High Flow Experiments in the Grand Canyon: An Evolving Water Management Paradigm for the Colorado River

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Abstract

Historical operations of Glen Canyon Dam have significantly altered the flow of water and sediment in the Colorado River, resulting in numerous ecogeomorphic changes to the Grand Canyon reach. The environmental and recreational impacts of these changes are being addressed to some extent through the release of high flow experiments (HFEs), large-volume, short-duration scheduled releases designed to mimic seasonal flooding aspects of the natural flow regime. This review addresses the evolution of scientific and political thinking regarding the role of HFEs in the management of Grand Canyon resources. Management trade-offs between power, water supply, recreation, and the environment are addressed, as well as the complex physical and ecological responses associated with changes to reservoir operations. The potential to apply lessons learned in the HFE adaptive management process to increasing hydrological uncertainty under climate change is discussed.

Goals of the paper

The goals of this paper are to (1) review the development, implementation, and adaptive management of HFEs in the Grand Canyon, and (2) evaluate the potential for scientific and political advancements to be applied to increasing hydrological uncertainties under climate change.

Literature synthesis

HFEs are large-volume, short-duration scheduled releases designed to mimic seasonal flooding aspects of the natural flow regime to diminish negative ecological and geomorphic impacts of normal reservoir operations. The magnitude of HFEs is physically constrained between powerplant capacity (32,000 cfs) and the combined discharge from the power plant and the river outlets of 45,000 cfs. Five HFEs have been released since 1996, and they are currently intended to maintain and restore downstream flood-dependent resources within the constraints of water and energy demands, laws and regulations, physical infrastructure, and environmental objectives (USBR 1995). However, release of the first HFE resulted from a decade-long evolution in scientific and political thinking about the role of floods in management of the Colorado River, which is reviewed in this paper.

Glen Canyon Dam: operations and impacts

The flow regime of the Colorado River through Grand Canyon historically increased starting in December and reached its peak around June depending on Rocky Mountains snow accumulation and melting rate. The largest recorded flood through Grand Canyon was approximately 210,000 ft^3/s (Jun-1884), and the average 2-year recurrence event was approximately 85,000 ft^3/s (Topping et al, 2003), almost three times greater than the current power plant capacity of Glen Canyon Dam.

The completion of Glen Canyon Dam in 1963 significantly altered the hydrology of the Colorado River through the Grand Canyon. The United States Bureau of Reclamation (USBR), an agency within the Department of the Interior, operates Glen Canyon Dam as a multipurpose storage facility in northern Arizona. Lake Powell, the reservoir created by Glen Canyon Dam, has a storage capacity of 32.33 billion cubic meters, making it the second-largest reservoir in the U.S. after Lake Mead downstream (USBR 1995). Annual discharge at Lees Ferry and the recurrence rate of floods changed dramatically under the dam's influence. The 5-year recurrence flow of 2,948 cms decreased to 1,093 cms (Schmidt 2007).

Glen Canyon Dam operations have been highly variable since its completion in 1963, reflecting changes in water management objectives as well as attempts to manage natural wet and dry cycles. In spite of this variability, major hydrologic patterns have emerged, including substantial reduction in annual spring flood flows and an increased magnitude of base flows to meet required downstream water transfers. Post-dam floods, defined as those releases exceeding powerplant capacity (33,200 ft^3/s) for a month or more, have only occurred in 1983 to 1986 (Melis et al 2011). The objective of maximizing energy production through hydropower has resulted in major diurnal variability in dam releases (from ~1,000 to 25,000 ft^3/s) in response to hourly changes in electricity demands. Electricity demands and resulting dam releases generally peak in January for heating and again in August for air conditioning (Melis et al 2011).

Major changes to the geomorphology have also occurred in response to reservoir development and operations. All upstream sediment inputs that historically moved through the Grand Canyon during floods are now trapped behind Glen Canyon Dam in Lake Powell. Sediment inflows from downstream tributaries are the only inputs to the canyon's sediment budget; these sand influxes are generally driven by episodic tributary flooding events (Melis et al 2011). Without floods or upstream sediment inputs, continuous sandbar erosion occurred, adversely affecting river recreation by limiting camping beach availability and quality and diminishing backwater habitats for native fish. Concern over beach availability was the main political driver for geomorphic research in the Grand Canyon (Schmidt et al 1999).

Ecological impacts of dam-induced changes to hydrology and geomorphology may include: loss of native fishes, increased invasions of nonnative species, and diminished backwater habitat (Melis et al 2011). The Grand Canyon is populated by numerous endangered aquatic and riparian species, including the humpback chub (*Gila cypha*), the Kanab ambersnail (*Oxyloma haydeni*), and the razorback sucker (*Xyrauchen texanus*) (NPS 2014). These species are adapted to highly variable conditions, whereas the hydrologic stability resulting from historic dam operations favors less resilient, exotic species. Ecologically, the role of floods as an essential disturbance regime for riverine habitat restoration and production has been well established (Poff et al 1997).

Historical context for HFEs

In the 1980s, USBR studied the relationship between the condition of downstream river resources and operations of Glen Canyon Dam, culminating in an environmental impact statement (EIS) finalized in 1995 promoting the release of HFEs (USBR 1995). Glen Canyon Environmental Studies (GCES) program was initiated in the 1980s to determine the relationship between the condition of downstream river resources and normal power plant operations. However, geomorphic and hydrologic studies were conducted during a period of unprecedented runoff, so goals quickly shifted towards examining the effects of higher magnitude releases on the canyon. Annual runoff in the upper Colorado River basin in 1983 and 1984 was the second and third largest since 1896, and high reservoir inflows required the USBR to use the dam's river outlet works from 1983 to 1986, as well the emergency spillways in 1983, to release floodwaters downstream. So much water was released in 1983 that the peak discharge through the Grand Canyon approximately equaled the mean annual flood of the pre-dam Colorado River (Webb et al 1989). Administrative pressures to only study the effects of discharges less than power plant capacity were overturned by the environmental impacts seen to be caused by the high discharges.

The monitoring results from these emergency flood releases were mixed. Two months after the 1983 high flows, more sandbars were large enough for camping and their average size was larger than they had been before the flood pulse (Brian and Thomas, 1984). However, these results were quickly followed by the subsequent erosion of the flood-driven sand bars in the sequence of high flows released between 1984 and 1986, the net result being a reduction in the area of sand bars in narrow reaches that already had limited beach options (Schmidt and Graf, 1990). A sediment mass balance study indicated that a large volume of sand had been removed from the channel bed and banks (Randle et al 1993). The GCES report following this sequence of events found no long-term negative effects on the river ecosystem (USBR 1995). However, it was assumed that these changes were representative of potential effects of *any* high release from the dam. Furthermore, it was the consensus that overall beach area would be lost in any flood event. The management implications were to revise the operations to reduce the likelihood of future high releases in excess of power plant capacity (USBR 1995).

Recognition of the environmental effects of floods as highly dependent on their magnitude, duration, and time since past flood event emerged over the period between the consensus opinion against their use in 1988 to their standing as a valuable "restoration tool" in the Final EIS for Glen Canyon Dam operations in 1995 (Schmidt et al 1999). This shift in understanding of the role of floods in the Grand Canyon was driven by numerous research programs over that period, as well as a subsequent evaluation of reservoir operations *without* floods in the several years of drought following the flood events. Interim Operation Criteria were adopted in 1991 to manage the drought until the EIS could be established, representing the first time dam operations had been significantly altered to protect downstream river resources. A minimum daily discharge, imposed for the protection of trout spawning areas upstream of Lees Ferry, and a daily maximum discharge were intended to keep the daily change in river stage within 1 meter in most months and reaches to reduce erosion and avoid stranding fish. Despite these efforts, erosion of sand bars continued, driven by wind, gullying, and debris flows, and it was eventually acknowledged by researchers that floods were needed to provide sand to the system that has been eroded in the months between floods (Schmidt et al 1999).

By the early 1990s, geomorphologists had the new objective of using prescribed floods to redistribute sand from the channel bed to its margins (Schmidt et al 1999). However, the location and volume of available sand and the magnitude and duration of flows to release it was unknown. Sand was believed to accumulate on the channel bed during extended low flows, and the Paria and Little Colorado rivers were identified as the primary sources of sediment delivered through the Grand Canyon downstream of the dam (Melis et al 2011). Coarse sediment budgets of these rivers indicated that average dam operations would be insufficient to remove the average annual volume of sand input by these tributaries, since floods are the only natural mechanism capable of rebuilding alluvial landforms such as high-elevation sand bars (Schmidt et al 1999). Researchers determined that the rates of mainstem transport increase and the rates of deposition decline as an eddy fills up (Schmidt 1990), suggesting that restoration floods should be of high magnitude but short duration. Modeling studies demonstrated that the distribution of new sand bars under known hydrologic and sediment transport conditions could be predicted (Wiele and Smith 1996; Nelson et al 1994). Over the same period, ecologists recognized the value of floods for riparian species recruitment through vegetation scour (Webb et al 1989), new habitat availability for endangered species (e.g. Kanab ambersnail), and hydrologic cues to which endemic fishes had adapted (Stevens et al 1995). However, it was also acknowledged that inappropriate magnitude, timing, or duration of flood releases could have significantly negative impacts the downstream environment, such as cold water releases decimating a year class of native fish too young to withstand such a disturbance (Valdez and Ryel 1995).

HFE implementation was further complicated by numerous regulations and stakeholder interests. The Colorado River Storage Project Act of 1956 mandated Glen Canyon Dam "to produce the greatest practicable amount of power and energy that can be sold" and to avoid any "anticipated spills" that bypass the power plant (Schmidt et al 1999). The Grand Canyon Protection Act of 1992, in contrast, required the dam to be operated for the protection and improvement of natural and cultural resources and visitor use. Despite these complexities, the final 1996 EIS allowed HFEs "because all impacts of the proposed action on downstream resources are consistent with natural processes, they are considered to be beneficial to the overall ecosystem" (DOI 1996a). Such a paradigm shift from the 1980s water- and power- focused management is indicative of the value of continued scientific investigation into river processes and an open dialogue between diverse stakeholders.

HFEs and adaptive management

Adaptive management drives the release of HFEs from Glen Canyon Dam "whereby the effects of dam operations on downstream resources would be assessed and the results of those assessments would form the basis of future modifications of dam operations" (DOI 1995). The main objective of HFEs is to provide an opportunity to measure geomorphic and ecologic processes under a large flooding event and test hypotheses about the flood's effects. HFE "success" depends on achieving the following objectives without negative impacts on the trout fishery, endangered species, cultural resources, or the regional economy: remove non-native fishes, rejuvenate backwater habitats for native fishes, redeposit sand bars at higher elevations, preserve and restore camping beaches, reduce near-shore vegetation, and provide water to the upper riparian vegetation zone (Melis et al 2011). The similar magnitude of HFEs released in 1996, 2004, and 2008 was intended to allow for the replication of measurements with some variables held constant. The duration and timing, however, were adjusted to evaluate alternative hypotheses related to sediment transport (Melis et al 2011) under the adaptive management protocol.

For example, before the first HFE, it was believed that tributary sediment inputs would accumulate on the channel bed over multiple years of low flow operations, making sand available for redistribution to sandbars in the event of a flood (Schmidt et al 1999). However, the 1996 HFE illustrated that tributary-supplied sediment does not accumulate over multiyear periods of normal dam operations; instead, it is transported downstream over short time periods (Rubin et al 2002). This discovery adjusted focus towards the strategic timing of HFEs to take advantage of episodic tributary floods that supply additional sand to the canyon downstream of the dam. The following HFE in the fall of 2004 followed sediment inputs from a large flood in the Paria River. The result was an increase in the total area and volume of sandbars in the upper half of the canyon. However, geomorphic results in the lower half of the canyon were similar to those of 1996, with sand initially redistributed onto beaches subsequently eroded to less available surface area than before the flood (Rubin et al 2002). The March 2008 HFEs were prompted by above-average sediment inputs from the Paria River in the falls of 2006 and 2007. The sand released in these flooding events had been partially depleted and coarsened by normal dam releases between the inputs and the HFE. The result was widespread increases in the volume and area of sandbars throughout the canyon greater than the first two HFEs (Melis et al 2011).

Adaptive management also accompanied the biological research being done regarding the influence of floods on the downstream environment. The operation of Glen Canyon Dam surrounding the 2008 HFE resulted in a 400% increase in survival and growth rates of rainbow trout that had hatched after the flood, as well as a 200% increase in expected 2009 trout abundance (Korman et al 2010). Such dramatic results led to concerns over the welfare of the endangered humpback chub, which is believed to compete with the invasive trout for habitat and food (Coggins and Walters 2009).

Conclusions

This review explored the evolving water management paradigm in the Grand Canyon of the Colorado River and the role of science and adaptive management under uncertainties in the complex physical and biological processes acting in the river and their interactions. However, uncertainty in hydrologic inputs also plays a large role in water management, and predicted long-term decreases in inflows and increasing magnitude and variability of flood events in the Colorado River Basin (USBR 2012) will have a large influence over Glen Canyon management decisions moving forward. Dams that are currently managed for environmental as well as human objectives may move towards managing solely for human needs under the reduced reservoir inputs projected with climate change. Such changes would reduce the potential for continued HFEs or the development of HFEs to encompass a broader, more natural range of flow releases.

The question also emerges as to whether large dams like Glen Canyon can serve as engineered resilience to climate change. The total volume of reservoir storage in the Colorado River (114 billion cubic meters) is approximately seven times the mean annual flow at Lees Ferry over the period of record (USBR 1995). This implies that reservoir operations have significant control over the storage and transport of water in the Grand Canyon. The traditional objectives of water management - to store water in times of ample (or excessive) supply and release it in times of scarcity- echo this sentiment of control. Furthermore, the past three decades of scientific research and experimentation regarding the influence of dam operations on downstream water- and sediment-dependent resources has led to advances in both scientific understanding and multi-objective water management for humans and the environment. This combination of factors suggests the potential to address climate change impacts on hydrologic and sediment inputs with continued operational changes to Glen Canyon Dam to reflect our current understanding of environmental water requirements and the sediment budget and flow regime characteristics required to provide them. As Schmidt *et al* (1999) described over a decade ago, "scientific understanding is an evolving venture, and implementation of management actions derived from scientific information … requires [both] the development of a clear scientific recommendation [and] the persistence of managers and constituents to ensure that those recommendations are implemented."

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