Overview

Lara M. Schmit

Steven P. Gloss

Christopher N. Updike

Introduction

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

The Study Area

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

The GCPA (see timeline) directs the Secretary of the Interior to operate Glen Canyon Dam and exercise other authorities "in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established, including, but not limited to natural and cultural resources and visitor use" (GCPA, sec. 1802(a)). As a result, the Glen Canyon Dam Adaptive Management Program, created by the 1996 Record of Decision (ROD) for the operation of Glen Canyon Dam, focuses on a study area that encompasses the Colorado River corridor from Glen Canyon Dam to the western boundary of Grand Canyon National Park. The study area includes the approximately 15 river miles (RM) of river from the dam to Lees Ferry within Glen Canyon National Recreation Area and the entire 277-RM river corridor below Lees Ferry and within Grand Canyon National Park. In total, the study area includes some 293 RM of the Colorado River (fig. 1).

Administrative History

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

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

Natural History

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

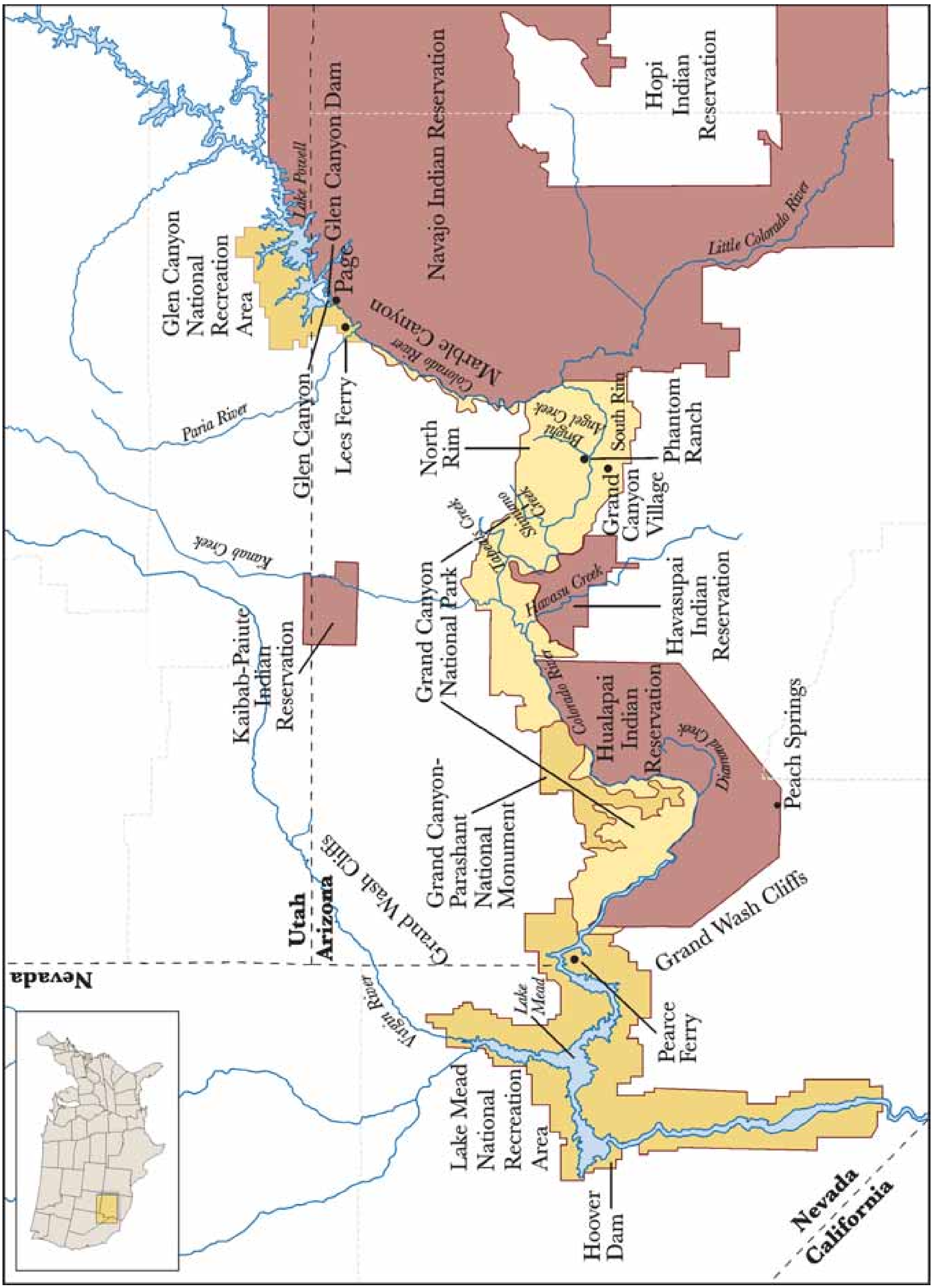


Figure 1. Study area.

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

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

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

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

Federal Efforts to Protect Grand Canyon

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

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

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

1893 President Benjamin Harrison creates Grand Canyon Forest Reserve

1902 Reclamation Act creates the Bureau of Reclamation

1908 President Theodore Roosevelt creates Grand Canyon National Monument

1916 National Park Service Organic Act passed

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

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

The Operation of Glen Canyon Dam Final Environmental Impact Statement (hereafter EIS) was filed in March 1995, and the Record of Decision was signed by Bruce Babbitt, Secretary of the Interior, in October 1996. The Record of Decision noted that the goal "was not to maximize benefits for the most resources, but rather to find an alternative dam operating plan that would permit recovery and long-term sustainability of downstream resources while limiting hydropower capacity and flexibility only to the extent necessary to achieve recovery and long-term sustainability" (U.S. Department of the Interior, 1996, p. G-11). Having established this goal, the Secretary's decision was to implement the modified low fluctuating flow (MLFF) alternative (the preferred alternative in the EIS) as described in the EIS but with minor changes in the upramp rate, maximum release rate, and the timing of beach/habitat-building flows (BHBF; see below). The document also formally established the Glen Canyon Dam Adaptive Management Program.

Glen Canyon Dam Adaptive Management Program

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

1919 Grand Canyon National Park created

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

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

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

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

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

The Role of Science

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

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

1935 Hoover Dam completed

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

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

1948 Upper Colorado River Basin Compact signed

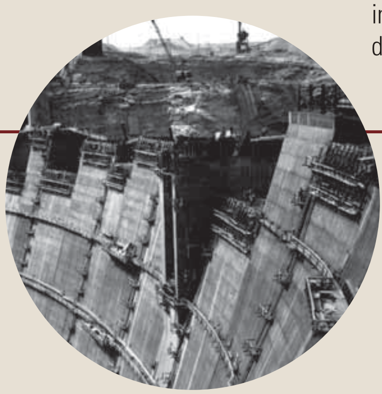
1956 Colorado River Storage Project Act passed authorizing Glen Canyon Dam priate to implement as experiments by the stakeholders and managers, (2) to conduct and communicate peer-reviewed research relevant to management decision needs and to better understand factors governing potential responses to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

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

Modified Low Fluctuating Flow Alternative and Experimentation

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

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



1956-63 Glen Canyon Dam constructed

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

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

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

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

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

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

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

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

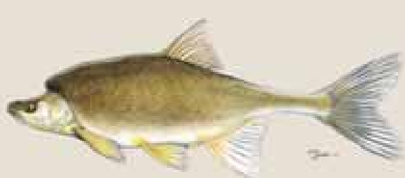
Experimentation has largely focused on experimental flows of the type described above to achieve downstream

1966 National Historic Preservation Act passed

1968 Colorado River Basin Project Act passed

1970 Long-range Operating Criteria developed for Glen Canyon Dam operations

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



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

Collaboration

As for collaboration, the EIS outlined an innovative organizational structure for pursuing the GCDAMP. The program is administered by a senior Department of the Interior official (designee) and facilitated by the Adaptive Management Work Group (AMWG), which is organized as a Federal Advisory Committee. The AMWG makes recommendations to the Secretary of the Interior on how to best alter the operating criteria at Glen Canyon Dam or other management actions to protect downstream resources in order to fulfill the Department of the Interior's obligations under the GCPA (U.S. Department of the Interior, 1995). The Secretary of the Interior appoints the group's 25 members, who include representatives from Federal and State resource management agencies, the seven Colorado River Basin States, Native American tribes, environmental groups, recreation interests, and contractors of Federal power from Glen Canyon Dam (fig. 2). The GCDAMP also includes a monitoring and research center (USGS Grand Canyon Monitoring and Research Center), the Technical Work Group, and independent scientific review panels.

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

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

Report Organization

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

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

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

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

Figure 2. Adaptive Management Work Group committee members.

Interior Secretary's Designee

Tribes

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

State and Federal Cooperating Agencies

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

Colorado River Basin States

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

Nongovernmental Groups

Environmental:
Grand Canyon Trust
Grand Canyon Wildlands Council

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

Contractors for Federal Power from Glen Canyon Dam:
Colorado River Energy Distributors Association
Utah Associated Municipal Power Systems

1975 Grand Canyon National Park Enlargement Act passed

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

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

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

Place Names and Units

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1992 Grand Canyon Protection Act of 1992 passed

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

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

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

References

Annerino, J., 2000, Canyons of the Southwest: a tour of the great canyon country from Colorado to northern Mexico: Tucson, University of Arizona Press, 144 p.

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

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

Hughes, T.C., 1991, Reservoir operations, *in* Committee to Review the Glen Canyon Environmental Studies, Commission on Geosciences, Environment, and Resources, eds., Colorado River ecology and dam management: proceedings of a symposium: Washington, D.C., National Academy Press, p. 207–225.

Ingram, H., Tarlock, D.A., and Oggins, C.R., 1991, The law and politics of the operation of Glen Canyon Dam, *in* Committee to Review the Glen Canyon Environmental Studies, Commission on Geosciences, Environment, and Resources, eds., Colorado River ecology and dam management: proceedings of a symposium: Washington, D.C., National Academy Press, p. 10–27.

National Research Council, 1996, River resource management in Grand Canyon: Committee to Review the Glen Canyon Environmental Studies, Commission on Geosciences, Environment, and Resources: Washington, D.C., National Academy Press, 226 p.

National Research Council, 1999, Downstream: adaptive management of Glen Canyon Dam and the Colorado River ecosystem: Committee on Grand Canyon Monitoring and Research, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources: Washington, D.C., National Academy Press, 230 p.

Pontius, D., 1997, Colorado River Basin study: Report to the Western Water Policy Review Advisory Commission, 126 p.

Roosevelt, T., ca. 1905, The works of Theodore Roosevelt, presidential addresses and state papers, pt. 1: New York, P.F. Collier and Sons, Publishers, p. 369–370.

Stevens, L., 1990, The Colorado River in Grand Canyon: a guide: Flagstaff, Ariz., Red Lake Books, 115 p.

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: Reston, Va., U.S. Geological Survey Professional Paper 1677, 118 p.

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

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

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

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

U.S. Department of the Interior, 1970, Glen Canyon Dam and powerplant: technical record of the design and construction: Denver, Colo., Bureau of Reclamation, Technical Center, 658 p.

U.S. Department of the Interior, 1988, Glen Canyon Environmental Studies final report: Salt Lake City, Utah, Bureau of Reclamation, 84 p.

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.

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, 15 p.

Walters, C., Korman, J., Stevens, L.E., and Gold, B., 2000, Ecosystem modeling for evaluation of adaptive management policies in the Grand Canyon: Journal of Conservation Ecology, v. 4, no. 2, http://www.consecol.org/vol4/iss2/art1, accessed July 14, 2005.

Walters, C.J., and Holling, C.S., 1990, Large-scale management experiments and learning by doing: Ecology, v. 71, no. 6, p. 2060–2068.

Water Education Foundation, 2001, Layperson's guide to the Colorado River: Sacramento, Calif., 28 p.

Webb, R.H., Wegner, D.L., Andrews, E.D., Valdez, R.A., and Patten, D.T., 1999, Downstream effects of Glen Canyon Dam 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: scientific experiment and management demonstration: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 1–21.

Wieringa, M.J., and Morton, A.G., 1996, Hydropower, adaptive management, and biodiversity: Environmental Management, v. 20, no. 6, p. 831–840.

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

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

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

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

Contact Information:

Lara M. Schmit
Associate Editor
Northern Arizona University
Center for Sustainable Environments
Flagstaff, AZ
lschmit@usgs.gov

Steven P. Gloss
Ecologist
U.S. Department of the Interior
U.S. Geological Survey
Southwest Biological Science Center
Tucson, AZ
sgloss@usgs.gov

Christopher N. Updike
Research Assistant
Northern Arizona University
Center for Sustainable Environments
Flagstaff, AZ
Chris_Updike@nau.edu

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