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A MANAGED FLOOD ON THE COLORADO RIVER: BACKGROUND, OBJECTIVES, DESIGN, AND IMPLEMENTATION

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Abstract. The Colorado River ecosystem in lower Glen Canyon and throughout Marble and Grand Canyons was greatly altered following closure of Glen Canyon Dam in 1963, as flood control and daily fluctuating releases from the dam caused large ecological changes. Ecosystem research was conducted from 1983 through 1990, and intensively from 1990 through 1995 when dam releases were modified both for scientific purposes and protection of the river ecosystem. High flows (e.g., beach/habitat building flows) were included in the Glen Canyon Dam Environmental Impact Statement (EIS), which identified a preferred strategy for dam operations and protection of the downstream ecosystem. Use of high flows partially fulfills recommendations of many river and riparian scientists for return of more natural flows, as part of initial efforts in river restoration. In 1996, a seven-day experimental controlled flood was conducted at Glen Canyon Dam to closely study the effects of a high flow event equivalent to those proposed for future dam management. It is an example of modification of operations of a large dam to balance economic gains with ecological protection. Limited to 1274 m^3/s, the test flood was lower than pre-dam spring floods. The experiment was conducted to (1) test the hypothesis that controlled floods can improve sediment deposition patterns and alter important ecological attributes of the river ecosystem without negatively affecting other canyon resources and (2) learn more about river processes, both biotic and abiotic, during a flood event. Along with an explanation of the planning and background of this flood experiment, this paper summarizes expected and realized changes in canyon resources studied during the flood. Responses of specific resources to the flood are synthesized in the following compendium papers.

Key words: canyon resources; Colorado River; dam operations; Glen Canyon Dam; Grand Canyon; managed flood; riparian habitat; riverine ecosystems; sediment deposition; test flood.

Introduction

In spring 1996, the Colorado River ecosystem in lower Glen Canyon and throughout Marble and Grand Canyons sustained a flood that altered many aspects of the river ecosystem (Collier et al. 1997, Webb et al. 1999). Unlike spring floods from past centuries that often reached flows of 3000 cubic meters per second (m^3/s), with flows as high as 8500 m^3/s, this flood reached only 1274 m^3/s. However, it was a unique flood in the history of the Grand Canyon because it was fully controlled. This test flood was planned for specific dates using a controlled release from Glen Canyon Dam. This short-duration high release was designed to rebuild sandbars above nonflood river levels, deposit nutrients, restore backwater channels, and provide some of the dynamics of a natural system. The goal was to test hypotheses about sediment movements and the response of aquatic and terrestrial habitats to controlled flood events.

The test flood was the culmination of many years of research and planning, and illustrated how policies for management of dams and regulated rivers have changed over the past three decades. These changes follow years of studying effects of dams on river ecosystems (Williams and Wolman 1984), and requirements for their restoration (Ward and Stanford 1979, NRC 1992, Poff et al. 1997). When Glen Canyon Dam was constructed in the early 1960s, there was little concern for the impacts of dams on either upstream or downstream river ecosystems. Since then, awareness of changes taking place below dams has greatly increased (Turner and Karpiscak 1980, Johnson 1991, 1992, Rood and Mahoney 1995). Two factors that control many aspects of the river ecosystem were altered by Glen Canyon Dam and its operations: sediment availability to the downstream ecosystem, which is reduced through entrapment in the reservoir behind the dam (Andrews 1991); and river hydrology (quantity and quality), which is altered by timing and penstock intake location of water released from the dam. Timing

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generally coincides with power and downstream water needs, rather than ecological requirements, and intake ports are usually below the reservoir thermocline. Existence of the dam as an upstream–downstream migratory barrier for aquatic organisms is also of great concern (Minckley 1991, Stanford et al. 1996), but at present, existence of Glen Canyon Dam is assumed to be a nonnegotiable alteration of canyon geomorphology.

Lack of available sediment below dams greatly alters the morphology of channel margins, bars, and eddy complexes (Schmidt and Graf 1990, Kearsley et al. 1994, Ligon et al. 1995). In many rivers, below-dam tributaries may contribute sufficient sediment to support biological systems dependent on substrates finer grained than those occurring if dam discharge scours existing sediment and leaves cobble-armored shorelines. However, below Glen Canyon Dam where there is little tributary input of sediment, especially in downstream reaches closer to the dam, there are no acceptable solutions for sediment augmentation to the river ecosystem. Suggestions of transporting sediment from upper Lake Powell to the Lees Ferry area, via a slurry pipeline, have met with little support.

When there is sufficient sediment input from tributaries (e.g., from the Paria and Little Colorado Rivers below Glen Canyon Dam) to build sand deposits within the river channel, altered hydrology then becomes the primary driving variable to change or restore the downstream ecosystem because most aspects of the river's hydrological patterns are controlled by dam operations. These include: (1) amount of annual downstream discharge if stored water is diverted from the upstream impoundment, (2) magnitude of hydrological peaks and low flows, (3) baseflow, and (4) timing and duration of peaks and low flows.

River regulation by dams or other structures created a demand to study streamflow requirements of organisms that may be affected by altered hydrological regimes. Initial streamflow studies were aimed at defining instream flow requirements of economically important commercial and sport fish species (e.g., Bartholow and Waddle 1995, Bovee 1995). These studies primarily addressed instream habitat needs and minimum flow requirements. Eventually, streamflow requirements of other river and riparian attributes, such as riparian vegetation, were also determined (Stromberg and Patten 1989, Auble et al. 1994). Satisfying hydrological requirements for all riverine attributes with managed releases from upstream dams became a balancing act for water and dam managers. Not only did ecosystem components have different requirements, there were different hydrological factors to be addressed. Riparian vegetation did not necessarily need a baseflow, but needed sufficient annual volume to maintain a shallow alluvial water table (Stromberg et al. 1996), while fish required some minimal flow in the river (Stanford et al. 1996). Occurrence and timing of high flows also was important to both (e.g., Stromberg et al. 1991, Rood and Mahoney 1995, Stanford et al. 1996), and, in many cases, timing needs of diverse biota were very similar, a consequence of long-term adaptation by river-oriented organisms to seasonal floods.

Several regulated rivers in the West have been studied to develop plans for alteration of dam operations to satisfy downstream ecological requirements. The Colorado and Columbia Rivers are primary examples, but there are many other small-river examples. Reasons for altering dam operations may differ, and can include, for example, salmon migration in the Columbia and Trinity Rivers in the Northwest; and native fish, recreation, and riparian habitat on the Colorado River. Planning and implementation of ecologically based, modified discharges from dams that were constructed for water storage and hydropower requires extensive study, sound science, agency cooperation, policy adaptation, and acceptance by the public and river users, as well as the political will to implement recommendations.

Fourteen years of data collection, specifically designed to understand the effects of Glen Canyon Dam operations on the river ecosystem (Wegner 1991), preceded the test flood and were used to help develop hypotheses that could be tested by a flood experiment. Implementation of the test flood occurred in March 1996, but the timing of this event culminated years of planning and proposal development by many groups. For planning of future controlled floods and managed dam releases on the Colorado River and other rivers, an understanding of the foundation of scientific and management decisions leading to the test flood and the associated integrated-research program described here and in the following compendium papers is useful. These papers address the impacts of the test flood on: Lake Powell reservoir limnology (Hueftle and Stevens 2001); flow, sediment transport, sandbar and fish habitat responses (Schmidt et al. 2001); aquatic food base and drift (Shannon et al. 2001); native and nonnative fish (Valdez et al. 2001); and the riparian ecosystem, including ethnobiological concerns (Stevens et al. 2001). Elsewhere, Rubin et al. (1998) described the consequences of sediment depletion during floods in Grand Canyon, and Smith (1999) identified and described the effects of an important secondary circulation process on sediment transport that occurs during flooding in this system. Balsom (1999) demonstrated flood-related deposition of sand deposits at the foot of pre-dam terraces, which may retard erosion of archeological materials, but otherwise has trivial impacts on cultural properties. Economic research was summarized by Harpman (1999), and numerous other individual studies of test-flood research were presented in Webb et al. (1999), which serve as background to the compendium papers presented in this Invited Feature.

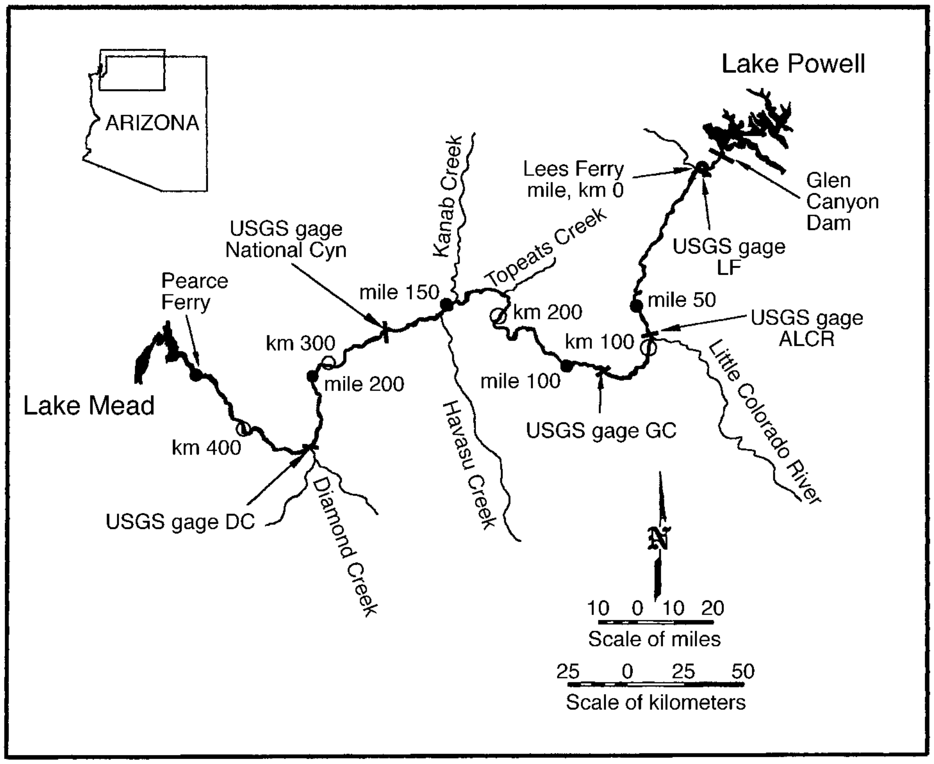

FIG. 1. Map of the Colorado River from Lake Powell to Lake Mead, Arizona. Distances along the river are measured from Lees Ferry, Arizona. Colorado River streamflow gages are monitored by the U.S. Geological Survey at the following locations: ALCR (Above Little Colorado River confluence [river km 98]); DC (Diamond Creek [river km 363]); GC (Grand Canyon near Phantom Ranch [river km 141]); and LF (Lees Ferry [river km 0]).

Background and Setting

Construction of Glen Canyon Dam was completed by the U.S. Bureau of Reclamation in 1963. As the largest unit of the Colorado River Storage Project Act (1956) Glen Canyon Dam controls flow from the upper to the lower Colorado River basins (Fig. 1). Located on the Colorado River upstream from Grand Canyon National Park, this 216 m high concrete arch dam controls a drainage basin of 281 671 km^2. Eight hydroelectric generators at the dam produce up to 1288 MW of electric power. The major function of Glen Canyon Dam (and 33-km^3 Lake Powell) is water storage. The dam is specifically managed to release a minimum objective of 10.2 km^3 of water annually to the lower basin.

River resources downstream from Glen Canyon Dam through Glen, Marble, and Grand Canyons are closely interrelated and virtually all resources are associated with or dependent on water and sediment (U.S. Bureau of Reclamation 1995). In such a system, changes in a single process can affect resources throughout the entire system. For example, changes in Glen Canyon Dam operations, such as the test flood, directly affect hydropower, water supply, sediment, fish, and recreation. Vegetation, cultural resources, fish, and recreation may be affected as dam operational changes influence sediment in the river. Wildlife habitat, and threatened and endangered species can be affected through their linkages to other resources and the effects of water and sediment on those resources.

The Grand Canyon river ecosystem originally developed in a sediment-laden, seasonally and sometimes daily, fluctuating environment. Pre-dam flows ranged seasonally from spring peaks sometimes greater than 3000 m^3/s to winter lows of 28 m^3/s to 85 m^3/s. During spring snowmelt periods and summer flash floods, daily and hourly flow fluctuations occurred. While annual variability in water volume was high, a generally consistent pattern of high spring flows followed by lower summer flows provided an important environmental cue to plants and animals in the river and along its shoreline.

The construction of Glen Canyon Dam altered the natural dynamics of the Colorado River. Today, the ecological resources of Glen, Marble, and Grand Canyons depend on water releases from the dam and variable water and sediment input from tributaries. A reduced sediment supply and regulated release of reservoir water now support aquatic and terrestrial systems that did not exist before Glen Canyon Dam.

In 1982, the U.S. Bureau of Reclamation announced that, as part of its regularly scheduled replacement program, it would upgrade the generators at Glen Canyon

Dam to increase efficiency of hydroelectric power production. Environmental concerns were voiced because this potential change in dam operations could increase maximum dam releases by ~57 m^3/s to ~950 m^3/s. Consequently, Secretary of the Interior (Secretary) James Watt directed the U.S. Bureau of Reclamation to address these issues by establishing a team to study the effects of Glen Canyon Dam operations on the downstream river ecosystem. Called the Glen Canyon Environmental Studies (GCES), this group planned and managed research funded through hydropower revenues from the dam.

Glen Canyon Environmental Studies

There was no established model for designing a research program to understand full effects of dam operations on a river ecosystem. Several studies funded by the National Park Service had described how modified river flows and reduction of spring floods and sediment had altered the riparian system (Turner and Karpiscak 1980, Johnson 1991). However, subtle ecological changes resulting from dam operations such as daily changes in releases of 566 m^3/s and winter low flows of 28 m^3/s were not well understood. It was to address this paucity of information that GCES developed a research program.

Glen Canyon Environmental Studies had two phases. Phase I extended from 1982–1988, and Phase II from 1989–1996. GCES Phase I consisted of a set of studies designed to evaluate the effects of widely fluctuating releases from the dam on selected river ecosystem components. The initial effort consisted of baseline descriptive studies of ecosystem components and processes that were not integrated or coordinated. Compounding the problems of this research was a series of abnormally high inflow years. Emergency releases from the dam in June 1983 reached a peak discharge of 2755 m^3/s and flows were $>$1274 m^3/s for more than six weeks. This wet year was followed by more wet years from 1984–1986, affecting an ecosystem that had been scoured and was sediment starved. The 1983–1986 flood flows transported sand stored within the river channel, eroded low elevation sandbars, and aggraded high elevation sandbars in wide reaches. In many places, vegetation that had developed since dam construction was scoured, drowned, or buried, apparently reducing biological diversity. Some archeological sites also were damaged. The high elevation sandbars eroded following the return to lower flows (as they did pre-dam). A GCES Phase I evaluation of the impacts of large, unplanned, clear water floods and recovery of the river ecosystem concluded that floods in Grand Canyon have negative effects on the river ecosystem and should be avoided. Had a management group suggested mimicking natural floods in the canyon at this time, data from GCES Phase I would not have supported that recommendation.

A National Research Council (NRC 1987) review of GCES Phase I challenged the conclusions that flooding, even unplanned flooding, was harmful to the downstream ecosystem. The NRC committee recommended that, in order to fully understand the response of the ecosystem to floods or altered dam releases, future research programs should be composed of studies that were integrated, had an ecosystem orientation, and were grounded in hypothesis testing. These recommendations became guidelines for planning the GCES Phase II research program, and the test flood.

The GCES Phase II research program was designed to determine effects of dam operations under more normal, or even minimum, release years to complement the data from Phase I. Although a four to five year program had been developed, a request by the Secretary (Lujan) for the U.S. Bureau of Reclamation to prepare a Glen Canyon Dam Environmental Impact Statement (EIS) in 24 mo truncated this program.

The purpose of the EIS was to analyze alternative ways for operating Glen Canyon Dam, leading to a record of decision (ROD) that would set long-term operational guidelines.

Research flows.—The GCES Phase II integrated research program included ''research flows'' (Patten 1991). These represented a series of two-week ''experimental flows'' using different combinations of dam operational parameters: (1) magnitude of high and low discharge rates, (2) magnitude of daily fluctuations, and (3) ramping rate (the rate at which releases are increased or decreased diurnally to meet electrical load) (controlled fluctuations, n = 9; constant, n = 3; mimicking normal operational fluctuations, n = 8). Manipulation of operational parameters was expected to result in different, measurable effects on the downstream environment. If normal dam operations were the only pattern of operations studied over the short period, there would be little hope of gaining much information on responses of the many riverine resources to dam releases; information needed for the EIS. When research flows were approved for a 13-mo period, it set a precedent for using dam operations as a research tool.

Interim flows.—Upon completion of the research flows, the EIS had not been finalized and dam operations functioned under interim operating criteria (interim flows). These flows were designed to protect or enhance downstream resources while allowing limited flexibility for power operations. The minimum dam release was maintained higher than 1963–1990 minima to protect the aquatic food base from exposure and desiccation. The maximum release was also reduced in order to reduce sand transport thereby allowing accumulation along the riverbed. The daily fluctuation was limited so that the daily change in river stage would be nearly the same during all months; about one meter in most reaches. The down-ramp rate was set to reduce seepage-based erosion of sandbars in Glen, Marble, and

Grand Canyons and to avoid stranding of fish. The upramp rate was set to reduce other operation-related impacts to canyon resources, such as scour. Interim flows represented one of the first times a major dam was operated with consideration of the downstream ecosystem. These flows, along with research flows, demonstrated that under present laws and regulations (e.g., National Environmental Policy Act [NEPA] and the Colorado River Compact of 1922), a dam constructed for water storage and hydropower could be operated to balance economic gains with ecological research and protection. This also was the objective of the Glen Canyon Dam EIS, which was to examine options that, ''. . . minimize, consistent with law, adverse impacts on downstream environmental and cultural resources and Native American interests . . . '' (U.S. Bureau of Reclamation 1995).

Managed high flows.—Under the Glen Canyon Dam EIS the preferred alternative, or modified low fluctuating flow (MLFF) was similar to interim flows in goals and operations. It restricted maximum dam discharge, minimum discharge, ramping rates, and the daily range of discharges. MLFF also specified a number of other management actions including periodic high discharges from the dam, some within power-plant capacity and some higher. High discharges within power-plant capacity were called ''habitat maintenance flows,'' and discharges greater than power-plant capacity were referred to as ''beach/habitat-building flows.'' Use of high flows for management and restoration of downstream ecosystems is, along with reestablishment of other components of natural flow regimes, a keystone of many river restoration recommendations (Stanford et al. 1996, Poff et al. 1997). Decisions on timing of the various high flows were to be made by an Adaptive Management Workgroup, which would make recommendations on dam operations based on the results of long-term research and monitoring activities under the Grand Canyon Monitoring and Research Center, the replacement for Glen Canyon Environmental Studies.

Test-flood approval

NEPA compliance.—Although the final EIS was published in March 1996, an ROD could not be issued until completion of a General Accounting Office audit. Consequently, in order to run the test flood as planned in March 1996, separate National Environmental Policy Act compliance was initiated. The U.S. Bureau of Reclamation published the *Glen Canyon Dam Beach/Habitat-Building Test Flow Final Environmental Assessment and Finding of No Significant Impact* (U.S Bureau of Reclamation 1996) to provide NEPA compliance for implementing the test flood. Following the test flood, on 5 October 1996, Secretary of the Interior Bruce Babbitt issued an ROD on the future operations of Glen Canyon Dam. He announced that the facility would be operated according to the modified low fluctuating flow alternative described in the EIS.

External interest groups.—Implementation of the test flood not only required extensive scientific planning and addressing regulatory issues, but also necessitated understanding and cooperation by groups concerned with the effects of high dam discharges on their well-being or resources under their care. Aside from obvious interests such as water and power that tended to resist change in dam management policies, these interest groups included American Indian tribes with cultural concerns, white-water rafting companies, anglers and fishing guides, the Arizona Game and Fish Department, and the U.S. Fish and Wildlife Service (see *Flood experiment: Planning*). Examples of concerns were that high flows would inundate tribal deltaic agricultural lands in Lake Mead, might destroy the blue-ribbon trout fisheries below the dam, or significantly impact endangered species. When the test flood was implemented, all interest groups understood the importance of high flows to river ecosystems and supported this flood experiment.

Flood Experiment: Rationale, History, Planning, and Implementation

Rationale for the test flood

Periodic high flows occurred regularly prior to the construction of Glen Canyon Dam and are believed to be necessary to maintain integrity of the downstream river ecosystem. The test flood of 1996 was needed to test the hypotheses that the dynamic nature of fluvial landforms and aquatic and terrestrial habitats can be wholly or partially restored by short-duration dam releases substantially greater than power-plant capacity. This experiment would provide an opportunity to measure essential geomorphic and ecological processes during flood passage and recession. Data collected during the test flood would provide the information needed to test predictive models, and help to establish an operational regime to maintain, manage, and protect the riparian and aquatic resources of the Colorado River in Glen and Grand Canyons.

History

Initial discussions about creation of a controlled flood in Glen and Grand Canyons dates to the National Research Council (NRC 1987) review of GCES Phase I. NRC discussed the importance of flooding to river ecosystems and mentioned that perhaps a periodic controlled flood, with less potential for successive floods, might be a positive event for the canyon's river ecosystem under the right sediment storage conditions.

With approval from the cooperating agencies, beach/habitat-building flows were incorporated into all alternatives in the draft EIS in 1993. This initiated a planning process to test floods of greater than power-plant magnitudes as a possible management tool for river ecosystem restoration.

Planning

After two years of planning and delays, in 1995 and early 1996, the U.S. Bureau of Reclamation and the U.S. Geological Survey developed and coordinated a detailed and integrated research program for a spring 1996 beach/habitat-building test flow. The research program was designed with a limited budget which helped facilitate a long-term goal of GCES to integrate studies by collecting data on several river ecosystem components within the same reach or area of the canyon. In this way, teams from different disciplines could assist each other, and logistic costs could be reduced.

The magnitude and duration of the test flood had been a contentious point from early planning. Most scientists thought that the greater the magnitude, the better. Early proposals were as high as 1700 m^3/s, with releases of >1400 m^3/s thought to be important for modification of sediment storage, scouring of backwaters and marshes, and possible alteration of debris fans. Information from GCES Phase I had demonstrated response of these resources to a high magnitude flood. The greater the magnitude, the greater the total amount of water needed for the experiment. After various compromises, 1274 m^3/s for one week (considered the minimum acceptable duration at that time) was accepted, and sufficient water for release during this period was planned into the annual operation plan for Glen Canyon Dam. The discharge was less than half that of the 1983 flood releases, where discharges lasted more than a week, and half to a third of the mean annual pre-dam spring flood peak.

The 1274-m^3/s level was accepted not only because of water limitations, but also because the river stage at 1274 m^3/s was considered by the U.S. Fish and Wildlife Service not likely to excessively damage the habitat and population of endangered species (i.e., Kanab ambersnail (*Oxyloma haydeni kanabensis*) and Southwestern Willow Flycatcher (*Empidonax traillii extimus*)). This demonstrates that water and power interests, as well as the Endangered Species Act of 1973, played an important role in the planning of the test flood.

The timing of the test flood was carefully considered. Although the time frame did not correspond to natural pre-dam May–June spring floods, the months of March and April were specifically selected to reduce impacts on river resources by conducting the test flood (1) prior to native fish spawning and larval dispersal periods, (2) after the period when rainbow trout spawn at Lees Ferry, (3) after concentrations of wintering Bald Eagles and waterfowl have mostly dispersed, (4) well prior to release of tamarisk (*Tamarix ramosissima*) seeds to reduce germination of this exotic plant, (5) prior to the beginning of the summer white-water boating season, and (6) prior to nesting of the endangered Southwestern Willow Flycatcher.

Description of the test flood

The test flood occurred in a year in which the dam was operated under interim operating criteria (interim flows), and modest flow fluctuations would have occurred had the test flood not been conducted (the ''no action alternative'' in Fig. 2). To accommodate the test flood, water volumes were redistributed from January and February to March and April (Harpman 1999). The test flood was conducted from 22 March to 8 April 1996 (Fig. 2). A four-day period of 227 m^3/s (8000 cfs) low steady flows preceded and followed the actual flood period. Releases were increased by 113 m^3/s in hourly increments (4000 cfs) until a maximum flow of 1274 m^3/s (45 000 cfs) was attained. This high release was maintained for seven days, and flow in excess of powerplant capacity was released from the river outlet works near the base of the dam (Fig. 2). To better mimic a natural receding limb of a flood, discharge was decreased hourly in steps of 42.5 m^3/s (1500 cfs), 28 m^3/s (1000 cfs), and 14 m^3/s (500 cfs), with the ramping rates reduced at 991 m^3/s (35 000 cfs), 566 m^3/s (20 000 cfs), and 227 m^3/s (8000 cfs), respectively.

Predicted effects of the test flood

The *Glen Canyon Dam Beach/Habitat-Building Test Flow Final Environmental Assessment and Finding of No Significant Impact* (U.S. Bureau of Reclamation 1996) provided NEPA compliance for the test flood, and presented a set of flood impact predictions for affected resources. These are briefly discussed along with some surprise findings from the test flood.

Water storage in Lake Powell.—Although the surface elevation of Lake Powell was expected to decrease during the test flood, its level at the end of the year was expected to be normal. During water year 1996, the total variation in the elevation of Lake Powell was 4.7 m, which is quite typical. Lake Powell was 0.6 m higher in February and 0.6 m lower in April than it would have been without the test flood. The elevation of Lake Powell dropped 1.1 m during the week of the test flood. These changes in lake level and the rapid withdrawal were expected to have small effects on limnology of the lake, especially the forebay region. Results of lake studies related to the test flood are presented in a compendium article by Hueftle and Stevens (2001) in this feature.

Flow and sediment.—Prior to the test flood, sediment researchers felt that sufficient sediment was available in the channel to permit development of elevated sediment deposits during the test flood, and some redistribution of sediment was also expected. However, the timing and location of flow and sediment changes could not be precisely predicted prior to the test flood, and improved modeling of these phenomena was expected

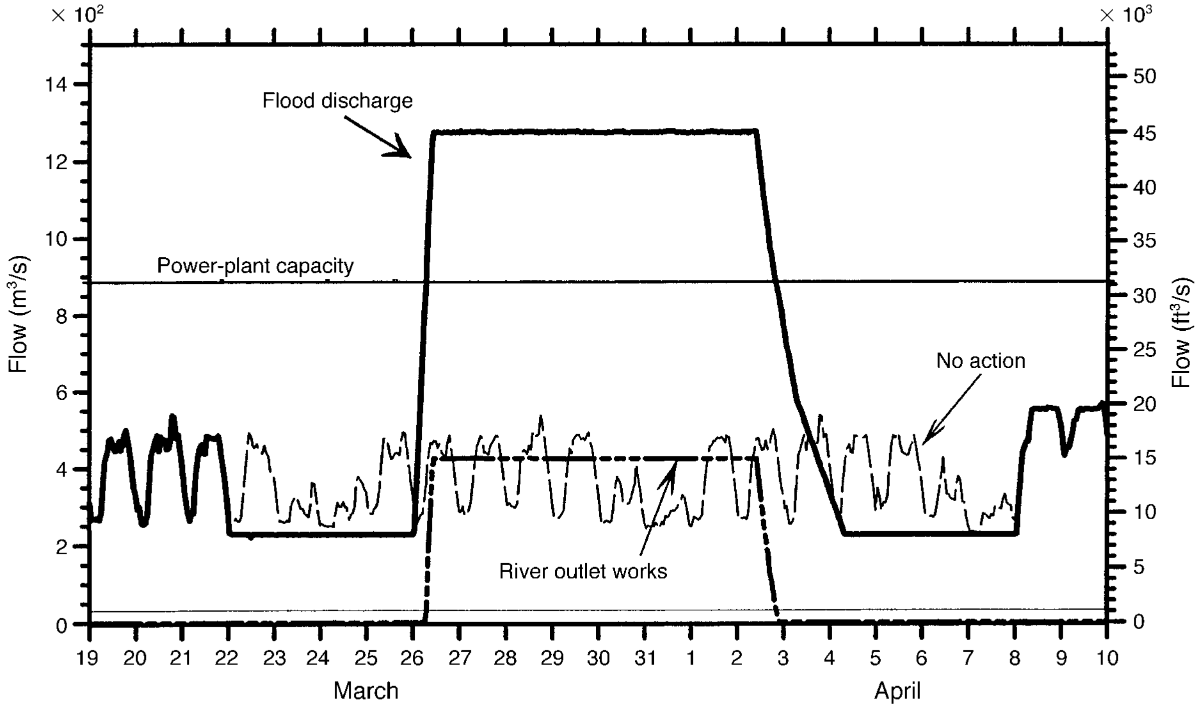

FIG. 2. The test-flood hydrograph from Glen Canyon Dam from 19 March to 10 April 1996. The graph shows the actual amount of water released (bold solid line), the ''no action'' alternative (thin dashed line), and the amount of water released from the river outlet works (bold dashed line). Power-plant capacity is 937 m^3/s.

as a primary scientific benefit of this experiment (Schmidt 1999; and see Schmidt et al. 2001 in this feature). Their research demonstrated that most sediment changes (i.e., scour, transport, and fill) occurred in the first few of days of the flood. On-the-ground sediment studies documented the volume of sediment changes from 33 large eddies and in several long reaches of the river corridor (Hazel et al. 1999). These sandbar response studies demonstrated a pattern of ''higher, not wider'' bar restoration from the test flood.

Aquatic food base and fish.—High flows were expected to scour and remove some components of the aquatic food base, particularly the abundant macrophytes that flourish in clear water below Glen Canyon Dam and above the confluence of the Little Colorado River. Impact of these changes on the native and nonnative fish populations was expected to be small. However, impact of high flows on young fish and nonnative species was not well understood, but long-term consequences were expected to be minor; and as it turned out, short-term changes were minimal as young fish used shorelines and tributary mouths as refugia from the flood. Results of aquatic food base and fish studies related to the test flood are presented in compendium articles by Shannon et al. (2001) and Valdez et al. (2001) in this feature, respectively.

Terrestrial habitat, riparian vegetation, and endangered species.—Riparian vegetation forms shoreline habitat for terrestrial species, including two endangered species, Kanab ambersnail and Southwestern Willow Flycatcher, as well as shoreline habitat and food resources for fish. High flows were expected to scour or fill low marsh areas but have little impact on woody riparian species. Sediment deposition was expected to bury or alter some riparian vegetation and habitat. Although the test flood buried ground-covering vegetation under the new sediment deposits, the magnitude of the flood was insufficient to scour perennial riparian vegetation. The endangered flycatcher was not nesting during the test flood and thus was not expected to be directly affected; however, the Kanab ambersnail habitat and population were reduced by the test flood. Results of riparian and habitat studies, and studies of the responses of endangered species related to the test flood are presented in Stevens et al. (2001) in this issue.

Cultural resources.—Most cultural resources were located above test-flood stage levels and direct impacts were not expected. However, restoration of eroded lower terraces was expected to reduce or slow the loss of cultural resources on higher terraces. Results of these and other cultural resource studies related to the test flood are presented in Balsom (1999) and in Stevens et al. (2001).

Recreation and hydropower.—Recreational use and hydropower economics are also important management considerations for this ecosystem (Harpman 1999).

Recreational potential was improved by the creation of more camping beaches (Kearsley et al. 1999, Schmidt et al. 2001). Direct recreational impacts were minimized by planning the test flood at a time when few white-water river trips occur in late March and early April (Myers et al. 1999). Economic impacts on angling, day-use rafting, and hydropower marketing were expected. During the eight days of the flood, day-use rafting was suspended and angling was largely curtailed. The income of some local businesses, which depend on anglers and day-use rafting, was slightly adversely affected; however, local expenditures by researchers, government officials, and the press more than offset those losses to the local economy.

The test flood affected hydropower economics not only during the event, but also during the remainder of water year 1996 (Harpman 1999). The test flood released 0.27 km^3 of water, and costs included $1.5 million (U.S.) for research and $2.52 million in lost revenue (3.3% of the total annual hydropower revenue), for a total cost of $4.02 million. Although it is commonly a misunderstood issue, research funds for the test flood were derived from hydropower revenue, not from the allocation of public funds from federal sources.

Conclusions

This compendium of papers describes many of the findings of the test-flood experiment, improvement of flow and sediment transport models, and updates information presented by Webb et al. (1999) and elsewhere. Eddy circulation processes under controlled conditions have helped illuminate our understanding of sediment storage and depletion mechanisms in canyon-constrained river ecosystems. Although more replication of this flow scenario is needed, the physical and biological responses of the ecosystem to a flow of this magnitude are now better understood, and new questions have arisen regarding how to use floods as management processes to improve resource conditions in Glen, Marble, and Grand Canyons.

Execution of this controlled flood, and the improved understanding of its influence on the Colorado River ecosystem, reinforce recommendations by many river and riparian scientists that restoring hydrological processes through mimicking or reestablishing natural flow regimes must be part of future river management. The test flood established an internationally recognized model for implementing future beach/habitat-building flows; however, many new questions exist around the timing and shape of future flood hydrographs. The frequency of future managed floods will be based on long-term monitoring and research programs under the Grand Canyon Adaptive Management Program. Continued cooperation among all interested parties is still needed to implement managed floods, because, as learned through this test flood, special interest groups are strongly resistant to change. Developing consensus among stakeholders on the use of scientific information and managed floods for sediment and resource management remains a primary challenge to the Adaptive Management Work Group.

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