997;

Table 1. Average water temperature and turbidity data for selected sites in the Colorado River, Arizona. Locations are denoted by river mile (RM) with the place name for each site noted parenthetically. River miles increase in the downstream direction. Lees Ferry is RM 0 and is 16 miles downstream from Glen Canyon Dam. The section of river between Glen Canyon Dam and Lees Ferry, within Glen Canyon National Recreation Area, is managed as a rainbow trout sport fishery. Sections of river below Lees Ferry that are within Grand Canyon National Park are managed for native fish populations. Values are the average ± 1 standard deviation (an indicator of the amount of variation inherent in the measurement). The period of record for both water temperature and turbidity is 2006 through 2009, with the exception of turbidity data for RM 0 (2006 through July 2009) and RM 88 (2008 through 2009). Turbidity is a measure of water clarity with low turbidity corresponding to high water clarity. Data courtesy of Nick Voichick, U.S. Geological Survey, unpub. data, 2010.

[°F, degrees Fahrenheit]

	River mile 0 (Lees Ferry)	River mile 30 (Fence fault)	River mile 61 (Upstream from confluence with Little Colorado River)	River mile 88 (Phantom Ranch)	River mile 225 (near Diamond Creek)
Water temperature (°F)	50.7 ± 2.7	51.3 ± 2.7	52.3 ± 3.0	53.5 ± 3.6	56.9 ± 5.5
Turbidity (nephelometric turbidity units)	2 ± 10.5	50 ± 347	71 ± 478	225 ± 672	347 ± 1,070

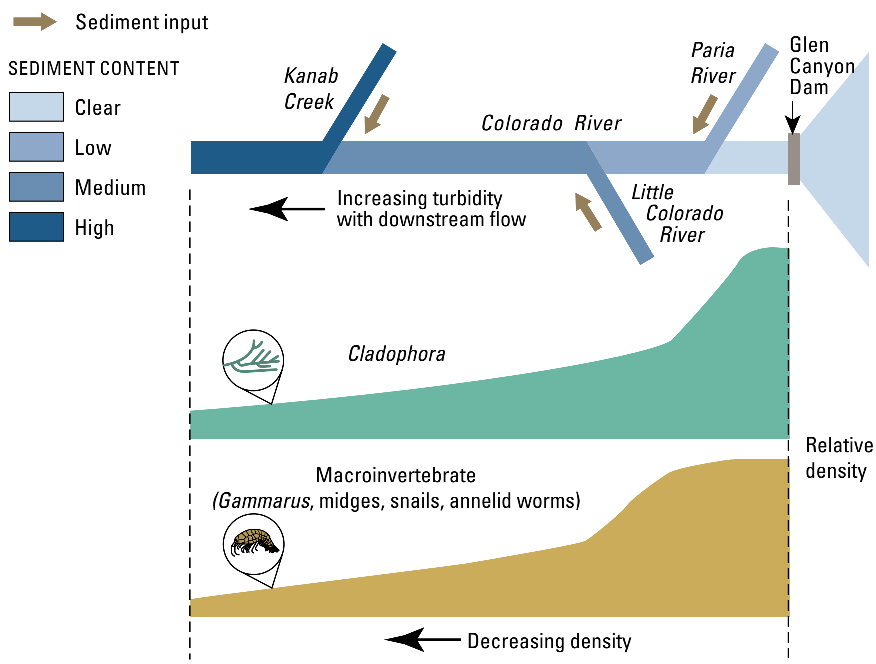


Figure 4. Downstream patterns of sediment concentration and biomass of *Cladophora* (a type of algae) and macroinvertebrates along the Colorado River ecosystem. Modified from Carothers and Brown (1991).

Topping and others, 2007). The first major tributary that enters below Glen Canyon Dam is the Paria River (RM 0; fig. 4). The next major tributary is the Little Colorado River (RM 61; fig. 4). Algae biomass (Carothers and Brown, 1991; Stevens and others, 1997) and production (Hall and others, 2010) decrease as water clarity decreases downstream (table 1; fig. 4). The progressive decrease in algae production drives a downstream decrease in aquatic invertebrate biomass (*Gammarus*, midges, snails, annelid worms; fig. 4; Carothers and Brown, 1991; Stevens and others, 1997; Kennedy and Gloss, 2005; Rosi-Marshall and others, 2010). Aquatic invertebrates are a high-quality food resource consumed by every species of fish present in the Colorado River (Valdez and Ryel, 1995; McKinney and Speas, 2001; Kennedy and Gloss, 2005). Increasing turbidity caused by increasing suspended-sediment concentrations also affects some fish populations, particularly rainbow and brown trout by influencing their ability to forage and detect food resources that are becoming scarce (Yard and others, in press).

The fish assemblage in the Colorado River below Glen Canyon Dam changes predictably with water temperature and water clarity along the downstream gradients (Makinster and others, 2010). Immediately below the dam, in the Lees Ferry reach (fig. 1), the Colorado River supports a rainbow trout sport fishery (Makinster and others, in press). Low water temperatures in the tailwater reach are close to ideal for rainbow trout spawning and growth (McKinney and others, 2001). The quality of overall rainbow trout habitat decreases precipitously below the Little Colorado River (Makinster and others, 2010). In the reach between Glen Canyon Dam and the Little Colorado River, the aquatic food web is fuelled almost exclusively by microscopic algae (Angradi, 1994; Shannon and others, 1994), invertebrate biomass is high (Stevens and others, 1997), and rainbow trout completely dominate the fish catch (Makinster and others, 2010).

Native flannelmouth sucker, bluehead sucker, and nonnative common carp dominate reaches far downstream from Glen Canyon Dam that are warm and turbid (Makinster and others, 2010). Main-stem water temperatures that are close to optimal for spawning and growth of these species likely contribute to their dominance there (Gloss and Coggins, 2005). These bottom-feeding species are also well adapted to foraging on the river bed for scarce food items in turbid conditions (Gloss and Coggins, 2005).

Tributaries also directly influence the fish assemblage in the main stem by supporting large, self-sustaining source populations of native and nonnative fishes. Humpback chub densities in the main-stem Colorado River are highest in the vicinity of its confluence with the Little Colorado

River, in spite of water temperatures that are about 20 °F below optimal for their growth (Hamman, 1982), because the Little Colorado River is their primary spawning habitat (Gorman and Stone, 1999). A great deal of humpback chub juvenile rearing occurs in the Little Colorado River itself, but the quality of rearing habitat in the main-stem river at the confluence with the Little Colorado River probably also contributes to humpback chub adult recruitment (Gloss and Coggins, 2005). Large numbers of rainbow trout in the vicinity of the Little Colorado River confluence are of great concern to resource managers because rainbow trout are known to prey on humpback chub (Yard and others, in press). Dietary overlap between humpback chub and rainbow trout is also high—both eat predominantly aquatic invertebrates and algae (Valdez and Ryel, 1995; McKinney and Speas, 2001)—so all of the conditions necessary for strong negative effects of competition on juvenile humpback chub that are rearing in the main stem also exist. The effects of competition and predation are inseparable—if competition for limited food resources leads a fish to spend more time foraging, that fish is more vulnerable to predation (Walters and Korman, 1999). The GCDAMP has long recognized the threats that competition and predation by rainbow trout pose to juvenile humpback chub rearing in the main stem near the confluence with the Little Colorado River (Minckley, 1991; Gloss and Coggins, 2005). In fact, more than 20,000 rainbow trout were experimentally removed from this reach of the Colorado River during 2003–06 to improve the quality of the rearing environment for juvenile humpback chub (Coggins, 2008; Coggins and Yard, 2010; Coggins and others, in press).

Other tributaries and various aspects of geography also influence fish populations throughout Grand Canyon. For example, Bright Angel Creek (at RM 88, fig. 1) is the primary spawning and rearing habitat for nonnative brown trout (Gloss and Coggins, 2005). Densities of brown trout in the main-stem Colorado River are highest near Bright Angel Creek and decrease precipitously upstream and downstream from this tributary (Makinster and others, 2010). Large numbers of both native suckers (flannelmouth and bluehead) are known to spawn in Kanab Creek and Havasu Creek (fig. 1; Gloss and Coggins, 2005), and densities of these species in the Colorado River are high near these spawning grounds (Makinster and others, 2010). Proximity to Lake Mead and the large source populations of warm-water species that it supports (for example, striped bass *Morone saxatilis* and common carp) may also influence fish assemblages in the Colorado River far downstream from Glen Canyon Dam (Gloss and Coggins, 2005; Makinster and others, 2010).

High-Flow Experiments

Hydrology and the seasonal and daily patterns of discharges are significant aspects of the Colorado River's physical template. Indeed, HFEs represent an attempt by resource managers to restore one aspect of the pre-dam flow regime—a dynamic flow pattern that featured annual floods—because providing "some of the dynamics of a natural system" might benefit native fish populations (U.S. Department of the Interior, 1995, p. 40). Additionally, HFEs are the only known means of creating backwaters through sandbar building. Backwaters are areas of low velocity in the lee of an eddy return-current channel (see chapter 3, this volume, for a description of backwaters and how they are formed by HFEs). Backwaters have at least some of the ingredients of high-quality native fish rearing habitat (for example, warm water temperatures and moderate levels of food resources; Brouder and others, 1999; Behn and others, 2010). An extensive fish capture dataset is available, documenting native fish use of these habitats (Brouder and others, 1999; Grams and others, 2010).

Synthesizing the response of humpback chub and other fish populations to previous HFEs is complicated by at least two factors: (1) long and variable generation times (time required for a fish to become capable of reproduction), and (2) the numerous direct and indirect pathways that connect HFEs to fish populations. Because it takes humpback chub at least 4 years to reach maturity, it takes years for a change in dam operations to lead to a response in the adult humpback chub population trends that are monitored (monitoring of juveniles is relatively imprecise; Coggins and Walters, 2009). If the effects of an experimental management action do not persist for more than a year, or they are weak relative to other factors, then the effects are unlikely to be seen in the humpback chub adult recruitment trends (Coggins and Walters, 2009). Long generation times of humpback chub also makes it critical to consider their status prior to HFE implementation because prior conditions can affect the eventual response. Therefore, documenting the effects of a single HFE on humpback chub populations requires, at a minimum, long-term data documenting adult population trends.

High-flow experiments can affect humpback chub both directly and indirectly, which further complicates the ability to understand whether the infrequent HFEs conducted to date have affected humpback chub. Downstream displacement and mortality of humpback chub during HFEs are examples of a direct effect that is negative. High-flow experiments create backwaters, so HFEs may also have indirect and positive effects on humpback chub populations through the creation of high-quality habitat. The creation of backwaters might also benefit nonnative fish species as well and, thus, would have an indirect and negative effect on humpback chub. Numerous other direct and indirect effects connecting HFEs to humpback chub have been hypothesized and studied (Shannon and others, 2001; Valdez and others, 2001). Understanding *why* an HFE affects humpback chub, therefore, requires primary research studies to evaluate the full array of direct and indirect effects that HFEs have on humpback chub.

In this section, evidence for a population-level response of fishes to HFEs is discussed first. Data from the March 2008 HFE are the focus of these population-level assessments for three reasons: (1) a major change in annual release volumes during 1995–99 confounded and complicated interpretation of fish population response to the 1996 HFE (Shannon and others, 2001; Valdez and others, 2001), (2) methods currently used for monitoring fish below RM 0 were only established in 2000, so adult population data for rainbow trout and native fish in Grand Canyon are not available in association with the 1996 HFE (Makinster and others, 2010), and (3) essentially no primary biology research studies were conducted during the 2004 HFE, so it is not possible to assess the strength of direct and indirect pathways connecting that HFE to any population-level responses. After reviewing population-level responses to the 2008 HFE, the evidence supporting potential direct and indirect pathways linking HFEs to these fish species is evaluated.

Rainbow Trout

Rainbow trout populations throughout Glen, Marble, and Grand Canyons increased dramatically in 2008 and 2009, dates for which the most recent data are available (figs. 5 and 6; Makinster and others, 2010). The 2008 rainbow trout cohort spawned in the Lees Ferry reach is the largest

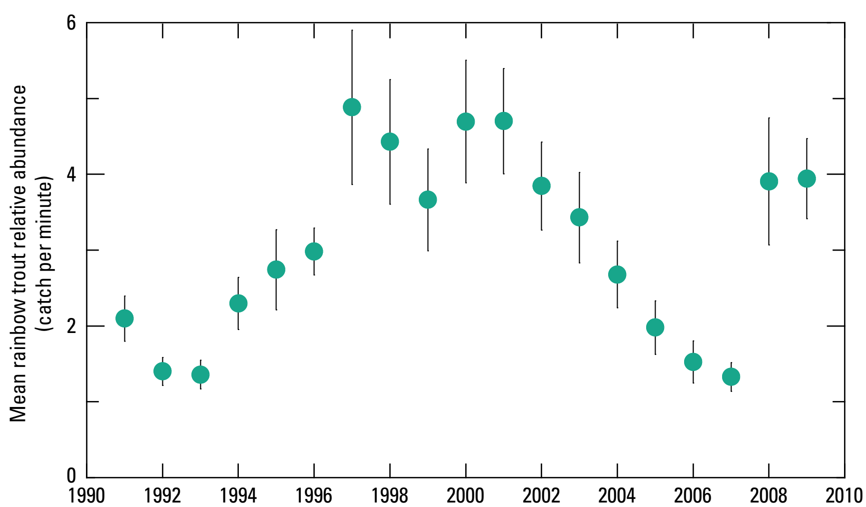


Figure 5. Rainbow trout mean relative abundance (catch per minute) in the Lees Ferry tailwater fishery, 1991–2009. Figure represents data from all size classes in both fixed and random transects. Points represent the average among sites and seasons, and bars represent ± 2 standard errors of the average, an approximation for a 95-percent confidence interval. See Makinster and others (in press) for details.

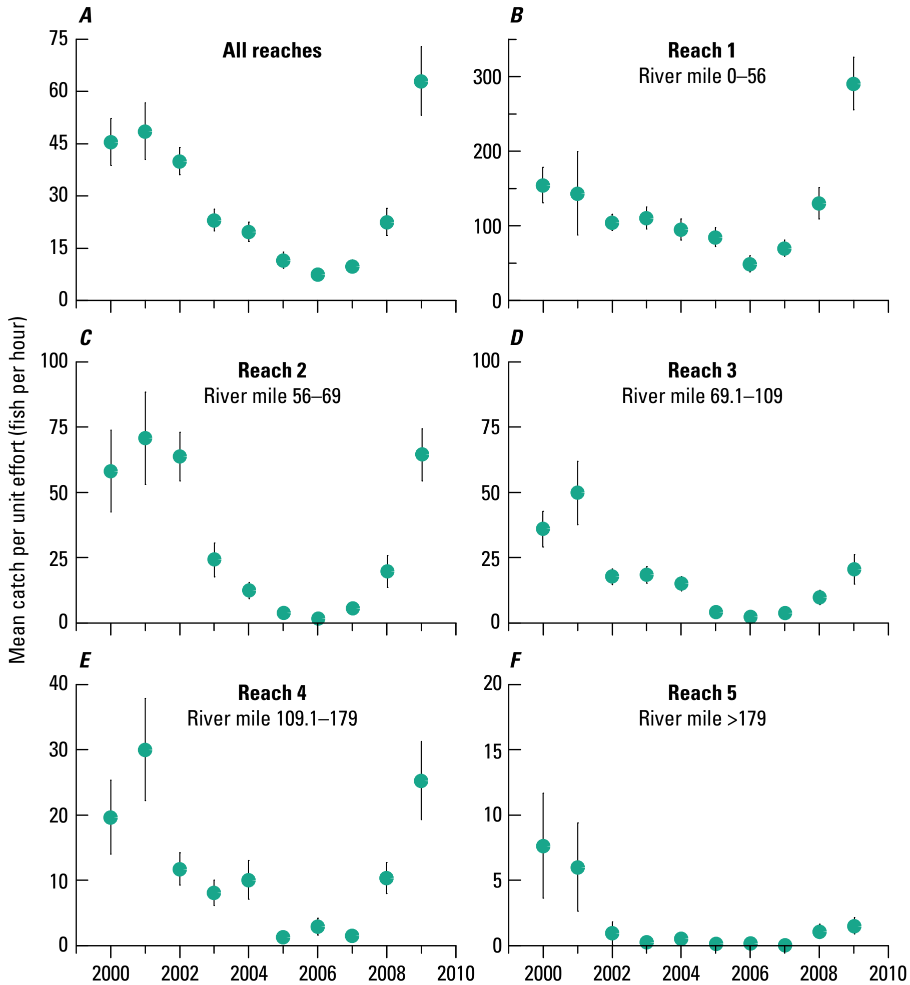


Figure 6. Mean catch per unit effort (fish per hour) of rainbow trout captured during electrofishing surveys on the Colorado River between Lees Ferry and Lake Mead, 2000–2009. *A*, All reaches. *B*, Reach 1. *C*, Reach 2. *D*, Reach 3. *E*, Reach 4. *F*, Reach 5. Points represent the average among sites and seasons, and bars represent ± 2 standard errors of the average, an approximation for a 95-percent confidence interval. From Makinster and others (2010).

on record (Korman and others, 2010; Korman and Melis, 2011; Korman and others, in press), and the 2009 cohort was also relatively strong compared to other years in the 20-year record (Korman and others, 2010; Makinster and others, in press; Korman and others, in press). Rainbow trout populations at the confluence of the Little Colorado River (RMs 56 to 69) were 800 percent larger in 2009 than in 2007 because of the large number of rainbow trout spawned in 2008 and 2009 (fig. 6). It should be noted that rainbow trout populations also increased in 1997, the year after the March 1996 HFE (Makinster and others, in press). Collectively, these data indicate that spring-timed HFEs benefit rainbow trout populations.

Rainbow trout response to the one fall-timed HFE that was conducted in November 2004 is poorly understood. Rainbow trout populations began declining in 2001–2002 and continued to decline until 2007 (Makinster and others, in press). Thus, the November 2004 HFE occurred in the midst of a population decline that had started 2 years before. This preexisting downward trend limits our ability to make inferences regarding the influence of fall-timed HFEs on rainbow trout populations.

The March 2008 HFE appears to have improved the quality of the spawning habitat used by rainbow trout in the Lees Ferry reach. Abundance of age-0 rainbow trout in July 2008 was more than four times greater than expected given the number of viable eggs that produced these fish (fig. 7). Expectations for the relation between viable eggs and age-0 trout were developed by quantifying the relation between egg abundance and juvenile rainbow trout among four pre-HFE years (Korman and others, 2010; Korman and Melis, 2011; Korman and others, in press). Comparison of the 2008 and 2009 data with these pre-HFE years (2003–04, 2006–07) demonstrates that spawning conditions improved in 2008. The amount of fine sediment (sand, silt, and clay) exported from the Lees Ferry reach during the 2008 HFE was higher than in 2004 and comparable to 1996, even though the 1996 HFE was 2.8 times longer in duration and had slightly higher peak discharge than the 2008 HFE (Melis and others, in press). In fact, enough fine sediment was exported from this reach to roughly cover the entire 16-mile-long Lees Ferry reach to a depth of 1.6 inches (Scott Wright, U.S. Geological Survey, written commun., 2010), which undoubtedly increased the porosity and overall quality of the rainbow trout spawning habitat (Korman and others, 2010; Korman and Melis, 2011; Korman and others, in press).

Adult rainbow trout (*Oncorhynchus mykiss*). Copyright Eric Engbretson, used with permission.

The growth and survival rates for juvenile fish that hatched after the 2008 HFE were also higher than expected (Korman and others, 2010; Korman and Melis, 2011; Korman and others, in press), indicating that the HFE improved the rearing environment for juvenile rainbow trout. Average growth rates of age-0 trout in the summer of 2008 were virtually the same as in 2006, even though abundance was eight times greater in 2008. The growth of juvenile salmonids generally declines at higher densities (Jenkins and others, 1999; Imre and others, 2005; Ward and others, 2007), so the unusually strong growth in 2008 that occurred under high densities indicates that the quality of the rearing environment for age-0 trout in the Lees Ferry reach was improved by the spring-timed HFE (Korman and others, 2010; Korman and Melis, 2011; Korman and others, in press). Interestingly, both age-0 growth and abundance in 2009 were also higher than expected given age-0 abundance and the number of viable eggs deposited in that year, which suggests that the effect of the 2008 HFE on early life stages persisted into 2009. Recent monitoring data suggest that the effect of the 2008 HFE on rainbow trout has subsided and did not persist into 2010 (fig. 7).

Increases in the amount of invertebrate prey available to rainbow trout in the Lees Ferry reach (Rosi-Marshall and others, 2010; Melis and others, in press) may be the ultimate cause of improvements in the rearing environment that was observed (Korman and others, 2010; Korman and Melis, 2011; Korman and others, in press). Rainbow trout consume food items that drift in the water column (Radar, 1997). Concentrations of invertebrate prey in drift increased following the 2008 HFE, and this effect persisted for at least 15 months (fig. 8; Cross and others, in press; Melis and others, in press). The increase in invertebrate drift that occurred after the 2008 HFE was due to large increases in the concentrations of chironomid midges and black flies (400 to 800 percent increase, depending on species and which post-HFE dataset is used for comparison; Melis and others, in press). Biomass and production of both species increased after the HFE (Rosi-Marshall and others, 2010; Cross and others, in press), suggesting the increases in drift that were observed were due to changes in abundance, but not drift vulnerability. This

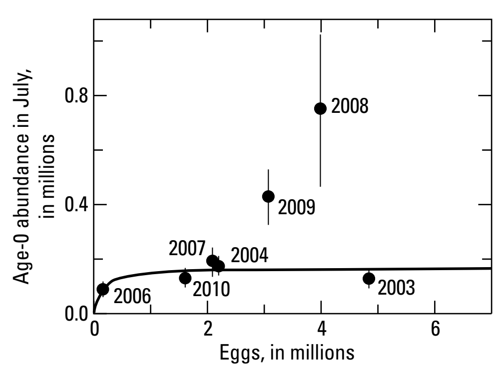


Figure 7. The relations between the number of viable rainbow trout eggs deposited in the Lees Ferry reach and the resulting population size of age-0 trout on July 15, 2003–09 (no data collected in 2005). The thick black line shows the best-fit curve (relation) between the number of viable eggs and age-0 trout abundance using data from 2003 to 2007 only. In general, this relation and similar ones for fish populations throughout the world suggest that at some point fish populations are not limited by the number of eggs produced, hence the constant juvenile abundance (flat line) once egg numbers exceed about 250,000. Conditions in 2008 and 2009 were much different and more favorable than pre-HFE years because the egg-juvenile data fall well above the flat line. Note that in 2010 the egg-juvenile relation again falls on this line, indicating that the positive effects of the 2008 HFE persisted for just 2 years. The vertical lines show the 95-percent confidence limits for the age-0 abundance estimates. From Korman and Melis (2011).

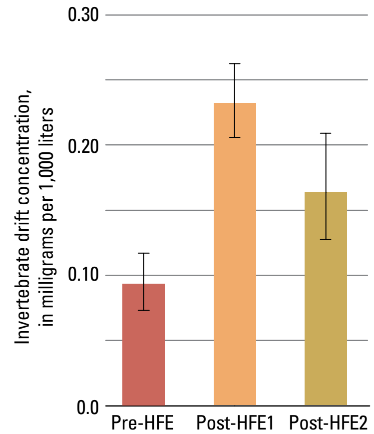


Figure 8. Average invertebrate drift concentrations (milligrams per 1,000 liters) from daytime collections at the downstream end of the Lees Ferry reach before and after the March 2008 HFE. Pre-HFE drift data were collected monthly between October 2007 and March 2008. Two different post-HFE drift averages are presented: (1) Post-HFE 1 is the average of samples collected from October 2008 to March 2009, which matches the exact seasonal timing of the pre-HFE dataset, and (2) Post-HFE 2 is the average of samples collected from April 2008 to October 2009, which represents the entire post-HFE dataset. The vertical lines that extend above and below the top of the colored bars represent 95-percent confidence intervals (from Melis and others, in press). The concentration of invertebrate drift was significantly higher after the 2008 HFE relative to before, regardless of which post-HFE dataset is used for comparison; confidence intervals for the pre-HFE data do not overlap with either post-HFE set of data. From Melis and others (in press).

is consistent with findings in other river systems—small-bodied and fast-growing species such as these often benefit from flood-type disturbances (Fisher and others, 1982; Robinson and Uehlinger, 2008; see text box, The Swiss Experience with High-Flow Experiments—Implications for the Management of Glen Canyon Dam). In addition, large quantities of these invertebrates are eaten by rainbow trout in other rivers (Radar, 1997).

Direct negative effects of HFEs on rainbow trout are probably limited to displacement of eggs and young fry because larger fish (greater than 4 inches) do not appear vulnerable to downstream displacement (Hilwig and Makinster, 2010). Korman and others (2010) found indirect evidence that mortality of eggs and young fry was relatively high, probably due to scouring and downstream displacement. Spawning and emergence are strongly seasonal (Korman, 2009), so slight differences in HFE timing could have a dramatic effect on direct mortality of these vulnerable young life stages.

Humpback Chub

Humpback chub population dynamics cannot definitively be attributed to any of the three HFEs (fig. 9; Coggins and Walters, 2009). It is premature to make any definitive conclusions regarding the effect of the 2008 HFE on humpback chub adult recruitment because it takes chub at least 4 years to recruit into the adult population (Coggins and Walters, 2009). Nevertheless, it seems reasonable to anticipate that the March 2008 HFE may ultimately have a measureable negative effect on populations of adult humpback chub because of the substantial increase in rainbow trout populations that resulted from the HFE.

Although the exact mechanisms underlying the trends in adult humpback chub abundance (fig. 9) remain unclear, evidence indicates that rainbow trout are a contributing factor; when rainbow trout populations are large, humpback chub populations generally decline, probably because of a combination of increased competition and predation. Numbers of adult humpback chub in 2009 were 50 percent greater than in 2002 (about 7,650 adult fish in 2009 as opposed to about 5,000 in 2002). However, data on rainbow trout populations in Marble Canyon and near the confluence with the Little Colorado River are only available beginning in 2000 (Makinster and others, 2010), so it is impossible to evaluate whether rainbow trout populations were affecting the long-term humpback chub population decline of the 1990s.

The creation of sandbar-bounded backwaters is the primary hypothesized benefit of HFEs for humpback chub (U.S. Department of the Interior, 2008a, b). Data and analyses regarding juvenile humpback chub growth and survival among habitat types, including backwaters, have not been published (William Pine, University of Florida, unpub. data, 2010). Without these data, assessing the importance of backwaters in humpback chub rearing and adult recruitment can only be accomplished with a weight-of-evidence approach. Note that because cold water temperatures in the main stem restrict humpback chub spawning to the Little Colorado River and other tributaries, HFEs in the context of cold water temperatures will not lead to improvements in main-stem spawning habitat.

The weight of evidence indicates that backwaters are not exceptionally high-quality rearing habitat for juvenile humpback chub compared to other potential rearing habitats. The availability of prey items (algae and invertebrates) in backwaters is comparable to their availability in other geomorphic features, such as rocky shorelines, that are more common and persistent than backwaters (Brouder and others, 1999; Behn and others, 2010; Rosi-Marshall and others, 2010), perhaps because daily fluctuations in discharge associated with changing demand for hydropower lead to frequent flushing and turnover of water in these habitats (Grand and others, 2006; Behn and others, 2010). On average, water completely turns over six times per day in backwaters when discharge fluctuates daily, compared to twice per day when discharge is stable (Behn and others, 2010). Daily fluctuations in discharge also lead to a rapid decrease in backwater area (Grams and others, 2010). In addition, backwater occurrence is low and areas are small near the confluence with the Little Colorado River where the majority of juvenile humpback chub main-stem rearing occurs (Grams and others, 2010).

Adult humpback chub (*Gila cypha*). Photograph courtesy of George Andrejko, Arizona Game and Fish Department.

The effects of HFEs downstream from the Little Colorado River do not appear to be as dramatic as changes that were observed in invertebrate biomass or production in the Lees Ferry reach (Shannon and others, 2001; Rosi-Marshall and others, 2010). Invertebrate biomass and production are approximately 10 times greater in the Lees Ferry reach relative to invertebrate biomass and production downstream from the Little Colorado River (Rosi-Marshall and others, 2010), so trends in invertebrate populations are easier to measure and quantify in the Lees Ferry reach. Potential benefits of the 2008 HFE on invertebrate biomass and production will likely be short lived because turbidity resulting from suspended sediment delivered by tributaries such as the Paria River represents a major constraint on the production of algae on which invertebrates rely (Stevens and others, 1997; Hall and others, 2010). Tributary flooding and suspended sediment inputs may mask or prevent a long-term and sustained invertebrate response to HFEs, similar to what was observed in the Lees Ferry reach, from ever occurring. This is not to say that HFEs do not have beneficial effects on the invertebrate prey base at downstream locations. Indeed, research from segments of the Colorado River upstream from Lake Powell suggests that natural floods increase production of food items (algae and invertebrates) by moving fine sediment off the bed and onto the shoreline (Osmundson and others, 2002), because sandy unstable substrates generally support lower densities of algae and invertebrates than hard and stable

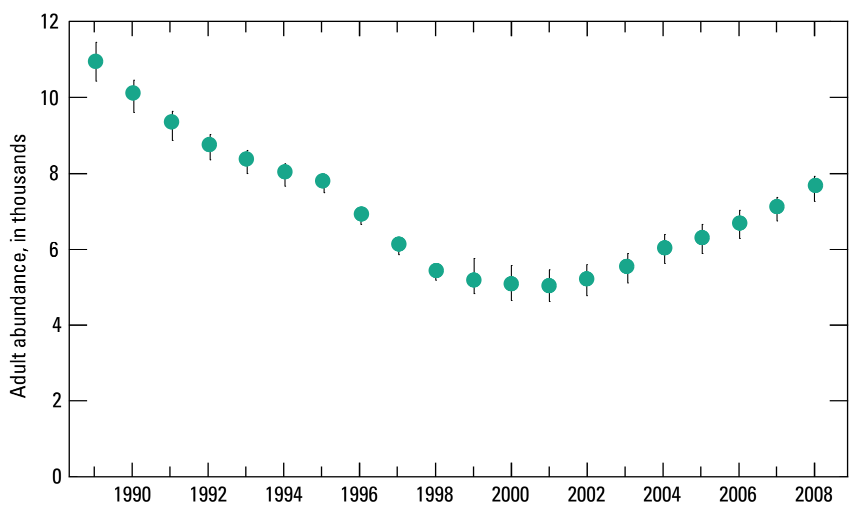


Figure 9. Estimated adult humpback chub (*Gila cypha*) abundance (age 4+). Point estimates are average values, and error bars represent maximum and minimum 95-percent confidence intervals. From Coggins and Walters (2009).

substrates (see text box, Channel Change in the Glen Canyon Reach). Any benefits of HFEs along downstream segments in Grand Canyon likely will be smaller in magnitude than were observed in the Lees Ferry reach, which means potential changes will be more difficult to detect statistically, and benefits to fish populations will also be smaller.

The 2008 Biological Opinion (U.S. Department of the Interior, 2008a) considers direct mortality of humpback chub one of two primary mechanisms linking HFEs to humpback chub (the other is the creation of backwaters). During HFEs, the shoreline habitat that young humpback chub occupy changes (Korman and others, 2004; Grams and others, 2010), and water velocities can exceed the swimming ability of humpback chub (Korman and others, 2004; Protiva and others, 2010). On the basis of laboratory investigations, it is known that juvenile humpback chub (about 4 inches in length) become fatigued much sooner when water temperatures are cool (57 °F) as opposed to when water temperatures are warm (68 °F; U.S. Department of the Interior, 2008a). If juvenile humpback chub are assumed to be completely vulnerable to habitat changes and higher velocities associated with an HFE (that is, the fish do not move to occupy lower velocity habitat with the onset of flooding, although this is an untested assumption), a single HFE could result in the mortality of as many as 900 juveniles (U.S. Department of the Interior, 2008a).

To mitigate the potential effects of downstream displacement and mortality, it has been suggested that future HFEs could be conducted in the spring when juvenile humpback chub rearing in the main stem would be larger relative to the fall (U.S. Department of the Interior, 2008a). Increases in humpback chub size due to the growth that would occur between November (preferred HFE timing based on tributary sand inputs) and March, it was reasoned, could help compensate for the poor-swimming performance that would be expected with overall cold main-stem water temperatures (U.S. Department of the Interior, 2008a). However, the temperature of water released from Glen Canyon Dam peaks in the fall (Vernieu and others, 2005; Voichick and Wright, 2007), so delaying HFEs until the spring to mitigate potential displacement mortality could actually have the undesired effect of reducing swimming performance (and potentially increasing mortality) due to colder water temperatures; water temperatures at Lees Ferry in November 2004, when an HFE was conducted, were 56 °F, but temperatures were just 47 °F in March 2005 (Voichick and Wright, 2007).

Other Native Fish

The catch-rate data indicate no evidence of a population-level response by flannelmouth sucker, bluehead sucker, or speckled dace to the two HFEs (2004 and 2008) conducted since continuous fish monitoring activities began in 2000 (figs. 10 and 11; Makinster and others, 2010); however, a lack of focused research studies on these species makes this conclusion highly uncertain. Because these species of fish dominate downstream reaches where rainbow trout are less abundant than near the Little Colorado River, the rainbow trout population increase following the 2008 HFE appears to pose less of a risk to other native fish relative to humpback chub. Populations of both species of sucker underwent periods of substantial expansion beginning about 2005 (figs. 10 and 11; Makinster and others, 2010). Data needed to evaluate potential mechanisms underlying this increase and also potential links between these fish and HFEs are lacking, because there have been no focused research studies in the tributaries that serve as important spawning and rearing habitat for these species (for example, the Little Colorado River, Kanab Creek, and Havasu Creek; Minckley and Deacon, 1991).

High-flow experiments do not appear to represent a major source of direct mortality to native fish, but the lack of data makes evaluating this relation difficult. Suckers and speckled dace dominate downstream reaches (figs. 10 and 11) where water temperatures are seasonally warmer relative to near the Little Colorado River confluence (Voichick and Wright, 2007). Swimming performance at the water temperatures present along downstream reaches is relatively high (Ward and others, 2003).

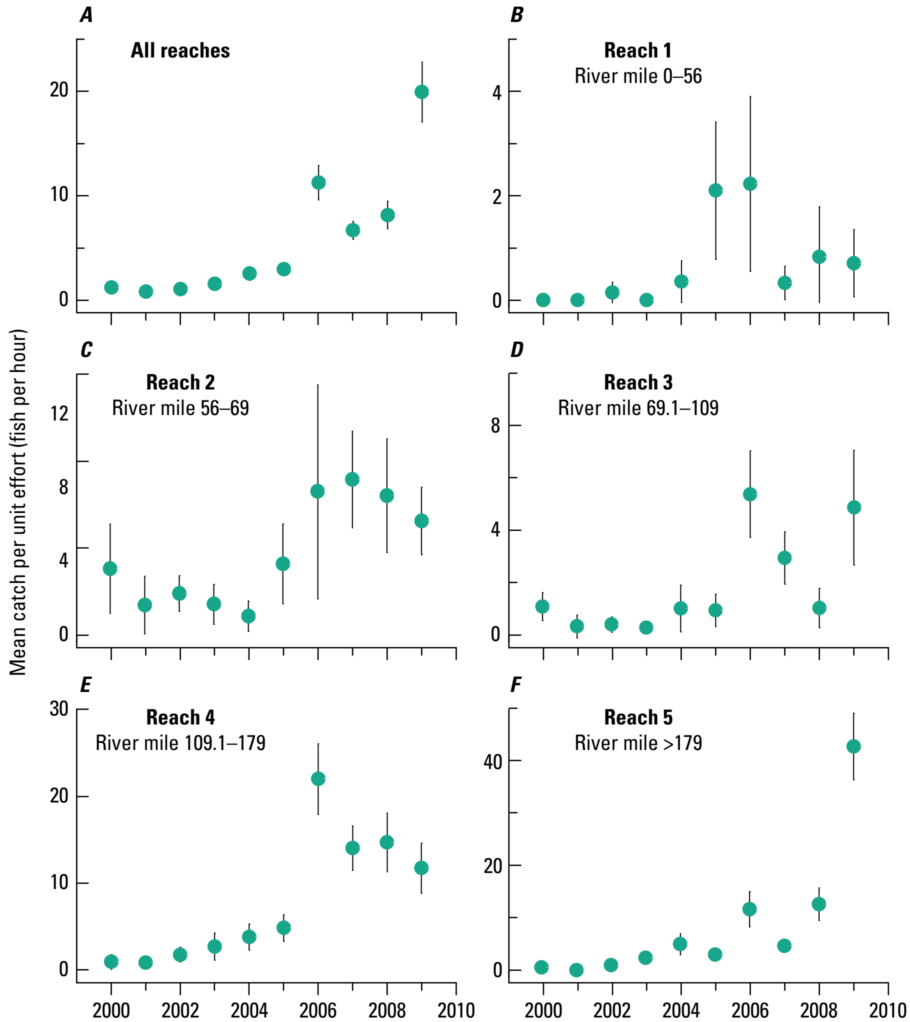


Figure 10. Mean catch per unit effort (fish per hour) of flannelmouth sucker (*Catostomus latipinnus*) captured during electrofishing surveys on the Colorado River between Lees Ferry and Lake Mead, 2000–2009. The bars represent ± 2 standard errors of the mean, a close approximation of 95-percent confidence intervals. From Makinster and others (2010).

Native fish (excluding humpback chub) could be spawning in the main-stem river because they are commonly found in downriver sections where water temperatures are suitable for spawning (Makinster and others, 2010); however, very little is known about sucker or speckled dace spawning in the Colorado River and its tributaries. It is impossible, therefore, to assess whether HFEs affect the dynamics of these species through improvements in spawning habitats.

Backwaters created during HFEs may represent an important improvement in the quality of rearing habitat available for suckers and dace because these fish dominate downriver sections of the Colorado River that experienced large and comparatively persistent increases in backwater area after the 2008 HFE, at least relative to the Little Colorado River confluence (Grams and others, 2010). Suckers, in particular, have been captured in backwaters in extremely high numbers (Hoffnagle and others, 1999; Grams and others, 2010). Focused research studies similar to the GCDAMP's nearshore ecology project (a conservation measure associated with the 2008 HFE that seeks to understand the relative importance of backwaters to overall humpback chub rearing and is scheduled from 2009 to 2012) will be necessary to determine whether backwaters are an important rearing habitat for other native fish.

High-flow experiments do not appear to lead to large or persistent improvements in available food at downriver locations (Shannon and others, 2001; Rosi-Marshall and others, 2010). For additional information, refer to the discussion in the humpback chub section.

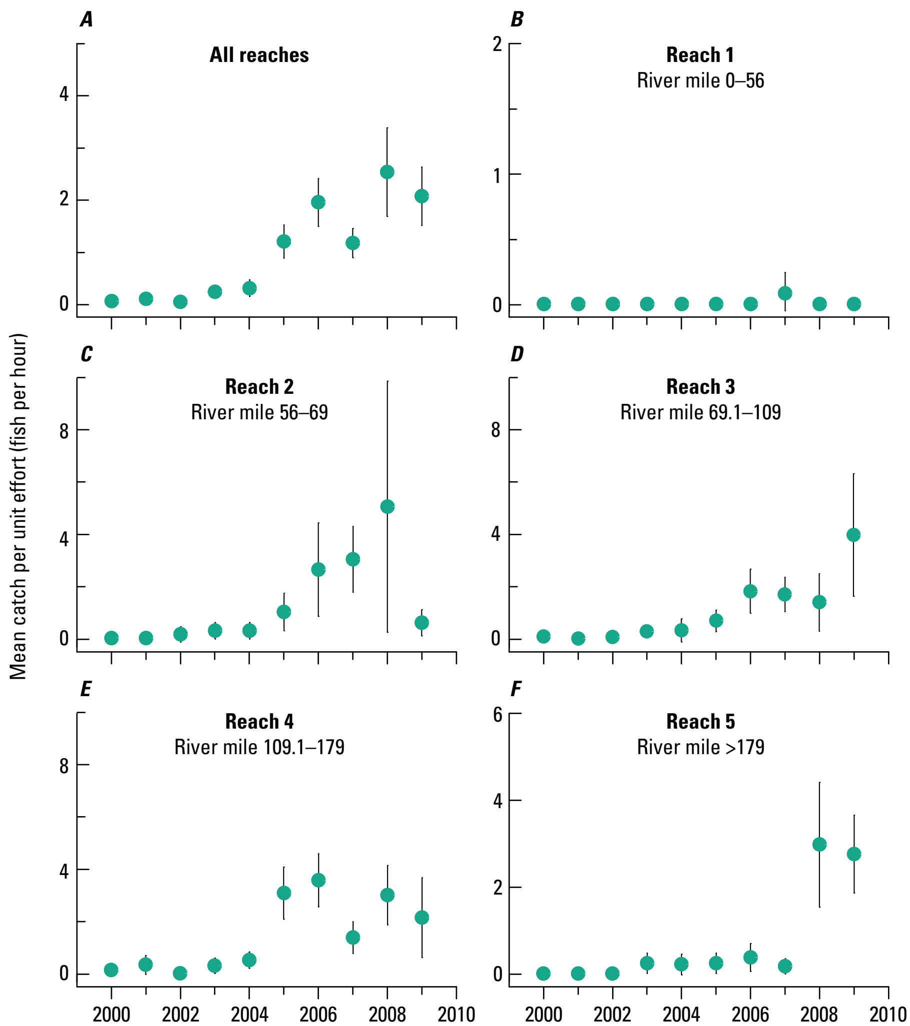


Figure 11. Mean catch per unit effort (fish per hour) of bluehead sucker (*Catostomus discobolus*) captured during electrofishing surveys on the Colorado River between Lees Ferry and Lake Mead, 2000–2009. The bars represent ± 2 standard errors of the mean, a close approximation of 95-percent confidence intervals. From Makinster and others (2010).

Synthesis

The strong rainbow trout response to the March 2008 HFE was not predicted or anticipated by resource managers or scientists (U.S. Department of the Interior, 2008a, b). A similarly counterintuitive response occurred with flow stabilization (a decrease in the daily range in discharge from the dam) that was implemented beginning August 1991 and was intended to benefit native fish populations, but it actually had the opposite effect (Pine and others, 2009). Before 1991, discharge from Glen Canyon Dam varied considerably over the course of a day due to changing demand for hydroelectricity. Restrictions were placed on hydroelectricity generation in 1990 and yet humpback chub populations declined for about 12 years after these constraints were in place, with populations only leveling off in about 2002 (Coggins and Walters, 2009; Pine and others, 2009). This same change in dam operations proved to be beneficial to rainbow trout recruitment. Although stocking continued until 1998, the Lees Ferry sport fishery went from being completely dependent on stocking to self recruiting and self sustaining in a matter of years (McKinney and others, 2001).

These kind of counterintuitive prediction failures are an indication that resource managers and scientists may have failed to identify key processes or variables when devising and developing management options to be evaluated as part of the adaptive management process (Pine and others, 2009). In Grand Canyon, these prediction failures may have occurred because the importance of geomorphology and flow regimes to humpback chub populations has been overestimated, while the overriding influence that water temperature has on humpback chub has been underestimated (Olden and Naiman, 2009; fig. 12). Stabilizing discharge and conducting HFEs were intended to improve two aspects of the physical template (geomorphology, specifically backwaters, and flow regime), but a different aspect of the physical template (water temperature) may severely constrain and limit humpback chub populations, such that improvements in geomorphology and flow regime are unlikely to elicit a positive response. In the context of cold water, the potential beneficial effects of HFEs on humpback chub appear to be weak and short lived. Furthermore, if these benefits exist, they appear to be completely overwhelmed by the negative effects of a large and persistent increase in nonnative rainbow trout. Thus, HFEs in the context of cold water do not appear to be a useful tool for sustaining humpback chub populations in Grand Canyon.

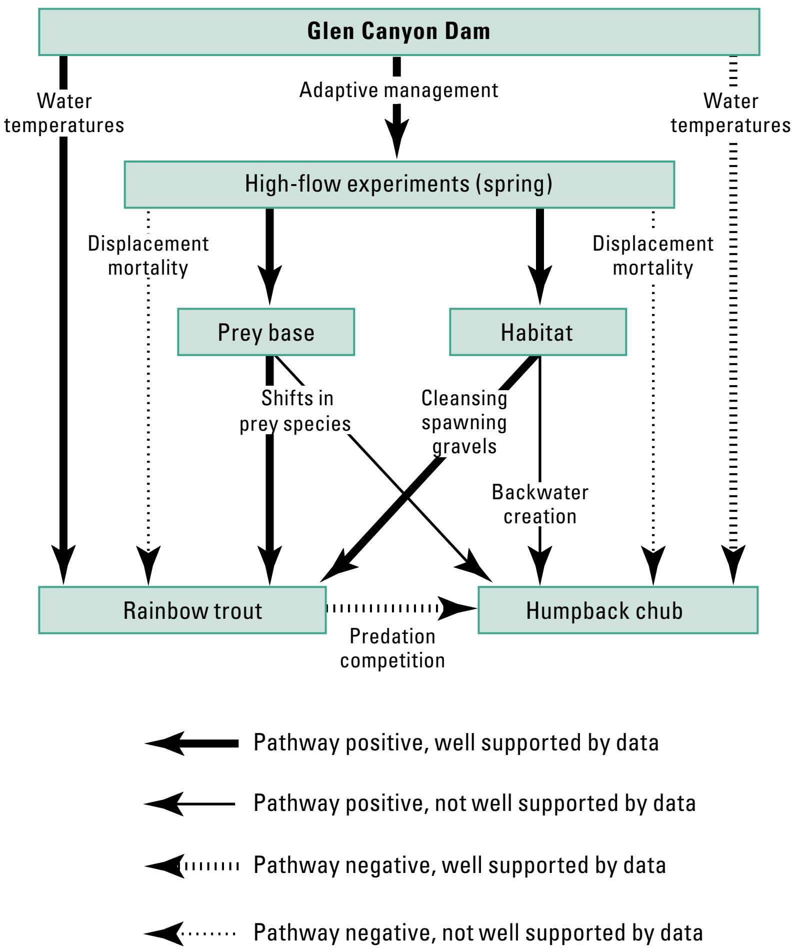


Figure 12. Path diagram depicting some of the influences that Glen Canyon Dam and its operations have on rainbow trout (*Oncorhynchus mykiss*) and humpback chub (*Gila cypha*) populations. Line width denotes the strength of scientific evidence for a given interaction; thick lines indicate effects that are well supported by data whereas thin lines are not well supported by data. Positive effects are shown as solid lines, and negative effects are shown as dashed lines. Glen Canyon Dam has a strong and direct negative effect on humpback chub due to its effect on water-release temperature. In contrast, this same alteration of water temperature has a strong and positive effect on rainbow trout populations. Spring high-flow experiments appear to have strong positive effects on rainbow trout due to improvements in spawning gravels and available food. Spring high-flow experiments may have positive effects on humpback chub due to increases in backwater habitat or increases in available food, but these effects are not well supported by data. Likewise, spring high-flow experiments may have a negative effect on humpback chub due to downstream displacement and mortality of juveniles, but this is not well supported by data either. The weight of evidence indicates humpback chub populations are affected by rainbow trout populations; when rainbow trout populations are large, humpback chub populations generally decline, probably due to a combination of increased competition and predation. Note that many other potential interactions that are weak or not supported by data are left out of this schematic. Studying strong pathways connecting high-flow experiments to populations of rainbow trout and humpback chub would be a logical focus for future research and monitoring efforts.

Descriptions of Selected Fish Species in Grand Canyon

Text by Richard A. Valdez and illustrations by Joseph R. Tomelleri

Humpback chub (*Gila cypha*)
(Native)

Endemic to Colorado River Basin. Federally listed as endangered. Maximum size 16–18 inches, 2½ pounds, with prominent fleshy hump behind head and large fins. Occurs as six populations, including largest of about 7,650 adults in Grand Canyon (Coggins and Walters, 2009). Warm-water species that reproduces at 61–72 °F (Hamman, 1982). Matures at 3–4 years of age and lives to 40 years. Eats primarily drift and bottom aquatic and terrestrial invertebrates, algae, plant material, and small fish (Valdez and others, 2001). Nine aggregations in Grand Canyon, including the largest at the mouth of the Little Colorado River. Most spawning occurs in the Little Colorado River, but main-stem spawning is suspected, as evidenced by young found in Middle Granite Gorge and near warm springs approximately 30 miles upstream from the Little Colorado River (Andersen and others, 2010).

Flannelmouth sucker (*Catostomus latipinnis*)
(Native)

Indigenous to Colorado River Basin. Maximum size 30 inches, 4 pounds, with prominent fleshy mouth. Occurs in most middle and lower elevation rivers and large tributaries. Warm-water species that reproduces at 48–64 °F (Weiss and others, 1998). Matures at 3–4 years of age and lives to 20 years. Eats primarily bottom vegetarian, benthic invertebrates, algae, organic detritus, and seeds. Found throughout Grand Canyon with concentrations at tributary mouths, including Little Colorado River and Bright Angel, Shinumo, Havasu, and Kanab Creeks. Evidence of successful reproduction in tributaries; main-stem spawning is suspected in western Grand Canyon (Weiss and others, 1998; Makinster and others, 2010).

Bluehead sucker (*Catostomus discobolus*)
(Native)

Indigenous to Colorado River Basin. Conservation species in range-wide plan. Maximum size 16 inches, 1 pound, with hardened cartilaginous mouth ridges. Warm-water species that reproduces and grows best at 59–68 °F. Matures at 1–3 years of age and lives to 18 years. Uses mouth ridges to scrape periphyton, debris, benthic invertebrates, and plant materials from submerged rocks. In Grand Canyon, locally common to abundant from the Little Colorado River to Lake Mead inflow with concentrations in and around tributary mouths, including the Little Colorado River and Shinumo, Havasu, and Kanab Creeks. There is evidence of successful reproduction in tributaries in Grand Canyon (Maddux and Kepner, 1988).

Razorback sucker (*Xyrauchen texanus*)
(Native)

Endemic to Colorado River Basin. Federally listed as endangered. Maximum size 36 inches, 13 pounds, with hardened cartilaginous dorsal ridge behind head and large fleshy mouth. Historically, found in middle and lower elevation rivers, tributaries, and flood-plain habitats. Presently found in small numbers in rivers and reservoirs. Warm-water species that reproduces and grows best at 54–64 °F. Matures at 1–3 years of age and lives to 44 years. Young feed on zooplankton (cladocerans, copepods, and rotifers), juveniles consume algae and bottom ooze, and adults eat immature mayflies (Baetidae), stoneflies (Plecoptera, *Protonemoura)*, and midges (Chironomidae), and algae and detritus (Tyus, 1998). Historically, small numbers reported from Grand Canyon but none reported since early 1990s (Makinster and others, 2010). Recently found spawning at the Colorado River inflow area to Lake Mead (Bureau of Reclamation, 2010).

Speckled dace (*Rhinichthys osculus*)
(Native)

Native to Colorado River Basin. Maximum size 5 inches, with distinct body speckles and black face mask. Found throughout western North America in cool mountain streams, medium and large rivers, small impoundments, and small isolated desert springs. Warm-water species that reproduces and grows best at 52–66 °F. Matures at 2 years of age and lives to 5 years. Young feed on mid-water zooplankton and algae, and juveniles and adults are bottom dwellers and feed on benthic insects or plant material (Carlander, 1969; Scott and Crossman, 1973).

Rainbow trout (*Oncorhynchus mykiss*)
(Nonnative)

Introduced as sport fish into cold rivers, streams, and reservoirs of the Colorado River Basin, including Grand Canyon. Maximum size 30 inches, 20 pounds, with distinct black body spots and small fleshy fin behind dorsal fin. Native to Pacific coast streams, but stocked in cold waters throughout North America. Typically spawn in late winter and early spring at temperatures of 43–55 °F with optimum of 50 °F. Matures at 3–5 years of age and lives to 12 years. Adults and juveniles feed mainly on aquatic and terrestrial invertebrates, and large adults may eat mostly fish. First introduced into Grand Canyon by National Park Service at Tapeats Creek in 1923 (National Park Service, unpub. report, 1932). Tailwater of Glen Canyon Dam was stocked regularly by Arizona Game and Fish Department from 1964 to mid-1990s. Natural reproduction in late winter and early spring supports self-sustaining population and sport fishery (Gloss and Coggins, 2005). Currently the primary species for the blue ribbon trout fishery below Glen Canyon Dam and locally abundant between Lees Ferry and the Little Colorado River and in tributary inflows at Nankoweap, Bright Angel, Tapeats, and Deer Creeks (Makinster and others 2010).

Brown trout (*Salmo trutta*)
(Nonnative)

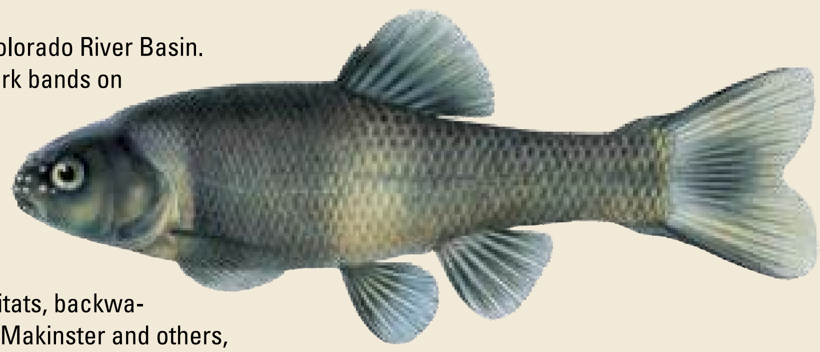
Introduced as sport fish into cold rivers, streams, and reservoirs of the Colorado River Basin, including Grand Canyon. Maximum size 36 inches, 25 pounds, with distinct large black spots and small red spots surrounded by blue halos; small fleshy fin behind dorsal fin. Native to Europe, but stocked in cold waters throughout North America. Typically spawn in fall and early winter at 45–54 °F, with optimum of 52 °F. Matures at 3–5 years of age and lives to 15 years. Aggressive and highly predaceous; consumes other fish early in life; also eats insects, amphibians, and fish eggs. First introduced into Grand Canyon by National Park Service at Shinumo Creek in 1926 and shortly after at Bright Angel Creek. Last reported stocking in 1934 (National Park Service, unpub. report, 1932). Presently in Bright Angel, Shinumo, and Tapeats Creeks and the main stem primarily near Bright Angel Creek inflow and occasionally in Glen Canyon Dam tailwater (Makinster and others, 2010).

Red shiner (*Cyprinella lutrensis*)
(Nonnative)

Introduced as bait fish into reservoirs of the Colorado River Basin.

Maximum size 3 inches, with dark red fins in spawning males. Native to mid-west and southern United States. Spawns March through June in backwaters, small riffles, and crevices over a variety of substrates, including fine gravel, boulders, logs, brush, roots, and aquatic vegetation at temperatures of 59–86 °F (Carlander, 1969). Present from Glen Canyon Dam to Diamond Creek into mid-1960s, but by 1968, only in small numbers above Lake Mead (Gloss and Coggins, 2005). Currently found in small numbers near warm tributary inflows and in backwaters (Grams and others, 2010). Occurs in large numbers in Lake Mead inflow (Makinster and others, 2010). Feeds on planktonic algae, crustaceans, and benthic invertebrates, but is highly competitive, aggressive, and is predaceous on young fish in isolated habitats (Bestgen and others, 2006).

Fathead minnow (*Pimephales promelas*)
(Nonnative)



Introduced as bait fish into various waters of the Colorado River Basin. Maximum size 3 inches, with enlarged head and dark bands on adult males. Native to central North America. First introduced to lower Colorado River in about 1940 from Lake Mead area bait shops, presumably moved into Grand Canyon shortly after. Presently absent or uncommon in main-stem Colorado River above Little Colorado River but locally common or abundant in warm tributary inflows, nearshore habitats, backwaters in lower Grand Canyon and upper Lake Mead (Makinster and others, 2010; Grams and others, 2010). Mature in 4–5 months and live 2–3 years. Fractional spawner May to August at 61–86 °F with optimum of 77 °F. A rapid colonizer that can survive in isolated pools with low oxygen and poor water quality. Feeds on algae, detritus, and small aquatic invertebrates (Carlander, 1969).

Common carp (*Cyprinus carpio*)
(Nonnative)

Introduced into warm rivers, streams, ponds, and reservoirs of the Colorado River Basin. Maximum size 48 inches, 100 pounds, with large scales, mouth barbells, and serrated dorsal spine. Matures at 2–4 years of age and lives to 20 years. Native to Asia. Imported to United States in mid to late 1800s and stocked into lower Colorado River in the late 19th century (Mueller, 2005). Presently found throughout Grand Canyon downstream from Lees Ferry. Spawns May to June at 64–86 °F with optimum of 73 °F. Eats variety of foods, including algae, seeds, and other plant matter and invertebrates. Efficient at finding and vacuuming small fish and eggs from substrate.

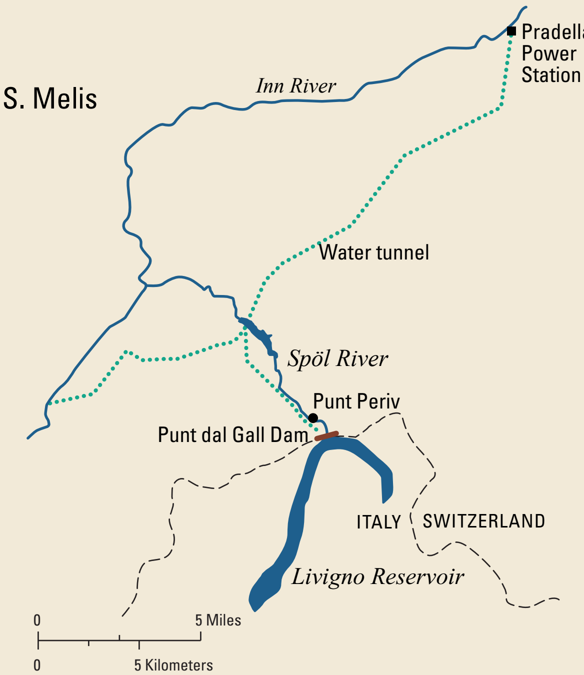
The Swiss Experience with High-Flow Experiments—Implications for the Management of Glen Canyon Dam?

Richard A. Valdez, Christopher T. Robinson, and Theodore S. Melis

Planning is currently underway by the U.S. Department of the Interior's Bureau of Reclamation for a long-term experimental plan that will implement a structured, long-term program of experimentation at Glen Canyon Dam over the coming decade. The program will include criteria for triggering repeated high-flow experiments (HFEs) on the basis of relatively frequent sand inputs to the Colorado River from tributaries below the dam (see chapter 5, this volume). If the experimental triggering protocol suggested by sediment scientists is adopted, then the frequency of HFEs during a future Glen Canyon Dam experiment is anticipated to be annual or possibly more frequent in some years. In all likely cases, the HFEs intended to conserve limited sand supply below the dam will include flows from the dam's hydropower plant in combination with varying magnitude bypass releases. As planning continues, results from other experimental river programs where repeated high-flow dam releases have also been studied may be informative.

Nearly two-thirds of the electricity produced in Switzerland comes from hydropower. It is estimated that over 80 percent of Switzerland's hydroelectric potential has already been exploited. With few suitable dam sites remaining, developing the remaining 10 to 20 percent of hydroelectric potential will have increasingly greater environmental consequences and costs, although climate change is expected to increase precipitation in Europe and provide greater flexibility for hydropower production. The Swiss Federal Institute of Environmental Science and Technology (EAWAG) has developed criteria for "green labeling" hydropower production (Bratrich and others, 2004). The so-called "Green Hydro" concept establishes ecological criteria for certification that generally are consistent with the concept of "environmental flows," which are designed to sustain select or key ecological and societal values (Acreman and Ferguson, 2010). By 2004, 13 Swiss facilities had successfully passed the certification procedure, producing a total of 186 gigawatts (GW) of green electricity per year, which is sufficient to power almost 40,000 households. Although this green energy is produced by hydropower, it is important to know that hydropower causes other ecological effects on regulated rivers.

To test whether an annual artificial flood (hereafter, high-flow experiment or HFE) regime can improve the ecology of regulated rivers below dams, a program of experimental high flows was implemented on the Spöl River in southeastern Switzerland in



The study area on the Spöl River. The main study reach is located about 1.4 miles downstream from Punt dal Gall Dam. The dashed lines show the tunnel infrastructure for water transport for hydropower production. This infrastructure allows the frequently repeated high-flow experiments to be a no-cost management strategy for the hydropower company. Modified from Scheurer and Molinari (2003).

2000 (see map) in cooperation with the Swiss National Park and the Engadiner Kraftwerke Power Company (Scheurer and Molinari, 2003). The Spöl River flows through a confined channel surrounded by mountainous terrain (see photographs on opposite page). About 20 separate high flows have been released between 2000 and 2010 from Punt dal Gall Dam that forms Livigno Reservoir on the Swiss-Italian border (see figure at end of text block).

A comprehensive study of the ecological effects of these repeated HFEs on the Spöl River was initiated in 1999 (Robinson and Uehlinger, 2003). The study included aquatic food production (periphyton, stream metabolism, and benthic macroinvertebrates; Robinson and others, 2003; Uehlinger and others, 2003), brown trout (*Salmo trutta*; Ortlepp and Mürle, 2003), longitudinal patterns (Jakob and others, 2003), and river morphology and riparian vegetation (Mürle and others, 2003). A major finding from these studies that may be relevant to a long-term Glen Canyon

Dam HFE protocol was that one or two high-flow events per year can enhance and sustain the long-term ecological integrity of the river (Scheurer and Molinari, 2003) and that flow releases must be repeated on a regular basis (annually) to maintain their benefits (Robinson and Uehlinger, 2008).

The HFEs in the Spöl River scour and immediately reduce primary producer biomass, which then recovers quickly after each event (Uehlinger and others, 2003), similar to the effects of natural floods observed in unregulated rivers. Importantly, the high flows shifted primary aquatic food producers from a moss-dominated streambed to one of diatoms and filamentous algae. There was also a longitudinal downstream effect of scouring on periphyton and benthic organic matter as a consequence of the degree of disturbance with generally greater effects in the most upstream reaches (Jakob and others, 2003). After the first 3 years of HFEs, periphyton assemblages now resemble those of unregulated Alpine mountain rivers where a snow and ice-melt-driven flow pulse results in a typical seasonal pattern of low periphyton biomass in summer and high biomass in autumn.

The HFEs significantly reduced macroinvertebrate densities, although densities typically recovered to pre-experiment levels within a matter of weeks (Robinson and Uehlinger, 2008). Some taxa have decreased in abundance since beginning the experimental program, including amphipods (Gammaridae) and flatworms (Turbellaria), whereas others have increased in abundance, including mayflies (Baetidae), midges (Chironomidae), and stoneflies (Plecoptera, *Protonemoura*). Other taxa, such as blackflies (Simuliidae), caddisflies (Trichoptera), and mayflies (Heptageniidae) that were negatively affected by high flows in 2000, have subsequently increased in abundance. The sequence of annual high flows imposed on this regulated river revealed that the response of macroinvertebrates to repeated HFEs occurs over a period of years rather than months, as species composition shifts to the new and more variable habitat template. The Swiss results showed that the high-flow experimental regime must be maintained if resource managers wish to sustain the development of a more natural macroinvertebrate assemblage, especially if it is important in maintaining a food web to support native brown trout.

The flow experiments on the Spöl River were intended to improve the fisheries potential (brown trout) of the river within the Swiss National Park. Despite increased food resources after flow regulation, the reproduction and recruitment of brown trout had declined, primarily because spawning areas were greatly reduced by the clogging of coarse sediments (Ortlepp and Mürle, 2003). Trout abundance was not reduced by the high flows, and relatively few fish (less than 2 percent) were killed or stranded. The quality of fish habitat, spawning grounds in particular, has noticeably improved, even though food resources (macroinvertebrate composition) have changed since the experiments began. The results showed that the condition of trout in the Spöl River has remained relatively constant, but the number of redds have increased sixfold since initiation of the experimental program, which presumably translates to increases in fish recruitment.

One important finding of the high flows was the lack of extensive effects on riparian vegetation. Mürle and others (2003) found that a lack of flow disturbance on the Spöl River had allowed woody vegetation to develop on

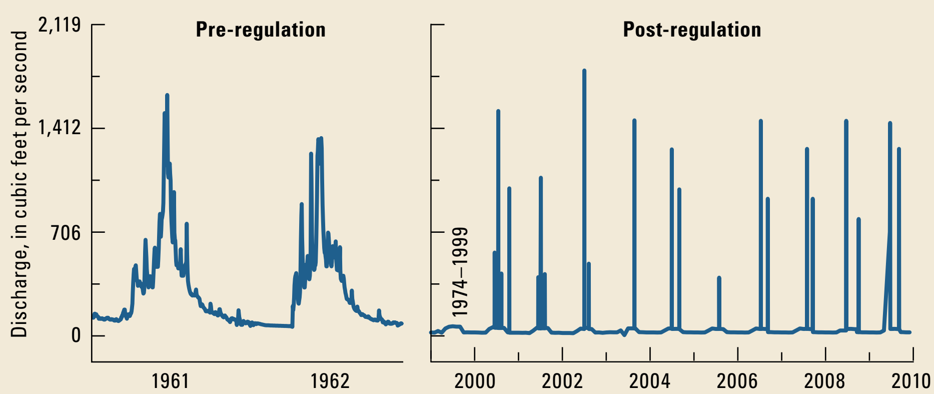

Left, the Spöl River at one of the study reaches (Punt Periv) under low-flow conditions (56 ft^3/s). Right, during one of the high-flow experimental releases (1,483 ft^3/s) on July 5, 2000. Photographs courtesy of Urs Uehlinger.

previously exposed gravel banks. Young trees developing on the river bank were only slightly affected by the high flows, suggesting that colonization of trees was not constrained by the experimental releases. Thus far, the number and duration of high flows have not been sufficient to restore former flood plains free of trees; however, the coverage (burial) of grass areas by sand and gravel partially created locations for pioneer plants. These effects on riparian vegetation may be related to the canyon-confined nature of the river valley in contrast to other rivers with more dynamic flood plains.

An evaluation of modified flow regimes worldwide (Murchie and others, 2008) and the experience of the Spöl River (Robinson and Uehlinger, 2008) reveal important issues in the evaluation of relatively frequent HFEs on river ecology. Study designs could include methods that target physical as well as all biological levels, including aquatic food producing organisms, fishes, and riparian vegetation. The most effective experimental designs also would provide sufficient data to allow for detailed statistical analyses to be performed. Rigorous study designs that include the use of appropriate controls and replicates are essential whenever feasible. Data on physical variables that respond to changes in flow can also be collected and examined to add explanatory power to results.

The HFEs on the Spöl River highlight some major effects of artificial floods on regulated river ecosystems. While the experiments affected the existing aquatic communities, recovery of primary and secondary producers (periphyton and macroinvertebrates) was rapid after each flood. Biotic assemblages have shifted to the new habitat template of the river, but these changes in slower variables have occurred over years as novel biological thresholds were passed and new ecosystem states were established. Whether biotic assemblages return to pre-dam levels is unknown, but the frequently repeated high flows have clearly increased the physical dynamics of the river, which has been translated to changes in biotic assemblages. It also is unknown, however, if repeated and continued high flows over time will eventually restore much of the ecosystem structure and function to those of a typical mountain river. Without consistent monitoring, the gradual nature and timing of this shift might not have been apparent.

The findings on the Spöl River may have general ecological application. Some of the learning that has occurred there is likely transferrable to the current Glen Canyon Dam HFE protocol planning process. However, it is clear that each river system is different because of its unique ecological setting and the specific manner in which each system is regulated. The Swiss experience clearly illustrates the benefits of cooperative efforts among stakeholders, especially power producers, water users, environmental groups, and State and Federal officials. The Spöl River experiment and other programs (Murchie and others, 2008) show how a good understanding of the relation of dam operations and resulting river flows to ecosystem components can help manage hydropower facilities to achieve large ecological benefits through relatively small modifications and costs.



The flow regime of the Spöl River (on the Swiss-Italian border) for 2 representative years before regulation, the year before the high-flow experimental program (1999) showing the typical seasonal regulated flow, and the flow after the experimental program, including each of the flow events. Data for 1999 and the years before regulation are daily values. Data are instantaneous values after 2000. Modified from Robinson and Uehlinger (2008).

References

Acreman, M.C., and Ferguson, A.J.D., 2010, Environmental flows and the European water framework directive: Freshwater Biology, v. 55, no. 1, p. 32–48.

Andersen, M.E., Ackerman, M.W., Hilwig, K.D., Fuller, A.E., and Alley, P.D., 2010, Evidence of young humpback chub overwintering in the mainstem Colorado River, Marble Canyon, Arizona, USA: The Open Fish Science Journal, v. 3, p. 42–50, doi:10.2174/1874401X01003010042.

Angradi, T.R., 1994, Trophic linkages in the lower Colorado River—Multiple stable isotope evidence: Journal of the North American Benthological Society, v. 13, no. 4, p. 479–495, accessed December 2, 2009, at *http://www.jstor.org/stable/1467845*.

Behn, K.E., Kennedy, T.A., and Hall, R.O., Jr., 2010, Basal resources in backwaters of the Colorado River below Glen Canyon Dam—Effects of discharge regimes and comparison with mainstem depositional environments: U.S. Geological Survey Open-File Report 2010–1075, 25 p. (Also available at *http://pubs.usgs.gov/of/2010/1075/*.)

Bestgen, K.R., Beyers, D.W., Rice, J.A., and Haines, G.B., 2006, Factors affecting recruitment of young Colorado pikeminnow—Synthesis of predation experiments, field studies, and individual-based modeling: Transactions of the American Fisheries Society, v. 135, no. 6, p. 1722–1742, doi:10.1577/T05-171.1.

Bratrich, Christine, Truffer, Bernhard, Jorde, Klaus, Markard, Jochen, Meier, Werner, Peter, Armin, Schneider, Matthias, and Wehrli, Bernhard, 2004, Green hydropower—A new assessment procedure for river management: River Research and Applications, v. 20, no. 7, p. 865–882, doi: 10.1002/rra.788.

Brouder, M.J., Speas, D.W., and Hoffnagle, T.L., 1999, Changes in number, sediment composition, and benthic invertebrates of backwaters, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 241–248.

Bureau of Reclamation, 2010, Razorback suckers found at Colorado River inflow area to Lake Mead: Upper Colorado Region, accessed November 3, 2010, at *http://www.usbr.gov/uc/feature/Razorback/index.html*.

Carlander, K.D., 1969, Handbook of freshwater fishery biology, v. 1: Ames, Iowa, The Iowa State University Press, 752 p.

Carothers, S.W., and Brown, B.T., 1991, The Colorado River through Grand Canyon—Natural history and human change: Tucson, University of Arizona Press, 235 p.

Clarkson, R.W., and Childs, M.R., 2000, Temperature effects of hypolimnial-release dams on early life stages of Colorado River Basin big-river fishes: Copeia, v. 2000, no. 2, p. 402–412, doi:10.1643/0045-8511(2000)000[0402:TEOHRD]2.0.CO;2.

Clover, E.U., and Jotter, Lois, 1944, Floristic studies in the canyon of the Colorado and tributaries: The American Midland Naturalist, v. 32, no. 3, p. 591–642, accessed December 7, 2009, at *http://www.jstor.org/stable/2421241*.

Coggins, L.G., Jr., 2008, Active adaptive management for native fish conservation in the Grand Canyon—Implementation and evaluation: Gainesville, University of Florida, Ph.D. dissertation, 173 p.

Coggins, L.G., Jr., and Walters, C.J., 2009, Abundance trends and status of the Little Colorado River population of humpback chub—An update considering data from 1989–2008: U.S. Geological Survey Open-File Report 2009–1075, 18 p. (Also available at *http://pubs.usgs.gov/of/2009/1075/*.)

Coggins, L.G., Jr., and Yard, M.D., 2010, Mechanical removal of nonnative fish in the Colorado River within Grand Canyon, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 227–234 (Also available at *http://pubs.usgs.gov/sir/2010/5135/*.)

Coggins, L.G., Jr., Yard, M.D., and Pine, W.E., III, in press, Nonnative fish control in the Colorado River in Grand Canyon, Arizona—An effective program or serendipitous timing?: Transactions of the American Fisheries Society.

Cross, W.F., Baxter, C.V., Donner, K.C., Rosi-Marshall, E.J., Kennedy, T.A., Hall, R.O. Jr., Wellard Kelly, H.A., and Rogers, R.S., in press, Ecosystem ecology meets adaptive management—Food web response to a controlled flood on the Colorado River, Glen Canyon, USA: Ecological Applications.

England, J.L., 1992, Endangered and threatened wildlife and plants; Final rule to list the Kanab ambersnail as endangered: U.S. Fish and Wildlife Service, Federal Register, v. 57, no. 75, p. 13657–13661, accessed December 9, 2009, at *http://ecos.fws.gov/docs/federal_register/fr2027.pdf*.

Fisher, S.G., Gray, L.J., Grimm, N.B., and Busch, D.E., 1982, Temporal succession in a desert stream ecosystem following flash flooding: Ecological Monographs, v. 52, no. 1, p. 93–110, accessed February 11, 2010, at *http://www.jstor.org/stable/pdfplus/2937346.pdf*.

Gloss, S.P., and Coggins, L.G., 2005, Fishes of Grand Canyon, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S.Geological Survey Circular 1282, chap. 2, p. 33–56. (Also available at *http://pubs.usgs.gov/circ/1282/*.)

Gorman, O.T., and Stone, D.M., 1999, Ecology of spawning humpback chub, *Gila cypha,* in the Little Colorado River near Grand Canyon, Arizona: Environmental Biology of Fishes, v. 55, p. 115–133, accessed February 12, 2010, at *http://www.springerlink.com/content/vq675171n84786p7/fulltext.pdf*.

Grams, P.E., Schmidt, J.C., and Andersen, M.E., 2010, 2008 high-flow experiment at Glen Canyon Dam—Morphologic response of eddy-deposited sandbars and associated aquatic backwater habitats along the Colorado River in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010–1032, 73 p. (Also available at *http://pubs.usgs.gov/of/2010/1032/*.)

Grand, T.C., Railsback, S.F., Hayse, J.W., and LaGory, K.E., 2006, A physical habitat model for predicting the effects of flow fluctuations in nursery habitats of the endangered Colorado pikeminnow (*Ptychocheilus lucius*): River Research and Applications, v. 22, no. 10, p. 1125–1142, doi:10.1002/rra.967, accessed December 3, 2010, at *http://onlinelibrary.wiley.com/doi/10.1002/rra.967/abstract*.

Hall, R.O., Jr., Kennedy, T.A., Rosi-Marshall, E.J., Cross, W.F., Wellard, H.A., and Baxter, C.F., 2010, Aquatic production and carbon flow in the Colorado River, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 105–112. (Also available at *http://pubs.usgs.gov/sir/2010/5135/*.)

Hamman, R.L., 1982, Spawning and culture of humpback chub: The Progressive Fish-Culturist, v. 44, no. 4, p. 213–216, accessed December 1, 2010, at *http://afsjournals.org/doi/abs/10.1577/1548-8659(1982)44%5B213:SACOHC%5D2.0.CO%3B2*.

Hilwig, K.D., and Makinster, A.S., 2010, Evaluating effects of a high-flow event on rainbow trout movement in Glen and Marble Canyons, Arizona, by using acoustic telemetry and relative abundance measures, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 219–226. (Also available at *http://pubs.usgs.gov/sir/2010/5135/*.)

Hoffnagle, T.L., Valdez, R.A., and Speas, D.W., 1999, Fish abundance, distribution, and habitat use, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 273–287.

Huntoon, P.W., 1981, Fault controlled ground-water circulation under the Colorado River, Marble Canyon, Arizona: Ground Water, v. 19, no. 1, p. 20–27, accessed January 28, 2011, at *http://dx.doi.org/10.1111/j.1745-6584.1981.tb03433.x*.

Imre, I., Grant, J.W.A., and Cunjak, R.A., 2005, Density-dependent growth of young-of-the-year Atlantic salmon *Salmo salar* in Catamaran Brook, New Brunswick: Journal of Animal Ecology, v. 74, p. 508–516, accessed December 1, 2010, at *http://dx.doi.org/10.1111/j.1365-2656.2005.00949.x*.

Jakob, Christian, Robinson, C.T., and Uehlinger, Urs, 2003, Longitudinal effects of experimental floods on stream benthos downstream from a large dam: Aquatic Sciences, v. 65, no. 3, p. 223–231, doi: 10.1007/s00027-003-0662-9.

Jenkins, T.M., Jr., Diehl, Sebastian, Kratz, K.W., and Cooper, S.D., 1999, Effects of population density on individual growth of brown trout in streams: Ecology, v. 80, no. 3, p. 941–956, accessed January 11, 2010, at *http://www.jstor.org/stable/177029*.

Kaplinski, Matt, Behan, Jeff, Hazel, J.E., Jr., Parnell, R.A., and Fairley, H.C., 2005, Recreational values and campsites in the Colorado River ecosystem, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 12, p. 193–205 (Also available at *http://pubs.usgs.gov/circ/1282/*.)

Kearsley, L.H., Schmidt, J.C., and Warren, K.D., 1994, Effects of Glen Canyon Dam on Colorado River sand deposits used as campsites in Grand Canyon National Park, USA: Regulated Rivers—Research & Management, v. 9, no. 3, p. 137–149, doi:10.1002/rrr.3450090302.

Kearsley, M.J.C., and Ayers, T.J., 1999, Riparian vegetation responses—Snatching defeat from the jaws of victory and *vice versa*, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 309–327.

Kennedy, T.A., and Gloss, S.P., 2005, Aquatic ecology—The role of organic matter and invertebrates, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 5, p. 87–101. (Also available at *http://pubs.usgs.gov/circ/1282/*.)

Kennedy, T.A., and Ralston, B.E., 2010, Regulation leads to increases in riparian vegetation, but not direct allochthonous inputs, along the Colorado River in Grand Canyon, Arizona: River Research and Applications, doi:10.1002/rra.1431.

Korman, Josh, 2009, Early life history dynamics of rainbow trout in a large regulated river: Vancouver, University of British Columbia, Ph.D. thesis, 214 p.

Korman, Josh, Kaplinski, Matthew, and Melis, T.S., 2010, Effects of high-flow experiments from Glen Canyon Dam on abundance, growth, and survival rates of early life stages of rainbow trout in the Lees Ferry reach of the Colorado River: U.S. Geological Survey Open-File Report 2010–1034, 31 p. (Also available at *http://pubs.usgs.gov/of/2010/1034/*.)

Korman, J., Kaplinski, M., and Melis, T.S., in press, Effects of fluctuating flows and a controlled flood on incubation success and early survival rates and growth of age-0 rainbow trout in a large regulated river: Transactions of the American Fisheries Society.

Korman, Josh, and Melis, T.S., 2011, The effects of Glen Canyon Dam operations on early life stages of rainbow trout in the Colorado River: U.S. Geological Survey Fact Sheet 2011–3002, 4 p. (Also available at *http://pubs.usgs.gov/fs/2011/3002/*.)

Korman, Josh, Wiele, S.M., and Torizzo, Margaret, 2004, Modelling effects of discharge on habitat quality and dispersal of juvenile humpback chub (*Gila cypha*) in the Colorado River, Grand Canyon: River Research and Applications, v. 20, no. 4, p. 379–400, doi:10.1002/rra.749.

Krebs, C.J., 2008, Ecology—The experimental analysis of distribution and abundance (6th ed.): San Francisco, Benjamin Cummings, 688 p.

Maddux, H.R., and Kepner, W.G., 1988, Spawning of bluehead sucker in Kanab Creek, Arizona (Pisces: Catostomidae): The Southwestern Naturalist, v. 33, p. 364–365.

Makinster, A.S., Persons, W.R., and Avery, L.A., in press, Status and trends of the rainbow trout population in the Lees Ferry tailwater reach of the Colorado River downstream from Glen Canyon Dam, Arizona, 1991–2009: U.S. Geological Survey Scientific Investigations Report 2011–5015.

Makinster, A.S., Persons, W.R., Avery, L.A., and Bunch, A.J., 2010, Colorado River fish monitoring in Grand Canyon, Arizona—2000 to 2009 summary: U.S. Geological Survey Open-File Report 2010–1246, 26 p. (Also available at *http://pubs.usgs.gov/of/2010/1246/*.)

Malanson, G.P., 1993, Riparian landscapes: Cambridge, Cambridge University Press, 308 p.

McKinney, Ted, and Speas, D.W., 2001, Observations of size-related asymmetries in diet and energy intake of rainbow trout in a regulated river: Environmental Biology of Fishes, v. 61, no. 4, p. 435–444, accessed November 1, 2010, at *http://www.springerlink.com/content/u177356554v07546/*.

McKinney, Ted, Speas, D.W., Rogers, R.S., and Persons, W.R., 2001, Rainbow trout in a regulated river below Glen Canyon Dam, Arizona, following increased minimum flows and reduced discharge variability: North American Journal of Fisheries Management, v. 21, no. 1, p. 216–222, accessed January 28, 2011, at *http://dx.doi.org/10.1577/1548-8675(2001)021<0216:RTIARR>2.0.CO;2*.

McLaughlin, S.P., 1989, Natural floristic areas of the western United States: Journal of Biogeography, v. 16, no. 3, p. 239–248, accessed November 19, 2010, at *http://www.jstor.org/stable/2845260*.

Melis, T.S., Korman, J., and Kennedy, T.A., in press, Abiotic and biotic responses of the Colorado River to a March 2008 controlled flood experiment at Glen Canyon Dam, AZ: River Research and Applications.

Meretsky, V.J., North, E.G., and Stevens, L.E., 2002, Kanab ambersnail and other terrestrial snails in south central Utah: Western North American Naturalist, v. 62, no. 3, p. 307–315, accessed November 19, 2010, at *https://ojs.lib.byu.edu/wnan/index.php/wnan/article/viewFile/1141/998*.

Minckley, W.L., 1991, Native fishes of the Grand Canyon region—An obituary?, *in* Colorado River ecology and dam management, Proceedings of a Symposium, May 24–25, 1990, Santa Fe, New Mexico: Washington, D.C., National Academies Press, p. 124–177.

Minckley, W.L., and Deacon, J.E., 1991, Battle against extinction—Native fish management in the American west: Tucson, University of Arizona Press, 517 p.

Mueller, G.A., 2005, Predatory fish removal and native fish recovery in the Colorado River mainstem—What have we learned?: Fisheries, v. 30, no. 9, p. 10–19.

Murchie, K.J., Hair, K.P.E., Pullen, C.E., Redpath, T.D., Stephens, H.R., and Cooke, S.J., 2008, Fish response to modified flow regimes in regulated rivers—Research methods, effects and opportunities: River Research and Applications, v. 24, no. 2, p. 197–217, doi: 10.1002/rra.1058.

Mürle, Uta, Ortlepp, Johannes, and Zahner, Margot, 2003, Effects of experimental flooding on riverine morphology, structure and riparian vegetation—The River Spöl, Swiss National Park: Aquatic Sciences, v. 65, no. 3, p. 191–198, p. 197–217, doi: 10.1007/s00027-003-0665-6.

Olden, J.D., and Naiman, R.J., 2009, Incorporating thermal regimes into environmental flows assessments—Modifying dam operations to restore freshwater ecosystem integrity: Freshwater Biology, v. 55, no. 1, p. 86–107, doi:10.1111/j.1365-2427.2009.02179.x.

Ortlepp, Johannes, and Mürle, Uta, 2003, Effects of experimental flooding on brown trout (*Salmo trutta fario* L.)—The River Spöl, Swiss National Park: Aquatic Sciences, v. 65, no. 3, p. 232–238, doi:10.1007/s00027-003-0666-5.

Osmundson, D.B., Ryel, R.J., Lamarra, V.L., and Pitlick, J., 2002, Flow-sediment-biota relations—Implications for river regulation effects on native fish abundance: Ecological Applications, v. 12, no. 6, p. 1719–1739, accessed October 14, 2010, at *http://www.esajournals.org/doi/pdf/10.1890/1051-0761(2002)012%5B1719%3AFSBRIF%5D2.0.CO%3B2*.

Parnell, R.A., Jr., Bennett, J.B., and Stevens, L.E., 1999, Mineralization of riparian vegetation buried by the 1996 controlled flood, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 225–239.

Pine, W.E., III, Martell, S.J.D., Walters, C.J., and Kitchell, J.F., 2009, Counterintuitive responses of fish populations to management actions—Some common causes and implications for predictions based on ecosystem modeling: Fisheries, v. 34, no. 4, p. 165–180.

Protiva, F.R., Ralston, B.E., Stone, D.M., Kohl, K.A., Yard, M.D., and Haden, G.A., 2010, Effects of Glen Canyon Dam discharges on water velocity and temperatures at the confluence of the Colorado and Little Colorado Rivers and implications for habitat for young-of-year Humpback Chub (*Gila cypha*) U.S. Geological Survey Open-File Report 2010–1137, 24 p. (Also available at *http://pubs.usgs.gov/of/2010/1137/*.)

Radar, R.B., 1997, A functional classification of the drift—Traits that influence invertebrate availability to salmonids: Canadian Journal of Fisheries and Aquatic Sciences, v. 54, no. 6, p. 1211–1234, doi:10.1139/cjfas-54-6-1211.

Ralston, B.E., 2005, Riparian vegetation and associated wildlife, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 6, p. 103–122. (Also available at *http://pubs.usgs.gov/circ/1282/*.)

Ralston, B.E., 2010, Riparian vegetation response to the March 2008 short-duration, high-flow experiment—Implications of timing and frequency of flood disturbance on nonnative plant establishment along the Colorado River below Glen Canyon Dam: U.S. Geological Survey Open-File Report 2010–1022, 30 p. (Also available at at *http://pubs.usgs.gov/of/2010/1022/*.)

Ralston, B.E., Davis, P.A., Weber, R.M., and Rundall, J.M., 2008, A vegetation database for the Colorado River ecosystem from Glen Canyon Dam to the western boundary of Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 2008–1216, 37 p. (Also available at *http://pubs.usgs.gov/of/2008/1216/*.)

Robinson, C.T., and Uehlinger, Urs, 2003, Using artificial floods for restoring river integrity: Aquatic Sciences, v. 65, no. 3, p. 181–182, doi: 10.1007/s00027-003-0002-0.

Robinson, C.T., and Uehlinger, Urs, 2008, Experimental floods cause ecosystem regime shift in a regulated river: Ecological Applications, v. 18, no. 2, p. 511–526, doi:10.1890/07-0886.1.

Robinson, C.T., Uehlinger, Urs, and Monaghan, M.T., 2003, Effects of a multi-year experimental flood regime on macroinvertebrates downstream of a reservoir: Aquatic Sciences, v. 65, no. 3, p. 210–222, doi: 10.1007/s00027-003-0663-8.

Rosi-Marshall, E.J., Kennedy, T.A., Kincaid, D.W., Cross, W.F., Kelly, H.A.W., Behn, K.A., White, Tyler, Hall, R.O., Jr., and Baxter, C.V., 2010, Short-term effects of the 2008 high-flow experiment on macroinvertebrates in Colorado River below Glen Canyon Dam, Arizona: U.S. Geological Survey Open-File Report 2010–1031, 28 p. (Also available at *http://pubs.usgs.gov/of/2010/1031/*.)

Scheurer, Thomas, and Molinari, Peter, 2003, Experimental floods in the River Spöl, Swiss National Park—Framework, objectives and design: Aquatic Sciences, v. 65, no. 3, p. 183–190, doi: 10.1007/s00027-003-0667-4.

Schmidt, J.C., and Graf, J.B., 1990, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1493, 74 p., accessed March 17, 2010, at *http://pubs.er.usgs.gov/usgspubs/citfor/pp/pp1493*.

Scott, W.B., and Crossman, E.J., 1973, Freshwater fishes of Canada: Ottawa, Fisheries Research Board of Canada, Bulletin 184, 966 p.

Shannon, J.P., Blinn, D.W., McKinney, Ted, Benenati, E.P., Wilson, K.P., and O'Brien, Chris, 2001, Aquatic food base response to the 1996 test flood below Glen Canyon Dam, Colorado River, Arizona: Ecological Applications, v. 11, no. 3, p. 672–685, accessed January 11, 2010, at *http://www.jstor.org/stable/3061109*.

Shannon, J.P., Blinn, D.W., and Stevens, L.E., 1994, Trophic interactions and benthic animal community structure in the Colorado River, Arizona, U.S.A.: Freshwater Biology, v. 31, p. 213–220, doi:10.1111/j.1365-2427.1994.tb00855.x.

Sher, A.A., Marshall, D.L., and Gilbert, S.A., 2000, Competition between native *Populus deltoides* and invasive *Tamarix ramosissima* and the implications for reestablishing flooding disturbance: Conservation Biology, v. 14, no. 6, p. 1744–1754, accessed January 12, 2010, at *http://www.jstor.org/stable/2641526*.

Simon, Andrew, Bennett, S.J., and Neary, V.S., 2004, Riparian vegetation and fluvial geomorphology—Problems and opportunities, *in* Bennett, S.J., and Simon, Andrew, eds., Riparian vegetation and fluvial geomorphology: Washington, D.C., American Geophysical Union, Water Science and Application, v. 8, p. 1–10.

Sogge, M.K., Felley, David, and Wotawa, Mark, 1998, Riparian bird community ecology in the Grand Canyon--Final report: Flagstaff, Arizona, U.S. Geological Survey, Colorado Plateau Field Station report, cooperative agreement no. 8031-8-0002, 276 p. + apps., accessed January 28, 2011, at *http://www.gcmrc.gov/library/reports/biological/terrestrial/Sogge2000b.pdf*.

Sorensen, J.A., 2005, Kanab ambersnail 2005 progress report—Status of translocation populations and initial results from the November 2004 habitat mitigation experiment: Phoenix, Arizona Game and Fish Department, Nongame and Endangered Wildlife Program Technical Report 243.

Sorensen, J.A., 2009, Kanab ambersnail habitat mitigation for the 2008 high flow experiment: Phoenix, Arizona Game and Fish Department, Nongame and Endangered Wildlife Program Technical Report 257, accessed January 26, 2011, at at *http://www.gcmrc.gov/files/2563/w-2563_2010-08-19-18-25-18-911_Sorensen%20(2009)%20AGF%20Dept%20Draft%202008%20HFE%20KAS%20Habitat%20Mitigation%20Cooperator%20Report.pdf*.

Stevens, L.E., Ayers, T.J., Bennett, J.B., Christensen, Kerry, Kearsley, M.J.C., Meretsky, V.J., Phillips, A.M., III, Parnell, R.A., Spence, John, Sogge, M.K., Springer, A.E., and Wegner, D.L., 2001, Planned flooding and Colorado River riparian trade-offs downstream from Glen Canyon Dam, Arizona: Ecological Applications, v. 11, no. 3, p. 701–710, accessed January 3, 2011, at *http://dx.doi.org/10.1890/1051-0761(2001)011%5B0701:PFACRR%5D2.0.CO%3B2*.

Stevens, L.E., Shannon, J.P., and Blinn, D.W., 1997, Colorado River benthic ecology in Grand Canyon, Arizona, USA—Dam, tributary, and geomorphological influences: Regulated Rivers—Research & Management, v. 13, p. 129–149, accessed January 3, 2011, at *http://www.gcmrc.gov/library/reports/biological/Foodbase/Stevens1997e.pdf*.

Topping, D.J., 1997, Physics of flow, sediment transport, hydraulic geometry, and channel geomorphic adjustment during flash floods in an ephemeral river, the Paria River, Utah and Arizona: Seattle, University of Washington, Ph.D. dissertation, 405 p.

Topping, D.J., Rubin, D.M., Grams, P.E., Griffiths, R.E., Sabol, T.A., Voichick, Nicholas, Tusso, R.B., Vanaman, K.M., and McDonald, R.R., 2010, Sediment transport during three controlled-flood experiments on the Colorado River downstream from Glen Canyon Dam, with implications for eddy-sandbar deposition in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010–1128, 111 p. (Also available at *http://pubs.usgs.gov/of/2010/1128/*.)

Topping, D.J., Rubin, D.M., and Melis, T.S., 2007, Coupled changes in sand grain size and sand transport driven by changes in the upstream supply of sand in the Colorado River—Relative importance of changes in bed-sand grain size and bed-sand area: Sedimentary Geology, v. 202, no. 3, p. 538–561, doi:10.1016/j.sedgeo.2007.03.016.

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport, 1. Natural sediment supply limitation and the influence of Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515–542, doi:10.1029/1999WR900285.

Topping, D.J., Schmidt, J.C., and Vierra, L.E., Jr., 2003, Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000: U.S. Geological Survey Professional Paper 1677, 118 p. (Also available at *http://pubs.usgs.gov/pp/pp1677/*.)

Turner, R.M., and Karpiscak, M.M., 1980, Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona: U.S. Geological Survey Professional Paper 1132, 125 p.

Tyus, H.M., 1998, Razorback sucker (*Xyrauchen texanus*) recovery plan: All U.S. Government Documents (Utah Regional Depository), Paper 467, 76 p., accessed November 3, 2010, at *http://digitalcommons.usu.edu/govdocs/467*.

Uehlinger, U., Kawecka, B., and Robinson, C.T., 2003, Effects of experimental floods on periphyton and stream metabolism below a high dam in the Swiss Alps (River Spöl): Aquatic Sciences, v. 65, no. 3, p. 199–209, doi:10.1007/s00027-003-0664-7.

U.S. Department of the Interior, 2008a, Final biological opinion for the operation of Glen Canyon Dam: Phoenix, Arizona, U.S. Fish and Wildlife Service, AESO/SE 22410-1993-F-167R1, 88 p., accessed January 26, 2010, at *http://www.usbr.gov/uc/envdocs/bo/FinalGCDBO2-26-08.pdf*.

U.S. Department of the Interior, 2008b, Final environmental assessment, Experimental releases from Glen Canyon Dam, Arizona, 2008 through 2012: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Region, 59 p. + apps., accessed January 13, 2010, at *http://www.usbr.gov/uc/envdocs/ea/gc/2008hfe/index.html*.

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam—Final Environmental Impact Statement, Colorado River Storage Project, Coconino County, Arizona: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Regional Office, 337 p., accessed November 18, 2010, at *http://www.usbr.gov/uc/library/envdocs/eis/gc/pdfs/Cov-con/cov-con.pdf*.

Valdez, R.A., Hoffnagle, T.L., McIvor, C.C., McKinney, Ted, and Leibfried, W.C., 2001, Effects of a test flood on fishes of the Colorado River in Grand Canyon, Arizona: Ecological Applications, v. 11, no. 3, p. 686–700.

Valdez, R.A., and Ryel, R.J., 1995, Life history and ecology of the humpback chub (*Gila cypha*) in the Colorado River, Grand Canyon, Arizona—Final report: Logan, Utah, BIO/WEST, Inc., submitted to Bureau of Reclamation, contract no. 0-CS-40-09110, technical report no. TR-250-08, 328 p., accessed January 28, 2011, at *http://www.gcmrc.gov/library/reports/biological/Fish_studies/Biowest/Valdez1995f.pdf*.

Vernieu, W.S., Hueftle, S.J., and Gloss, S.P., 2005, Water quality in Lake Powell and the Colorado River, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 4, p. 69–85. (Also available at *http://pubs.usgs.gov/circ/1282/*.)

Voichick, Nicholas, and Wright, S.A., 2007, Water-temperature data for the Colorado River and tributaries between Glen Canyon Dam and Spencer Canyon, northern Arizona, 1988–2005: U.S. Geological Survey Data Series 251, 24 p. (Also available at *http://pubs.usgs.gov/ds/2007/251/*.)

Walters, Carl, and Korman, Josh, 1999, Linking recruitment to trophic factors—Revisiting the Beverton-Holt recruitment model from a life history and multispecies perspective: Reviews in Fish Biology and Fisheries, v. 9, no. 2, p. 187–202, accessed October 7, 2010, at *http://www.springerlink.com/content/x206g776q7838050/*.

Ward, D.L., Schultz, A.A., and Matson, P.G., 2003, Differences in swimming ability and behavior in response to high water velocities among native and nonnative fishes: Environmental Biology of Fishes, v. 68, p. 87–92, accessed September 9, 2010, at *http://www.springerlink.com/content/x22ux2r131873615/fulltext.pdf*.

Ward, D.M., Nislow, K.H., Armstrong, J.D., Einum, S., and Folt, C.L., 2007, Is the shape of the density-growth relationship for stream salmonids evidence for exploitative rather than interference competition?: Journal of Animal Ecology, v. 76, no. 1, p. 135–138, doi:10.1111/j.1365-2656.2006.01169.x.

Ward, J.V., and Stanford, J.A., 1983, The serial discontinuity concept of lotic ecosystems, *in* Fontaine, T.D., III, and Bartell, S.M., eds., Dynamics of lotic ecosystems: Ann Arbor, Michigan, Ann Arbor Science Publishers, chap. 2, p. 29–42.

Weiss, S.J., Otis, E.O., and Maughan, O.E., 1998, Spawning ecology of flannelmouth suckers, *Catostomus latipinnis* (Catostomidae), in two small tributaries of the lower Colorado River: Environmental Biology of Fishes, v. 52, no. 4, p. 419–433.

Yard, H.K., Van Riper, Charles, III, Brown, B.T., and Kearsley, M.J., 2004, Diets of insectivorous birds along the Colorado River in Grand Canyon, Arizona: The Condor, v. 106, no. 1, p. 106–115, accessed December 28, 2009, at *http://www.jstor.org/stable/pdfplus/1370520.pdf*.

Yard, M.D., Coggins, L.G., Baxter, C.V., Bennett, G.E., and Korman, Josh, in press, Trout piscivory in the Colorado River, Grand Canyon—Effects of turbidity, temperature, and fish prey availability: Transactions of the American Fisheries Society.

Anne Phillips, U.S. Geological Survey

CHAPTER 5

Science-Based Strategies for Future High-Flow Experiments at Glen Canyon Dam

By Scott A. Wright[1,2] and Theodore A. Kennedy[2,3]

As detailed in the preceding chapters of this report, the presence and operation of Glen Canyon Dam has drastically altered physical and biological processes along the Colorado River corridor downstream from the dam (fig. 1). These changes have led to a variety of effects on Colorado River fluvial geomorphology and biological resources in Grand Canyon. The Glen Canyon Dam Adaptive Management Program (GCDAMP) has conducted three high-flow experiments (or HFEs)—in 1996, 2004, and 2008—to benefit sandbar resources and increase learning about the role that HFEs play in the geomorphology and ecology of the Colorado River. The results of these HFEs are not reviewed in detail in this chapter; instead, the reader is referred to chapters 2–4 of this report as well as other recent review articles (Lovich and Melis, 2007; Melis and others, 2010). The purpose of this chapter is to provide a brief overview and synthesis of physical and biological findings from previous HFEs and, on the basis of key physical and biological findings, develop a strategy for future HFEs that seeks to

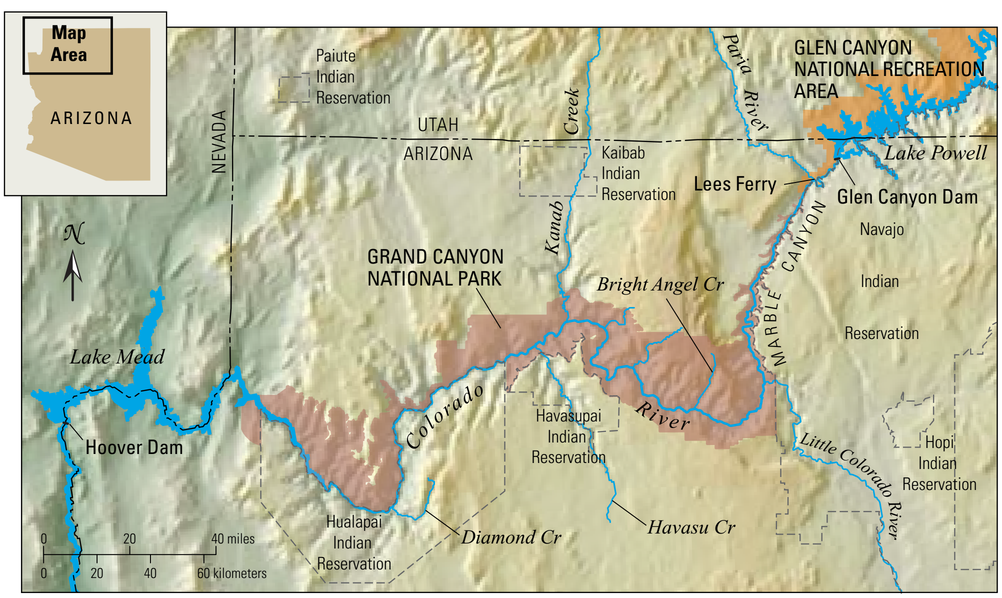


Figure 1. The Glen Canyon Dam Adaptive Management Program study area includes the Colorado River corridor that stretches approximately 293 river miles from the forebay of Glen Canyon Dam to the westernmost boundary of Grand Canyon National Park, Arizona.

[1] U.S. Geological Survey, California Water Science Center, 6000 J Street, Sacramento, CA 95819.

[2] Both authors contributed equally to the development of this chapter.

[3] U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, 2255 N. Gemini Drive, Flagstaff, AZ 86001.

achieve two goals: (1) benefit sandbar resources while maintaining neutral trends in key biological resources and (2) increase learning about important resource responses to HFEs.

Physical Processes

The links between dam operations and geomorphology are direct and strong and, therefore, can be well understood. Two major effects on geomorphology are a reduction in sand supply due to trapping of sediments in Lake Powell, the reservoir formed by Glen Canyon Dam (fig. 1), and a reduction in natural flood peaks caused by multiyear water storage in Lake Powell. In the post-dam period, shoreline sandbar deposits are dependent on sand supplied from the tributaries downstream

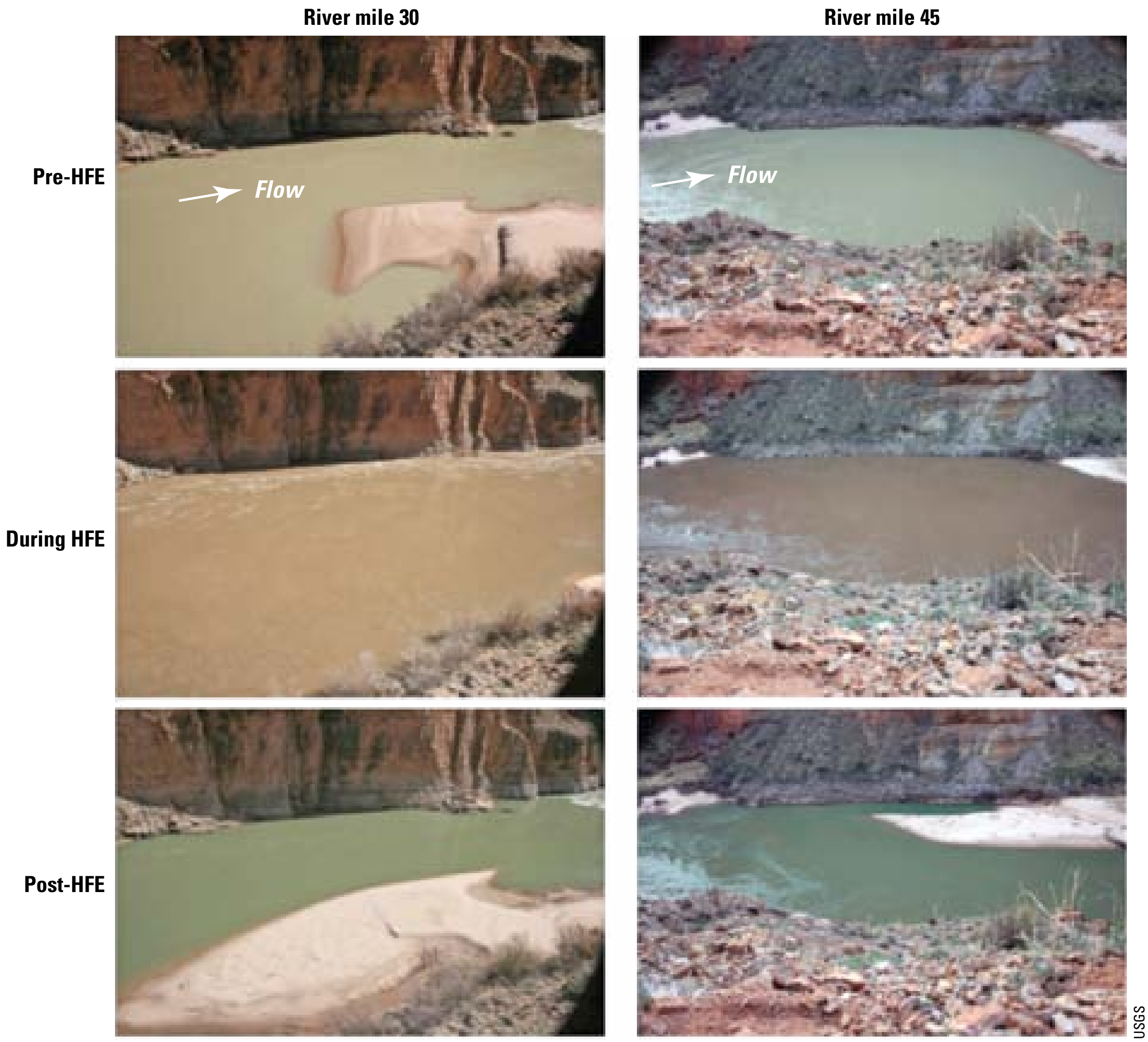


Figure 2. Repeat views looking across the Colorado River from the right shore of two sandbars in Marble Canyon before and after the March 2008 high-flow experiment (HFE). These examples are for illustrative purposes only (that is, these results are not necessarily representative of the system response); for detailed sediment-response studies, see chapter 2, this volume; Hazel and others (2010); Grams, Hazel, and others (2010); and Topping and others (2010). Flow direction is from left to right at both locations.

from the dam and occasional HFEs to redistribute sand from the river bottom to the shoreline and riparian corridor. With reduced sand supply and HFEs, which have been less frequent and smaller than natural floods, sandbars have persistently eroded during the post-dam period (chapters 2–3, this volume). Sandbars were a prominent geomorphic feature of the pre-dam river, and maintaining these features has been deemed desirable because they provide ideal campsites for river rafters (Hazel and others, 2010; Kaplinski and others, 2010), low-velocity shoreline habitat that is used by native fishes (hereafter referred to as backwaters; see chapters 2–4 for further description), and a source of sand that is transported upslope through eolian processes and may help preserve archaeological sites (Draut and Rubin, 2008; Draut and others, 2010).

High flows from Glen Canyon Dam are the only known tool for rebuilding sandbars using the existing post-dam sand supply (fig. 2). Three HFEs have been released from Glen Canyon Dam, in 1996, 2004, and 2008, as detailed in chapters 2–3 of this report. Although these HFEs were much smaller in magnitude and duration than typical natural pre-dam snowmelt floods in the spring (chapters 2–3, this volume), the HFEs were comparable in size to many natural pre-dam floods that resulted from rainfall events in the late summer and early fall. Numerous focused research projects were conducted during these HFEs, each resulting in a wealth of knowledge about key processes. For example, on the basis of research conducted during the 1996 HFE, the two subsequent HFEs were conducted under the general concept of sand-input "triggering" and in response to substantial inputs of sand from natural Paria River floods. The hypothesis that was evaluated in these two recent events was that HFEs conducted soon after new sand had been delivered by tributaries would enhance sand deposition on sandbars and minimize erosion of sand stored on the channel bed prior to the tributary inputs. Continuous suspended-sediment monitoring established in 2000 yielded the data needed to identify links between sand storage and sandbar building during HFEs, as well as sandbar erosion afterward (Grams, Hazel, and others, 2010; Hazel and others, 2010; Topping and others, 2010; chapter 3, this volume).

Three definitive conclusions that have important implications for designing future sediment-management strategies can be drawn from these studies:

- HFEs are effective at building sandbars by transferring sand from the channel bed to sandbars along the channel margins
- HFEs conducted soon after tributary-derived sand has accumulated on the channel bed are more effective at building sandbars and less likely to result in erosion of sand stored on the channel bed and in sandbars prior to the tributary inputs compared to HFEs conducted when sand is depleted
- Sandbars tend to erode quickly in the weeks and months following HFEs, depending on flow releases from the dam as well as ongoing tributary sand supply

Biological Processes

Glen Canyon Dam has directly contributed to the decades-long declines and local extinctions of native fish populations in Grand Canyon. For example, water storage in Lake Powell has substantially reduced summer water temperatures (Vernieu and others, 2005), which restricts native fish spawning and early rearing to tributaries or segments of the river that are far downstream from the dam (Gloss and Coggins, 2005). Humpback chub (*Gila cypha*), one of four native fish present in Grand Canyon and federally listed as endangered, now spawn almost exclusively in the Little Colorado River (fig. 1; Gorman and Stone, 1999). In addition, four other species of native Colorado River fish are no longer present in Grand Canyon (Gloss and Coggins, 2005). In contrast, cold water temperatures create ideal spawning and rearing conditions for nonnative rainbow trout (*Oncorhynchus mykiss*) in the tailwater below Glen Canyon Dam (Korman, 2009), and this reach of the river is managed as a sport fishery. Monitoring, research, and ecosystem modeling are beginning to identify some of the complex, indirect pathways linking dam operations to native fish populations that are mediated by (linked to) changes in the distribution and abundance of rainbow trout.

Rainbow Trout

High-flow experiments conducted in the spring (1996 and 2008) have been associated with strong increases in rainbow trout populations in the Lees Ferry tailwater reach and downriver sections of the Colorado River in Grand Canyon (Makinster and others, 2010). The effect of the March 2008 HFE was particularly strong, resulting in the largest cohort, or fish born in the same year, of new rainbow trout on record (monitoring began in 1991; Makinster and others, 2010, Korman and Melis, 2011; Korman and others, in press). High-flow experiments apparently increase hatch rates for rainbow trout eggs because of improvements in spawning habitats (Korman and others, 2010; Korman and Melis, 2011; Korman and others, in press). Increases in growth and survival of young trout were also observed in 2008 (Korman and others, 2010; Korman and others, in press), likely due to improvements in available food (Rosi-Marshall and others, 2010; Cross and others, in press).

The response of rainbow trout to the one fall-timed HFE that was conducted in 2004 is poorly understood. The November 2004 HFE did not benefit rainbow trout populations, but several factors limit the ability to understand *why* this occurred. Rainbow trout populations started declining in 2001/2002 and continued to decline until 2007 for reasons that are unknown (Makinster and others, 2010). Thus, the November 2004 HFE occurred in the midst of a population decline that had started 2 years before. In addition, two studies that identified key indirect pathways linking major changes in adult rainbow trout to the 2008 HFE (detailed studies of rainbow trout eggs and juveniles, and food-web studies) were not conducted during 2004/2005.

Humpback Chub

High-flow experiments have had no measurable positive effects on humpback chub populations (Coggins and Walters, 2009; chapter 4, this volume). The majority of humpback chub early juvenile rearing occurs in the Little Colorado River (Gorman and Stone, 1999), but the quality of main-stem rearing habitats is probably also important because large numbers of juvenile humpback chub are regularly captured in the vicinity of the Little Colorado River confluence (Valdez and Ryel, 1995; Gloss and Coggins, 2005). High-flow experiments were thought to benefit humpback chub through the creation of backwaters, a potentially high-quality rearing habitat formed in the lee of an eddy reattachment sandbar (see chapters 2–3, this volume). Daily fluctuations in discharge due to changing demand for hydroelectricity, however, lead to frequent flushing and turnover of water in backwaters (Behn and others, 2010), which likely limits the quality of backwaters as rearing habitats (Grand and others, 2006; Behn and others, 2010). These same fluctuations in discharge also lead to rapid reductions in the area and volume of this habitat type (Grams, Hazel, and others, 2010; Grams, Schmidt, and Andersen, 2010). High-flow experiments do not lead to substantial improvements in available food at downriver locations (Shannon and others, 2001; Rosi-Marshall and others, 2010). Because humpback chub spawning occurs predominantly in the Little Colorado River, HFEs also do not improve the quality of their spawning habitat. Collectively, these studies indicate that potential benefits of HFEs on the quality of rearing habitats used by humpback chub are weak and short lived.

Although the exact mechanisms underlying trends in adult humpback chub abundance remain unclear, the weight of evidence indicates that rainbow trout are playing an important role; when rainbow trout populations are large, humpback chub populations generally decline, probably due to a combination of increased competition and predation (fig. 3; Coggins, 2008; Coggins and Walters, 2009; Coggins and Yard, 2010; Coggins and others, in press; Yard and others, in press). Downriver migration of the large 2008 rainbow trout cohort spawned in the Lees Ferry tailwater reach, together with local recruitment along downriver sections, has contributed to an approximately

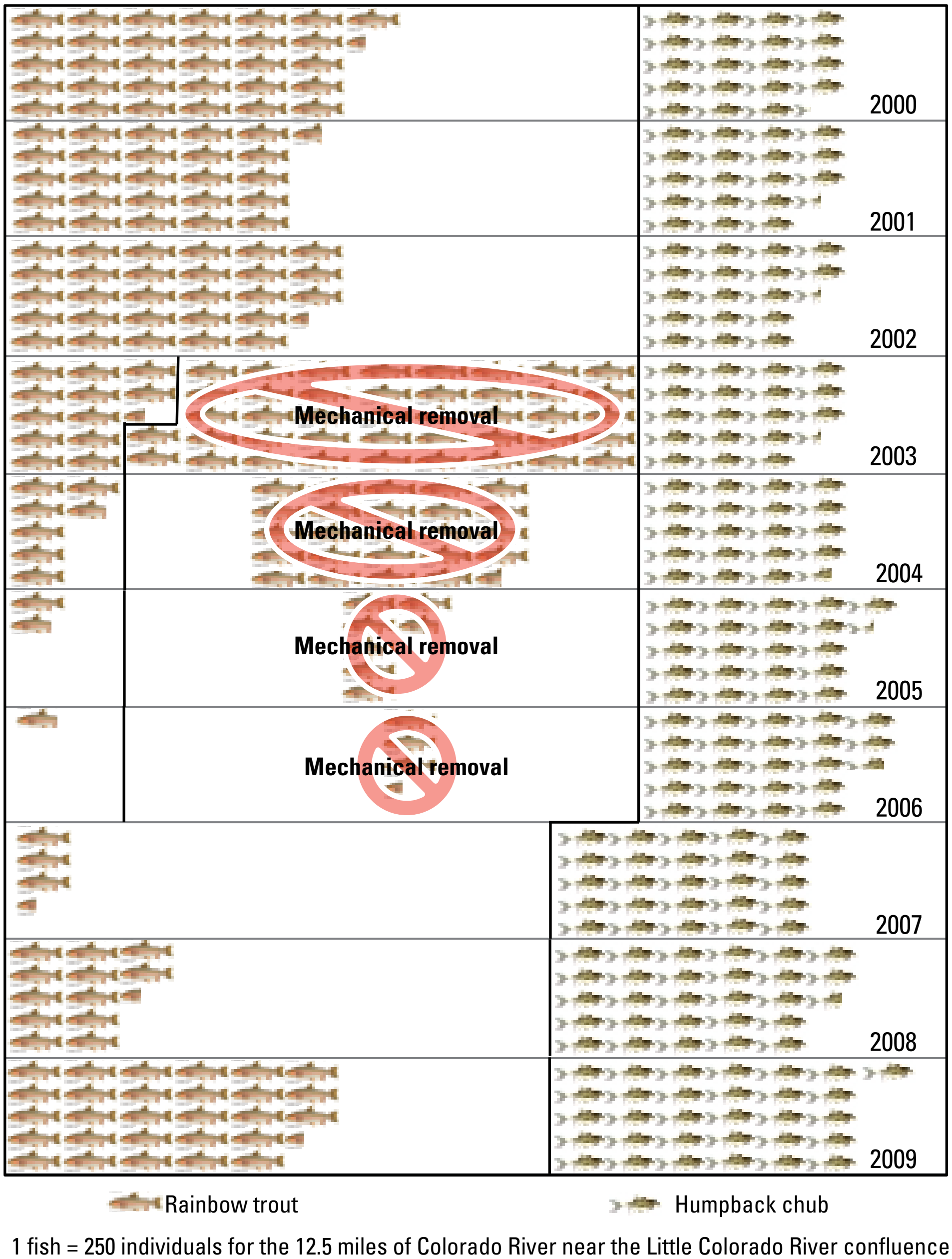


Figure 3. Changes in the abundance of rainbow trout and adult humpback chub in the Colorado River near the confluence with the Little Colorado River and the number of rainbow trout mechanically removed from this reach during 2003–06. The March 2008 HFE created favorable spawning and rearing conditions for rainbow trout in the Glen Canyon Dam tailwater, which resulted in the largest cohort of rainbow trout on record (monitoring began in 1991), which contributed to the 800-percent increase in rainbow trout densities observed near the Little Colorado River since 2007. Rainbow trout densities in 2006 were the lowest on record, in part because of mechanical removal of rainbow trout that occurred from 2003 to 2006. Density estimates for rainbow trout are from Makinster and others (2010), number of rainbow trout removed is from Coggins (2008), and adult humpback chub abundance estimates are from Coggins and Walters (2009). Note: It is possible for the number of rainbow trout removed in any given year (for example, 2003) to exceed the estimated abundance of rainbow trout in that same year because of immigration of new individuals into the reach between the first removal trip of the year (January) and the last (September).

800-percent increase in rainbow trout densities in the vicinity of the Little Colorado River since 2007 (fig. 3; Makinster and others, 2010). This increase is of concern because the Little Colorado River population of humpback chub is the largest anywhere in the Colorado River Basin (Gloss and Coggins, 2005). In fact, over 20,000 rainbow trout were removed from this section of the river from 2003 to 2006 to reduce the threats that competition and predation pose to the persistence of humpback chub populations (Coggins, 2008; Coggins and others, in press). It is too early to draw any definitive conclusions regarding the effect of the 2008 HFE on humpback chub adult recruitment because it takes chub at least 4 years to recruit into the adult population (Kaeding and Zimmerman, 1983; Coggins and Walters, 2009). Nevertheless, it seems reasonable to anticipate the 2008 HFE may ultimately have a measureable negative effect on populations of adult humpback chub because of the substantial increase in rainbow trout populations that resulted from the HFE. The rainbow trout population increase is strong and persistent and represents a substan-

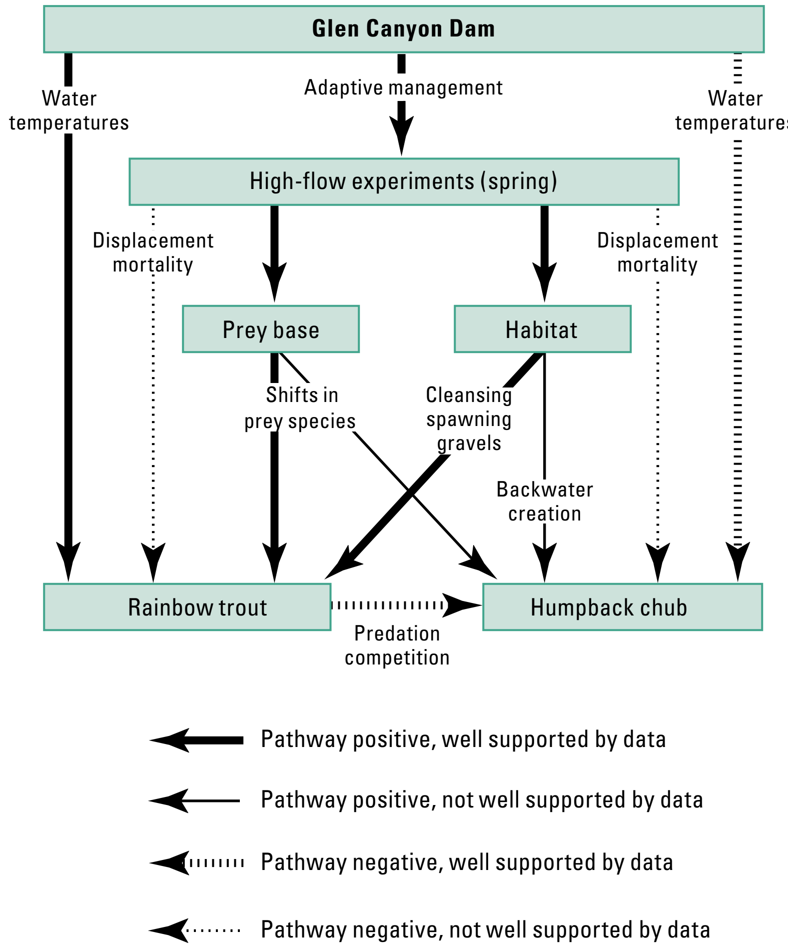


Figure 4. Path diagram depicting some of the influences that Glen Canyon Dam and its operations have on rainbow trout and humpback chub populations. Line width denotes the scientific evidence for a given interaction; thick lines indicate effects that are well supported by data whereas thin lines are not well supported by data. Positive effects are shown as solid lines and negative effects are shown as dashed lines. Glen Canyon Dam operations have a strong and direct negative effect on humpback chub due to its effect on water release temperature. In contrast, this same alteration of water temperature has a strong and positive effect on rainbow trout populations. Spring HFEs appear to have strong positive effects on rainbow trout due to improvements in spawning gravels and the prey base. Spring HFEs may have positive effects on humpback chub due to increases in backwater habitat or improvements in the prey base, but these effects are not well supported by data. Likewise, spring HFEs may have a negative impact on humpback chub due to downstream displacement and mortality of juveniles, but this is not well supported by data either. The weight of evidence indicates humpback chub populations are linked to rainbow trout populations; when rainbow trout populations are large, humpback chub populations generally decline, probably due to a combination of increased competition and predation. Note that many other potential interactions that are weak or not supported by data are left out of this schematic. Studying strong pathways connecting HFEs to populations of rainbow trout and humpback chub is a logical focus for future research and monitoring efforts.

tial decrease in the quality of the rearing environment for humpback chub, while the potential beneficial effects of HFEs on the rearing environment appear weak and short lived (fig. 4).

Three definitive conclusions that have important implications for the design of future sediment-management strategies can be drawn from these studies:

- HFEs conducted in the spring benefit rainbow trout populations as a result of improvements in spawning and rearing habitat
- HFEs have had no measurable positive effects on humpback chub populations
- Large increases in rainbow trout populations near the Little Colorado River that occurred after the 2008 HFE are inconsistent with both the GCDAMP goals for humpback chub and rainbow trout, as well as native fish management objectives of Grand Canyon National Park

Other Resources

The GCDAMP has established goals for several other Colorado River resources, including recreation (for example, rafting and fishing), riparian vegetation and spring ecosystems, cultural properties (for example, archaeological sites), the Kanab ambersnail (*Oxyloma haydeni kanabensis*), and water quality (for example, salinity). These other resources were not considered in the development of this HFE strategy because there are few definitive studies to guide HFE planning on the basis of these other resources. There are, however, direct or indirect pathways connecting dam operations to virtually every resource of the river. Thus, resources and pathways that appear linked to HFEs could continue to be studied so that information on these resources may help inform adaptive management. Additional monitoring and research data are necessary, however, before a meaningful analysis of the complex tradeoffs between sandbars, fish, recreation, archaeological sites, and other resources can be conducted.

Synthesis

High-flow experiments are an important tool for rebuilding sandbars. The three previous HFEs have demonstrated the effectiveness of individual HFEs for rebuilding sandbars, particularly when they occur after sand has been stored on the channel bed downstream from the dam. A logical next step in the adaptive-management process of the GCDAMP is to evaluate the cumulative effects of multiple HFEs over longer periods of time. Although many sandbars at high elevation were larger in October 2008 than in February 1996 (before the first HFE), an equal number of sites in Marble and eastern Grand Canyon were smaller. This finding reflects the uncertainty as to whether sandbar building during HFEs can offset or exceed the sandbar erosion that occurs during periods of typical dam operations between HFEs. Thus, it is important to consider the frequency of HFEs and the erosion of sandbars between HFEs for future HFE planning. The fundamental sandbar-related science question therefore is:

> **Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years?**

On the basis of studies that have been conducted to date, HFEs do not appear to be a tool that can be used to benefit humpback chub. Rainbow trout pose a threat to juvenile humpback chub rearing in the main stem near the confluence with the Little Colorado River because of increased competition and predation. Beneficial effects of the March 2008 HFE on rainbow trout populations appear to be largely responsible for the 800-percent increase in rainbow trout observed near the confluence between 2007 and 2009. A large increase in rainbow trout near the confluence with the Little Colorado River also occurred in the year following the 1996 HFE. The November 2004 HFE did not benefit rainbow trout populations, but a preexisting downward trend in rainbow trout populations and the absence of data make this finding highly uncertain. Thus, natural-resource managers might consider proceeding with caution when implementing any HFE strategies, particularly those involving frequent spring-time events, because currently the biological response to HFEs appears to be inconsistent with management goals for humpback chub. A logical next step in the HFE process is evaluating whether the seasonal timing of HFEs affects the rainbow trout recruitment response. If fall-timed HFEs do not lead to increases in rainbow trout populations near the confluence with the Little Colorado River (or it is later demonstrated that rainbow trout do not exert strong influence on humpback chub rearing), then managers might be able to balance goals for sandbars and native fish without the need for substantial rainbow trout mitigation or removal. The fundamental fish-related science question therefore is:

> **Does the seasonal timing of HFEs influence the rainbow trout response?**

An adaptive-management process for HFE decisionmaking would be flexible and incorporate relevant scientific information, such as near real-time information about sediment conditions downstream from the dam and information on adult population trends for rainbow trout and humpback chub, as well as other resources. Indeed, as more HFEs are conducted, strong links connecting other resources to dam operations may be identified and incorporated into subsequent HFE strategies. An integrated science-based strategy would allow for effective management of the available post-dam sand supply while considering the effects of the strategy on other resources within an adaptive-management framework. The objective of this chapter is to outline such a science-based strategy for future HFEs at Glen Canyon Dam.

Sand Accounting and High-Flow Experiments

A useful analogy for sand storage in the Colorado River downstream from Glen Canyon Dam is a checking account. Deposits to the account come from natural tributary flooding that brings sand into the main stem, increasing sand storage and the account balance. Withdrawals occur continuously during typical dam operations (that is, export of sand downstream to Lake Mead), and the rate of the withdrawals depends on the volumes of water released from the dam and the pattern of the releases. Even though HFEs help build sandbars, they also cause a withdrawal because the higher flows export sand downstream. That is, there is a cost in terms of overall sand storage that must be paid in order for the process of sandbar building to occur. An important aspect of any sustainable HFE strategy is to attempt to remain budget neutral, such that the total withdrawals do not exceed deposits over the long term. A long-term sand-budget deficit would lead to persistent erosion of the remaining sand storage, thus making it progressively more difficult to rebuild sandbars. However, it may be desirable to have an initial negative sand budget for several years while the river adjusts to the effects of frequent HFEs; that is, the river may quickly evolve to have less sand in storage overall but with more sand at high elevation in sandbars. Although this may be acceptable, if the negative sand budget continues indefinitely, the strategy would not be sustainable.

The preceding analogy illustrates why HFEs cannot be considered in a vacuum. Sand-storage conditions are closely linked to sand supply from the tributaries downstream from the dam, basin hydrology, and dam operations (for example, Wright and others, 2008; Wright and Grams, 2010). Thus, all of these factors must be taken into consideration during HFE planning. The supply of sand from tributaries is highly variable with large quantities delivered during episodic natural flooding events. Sand storage in the main stem typically is greatest immediately following these natural tributary floods. The rate at which this "new" sand is exported from the river reaches of interest depends on basin hydrology as well as dam operations. Basin hydrology (for example, upper Colorado River Basin snowpack) and reservoir-storage conditions in Lake Powell and Lake Mead determine the required amount of water to be released from Glen Canyon Dam in a given year. Because sand-transport rates depend on river flow rates, more sand is exported during years with larger releases, and less sand is exported during years with smaller releases. Sand-export rates also depend on the seasonal and hourly patterns of water releases that typically are scheduled to meet hydroelectricity demand. As shown by Wright and Grams (2010), flows that fluctuate monthly and daily tend to export more sand than steady flows.

Because these various controls on sand storage are not predictable with a high degree of accuracy, it is not possible to determine far in advance whether or not a given month or year is the optimal time for an HFE. If sand-storage conditions are monitored continually, however, this information can be used in the decisionmaking process throughout the year. Numerical modeling tools could also be used within the planning process to help estimate sand-storage conditions and to design the optimal magnitude and duration of the HFE for a given event. Several tools have been developed for the reach of the Colorado River downstream from Glen Canyon Dam specifically to support future HFE planning. The most important of these is the sand-transport monitoring program that was implemented by the Grand Canyon Monitoring and Research Center in the early 2000s (Topping and others, 2010). This program provides high-resolution, near real-time measurements of sand transport in the major tributaries and at several main-stem sites. These data are currently used to estimate sand-storage conditions in the main stem and thus already provide much of the information necessary for HFE decisionmaking. Information from other monitoring and research programs, such as sandbar monitoring, can also be used to make adjustments as more is learned about how the river responds to repeated HFEs.

In addition to monitoring data, several modeling tools exist that can provide useful information for the decisionmaking process. For example, a numerical model of sand transport and storage (such as Wright and others, 2010) is currently being used to predict sand-storage conditions into the near future, both with and without an HFE. Also, because HFEs would be conducted under a variety of sand-storage conditions, numerical models could be used to design the optimal HFE magnitude and duration to achieve the desired outcome. In a year with relatively high sand storage, a "larger" HFE may be warranted compared to a year with less sand storage. Wright and Grams (2010) demonstrated how the sand-storage model can be used together with a numerical model of flow releases (Wiele and Smith, 1996) to estimate sand-storage conditions for a range of dam operations. A similar approach would be useful for supporting HFE decisionmaking in near real time, as described in the following section.

Options for High-Flow Experiment Strategies

Numerous factors are considered in the design of an HFE strategy, such as timing, magnitude, duration, and frequency. The seasonal timing of HFEs is especially relevant given our understanding of biological resource responses. A range of possible options for HFEs that vary in frequency and by season is presented in table 1. The options in table 1 generally trend top to bottom from options based solely on "sand triggers" (that is, HFEs are tied to the amount of sand stored in the river) to those that are less dependent on sand storage but more dependent on seasonal timing (for example, HFEs occur every spring, which would approximate pre-dam patterns of natural floods). Each of these options has strengths and weaknesses and large uncertainties in outcomes, particularly in relation to biological resources. For example, option 1 would allow for HFEs any time of the year when there is sufficient new sand stored in the main stem of the Colorado River, whereas option 7 specifies a fall HFE every year regardless of sand storage in the river.

Previous research indicates that HFEs that are tied to antecedent (preexisting) sand-storage conditions in the river (that is, sand-triggered HFEs) probably result in greater sandbar building and are less likely to contribute to long-term erosion of sand stored on the channel bed (chapter 3, this volume). Thus, options such as options 4, 6, and 7 (table 1) that include annual HFEs that are not linked to sand storage are unlikely to be as effective as sand-triggered HFEs at increasing and sustaining sandbar sizes. Also, because the majority of tributary-derived sand inputs occur in the summer and fall (fig. 5), sand-triggered fall HFEs are most likely to result in sustainable increases in sandbar sizes. Fall timing is considered in options 1, 2, and 3, but not in option 5, which only includes sand-triggered spring HFEs. Sand-triggered HFEs that occur only in the spring would be less likely than sand-triggered fall HFEs to result in sustainable increases in sandbar sizes. However, spring HFEs have been shown to increase (1) campsite area preceding the peak river recreation season (Hazel and others, 2010), (2) eolian sand transport prior to the windy season (Draut and others, 2010), and (3) rainbow trout population in the Lees Ferry reach. Also, because occasional large tributary sand inputs do occur in the winter and spring, spring HFEs are a potentially useful tool for sandbar building. Thus, because both fall and spring HFEs have potential

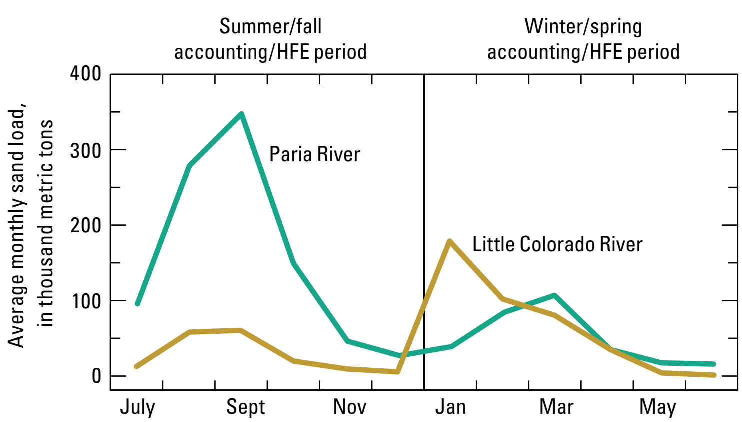


Figure 5. A year with two sand-budget accounting periods and two HFE windows (fall and spring). Vertical axis shows the average monthly sand loads from the major tributaries. The presence of two main periods of tributary activity supports the concept of two accounting/HFE periods per year.

positive and negative resource responses, an adaptive strategy that includes options for sand-triggered fall and spring HFEs is most likely to result in sustainable increases in sandbar sizes and contribute information about other resource responses. In addition, this strategy is consistent with pre-dam flow data, which indicate that natural floods comparable in magnitude to previous HFEs occurred in both the fall and spring (fig. 6).

From a purely sediment perspective, the scientific evidence suggests that a strategy based on sand-triggered HFEs that combines options 1 and 2 (table 1) would be a logical starting point for future experimentation, as described in more detail below. Option 1 would allow for sand-triggered HFEs any time of the year, depending on tributary sand inputs, with the possibility of multiple HFEs occurring in a given year. Option 2 is similar in that HFEs would also be sand triggered, the difference being that HFEs would only occur at certain times of the year (fall and spring, with the potential for two HFEs in a given year). Without additional research, it is difficult to determine which of these approaches would be most effective for long-term, sustainable sandbar building. Option 1 is the most proactive for managing new tributary-derived sand inputs but would likely lead to more frequent, smaller HFEs because sand inputs would not be allowed to accumulate. Option 2 is less proactive but allows for potential accumulation of multiple tributary-derived sand inputs and, thus, HFEs with larger peaks and longer durations. The most effective strategy for the purpose of sandbar building likely would be a combination of these approaches. Option 1 may be more effective during years when release volumes are high because the residence time of new sand in the river would be shorter, justifying the need to act quickly to manage the resource. During years of lower release volumes, it may be beneficial to allow for sand accumulation during the tributary input season with an HFE occurring following multiple inputs. This hybrid approach is outlined in more detail below through specific questions about HFE timing, triggering, peak and duration, and frequency.

Table 1. Various options for high-flow experiments (HFEs). The options in this table generally trend from top to bottom, from options based solely on "tributary sand-input triggers" (HFEs are tied to the amount of sand stored in the river) to those that are less dependent on sand storage but more dependent on seasonal timing.

Option number	HFE timing and frequency	HFE magnitude and duration
1	Immediately following sand inputs, if sand storage in the river reaches the trigger level	Based on sand storage conditions in the river before the HFE
2	Fall and spring, if sand storage in the river reaches the trigger level	Based on sand storage conditions in the river before the HFE
3	Fall, if sand storage in the river reaches the trigger level	Based on sand storage conditions in the river before the HFE
4	Every spring; fall, if sand storage in the river reaches the trigger level	Spring HFEs unknown because not based on sand storage conditions in the river before the HFE; fall HFEs based on sand storage conditions
5	Spring, if sand storage in the river reaches the trigger level	Based on sand storage conditions in the river before the HFE
6	Every spring	Unknown because not based on sand storage conditions in the river before the HFE
7	Every fall	Unknown because not based on sand storage conditions in the river before the HFE

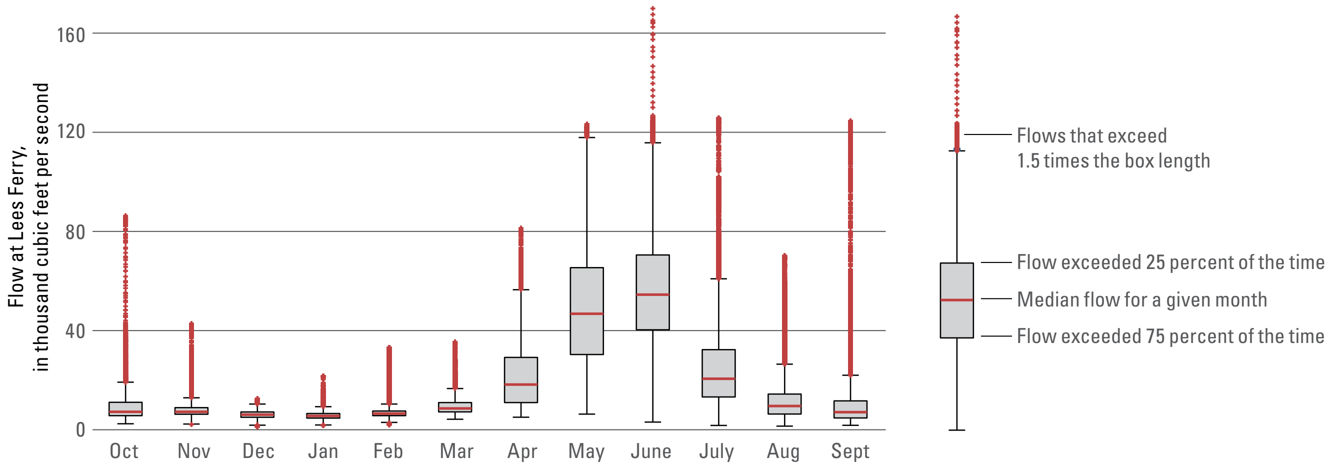


Figure 6. The pre-dam flow regime on the Colorado River at Lees Ferry (data from Topping and others, 2003). The plot shows box-and-whisker diagrams for each month of all instantaneous flow measurements from the beginning of the record (1921) to the beginning of flow regulation by Glen Canyon Dam (1963). The plot illustrates the strong snowmelt signal from April to July as well as the higher flows in the late summer and early fall.

An HFE strategy that combines options 1 and 2 would also assist scientists in better understanding the effects of HFEs on biological resources, such as humpback chub and rainbow trout. For example, HFEs conducted thus far (through 2008) do not appear to have benefited humpback chub populations likely because the HFEs benefited nonnative rainbow trout that compete with humpback chub. Because mechanical removal of rainbow trout is costly (costs have averaged $150,000 per removal trip (Runge and others, 2011)), it would be useful to determine whether seasonal timing of HFEs affects rainbow trout response. If rainbow trout response can be minimized, for example by conducting HFEs at a time of year other than in the spring, this would greatly reduce the cost of rainbow trout mitigation efforts. A strategy that combines options 1 and 2 would allow scientists to study rainbow trout population response to HFEs conducted in the fall, which currently is not well known.

Strategy Based on Sand-Triggered High-Flow Experiments

A strategy for HFEs that is based on sand triggers would consider the amount of sand storage in the river prior to HFEs, and HFEs would only be scheduled once sand storage reached a threshold (the “trigger level”). The design (magnitude and duration) of the HFE would be based on the sand-storage conditions in the river prior to the HFE.

What time of year would high-flow experiments occur?

An HFE strategy that combines options 1 and 2 (table 1) would result in HFEs that could occur essentially any time of year or only at the end of the fall or spring sand-accumulation periods. Such a strategy would be consistent with previous HFEs that occurred during both fall (November 2004) and spring (March 1996 and 2008). The fall and spring are logical “windows” for HFEs on the basis of the seasonal pattern of sand supply from the tributaries (fig. 5). Natural tributary flooding typically is greatest in the late summer and early fall, and thus the summer/fall accounting/HFE period (July–December) is most advantageous for managing the sand that enters the main stem. The specific timing of HFEs within this period would need to be evaluated on a year-to-year basis with incorporation of new information as it becomes available. For example, if flow releases from the dam under standard operating procedures are expected to be low through the fall, it likely would be most advantageous to wait until the end of the accounting/HFE period (fig. 5) to allow for the accumulation of tributary-derived sand inputs. However, if flow releases are expected to be high, it may be more advantageous to conduct HFEs immediately following, or even during, tributary input events (Lucchitta and Leopold, 1999). Use of a numerical model to predict possible outcomes prior to an HFE would be valuable for evaluating these scenarios.

Natural tributary flooding can also occur during the winter and spring (fig. 5), and thus a winter/spring accounting period (January–June) is also justified. The strategy would be identical for this period as for the summer/fall period. The same general guidelines for dry as opposed to wet periods would apply, with HFEs likely being more effective at the end of the period during low-flow conditions. A more proactive approach, however, may be justified during wet conditions because of the short residence time of new tributary sand under high-flow conditions (for example, figure 4B in Rubin and others, 2002).

How would high-flow experiments be "triggered"?

All HFEs would be triggered on the basis of tributary sand inputs and resultant sand storage along the main-stem Colorado River. During the accounting periods (fig. 5), HFEs would be triggered and designed on the basis of recent tributary-derived sand inputs and sand storage. For example, if summer and fall tributary sand inputs were small, then a fall HFE would not be conducted. High-flow experiments would only be conducted when enough new sand supply could be documented such that a short-duration powerplant-capacity release (about 31,000 cubic feet per second (ft^3/s)) could be conducted without exporting more sand from Marble Canyon (fig. 1) than had accumulated during the preceding accounting period (that is, a net positive sand budget would be maintained for Marble Canyon). Thus, the two accounting periods would be treated separately for HFE-triggering purposes. By requiring maintenance of a net positive sand budget for each accounting period, HFEs would be conducted with the goal of avoiding erosion of sand stored on the channel bed prior to the accounting period. The magnitude and duration of the HFEs would be designed on the basis of the sand-storage conditions in each accounting period, as described in the next section. Existing near real-time monitoring data and numerical modeling tools could be used to evaluate the effect of HFEs on the sand budget for a range of potential magnitudes and durations.

What high-flow experiment magnitude and duration would be used?

The magnitude and duration of HFEs would be designed on the basis of sand storage in the river. In years with large tributary sand inputs and low-volume water releases, sand storage is likely to be greatest and would allow for HFEs with higher peaks and longer durations. Longer-duration HFEs with larger sand supply should result in increased sandbar building. In other years, when sand is stored in the river but the amounts are not as large, an HFE with a lower peak and shorter duration would be appropriate. The overarching goal would be to maximize sand transport during higher magnitude HFEs for the purpose of sandbar building, without exporting more sand than is available in order to avoid erosion of the sand stored on the channel bed at the end of the previous accounting period. As with the trigger evaluations, near real-time data and numerical models could be used to support the decisionmaking process in designing any long-term experiment of repeated HFEs intended to optimize sandbar rebuilding and maintenance.

Because the magnitude and duration of the HFE would be tied to sand-storage conditions in the main-stem river, it is not possible to specify HFE details far in advance. Also, additional experimentation is necessary to determine the most effective magnitudes and durations of HFEs for building sandbars. Previous HFEs had peak flows of 42,000–45,000 ft^3/s and durations of 7 days (1996) and 2.5 days (2004 and 2008). To facilitate the proposed adaptive strategy for future HFEs, it would be desirable to experiment with a broader range of peak flows and durations. In the past, several powerplant-capacity (about 31,000 ft^3/s) flows have also been released from the dam. Although it is known that these flows are not nearly as effective at building sandbars as the larger HFEs (chapter 3, this volume), further experimentation would be required to evaluate their effectiveness in a long-term, multiple HFE strategy. The strategy outlined in this chapter would allow for short-duration powerplant-capacity releases, at least initially, when sand-storage conditions in the river do not support larger peaks and longer durations. The maximum peak and duration would depend on sand-storage and water-supply conditions. Testing of peak flows greater than 45,000 ft^3/s is scientifically justified, but is constrained by current low reservoir levels such that the spillways at Glen Canyon Dam are inaccessible. Higher peak flows could be considered in the future if reservoir levels permit. As outlined in the section *How would high-flow experiments be "triggered"?*, the maximum duration would be constrained so as not to export more sand from Marble Canyon than is available. On the basis of the sand-transport data from the 2004 and 2008 HFEs (Topping and others, 2010), most HFEs would warrant durations of only a few days or less.

How frequently would high-flow experiments occur?

The frequency at which future HFEs would occur is difficult to estimate because it would be based on future tributary sand supply, hydrologic conditions in the basin, and dam operations; there is uncertainty and unpredictability regarding all of these conditions. A rough estimate of frequency, however, can be derived from historical data. Such an estimate requires information about tributary-derived sand inputs and sand-export rates downstream to Lake Mead (fig. 1) during and between HFEs. Long-term records of Paria River sand inputs (1925–2008, see Topping and others (2010) and Topping (1997) for methods) suggest an average sand supply during the summer/fall accounting period (July–December) of about 900,000 metric tons with about 300,000 metric tons on average during the winter/spring (January–June) accounting period. Both periods experience substantial variability in tributary sand inputs from year to year. The rate of sand export downstream to Lake Mead is also highly variable depending on hydrologic conditions in the basin and dam operations. During the period 2002–09, for which sand-transport monitoring data are available, the average sand-export rate from Marble Canyon (fig. 1) was about 250,000–300,000 metric tons for each accounting period. Thus, if 2002–09 can be considered representative of future conditions (an uncertain and likely incorrect assumption because flow releases were relatively low during this period, but nonetheless useful for illustrative purposes here), the summer/fall accounting period would be expected to have substantial sand accumulation (inputs of about 900,000 and export of about 300,000 metric tons), whereas the winter/spring accounting/HFE period would not (inputs and export both about 300,000 metric tons). The smallest HFE that would be conducted, a powerplant-capacity release, would likely export 200,000 metric tons of sand or less (depending on HFE duration) on the basis of the releases in May and September 2000, which exported about 340,000 and 220,000 metric tons, respectively, from Marble Canyon (Schmidt and others, 2007). These releases had peak durations of about 3 days (Schmidt and others, 2007); thus, the total export could be reduced substantially by reducing the duration of the release. These approximate numbers suggest that fall HFEs would be triggered frequently, nearly every year, on the basis of historical averages of sand accumulation, but that spring HFEs would be triggered much less frequently, for example, only in years when winter/spring tributary-derived sand inputs are well above average. However, these historical average conditions do not tell the whole story because of the variability in tributary inputs. This variability would almost certainly result in multiyear periods when HFEs would not be justified on the basis of sand-trigger considerations, as well as multiyear periods when one or two HFEs per year would be justified. The actual frequency of HFEs would vary with future tributary sand supply, future hydrologic conditions in the basin, and future dam operations.

Little Colorado River Contingencies

The HFE-trigger strategy described above is based on sand storage in Marble Canyon, which primarily depends on sand supplied by the Paria River (fig. 1). This approach would be scientifically justified because Marble Canyon is the reach most at risk of progressive erosion because it is closest to the dam and thus has the smallest post-dam sand supply (not including Glen Canyon, see discussion in chapter 3, this volume). However, it would be desirable to have contingencies built into the strategy by also considering the Little Colorado River (fig. 1), which joins the main stem at the lower end of Marble Canyon, because it is the other major sand-supplying tributary downstream from the dam. In many instances, natural flooding on the Little Colorado River occurs simultaneously with natural flooding on the Paria River. In cases where the Marble Canyon trigger is close to being met, it may be useful to consider recent Little Colorado River sand inputs in the decisionmaking process. Also, if an extremely large natural flood were to occur on the Little Colorado River, for which there is historical precedent (the area drained by the Little Colorado River is about 18 times larger than that of the Paria River), the effects of such a natural flood should be taken into consideration. Under this scenario, it may be possible to time an HFE release to coincide with natural flooding on the Little Colorado River as a means of producing a higher HFE peak downstream from the confluence (Lucchitta and Leopold, 1999). In order to take advantage of such a situation, it may be deemed acceptable to conduct an HFE that results in a slightly negative sand budget for Marble Canyon.

Decision Flow Chart

An example flow chart of the decisionmaking and implementation process for the strategy described above is shown in figure 7. The chart illustrates the flow of information through time for 1 year. Phase numbers are shown in the squares in figure 7.

Phase 1 — Summer/fall accounting period

Beginning on July 1 each year, currently available sand-transport monitoring data would be used to track tributary-derived sand inputs to, and sand-storage conditions in, Marble Canyon.

Phase 2 — Summer/fall HFE deliberations

Once tributary-derived sand inputs occur, deliberations could begin to determine if and when to conduct a fall HFE. These deliberations would include evaluating water forecasts (that is, what are the flow releases from the dam expected to be in the near future) and conducting numerical modeling simulations. On the basis of these analyses, a decision would be made regarding the most appropriate HFE timing for the current year. If tributary-derived sand inputs are small throughout the accounting period, no HFE would be conducted.

Phase 3 — Summer/fall HFE implementation

If the decision is made to conduct an HFE, this phase would consist of further refining the magnitude and duration of the HFE and conducting scientific studies in association with the HFE.

Phase 4 — Winter/spring accounting period

As during the summer/fall accounting period, sand-transport monitoring data would be used to track the sand-storage conditions in Marble Canyon. If a fall HFE occurred, the sand budget would be reset to zero. If no fall HFE occurred, then the sand-budget information from the summer/fall accounting period would be carried forward to the winter/spring accounting/HFE period.

Phase 5 — Winter/spring HFE deliberations

The decisionmaking process in this phase would be identical to that of phase 2; that is, water forecasts and numerical model simulations would be used to evaluate the most appropriate HFE timing, if tributary-derived sand inputs are large enough to support a spring HFE.

Phase 6 — Winter/spring HFE implementation

This phase would be identical to phase 3.

Annual Status Check and Strategy Revision

As described above, an integrated and science-based adaptive strategy would allow for effective evaluation of flow options for managing the available post-dam sand supply while considering the effects of the strategy on biological, physical, and cultural resources within an adaptive-management framework. This adaptive approach is incorporated in the flow chart (fig. 7) through an annual status check of river resources and a subsequent step that allows for revisions of the strategy. The annual status check would consist of reviewing available monitoring data and scientific interpretations. If any resource trends are deemed to be unacceptable by natural-resource managers (for example, rainbow trout response), other HFE implementation options could be considered (some examples are presented in table 1), and (or) mitigation strategies could be devised (for example, removal of nonnative trout). Such an approach also allows for new information to be incorporated into the strategy, even if resource trends are considered acceptable.

Adaptive Management, Monitoring, and Research

Because there is substantial uncertainty about the outcome that may result from implementation of the outlined HFE strategy, other reasonable options are available (table 1). In particular, the biological responses to HFEs conducted in the fall, and to a lesser extent those conducted in the spring, are difficult to predict. Thus, modification of the strategy may be required on the basis of knowledge gained from biological responses to future HFEs. High-flow experiments appear to be a critical tool for managing the post-dam sand supply to rebuild and maintain sandbars, so if a strong rainbow trout response occurs following HFEs in the fall, it may be necessary to explore whether dam operations between HFEs could be changed as a means of mitigating rainbow trout response to

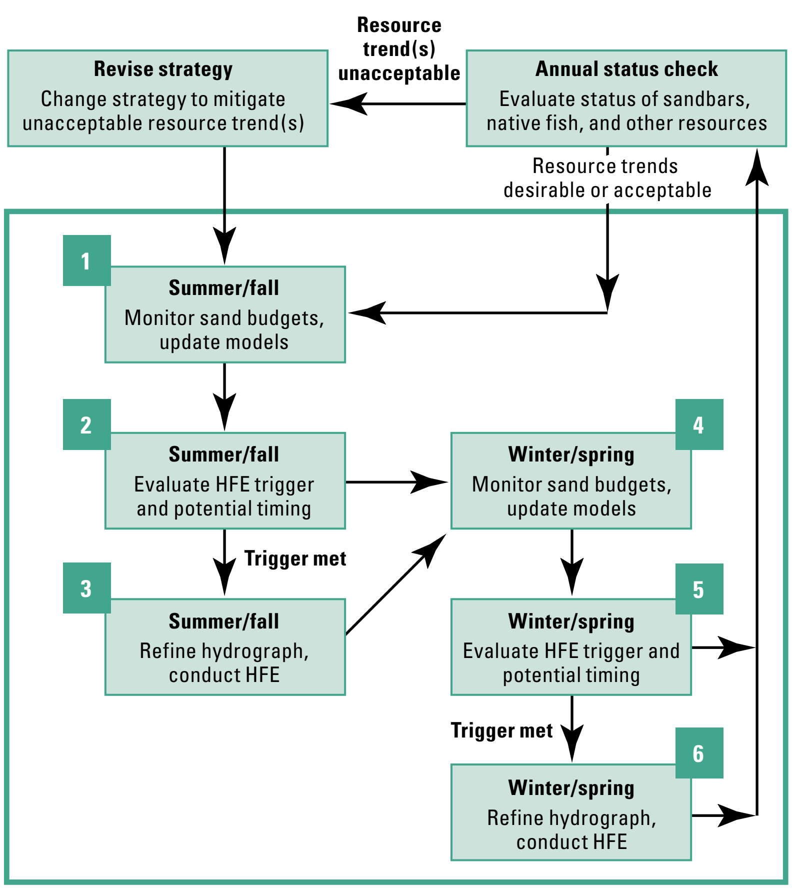


Figure 7. The decisionmaking process for a science-based experimental strategy for tributary sand-input-triggered HFEs with two sand-budget accounting periods and two HFE windows per year. Each box and decision point is described in detail in the text.

HFEs. Modification of the strategy in response to sandbar-monitoring results may also be required, and a different HFE strategy may be justified during wet and dry climatic periods. Also, if sandbars erode too quickly after HFEs are released, it may be necessary to explore whether altering dam operations in between HFEs (for example, Wright and others, 2008; Hazel and others, 2010; Wright and Grams, 2010) or augmenting the post-dam sand supply (Randle and others, 2007), or both, would allow natural-resource managers to meet goals for sand-based river resources. Because of these uncertainties, the annual "status check" would be a critical component of an adaptive HFE strategy. This status check could include reviewing recent monitoring data for sand budgets, sandbar size, and native and nonnative fish population trends. On the basis of the findings of these reviews, the HFE strategy could be adapted, if necessary, to incorporate new knowledge and learning. Adaptive management could only be achieved, however, by integrating a robust monitoring and research program into a science-based strategy.

Robust monitoring and research projects supported by the GCDAMP have allowed scientists to develop a clear understanding of the pathways linking previous HFEs to the key river resources of sandbars and rainbow trout populations. Implementation of an HFE strategy on the basis of sand-input triggers requires continued monitoring of tributary-derived sand inputs to, and sand transport in, the main stem, so that sand budgets can be computed for the evaluation of triggers. Sandbar and sand-storage monitoring are also required to evaluate the cumulative long-term influence of HFEs and dam operations between HFEs in support of adaptive management. Other more process-based studies may also be warranted, for example daily surveys of sandbars during HFEs to improve numerical modeling tools, such as eddy-sandbar simulations.

Continued monitoring of humpback chub, rainbow trout, and other fish populations is critical to understanding how these important resources are affected by repeated HFEs. Process-based studies focused on evaluating whether rainbow trout response is affected by HFE timing would be a logical focus for future biological research (see figure 3). Food-base response might be strongly affected by HFE timing because of seasonal differences in recovery times of organisms, whereas cleansing of gravels by flushing of fine sediments may benefit survival of rainbow trout eggs and fry, even if HFE cleansing of spawning gravels occurs in fall, months prior to initiation of spawning (Topping and others, 2010; Melis and others, in press). Research on the ecology of nearshore habitats near the Little Colorado River is critical for better understanding the complex interactions between flow regimes and habitat use by humpback chub and rainbow trout and other nonnative fish in Marble and Grand Canyons.

The links between HFEs and cultural resources warrant further study. More information is needed to evaluate the tradeoffs between, for example, potential lost revenue from guided fishing as opposed to improved experience due to increased trout populations. Future HFE strategies could include studies of recreation economics. Eolian-transport studies were started in 2001 and documented only weak benefits of the November 2004 HFE on transport rates relative to the March 2008 HFE. The weak response following the November 2004 HFE, however, was at least in part driven by the larger experimental fluctuating flows evaluated for rainbow trout suppression during January through March 2005 (Korman and Melis, 2011), which quickly eroded the sandbars that provide a source of windblown sand during the spring. Thus, continued eolian-transport monitoring would be useful, particularly following fall HFEs without the large experimental fluctuations that occurred during the winter of 2005 (with more typical dam operations following the fall HFE).

Importance of Dam Operations Between High-Flow Experiments

In this chapter a possible strategy for future HFEs at Glen Canyon Dam that incorporates the findings of previous scientific research has been outlined. Where appropriate, it has been noted that the ecosystem response to HFEs is strongly dependent on the "intervening dam operations," that is, the flow releases that occur between the HFEs. For sandbars, the intervening dam operations are important because they determine the rate of post-HFE sandbar erosion, the rate of export of sand from the system following tributary-derived sand inputs, and thus the amount of sand available for building sandbars during a given HFE. This link led Wright and others (2008) to conclude that the optimal intervening dam operation for rebuilding and maintaining sandbars is year-round steady flows, which would export the least amount of sand compared to other potential dam operations (see also Wright and Grams, 2010). Thus, if implementation of the strategy outlined in this chapter led the GCDAMP to conclude that the goal for sandbars was not being achieved, the next step in the adaptive-management process logically would be to reduce daily and seasonal flow fluctuations—that is, to move to a steadier flow regime.

The changes, however, in intervening dam operations that occurred in the early 1990s, which substantially reduced the daily-flow fluctuations that are caused by varying demand for hydroelectricity, allowed rainbow trout populations in the Lees Ferry tailwater reach to become self sustaining and self recruiting (Pine and others, 2009). Therefore, it is reasonable to assume that further stabilizing flows to conserve sand would lead to further increases in rainbow trout juvenile growth and survival. The national importance of the Grand Canyon humpback chub population (it is the largest anywhere), combined with the current information about rainbow trout and humpback chub dynamics, suggests a move toward increasing the number of rainbow trout would be unacceptable to natural-resource managers and inconsistent with GCDAMP and National Park Service goals for native fish.

Thus, it is apparent that changes in intervening dam operations must be considered carefully and in the context of an ecosystem approach. For example, as outlined above, intervening dam operations that may conserve sandbars may not benefit native fish. Also, other resources, such as recreation, riparian vegetation, and hydropower, would be affected by a change in intervening dam operations and would need to be considered. Because of these complexities, evaluation of alternative intervening dam operations was beyond the scope of this chapter. The issue was raised in this chapter to illustrate the tradeoffs that would likely need to be evaluated in order to develop any new experimental strategy for intervening dam operations, if a new strategy is deemed necessary. For example, one tradeoff that may be necessary to balance sand and native fish goals is the use of large daily fluctuations in flow, for short periods at certain times of the year following HFEs, to disadvantage rainbow trout spawning and juvenile survival (Korman and Melis, 2011). This could potentially occur from late spring through mid-summer and would likely reduce egg and juvenile survival without adversely affecting the invertebrate prey base that supports the adult fish that are a valued recreational resource. Trout-suppression flows could be stopped at the onset of the summer monsoon season in the Southwestern United States, when substantial sand inputs typically begin to occur and juvenile humpback chub begin entering the main stem because of natural flooding in the Little Colorado River. While it is known that these types of flows erode sandbars and export sand at high rates, these fluctuations may be required to mitigate the potential strong positive effect of HFEs (which are necessary for sandbar building) on the rainbow trout population. Short-term reductions in sandbar area could potentially be offset by stable and low flows at other times of the year, if such dam operations were also part of a future long-term experimental design.

Conclusions

The most effective strategy for future releases from Glen Canyon Dam is one that provides flexibility and adaptability—flexibility would allow the best scientific information to be used in decisionmaking, and adaptability would allow ongoing learning to be readily incorporated in the process. Previous HFEs have provided a wealth of information and dramatically increased our knowledge of key physical and biological processes. However, it is still not possible to write a detailed HFE prescription with a known outcome, particularly in relation to biological resource responses. Experimentation, monitoring, research, and adaptive management are the necessary tools for implementing a long-term science-based strategy for improving sandbar resources while simultaneously ensuring that trends for native fish are at least neutral.

The HFE-triggering strategy outlined in this chapter strives to achieve these goals of flexibility and adaptability. The various components of the strategy are derived from previous monitoring and research during HFEs, and the process is specifically designed to use, where appropriate, the monitoring and numerical modeling tools that have already been developed for the Colorado River downstream from Glen Canyon Dam. The strategy is designed to rebuild sandbars while eliminating or minimizing long-term progressive erosion of sand from Marble Canyon. Uncertainty in future climate and dam operations, however, dictates that this outcome is not guaranteed, and thus it is critical that long-term monitoring be conducted and evaluated within the context of HFEs. Maximizing benefits to sandbars was the primary goal of the strategy outlined here, with potential effects to biological resources being considered within the context of the sand-based strategy. The design strategy outlined allows for new data on physical, biological, and cultural resources to be incorporated into the decisionmaking process on a regular basis. Finally, implementation of HFEs in the future does not guarantee progressive sandbar building through time. However, sandbar trends without HFEs are one of the few outcomes that can be predicted with absolute certainty: without HFEs, sandbar size (above typical shorelines) will decrease through time because HFEs are the only documented tool for rebuilding sandbars (Rubin and others, 2002; Wright and others, 2005).

Acknowledgments

Many people have contributed to the information in this chapter through the countless discussions that the authors have had over the past 8 years in formal workshops and meetings, informal meetings, hallway discussions, phone calls, and evening sessions. The following list is likely not comprehensive and is in no particular order: Ted Melis, David Topping, David Rubin, Jack Schmidt, Paul Grams, Matt Kaplinski, Joe Hazel, Amy Draut, Helen Fairley, Jonathan Nelson, Steve Wiele, Barbara Ralston, Josh Korman, Colden Baxter, Wyatt Cross, Bob Hall, Emma Rosi-Marshall, Matthew Andersen, Mike Yard, Bill Persons, Rich Valdez, and Carl Walters.

References

Behn, K.E., Kennedy, T.A., and Hall, R.O., Jr., 2010, Basal resources in backwaters of the Colorado River below Glen Canyon Dam—Effects of discharge regimes and comparison with mainstem depositional environments: U.S. Geological Survey Open-File Report 2010–1075, 25 p. (Also available at *http://pubs.usgs.gov/of/2010/1075/*.)

Coggins, L.G., Jr., 2008, Active adaptive management for native fish conservation in the Grand Canyon—Implementation and evaluation: Gainesville, University of Florida, Ph.D. dissertation, 173 p.

Coggins, L.G., Jr., and Walters, C.J., 2009, Abundance trends and status of the Little Colorado River population of humpback chub—An update considering data from 1989–2008: U.S. Geological Survey Open-File Report 2009–1075, 18 p. (Also available at *http://pubs.usgs.gov/of/2009/1075/*.)

Coggins, L.G., Jr., and Yard, M.D., 2010, Mechanical removal of nonnative fish in the Colorado River within Grand Canyon, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 227–234 (Also available at *http://pubs.usgs.gov/sir/2010/5135/*.)

Coggins, L.G., Jr., Yard, M.D., and Pine, W.E., III, in press, Nonnative fish control in the Colorado River in Grand Canyon, Arizona—An effective program or serendipitous timing?: Transactions of the American Fisheries Society.

Cross, W.F., Baxter, C.V., Donner, K.C., Rosi-Marshall, E.J., Kennedy, T.A., Hall, R.O. Jr., Wellard Kelly, H.A., and Rogers, R.S., in press, Ecosystem ecology meets adaptive management—Food web response to a controlled flood on the Colorado River, Glen Canyon, USA: Ecological Applications.

Draut, A.E., Hazel, J.E., Jr., Fairley, H.C., and Brown, C.R., 2010, Aeolian reworking of sandbars from the March 2008 Glen Canyon Dam high-flow experiment in Grand Canyon, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 325–331. (Also available at *http://pubs.usgs.gov/sir/2010/5135/.*)

Draut, A.E., and Rubin, D.M., 2008, The role of eolian sediment in the preservation of archeologic sites along the Colorado River corridor in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1756, 71 p. (Also available at *http://pubs.usgs.gov/pp/1756/.*)

Gloss, S.P., and Coggins, L.G., 2005, Fishes of Grand Canyon, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 2, p. 33–56. (Also available at *http://pubs.usgs.gov/circ/1282/.*)

Gorman, O.T., and Stone, D.M., 1999, Ecology of spawning humpback chub, *Gila cypha,* in the Little Colorado River near Grand Canyon, Arizona: Environmental Biology of Fishes, v. 55, p. 115–133, accessed February 12, 2010, at *http://www.springerlink.com/content/vq675171n84786p7/fulltext.pdf*.

Grams, P.E., Hazel, J.E., Schmidt, J.C., Kaplinski, Matt, Wright, S.A., Topping, D.J., and Melis, T.S., 2010, Geomorphic response of sandbars to the March 2008 high-flow experiment on the Colorado River downstream from Glen Canyon Dam, *in* Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, 2010, June 27–July 1, 2010, Las Vegas, Nevada, Proceedings: Advisory Committee on Water Information, CD-ROM.

Grams, P.E., Schmidt, J.C., and Andersen, M.E., 2010, 2008 High-flow experiment at Glen Canyon Dam—Morphologic response of eddy-deposited sandbars and associated aquatic backwater habitats along the Colorado River in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010–1032, 73 p. (Also available at *http://pubs.usgs.gov/of/2010/1032/.*)

Grand, T.C., Railsback, S.F., Hayse, J.W., and LaGory, K.E., 2006, A physical habitat model for predicting the effects of flow fluctuations in nursery habitats of the endangered Colorado pikeminnow (*Ptychocheilus lucius*): River Research and Applications, v. 22, no. 10, p. 1125–1142, doi:10.1002/rra.967, accessed December 3, 2010, at *http://onlinelibrary.wiley.com/doi/10.1002/rra.967/abstract*.

Hazel, J.E., Jr., Grams, P.E., Schmidt, J.C., and Kaplinski, Matt, 2010, Sandbar response in Marble and Grand Canyons, Arizona, following the 2008 high-flow experiment on the Colorado River: U.S. Geological Survey Scientific Investigations Report 2010–5015, 52 p. (Also available at *http://pubs.usgs.gov/sir/2010/5015/.*)

Kaeding, L.R., and Zimmerman, M.A., 1983, Life history and ecology of the humpback chub in the Little Colorado and Colorado Rivers of the Grand Canyon: Transactions of the American Fisheries Society, v. 112, no. 5, p. 577–594, accessed January 27, 2011, at *http://dx.doi/org/10.1577/1548-8659(1983)112<577:LHAEOT>2.0.CO;2*.)

Kaplinski, Matt, Hazel, J.E., Jr., and Parnell, Rod, 2010, Colorado River campsite monitoring, 1998–2006, Grand Canyon National Park, Arizona, *in* Melis, T.S., Hamill, J.F., Bennett, G.E., Coggins, L.G., Jr., Grams, P.E., Kennedy, T.A., Kubly, D.M., and Ralston, B.E., eds., Proceedings of the Colorado River Basin Science and Resource Management Symposium, November 18–20, 2008, Scottsdale, Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5135, p. 275–284 (Also available at *http://pubs.usgs.gov/sir/2010/5135/.*)

Korman, Josh, 2009, Early life history dynamics of rainbow trout in a large regulated river: Vancouver, University of British Columbia, Ph.D. thesis, 214 p.

Korman, Josh, Kaplinski, Matthew, and Melis, T.S., 2010, Effects of high-flow experiments from Glen Canyon Dam on abundance, growth, and survival rates of early life stages of rainbow trout in the Lees Ferry reach of the Colorado River: U.S. Geological Survey Open-File Report 2010–1034, 31 p. (Also available at *http://pubs.usgs.gov/of/2010/1034/.*)

Korman, Josh, Kaplinski, Matthew, and Melis, T.S., in press, Effects of fluctuating flows and a controlled flood on incubation success and early survival rates and growth of age-0 rainbow trout in a large regulated river: Transactions of the American Fisheries Society.

Korman, Josh, and Melis, T.S., 2011, The effects of Glen Canyon Dam operations on early life stages of rainbow trout in the Colorado River: U.S. Geological Survey Fact Sheet 2011–3002, 4 p. (Also available at *http://pubs.usgs.gov/fs/2011/3002/*.)

Lovich, Jeff, and Melis, T.S., 2007, The state of the Colorado River ecosystem in Grand Canyon—Lessons from 10 years of adaptive ecosystem management: International Journal of River Basin Management, v. 5, no. 3, p. 207–221, accessed August 10, 2010, at *http://sbsc.wr.usgs.gov/products/pdfs/P0151_10sep.pdf*.

Lucchitta, Ivo, and Leopold, L.B., 1999, Floods and sandbars in the Grand Canyon: GSA Today, v. 9, no. 4, p. 1–7, accessed November 15, 2010, at *ftp://rock.geosociety.org/pub/GSAToday/gt9904.pdf*.

Makinster, A.S., Persons, W.R., and Avery, L.A., in press, Status and trends of the rainbow trout population in the Lees Ferry tailwater reach of the Colorado River downstream from Glen Canyon Dam, Arizona, 1991–2009: U.S. Geological Survey Scientific Investigations Report 2011–5015.

Makinster, A.S., Persons, W.R., Avery, L.A., and Bunch, A.J., 2010, Colorado River fish monitoring in Grand Canyon, Arizona—2000 to 2009 summary: U.S. Geological Survey Open-File Report 2010–1246, 26 p. (Also available at *http://pubs.usgs.gov/of/2010/1246/*.)

Melis, T.S., Korman, J., and Kennedy, T.A., in press, Abiotic and biotic responses of the Colorado River to a March 2008 controlled flood experiment at Glen Canyon Dam, AZ: River Research and Applications.

Melis, T.S., Topping, D.J., Grams, P.E., Rubin, D.M., Wright, S.A., Draut, A.E., Hazel, J.E., Jr., Ralston, B.E., Kennedy, T.A., Rosi-Marshall, Emma, Korman, Josh, Hilwig, K.D., and Schmit, L.M., 2010, 2008 high-flow experiment at Glen Canyon Dam benefits Colorado River resources in Grand Canyon National Park: U.S. Geological Survey Fact Sheet 2010–3009, 4 p. (Also available at *http://pubs.usgs.gov/fs/2010/3009/*.)

Pine, W.E., III, Martell, S.J.D., Walters, C.J., and Kitchell, J.F., 2009, Counterintuitive responses of fish populations to management actions—Some common causes and implications for predictions based on ecosystem modeling: Fisheries, v. 34, no. 4, p. 165–180.

Randle, T.J., Lyons, J.K., Christensen, R.J., and Stephen, R.D., 2007, Colorado River ecosystem sediment augmentation appraisal engineering report: Denver, Colorado, Bureau of Reclamation, Technical Service Center, 71 p., accessed December 30, 2010, at *http://www.gcmrc.gov/library/reports/physical/Fine_Sed/Randle2007.pdf*.

Rosi-Marshall, E.J., Kennedy, T.A., Kincaid, D.W., Cross, W.F., Kelly, H.A.W., Behn, K.A., White, Tyler, Hall, R.O., Jr., and Baxter, C.V., 2010, Short-term effects of the 2008 high-flow experiment on macroinvertebrates in the Colorado River below Glen Canyon Dam, Arizona: U.S. Geological Survey Open-File Report 2010–1031, 28 p. (Also available at *http://pubs.usgs.gov/of/2010/1031/*.)

Rubin, D.M., Topping, D.J., Schmidt, J.C., Hazel, J., Kaplinski, M., and Melis, T.S., 2002, Recent sediment studies refute Glen Canyon Dam hypothesis: Eos, Transactions, American Geophysical Union, v. 83, no. 25, p. 273, 277–278.

Runge, M.C., Bean, Ellen, Smith, D.R., and Kokos, Sonja, 2011, Non-native fish control below Glen Canyon Dam—Report from a structured decision-making project: U.S. Geological Survey Open-File Report 2011–1012, 74 p. (Also available at *http://pubs.usgs.gov/of/2011/1012/*.)

Schmidt, J.C., Topping, D.J., Rubin, D.M., Hazel, J.E., Jr., Kaplinski, Matt, Wiele, S.M., and Goeking, S.A., 2007, Streamflow and sediment data collected to determine the effects of low summer steady flows and habitat maintenance flows in 2000 on the Colorado River between Lees Ferry and Bright Angel Creek, Arizona: U.S. Geological Survey Open-File Report 2007–1268, 79 p. (Also available at *http://pubs.usgs.gov/of/2007/1268/*.)

Shannon, J.P., Blinn, D.W., McKinney, Ted, Benenati, E.P., Wilson, K.P., and O'Brien, Chris, 2001, Aquatic food base response to the 1996 test flood below Glen Canyon Dam, Colorado River, Arizona: Ecological Applications, v. 11, no. 3, p. 672–685, accessed January 11, 2010, at *http://www.jstor.org/stable/3061109*.

Topping, D.J., 1997, Physics of flow, sediment transport, hydraulic geometry, and channel geomorphic adjustment during flash floods in an ephemeral river, the Paria River, Utah and Arizona: Seattle, University of Washington, Ph.D. dissertation, 405 p.

Topping, D.J., Rubin, D.M., Grams, P.E., Griffiths, R.E., Sabol, T.A., Voichick, Nicholas, Tusso, R.B., Vanaman, K.M., and McDonald, R.R., 2010, Sediment transport during three controlled-flood experiments on the Colorado River downstream from Glen Canyon Dam, with implications for eddy-sandbar deposition in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010–1128, 111 p. (Also available at *http://pubs.usgs.gov/of/2010/1128/*.)

Topping, D.J., Schmidt, J.C., and Vierra, L.E., Jr., 2003, Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000: U.S. Geological Survey Professional Paper 1677, 118 p. (Also available at *http://pubs.usgs.gov/pp/pp1677/*.)

Valdez, R.A., and Ryel, R.J., 1995, Life history and ecology of the humpback chub (*Gila cypha*) in the Colorado River, Grand Canyon, Arizona—Final report: Logan, Utah, BIO/WEST, Inc., submitted to Bureau of Reclamation, Glen Canyon Environmental Studies, contract no. 0-CS-40-09110, technical report no. TR-250-08, 286 p.

Vernieu, W.S., Hueftle, S.J., and Gloss, S.P., 2005, Water quality in Lake Powell and the Colorado River, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap 4, p. 69–85. (Also available at *http://pubs.usgs.gov/circ/1282/*.)

Wiele, S.M., and Smith, J.D., 1996, A reach-averaged model of diurnal discharge wave propagation down the Colorado River through the Grand Canyon: Water Resources Research, v. 32, no. 5, p. 1375–1386, doi:10.1029/96WR00199.

Wright, S.A., and Grams, P.E., 2010, Evaluation of water year 2011 Glen Canyon Dam flow release scenarios on downstream sand storage along the Colorado River in Arizona: U.S. Geological Survey Open-File Report 2010–1133, 19 p. (Also available at *http://pubs.usgs.gov/of/2010/1133/*.)

Wright, S.A., Melis, T.S., Topping, D.J., and Rubin, D.M., 2005, Influence of Glen Canyon Dam operations on downstream sand resources of the Colorado River in Grand Canyon, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, chap. 1, p. 17–31. (Also available at *http://pubs.usgs.gov/circ/1282/*.)

Wright, S.A., Schmidt, J.C., Melis, T.S., Topping, D.J., and Rubin, D.M., 2008, Is there enough sand? Evaluating the fate of Grand Canyon sandbars: Geological Society of America Today, v. 18, no. 8, p. 4–10, doi: 10.1130/GSATG12A.1.

Wright, S.A., Topping, D.J., Rubin, D.M., and Melis, T.S., 2010, An approach for modeling sediment budgets in supply-limited rivers: Water Resources Research, v. 46, no. W10538, p. 1–18, doi: 10.1029/2009WR008600.

Yard, M.D., Coggins, L.G., Baxter, C.V., Bennett, G.E., and Korman, Josh, in press, Trout piscivory in the Colorado River, Grand Canyon—Effects of turbidity, temperature, and fish prey availability: Transactions of the American Fisheries Society.

Melis—**Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from Glen Canyon Dam, Arizona**—Circular 1366