High Flow Experiments and Sediment Transport in the Grand Canyon

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Abstract

Flood experiments (FEs) originated in Glen Canyon Dam in 1996 (Olden *et al.,* 2014). FEs are now conducted around the world for different (sometimes multi-objective) purposes. They were originally implemented to increase sandbar size and benefit the downstream ecosystem. The establishment of Grand Canyon National Park (GCNP) provided a strong incentive for the implementation of a reservoir operation policy that is growing in popularity. The new dam operation of Glen Canyon Dam are one of the first long-term flood experiment models. Previous FEs have successfully increased sandbar volume, but the practice has not been implemented over the long term. It is unknown whether FEs will sustain sandbar size. Neither are the direct effects on fish and vegetation populations well understood.

Introduction

Flood Experiments (FEs) are becoming more and more popular in water resources management. Glen Powell Dam was one of the first dams to implement this idea. Currently, 113 FEs have been conducted around the world (Olden *et al.*, 2014). The incorporation of one FE in dam releases increases the understanding of the effect of dam operations on the ecosystem, society, and geomorphology downstream of a dam. However, FEs are usually limited to flow control for a short-term experimental period. FE testing in conjunction with constituent concentrations over a long-term study period has yet to be completed. The use of FEs must be incorporated over the long term-scale for a better understanding of the downstream environmental effects. Also, as an understanding of a single objective is developed, other objectives (e.g. temperature) should be incorporated into the FE plan (Olden *et al.*, 2014).

The Colorado River Basin is the subject of much scientific, political, cultural, and societal interest. The beaches of the Grand Canyon provide campgrounds for rafters and are important to the riparian and aquatic ecosystem. Decrease in beach size was first noticed in the early 1970s. The maintenance of beaches became one of the top priorities for Glen Canyon Dam operations (Andrews and Pizzi, 2001). Interest in preserving the sandbars as well as the enormous storage capacity of Lake Powell made the perfect setting for FEs. For the rest of this report, FEs will be described as High Flow Experiments (HFEs) to maintain the specific convention used to describe flood experiments from Glen Canyon Dam.

Pre-Dam Conditions

The sediment and water have different source areas. About 70% of the sediment load comes from the Colorado Plateau, providing about 15% of the total annual flows. The rest of the annual flow and sediment comes from the Rocky Mountains as snowmelt. The inflow from the Rocky Mountains arrives in early Spring, while monsoons of the Colorado Plateau are occur during the Summer. The Canyon used to be filled with sediments from the monsoon storms, then cleared through by the large snowmelt flood in the following Spring. The flood would flush sediment through the channel bed and build up sandbars in the eddie zones.

The seasonal variation in flows and sediment transport is illustrated in Figure 1. The average peak flow was 86,000 cfs. The 10-year recurrence interval flood was 123,000 cfs. The median sediment concentration was 1,250 ppm and the sediment concentration equaled or exceeded 28,000 ppm 1% of the time at the USGS Grand Canyon gauging station.

Between 1935 and 1948, the average sediment transport was 140 million tons per year at the Phantom Ranch station. This same quantity of transport was also measured at Lake Meade during the same time period. Therefore, most of the sediment in the Grand Canyon maintained suspension and flowed through the canyon over the course of these years. From the data provided, the Canyon was in sediment equilibrium over the long-term.

Post-Dam Conditions

The post-dam total volume flux through the Canyon roughly matches the pre-dam volume. However, the diurnal and seasonal patterns changed dramatically. The flow used to exceed 7,000 cfs during the snowmelt period, from May through July, or during a summer monsoon in the Colorado Plateau. The low to medium flows have significantly increased, but peak flow rarely exceeds 33,000 cfs, the allowable peak discharge of the hydroelectric power plant. The range of flows during a day has greatly increased to maximize power plant revenues. Needless to say, the flow regime was significantly altered by Glen Canyon Dam (Figure 1).

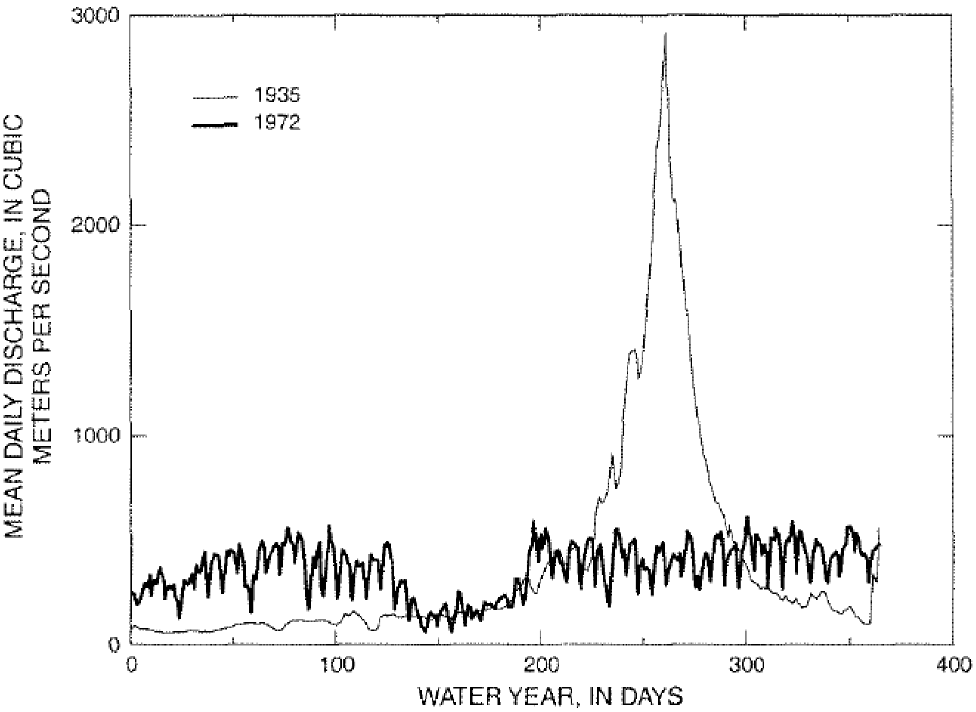

Figure 1. Comparison of annual hydrographs at the Colorado River at Lees Ferry (Andrews and Pizzi, 2000)

Currently, 94% of the original sediment flux through the Grand Canyon is impeded by Glen Canyon Dam. Now, the Paria and Little Colorado Rivers are the main providers of sediment. The median sediment concentration from 1966 to 1974 at the USGS Grand Canyon gauging station decreased to 350 ppm and the sediment concentration equaled or exceeded 15,000 ppm 1% of the time (Dolan et al., 1974).

Loss of Sandbars

In 1983, the Glen Canyon Environmental Studies (GCES) was initiated to address whether increasing the production capacity of the hydropower plant would increase the rate of erosion of the sand bars. Initially, the study assumed that the reduction of sandbars was solely due to the closure of Glen Canyon Dam and its hydropower operations. The low sediment concentration water from the dam in combination with its large daily fluctuations led to the depletion in sandbars. The Bureau of Reclamation (USBR) wanted to know if an increase in daily fluctuations would increase erosion. The GCES found four factors leading to the loss of sandbars "(1) a decreased supply of sand from upstream, (2) a reduction in annual peak discharge, (3) large daily variations in flow that accelerate erosion, and (4) extensive human use" (Andrews and Pizzi, 2001). Based on this declaration, operating restrictions were imposed on Glen Canyon Dam in 1992. The maximum release was reduced to 20,000 cfs and the ramping rates (or the rate at which the flow can change) were also reduced (Andrews and Pizzi, 2001).

Even with the operating restriction of 1992, the sandbars were eroding rapidly. Sediment budgets became a top priority. Randle *et al.* found that the sediment supply from the tributaries exceeded the export downstream of the Canyon. Through this paper, it was discovered that the erosion of sandbars was not a result of decreased sediment input. The sediment remained on the river bed instead of being carried up to sandbars in eddie zones (Andrews and Pizzi, 2001).

Restoring the eroding sandbars became a topic of much research. The sediment transport and sandbar deposition was thoroughly examined and described in journal papers of the nineties. Maintaining sandbars commenced as a function of restoration. Limiting the rafters and changing hydropower regulations were the first, yet inadequate, steps in maintaining sandbars.

High Flow Experiment (HFEs)

The 1996 Experimental Flood

The idea of a pulse flow came shortly after the Little Colorado Flood of 1993. The sandbar height downstream of the Little Colorado increased briefly as a result of this flood. The total volume of sand deposited on the beaches greatly exceeded the sediment contribution by the Little Colorado (Wiele *et al*., 1996). The flood wave entrained the sediment on the channel bed resulting in increased sandbar volume. This flood spurred the discussion of an experimental flood at a GCES meeting in 1993 (Andrews and Pizzi, 2001).

The main objectives of the 1996 HFE were to: "(1) rejuvenate low-velocity habitats for native fishes, (2) enlarge sand deposits, (3) preserve and restore sandbars used as campsites, and (4) provide water to vegetation in the upper riparian zone" (USGS, 2010). HFEs do not match any specific hydrologic aspect of the natural flow regime. They are similar to the spring snowmelt event, but at a shorter duration to prevent too much sand output from the system.

Though they do not match the natural hydrologic cycle, they were designed to maintain the environment and aid the native ecosystem (i.e. endangered species).

The proposition of an experimental flood was subjected to several constraints, legal, physical, ecological and economic. The releases of Glen Canyon Dam are subject to 17 legal documents. The main purpose of the dam is to provide 7.5 million acre-feet of water annually for the Colorado River Compact. The experimental flow does not threaten water allocation, so much of the legal discussion focused on the loss of hydropower, a secondary function of the dam. Legally, the experimental flood was favored as releases should "produce the greatest *practicable* amount of power" (Andrews and Pizzi, 2001). If releases for hydropower were further eroding dams, they are not considered *practicable*, as the preservation of Grand Canyon National Park is a federal objective according to the National Park Service Act. Therefore, the experimental flows are legally sound.

The economic and physical constraints of the dam were also considered. Without the use of the spillway, the dam has the capacity to release 45,000 cfs through the hydropower and hollow jet tubes. The use of the spillway was prohibited by the USBR for fear of cavitation and erosion of the spillway. Though the spillway was reconstructed and tested after the flooding of 1983, the risk of damaging the spillway for a test flood was not of interest to the USBR. The flood maximized hydropower capacity and used the rest of the available supply through the hollow jet tubes. It is estimated that the 1996 experimental flow loss in hydropower revenues was about $2.5 million as compared to the $80 million annual revenue from the rafting industry. It is suggested that the cost of the flows are insignificant compared to the economic damages associated with the rafting industry.

The area commonly used by river runners increased significantly after the 1996 HFE. No negative impacts on the aquatic organisms or riparian vegetation were observed. The success of the 1996 HFE led to further research and adapted applications of new HFEs.

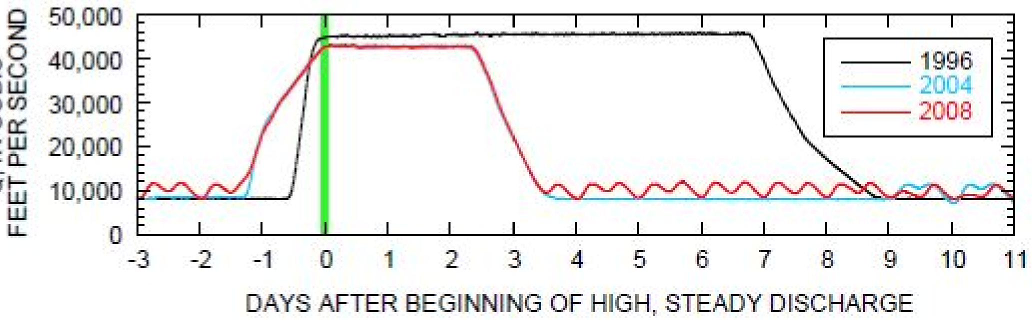

Figure 2. Flow Hydrographs of the 1996, 2004, and 2008 controlled flood experiments at the Lees Ferry gaging station (USGS, 2010).

The Proceeding HFEs

HFEs occurred in 1997, 2000, 2004, and 2008. The HFEs in 1997 and 2000 were of shorter duration (3 days) and smaller magnitudes (31,000 cfs). Their effects were negligible compared to the other HFEs. The 2004 and 2008 HFE were conducted at different times of the year for different flood durations and magnitudes. Researchers collected more sediment data of the Colorado River before and after these events. With each new flood, the hypotheses for HFE effects evolved.

The peak discharge of the 2004 and 2008 floods were slightly lower (42,000 cfs) than the 45,000 peak discharge of the 1996 HFE. This is due to maintenance on Glen Canyon Dam, limiting the peak flow capacity. Hydrographs of the HFEs are shown in Figure 2. The duration of peak discharge was much shorter during the 2004 and 2008 HFEs. Peak discharge was maintained for 60 hours instead of a full 7 days during the 1996 HFE. Calculations for sediment concentration were underestimated before the 1996 HFE. Therefore USBR found that shorter flood duration would transport the amount of sediment.

It is believed that the 1996 HFE eroded the upstream sandbars and increased sandbar size on the downstream portion of the river because the 1996 HFE was conducted in sand-depleted conditions. The 2004 and 2008 HFEs were conducted during greater levels of sand enrichment to test whether HFEs results in sustainable sandbar deposition in GCNP. The 2004 and 2008 were more successful in re-establishing sandbars, but long-term effects of HFEs are still unknown.

The most important finding of these experiments and resulting studies is the importance of sand grain size in relation to beach building capacity of HFEs. Sand enrichment, or total sand volume in the channel bed, is not the only factor that controls the success of HFEs. The study by USGS in 2010 states that sand grain distribution plays a significant role in the augmentation of sandbars. The role of HFEs is to pick up fine sand and place it upon sandbars in eddie zones. Even with a large accumulation of sand on the channel beds upstream of the Grand Canyon, there may be little augmentation of sandbars if the sand grains are too large.

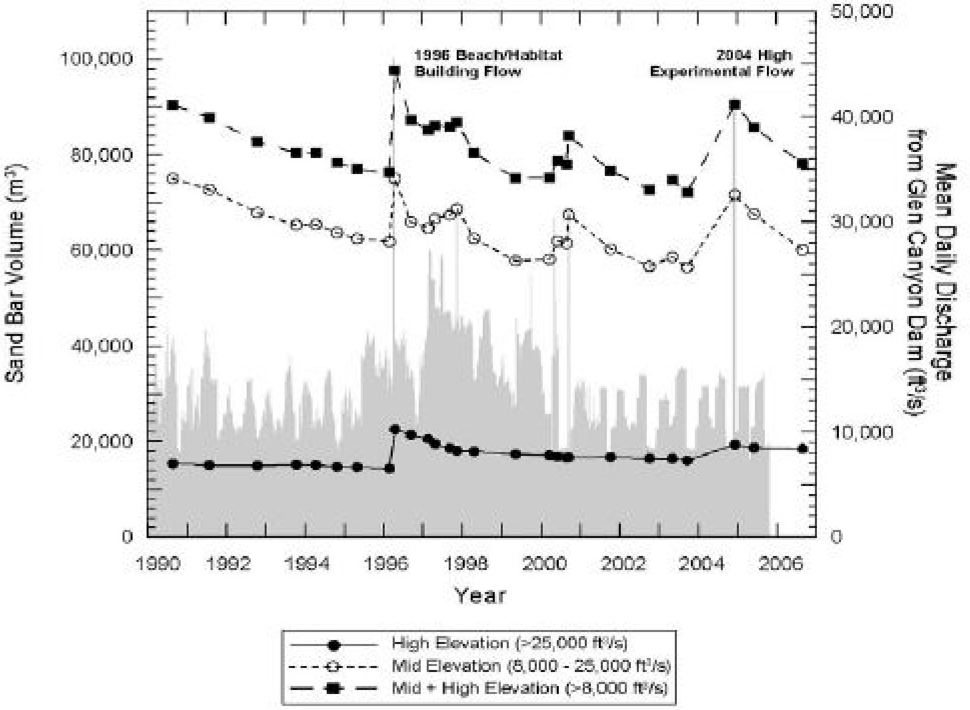

Figure 3. Total sandbar volume at 12 sites in Marble Canyon (USBR, 2011).

The total volume of sandbars at 12 sites in Marble Canyon is shown in Figure 3. The HFEs in 1996, 1997, 2000, and 2004 each increased the total sandbar volume for mid-elevation deposits. However, only the 1996 and 2004 floods increased the total high elevation volume (above the 25,000 cfs mark). The 1997 and 2000 HFEs only made a slight change to the sandbar composition. The initial increases in sediment volume are followed by a sharp decrease shortly after an HFE. Therefore, more frequent applications of HFEs could maintain sandbar volume.

Current HFE Protocol

Under the dam operation protocol established in 2012, the goal of HFEs is to increase the overall size of sandbars in the Colorado River downstream of Glen Canyon Dam over a long-period of time. HFEs are proposed through a model that determines when and if an HFE will effectively increase sandbar volume. The model only considers water and sediment. A review process is incorporated into the protocol to consider effects on other resources.

The protocol for HFEs follows directions provided in Environmental Assessment: Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam, Arizona, 2011 through 2020. This protocol was signed into practice in May of 2012. The protocol stipulates that HFEs can only occur in March, April, October, or November. Their magnitude and duration can range from 31,500 cfs to 45,000 cfs and 1 hour to 96 hours, respectively.

The HFEs follow the store and release approach. "The sand availability at the onset of each release window is determined by the amount of sand received from the Paria River during the accrual period less the amount transported downstream to the Little Colorado River as estimated by the sand routing model" (USBR, 2011). During the release window, the sediment budget is evaluated to determine if an HFE will produce a positive sand balance at the end of the accounting period. The largest (with regards to flow rate and duration) HFE possible that produces a positive sand balance will be chosen. Higher flows are preferable as they result in a higher accumulation in sandbar height and area. With this model, it is possible for two HFEs to be produced in one year.

Rapid response HFEs are another proposed option of long-term HFE implementation. Rapid response HFEs entail a HFE occurring immediately after or during a flood of the Paria or Little Colorado Rivers. This idea is proposed by Western Area Power Administration because rapid response HFEs do not require such high releases from Glen Canyon Dam. It is speculated that the combination of the release and the flood will be more than enough to build up sandbars. The benefits of rapid response HFEs include a possibly better sandbar building efficiency by combining dam release flows with floods on the Paria River, increasing the variability of flow magnitude and duration to add a greater variation of sediments, and a minimizing hydropower revenue loss to HFEs. However, HFE decisions will need to be made in a matter of hours instead of days, resulting is a less strict review process. Thus far, there has been no implementation of a rapid response HFE to floods in either the Paria or Little Colorado Rivers (USBR, 2011).

Furthermore, it is known that HFEs result in short-term increase in sandbar size. However, there is no assurance that HFEs are a sustainable practice for maintaining sandbar size in GCNP. At the end of 2020, more data should illustrate the feasibility of sustainable sandbar size with HFEs. If HFEs are unable to maintain sandbar size, methods of dredging or transporting sediment from Lake Powell are under consideration.

Conclusion

HFEs are specifically designed to increase sandbar volume. Increased sandbar volume increase backwater habitats to benefit fish populations and riparian vegetation. The models for determining beneficial HFEs focus solely on sediment transport, but other resources (e.g. native fish and archeological sites) are considered in the decision making process. The previous HFEs have increased backwater habitats, but direct effects on vegetation and fish populations are less understood.

Based on previous HFEs, little impact to vegetation is expected with the new protocol. The low-lying grasses and shrubs will be buried during an HFE, but are expected to recover in the within a year (USBR, 2011). There are concerns with spreading Tamarisk seeds during an HFE. Grand Canyon Tamarisk produce seeds from April through September, mainly outside the HFE window. If an HFE is conducted in April, a flow magnitude flow may be used to prevent the further spread of Tamarisk.

Based on the 2011 report by the USBR, the effects HFEs on humpback chub are not expected to significantly change the population of the species. Humpback chub populations were assessed before and after the 2004 and 2008 HFEs. There was a decline in population following the 2004 HFE, but the overall population trend increased throughout the decade. The 2008 HFE did not negatively affect the humpback chub population. Years passed between each HFE from 1996 to 2008. The effects of a more consistent regiment over the long term are unknown.

Historically, the accrued sediment in the Grand Canyon varied seasonally while in a long-term equilibrium. The sediment supplied by the summer monsoons of the Colorado Plateau was washed away by the spring snowmelt flood in May. Now, HFEs control sediment flux through the Grand Canyon in during March, April, October or November. The goal of these floods is to increase sediment in sandbars on the Grand Canyon. As only 6% of the naturally occurring sediment flows through the canyon, will the sandbars ever acquire their previous size? Are these practices sustainable over the course of this century? Or are more dramatic actions, like dredging of Lake Powell, required to maintain the sandbars?

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