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Three Experimental High-Flow Releases from Glen Canyon Dam, Arizona—Effects on the Downstream Colorado River Ecosystem

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. Also known as artificial or controlled floods, these scheduled releases of water above the dam's powerplant capacity were designed to mimic pre-dam seasonal flooding on the Colorado River. The goal of the HFEs was to determine whether high flows could be used to benefit important downstream resources in Glen Canyon National Recreation Area and Grand Canyon National Park that have been affected by the existence and operation of Glen Canyon Dam. These downstream resources include native fish, particularly endangered humpback chub (**Gila cypha*****), terrestrial and aquatic sandbar habitats, cultural sites, and recreational resources. This Fact Sheet summarizes HFE-related studies published since 1996 and outlines a possible strategy for implementing future HFEs.***

Anne Phillips, USGS

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Jet tubes at Glen Canyon Dam release Colorado River water on the morning of March 5, 2008, during a high-flow experiment (HFE). This and two similar HFEs sought to determine whether high flows could be used to move sand from the riverbed to Grand Canyon sandbars, used as camping beaches (lower left), and to benefit other resources. Following the 2008 HFE, rainbow trout (*Oncorhynchus mykiss*; lower right) numbers increased, which may adversely affect native humpback chub *(Gila cypha)*, an endangered species.

Background

The construction and operation of dams results in numerous physical and ecological changes to river systems. Since its completion in 1963, Glen Canyon Dam, Arizona (lat 36.9375º and long -111.4843º), traps in Lake Powell all of the upstream sediment—gravel, sand, silt, and clay—formerly carried by the Colorado River through Grand Canyon National Park. Additionally, the dam reduced the magnitude and duration of flooding downstream, and dam operations result in a dominance of moderate flows compared to pre-dam seasonal floods and periods when flows were reduced to a relative trickle. Before the dam was built, Colorado River flow gradually increased from mid-December to March, precipitously increased in April and May, and reached its peak in early June. This pre-dam seasonal flooding moved sand from the riverbed to the shoreline, creating and maintaining sandbars.

Dam-induced changes in the Colorado River's temperature, flow, and sediment-carrying capacity have been implicated in losses of native fish, invasion of nonnative species, sandbar erosion, and the narrowing of rapids. Through the periodic use of high-flow experiments (HFEs), which are scheduled releases of water from the dam above powerplant capacity, managers have attempted to benefit key resources by simulating one aspect of the pre-dam river—floods. Three HFEs, also known as artificial or controlled floods, were conducted by the U.S. Department of the Interior at Glen Canyon Dam in March 1996, November 2004, and March 2008. Research and long-term monitoring have allowed scientists to unravel many, but not all, of the uncertainties that existed about how HFEs might affect downstream river resources.

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Map of the Colorado River downstream of Glen Canyon Dam showing the river corridor between Lake Powell and Lake Mead reservoirs.

Physical Processes

Studies conducted in conjunction with each HFE have allowed scientists to better understand the physical processes of the post-dam Colorado River, especially how the river transports and reworks the now greatly reduced sand supply (about 10 percent of historical values). With the upstream sand supply trapped behind Glen Canyon Dam, the Paria and Little Colorado Rivers, tributaries that enter the river downstream of the dam, are the primary sources of sand to the system. Sand provided by these and other, smaller tributaries is deposited on the riverbed and eventually carried downstream to Lake Mead, particularly during high-volume dam releases. Because HFEs to some extent mimic natural flooding, they have been conducted to evaluate their ability to benefit sediment-dependent resources, including sandbars and camping beaches, marsh and riverside vegetation, and aquatic habitats such as backwaters, which are nearshore areas of low-velocity flow used as rearing habitat by native fish. Sandbars are of particular concern because they eroded from the time the dam was completed in 1963 to 1991. During this period, the dam was operated to meet required downstream water transfers and to maximize the generation of electricity around peak daily demand, causing daily flows to vary greatly (from ~1,000 to ~25,000 ft^3/s) and resulting in sandbar erosion. Constraints were placed on dam operations starting in 1991, in part to reduce sandbar erosion and increase retention of sediment from tributaries.

The first HFE took place between March 26 and April 7, 1996, including a 7-day steady peak release at 45,000 ft^3/s—a peak flow about 50 percent greater than powerplant capacity. Scientists learned after this HFE that the sand delivered from tributaries does not accumulate on the riverbed over multiple years during typical operations. It had been thought that tributary-supplied sand would be stored on the riverbed in response to the 1991 operational changes and that this stored sand would be the primary source of sand available to rebuild sandbars during HFEs. Although the 1996 HFE demonstrated that high flows can build sandbars, sandbars at higher elevations were built from sand scoured from the lower elevation portions of existing sandbars rather than from sand stored on the riverbed. In other words, in these cases sandbars became higher but not wider. On the basis of these findings, the 2004 and 2008 HFEs were shorter in duration and strategically timed to follow tributary floods that provided “new” sand to the system before it was carried downstream. Research indicates that from February 1996 to October 2008—the span of the three HFEs—75 percent of the sandbars at long-term study sites in Grand Canyon experienced net increases in volume, despite ongoing sandbar erosion between HFEs.

Three conclusions related to sediment have important implications for designing future HFEs. First, HFEs build sandbars by eroding existing low-elevation portions of sandbars or by using tributary-supplied sand. Second, HFEs conducted soon after new sand has been supplied to the river channel by tributary floods are effective at increasing sandbar area and volume and less likely to result in the erosion of low-elevation portions of sandbars. Sandbars are built relatively quickly (hours to a few days) under these sand-enriched conditions, but they also tend to erode quickly (days to several months) following an HFE. Third, monitoring data show that sandbars erode more quickly as release volumes and daily fluctuations increase, whereas the rate of erosion is reduced when tributary sand inputs continue to occur following sandbar building.

Biological Processes

As the Colorado River flows downstream from Glen Canyon Dam, the management goals for aquatic resources shift from maintaining naturally reproducing populations of nonnative fish to maintaining or attaining viable populations of native fish, particularly the endangered humpback chub (*Gila cypha*). The Lees Ferry reach, a 16-mile-long stretch of the river immediately downstream from the dam in Glen Canyon National Recreation Area, supports a nonnative rainbow trout (*Oncorhynchus mykiss*) sport fishery. Despite management efforts to benefit native fish in the main stem within Grand Canyon National Park, rainbow trout are the dominant fish in the main stem as far downstream as its confluence with the Little Colorado River. Most humpback chub are found in the Little Colorado River and near its confluence with the Colorado River. Native flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), and nonnative common carp (*Cyprinus carpio*) dominate downstream reaches of the Colorado River as it nears Lake Mead.

It had been thought that HFEs would benefit native fish by creating nearshore backwater habitats that might serve as important rearing environments. On the other hand, scientists also anticipated that HFEs would displace both native and nonnative fish downstream and that some rainbow trout eggs and juvenile fish would experience mortality. Research associated with the 2008 HFE, however, indicates that high flows actually benefit rainbow trout populations by improving spawning and rearing habitats in the Lees Ferry reach. Survival rates of juvenile rainbow trout in this reach in 2008 were more than four times higher than observed in years before the experiment for which data are available (2003 to 2007). This response persisted into 2009, with juvenile survival rates that were twice those in pre-HFE years; in 2010, however, juvenile rainbow trout survival was much lower and similar to levels between 2003 and 2007. This pattern indicates that the effect of an HFE on early life stages of trout may persist for as long as 2 years. Increased survival rates recorded in 2008 and 2009 appear to be the result of HFE-induced increases in aquatic invertebrates, such as midges and black flies, which are high-quality food items preferred by trout. These high survival rates led to increases in adult populations of rainbow trout throughout the river.

Downstream migration of the large number of rainbow trout that were spawned in the Lees Ferry reach in 2008, as well as spawning that may have occurred downstream, contributed to a roughly 800 percent increase in rainbow trout densities between 2007 and 2009 in the main stem near the confluence with the Little Colorado River, where most humpback chub are found. This large increase followed efforts to control nonnative fish in this reach that resulted in the removal of about 20,000 rainbow trout from 2003 through 2006. Because rainbow trout are known predators of young humpback chub and may also compete with them for limited food resources, the increase of rainbow trout in the vicinity of the Little Colorado River has been cause for concern. Although the HFEs have been shown to result in temporary increases in the number and size of backwater habitats, corresponding beneficial effects on humpback chub populations have not been documented.

Research related to the 1996 and 2008 experiments[1] indicates that HFEs conducted during early spring and late winter can be a tool for maintaining native marsh and riparian plant communities and reducing nonnative vegetation. One of the primary concerns regarding HFE timing is the risk of dispersing seeds of nonnative species, especially tamarisk (*Tamarix* spp.). The 1996 and 2008 HFEs occurred before tamarisk begins producing seeds—seed production generally occurs between April and September. Thus, the establishment of tamarisk seedlings was low (less than 2 percent) in 1996 and 2008. Plants that recovered quickly following the 2008 HFE were those well adapted to burial. Clonal wetland plants also quickly occupied bare sandbars and shorelines following both the 1996 and 2008 HFEs. Therefore, reductions in campsite area because of vegetation recovery and expansion following HFEs might offset the temporary increases in campsite area that resulted from sandbar building during HFEs.

Three biological conclusions have important implications for designing future HFEs. First, on the basis of 2008 HFE research, spring-timed HFEs have the potential to significantly increase the rainbow trout population in the Lees Ferry reach and in downstream reaches that support native fish. Second, the large increases of rainbow trout documented in the Colorado River near its confluence with the Little Colorado River may adversely affect adult populations of endangered humpback chub. Third, HFEs have had no measurable positive impacts on juvenile or adult humpback chub populations.

A Science-Based Strategy for Future High-Flow Experiments

The U.S. Department of the Interior directed the U.S. Geological Survey (USGS) to develop a science-based strategy for conducting future HFEs as part of the Department's efforts to produce a new protocol for these experiments. The strategy outlined below is based on adaptive management, or "learning by doing," meaning that the strategy is anticipated to change as new scientific findings improve the understanding of how HFEs affect the river ecosystem. The primary goal of the strategy is to sustainably rebuild and maintain Grand Canyon sandbars, but it would also assist scientists to better understand the effects of HFEs on biological resources, particularly rainbow trout and humpback chub.

Although HFEs can rebuild sandbars by depositing a fraction of new tributary sand at higher elevations along shorelines, higher flows also efficiently export available sand supplies downstream. An important objective of any HFE strategy would be to achieve a neutral sand budget, so that the total sand exported downstream does not exceed ongoing tributary sand inputs over the long term. Sand storage in the main stem is greatest immediately following tributary floods, before downstream export results from daily dam releases. With only about 10 percent of the pre-dam sand supply still entering Grand Canyon, primarily from the Paria and Little Colorado Rivers, the best possibility for rebuilding and maintaining sandbars is conducting frequent HFEs following tributary floods that deliver large quantities of sand to the river. This is

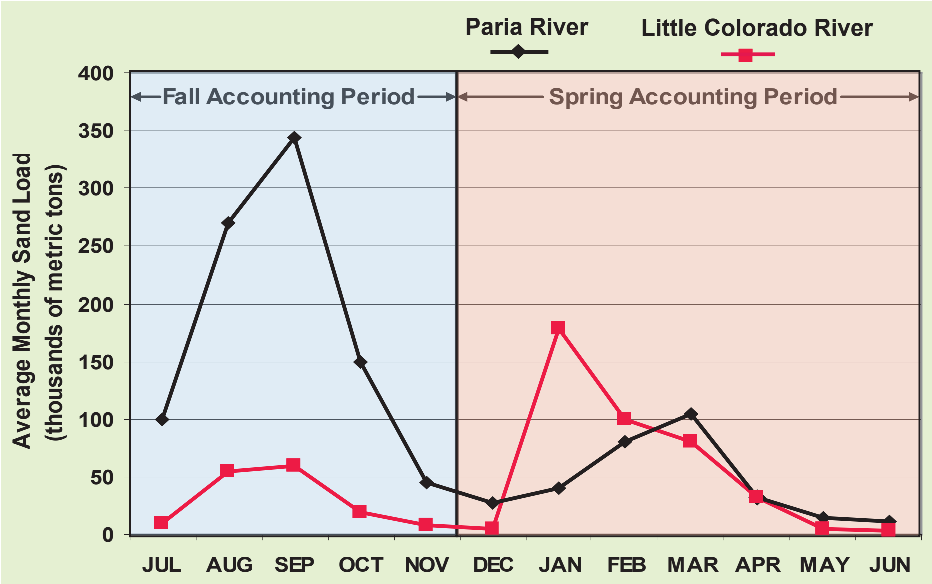
March 4, 2008 (before the HFE)

March 11, 2008 (immediately after the HFE)

September 30, 2008 (about 6 months after the HFE)

Repeat photographs of a long-term sandbar study site on the Colorado River about 45 miles downstream from Lees Ferry, Arizona, showing how that sandbar was affected by the 2008 high-flow experiment (HFE) and by erosion in the subsequent 6 months. All of the photographs were taken by a remote camera at about 4 p.m. and at a water level associated with a flow rate from Glen Canyon Dam of about 8,500 cubic feet per second (ft^3/s). The river flows from left to right. Boat (18 feet long) in bottom photo indicates scale.

[1] No published research is available about the effects of the November 2004 HFE on vegetation.



Historical data on sand delivery to the Colorado River from flooding on the Paria and Little Colorado Rivers support a high-flow experiment (HFE) strategy with spring and fall releases from Glen Canyon Dam for the purpose of building and maintaining sandbars in Marble and Grand Canyons.

because (1) typical dam operations do not allow multiyear accumulation of tributary sand inputs on the riverbed and (2) new sandbars are eroded by typical dam releases following each HFE. If future HFEs are strategically timed to follow tributary floods, and the duration and magnitude of HFEs are designed to match the volume of new sand delivered to the river (short-duration, low-magnitude HFEs when sand inputs are small and long-duration, high-magnitude HFEs when sand inputs are large), then it may be possible to enlarge and maintain sandbars through time.

Paria River flooding is the primary source of new sand inputs, and these floods typically occur from mid-summer through early fall. Therefore, conducting HFEs in the fall, following the typical Paria River flood pattern, would likely maximize sandbar building. On rare occasions, the Paria River floods between December and April, so spring-timed HFEs would maximize sandbar building in that situation. Because of the typical timing of Paria River flooding, about two-thirds of future HFEs would occur during the fall, if resource managers were to implement this strategy. The Little Colorado River also delivers sand to Grand Canyon at various times during the year, so managers could also consider timing HFEs to coincide with flooding on that tributary.

During years when dam release volumes are below average and downstream sand transport occurs more slowly, allowing multiple new sand inputs to accumulate before an HFE would likely result in the greatest sandbar-building response. This accumulate-and-release strategy is likely to be most effective if the magnitude and duration of each HFE are designed in response to the volume and location of new sand in the system. However, during years of average or wet upper Colorado River Basin hydrology, when releases from Glen Canyon Dam are higher and sand is exported downstream more rapidly, HFEs might be more effectively conducted immediately following or even during tributary flooding. This option would be particularly appropriate when new sand would otherwise be rapidly exported downstream (days to weeks) because of large-volume dam releases required to meet downstream water delivery requirements. Although the science-based strategy described above was developed on the basis of monitoring data and published results, uncertainties exist about its ability to maximize future sandbar building and how HFEs will affect other resources over the long term. Climate change and consequent changes to dam operations add to these uncertainties.

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. For example, if monitoring indicates that sandbars continue to erode or cannot be rebuilt and sustained at a desired level using this strategy, then managers may choose other experimental options, such as further constraining daily and seasonal water-release patterns, augmenting the Colorado River's sand supply from sources in Lake Powell, or both. Monitoring and research associated with other key resources, such as native and nonnative fish, cultural sites, and recreational resources, would allow managers to detect any adverse effects resulting from HFEs and make changes as appropriate. Managers, for example, might choose to alter the timing of future HFEs to try to reduce the rainbow trout response, if ongoing monitoring indicates that the large increase in rainbow trout associated with the 2008 HFE is negatively affecting the adult population of humpback chub or other native fish. Although the described strategy does not guarantee success, sandbar trends without HFEs are one of the few outcomes that can be predicted with certainty—sandbar size will decrease through time without HFEs that follow tributary sand inputs.

A fuller exposition of these HFE-related research results can be found in Melis, T.S., editor, (in press), Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from Glen Canyon Dam, Arizona (U.S. Geological Survey Circular 1366).

Theodore S. Melis, Paul E. Grams, Theodore A. Kennedy, Barbara E. Ralston, Christopher T. Robinson, John C. Schmidt, Lara M. Schmit, Richard A. Valdez, and Scott A. Wright

Edited by
Peter H. Stauffer
Graphic design by
Judy Weathers

For more information contact:

U.S. Geological Survey
Southwest Biological Science Center
Grand Canyon Monitoring and Research Center
Flagstaff, Arizona
928-556-7094
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