The Glen Canyon Dam High Flow Experiments: Lessons Learned and Potential Climate Change Implications

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Introduction

The Glen Canyon Dam was constructed in 1963 and impounds Lake Powell, storing up to 26.2 million acre feet (MAF) per year, making it the second largest reservoir in the United States (Schmit and Schmidt 2011). A major landmark that separates the Upper Colorado River Basin from the Lower Colorado River Basin, the dam provides hydropower to approximately 27 million people in the six states of Wyoming, Utah, Colorado, New Mexico, Arizona, Nevada, and Nebraska (Gao, et al. 2011; Bureau of Reclamation 2019). Although the dam has been a major source of energy and economy to regional stakeholders, it has also affected the downstream hydrological and ecological dynamics in the Lower Colorado River Basin.

One major impact of the Glen Canyon Dam has been the decline of sandbars. Sandbars are ecologically and recreationally significant as they provide habitat to wildlife and a place to camp for visitors. The noticeable loss of these sandbars in the 1970s led to major science and management efforts in the following decades to understand the effects of the dam and sandbar formation. In order to balance the economic and environmental goals, the High Flow Experiments (HFEs) were developed and implemented using an adaptive management approach beginning in the 1990s. Through these HFEs, several lessons have been learned about Glen Canyon Dam's management. However, no HFE has led to a long term solution for sandbar sustainability. High uncertainty surrounding physical stream processes and climate change effects have remained as barriers, calling for the continued strategy of monitoring, evaluation, and adjustment.

This paper aims to understand what the potential climate change implications may be to the Glen Canyon Adaptive Management Program for successful sandbar formation. Although there are several downstream resources that are impacted by the Glen Canyon Dam such as the humpback chub, nonnative trout, and riparian habitat, this paper will focus on the formation and maintenance of sandbars that are ecologically and recreationally significant. To do so, this paper will discuss the history of developing the Glen Canyon Dam management, lessons learned about sandbar formation from three major HFEs, and potential climate change impacts on future HFEs based on existing predictions.

The Evolution of Glen Canyon Dam Management

Sandbars are known to be a major source of wildlife habitat and recreation. They are believed to be used as rearing environments for fish and other wildlife, and serve as camping spots for visitors (Schmit and Schmidt 2011). Sandbar formation is highly dependent on physical processes involving sediment input and hydrologic flow. As water flows down the canyon, it erodes away river bedrock and carries fine sediment like sand downstream. Throughout the river, debris fan formations narrow the channel, which slow down the water and cause it to circulate and deposit sand on the banks of the river. The location where this physical process occurs is known as an eddy area (Fig. 1) (Mueller, et al. 2016).

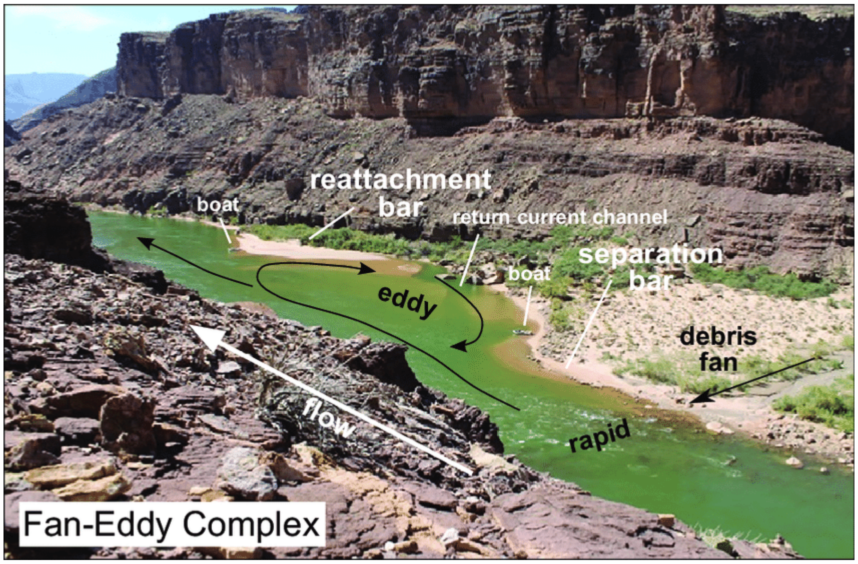


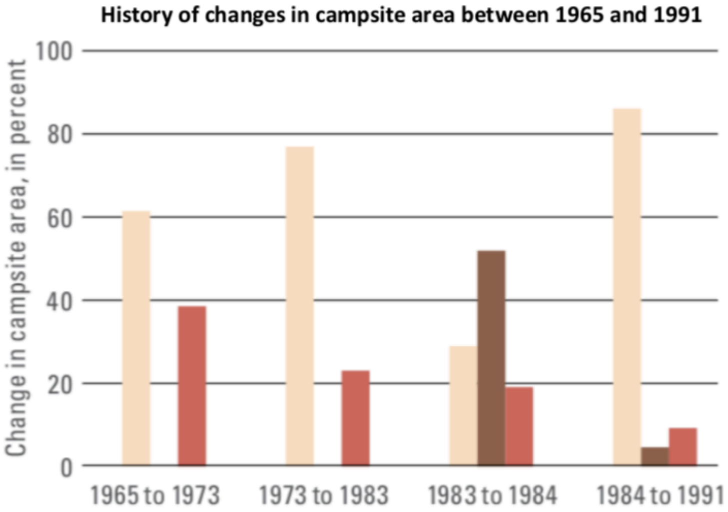
Figure 1 Fan-eddy complex, or an eddy area. Photo from Mueller, et al. 2016.

In 1974, it was recognized that many downstream river sandbars were eroding away following the construction and operation of the Glen Canyon Dam. Scientists began to investigate the effects of the dam on the Lower Colorado River Basin, and learned that sandbar formation processes were significantly altered. Before the dam's construction, the Colorado River exhibited a snowmelt regime with low daily fluctuations and early springtime floods that coincided with Rocky Mountain snowmelt. The snowmelt regime began with precipitation (snow) falling at higher elevations during the winter, and which would melt in the spring with warmer temperatures (National Research Council 2007). Snowmelt flows combined with heavy storm precipitation in April and May resulted in peak flows in June. However, the post-dam studies recognized that the Glen Canyon Dam eliminated the natural flow regime, and spring seasonal flooding was shifted to summer and winter floods with high daily fluctuations that coincided with energy demands around the Colorado River Basin.

In addition to flow, sediment input drastically changed with the dam. Prior to the dam, most of the sediment came from the nearby desert watersheds of the Colorado Plateau and was carried by the main stem of the Colorado River. Before the dam's construction, it was unknown how much of the sediment came from the main stem and how much came from tributaries (Schmit and Schmidt 2011). After the dam, all of the sediment from the main Colorado River became impounded in Lake Powell, which created a major sediment deficit downstream. It is now known that the main stem provided most of the sediment for sandbars. Now, sediment inputs primarily come from the Paria and Little Colorado River tributaries, which are estimated to only contribute about 16% of pre-dam sand supply (Wright, et al. 2005).

Without the two main processes of natural flooding or sediment input, sandbars have shown a net decrease in area since 1965 (Fig. 2). Many of these conclusions about Glen Canyon Dam impacts to sediment and flow arose out of environmental studies that were conducted in the 1970s and 1980s. Initial studies began in the 1970s, but were expedited after 1983 when a major flooding event broke Glen Canyon Dam and released about 100,000 cubic feet per second (cfs).

After this flood, it was observed that many downstream sandbars were restored, highlighting the benefits of flooding on sandbar formation. A series of Environmental Studies were pursued, which contributed to the scientific background about post-dam flow and sand transportation for the 1995 Environmental Impact Statement (EIS). The 1995 EIS was required by the Grand Canyon Protection Act[1] of 1992 to understand the effects to downstream resources (National Research Council 1999) and was a major influence in the development of the HFEs.



Tan = % of sites that remained approximately the same size
Brown = % of sites that increased in size
Red = % of sites that decreased in size

Figure 2 History of changes in campsite area between 1965 and 1991. Records show a net decrease in sandbar area, due to the fact that most sandbars have remained the same or decreased in size. Graph from Schmidt and Grams 2011.

The 1995 EIS proposed nine different alternatives for Glen Canyon Dam management, one of which included the Modified Low Fluctuating Flow (MLFF) protocol. The MLFF protocol proposed to minimize daily fluctuations and provide controlled flooding to mimic pre-dam variability (Martinez and Babbitt 1996). Under this alternative, managers intended to release large amounts of water for short periods of time in the winter and summer seasons (Melis, et al. 2015) with the intent to "rebuild high elevation sandbars, deposit nutrients, restore backwater channels, and provide some of the dynamics of a natural system" (Schmit and Schmidt 2011). During these releases, water would enter the dam turbines and then the bypass tubes, and then be released downstream (Fig. 3). During this process, some of the water would produce hydropower while the rest would be bypassed (Bureau of Reclamation 2019). This strategy aimed to balance the downstream environmental needs with the energy and water delivery needs, and was implemented with the EIS Record of Decision (ROD) in October 1996 (National Research Council 1999).

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[1] Concerns about the dam's impact to downstream resources led to the enactment of the Grand Canyon Protection Act of 1992. This Act intended to protect the Grand Canyon National Park and Glen Canyon National Recreation Area (National Research Council 1999).

Figure 3 Images of the Glen Canyon Dam releasing water through bypass tubes. Images from the US Bureau of Reclamation 2019.

With the decision to pursue the MLFF alternative, managers understood that there was high uncertainty surrounding these releases. To address this, an adaptive management strategy was implemented to allow for continuous improvement in dam management and "learn how to better manage [a] complex and uncertain [system]" (Melis, et al. 2015). The Glen Canyon Adaptive Management Program was developed to implement this strategy by establishing a general framework to monitor and evaluate the results of MLFFs, and adjust future methods based on lessons learned (Fig. 4) (Wright and Kennedy 2011). The Program was comprised of several different actors including an appointed official by the Secretary of the Interior, stakeholder groups, the Grand Canyon Monitoring and Research Center, and panels to provide independent review of the program and documents (National Research Council 1999). Under the Program, three major HFEs were conducted in 1996, 2004, and 2008. All HFEs were monitored and evaluated through downstream gages, surveys, and topographic data to understand their results and extract lessons for subsequent experiments (Schmidt and Grams 2011).

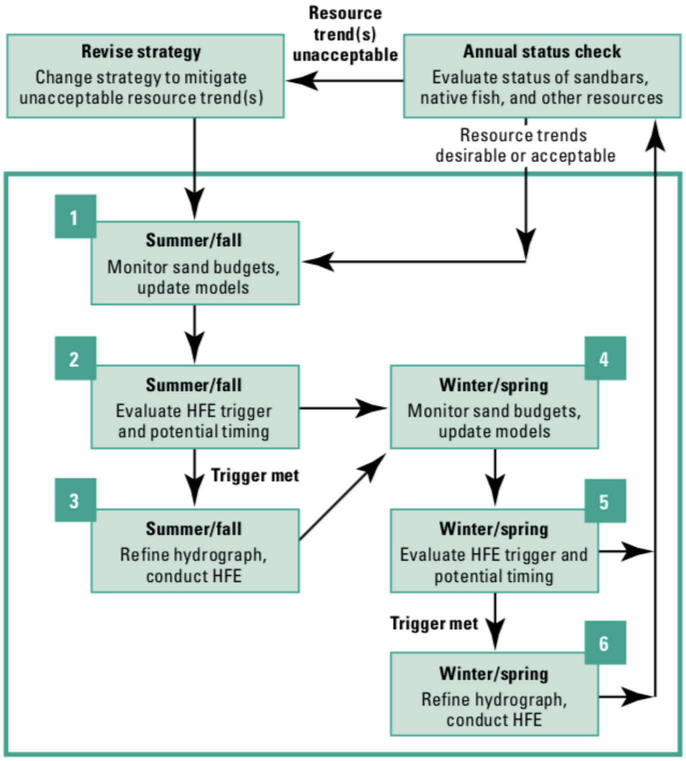

Figure 4 The Program's adaptive management strategy for Glen Canyon Dam management (Wright and Kennedy 2011).

The Development of High Flow Experiments and Lessons Learned

Three major controlled floods occurred in March 1996, November 2004, and March 2008. The first release in 1996 implemented the original MLFF protocol that aimed to mimic pre-dam variability through controlled flooding in the winter and summer. One major assumption of this protocol was that sand from tributaries accumulated in the channel bed and was available for redistribution at any time. Under this assumption, it was believed that flooding at any time would redistribute that sand and build sandbars (Schmit and Schmidt 2011). Results from the 1996 MLFF demonstrated that high flows could build sandbars, but also that they quickly eroded away within a few days (Fig. 5). Additionally, scientists discovered that the assumptions about sand availability in the 1995 EIS were incorrect. Sand was not available for redistribution at any time, and flooding without recent sand input caused the primary source of sediment to come from the lower portions of existing sandbars. As a result, many sandbars became higher and not wider (Melis and Ralston 2011) and did not increase in overall size.

Recognizing that sand did not exist indefinitely in the main channel until disturbed, managers proposed to time subsequent controlled releases immediately following tributary flooding so that flows would be released immediately after sand was deposited in the channel bed (Wright, et al. 2005). This decision led to a shift from winter and summer releases under the MLFF protocol to fall and spring releases that followed summer and winter tributary sand inputs. These timed releases were implemented in November 2004, and became known as the High Flow Experiments (HFE) (Melis, et al. 2015). After the 2004 HFE, scientists learned that timed releases were the most effective method of increasing the area and volume of sandbars, and replicated this strategy in 2008. The 2008 HFE followed abnormally high amounts of sand input and produced much larger sandbars than 2004, but also reconfirmed the benefits of timed HFEs (Fig. 6).

Some of the primary lessons learned from the 1996, 2004, and 2008 HFEs were (1) that HFEs are effective at developing sandbars, (2) that HFEs are most effective when timed with tributary floods, and (3) that sandbars will continue to erode if HFEs aren’t repeated (Wright and Kennedy 2011). Erosion continues to be a problem, but timed HFEs are still currently the primary strategy for these controlled releases (Schmit and Schmidt 2011). Many of these lessons were incorporated into the most recently updated 2016 Long-Term Experimental and Management Plan (LTEMP), which continues to use an adaptive management strategy while incorporating new data and information. The LTEMP provides a release protocol for the next 20 years, and continues to call for spring and fall releases after seasonal tributary flooding (Department of Interior 2016). The first HFE under the new management plan was conducted in November 2018, and results still appear to be under analysis (Department of the Interior 2016).

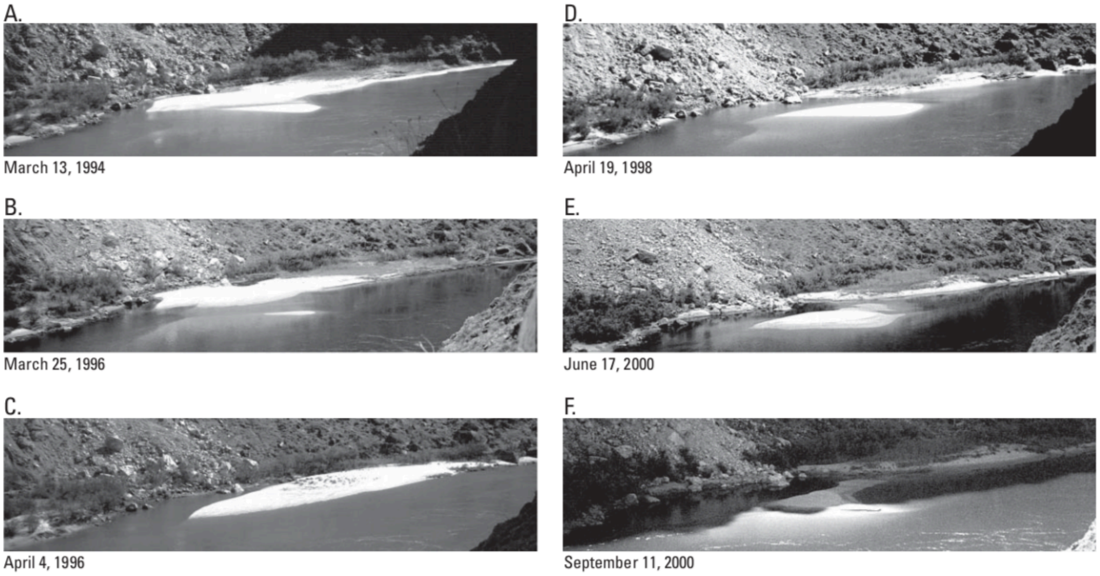

Figure 5 Photos taken before, during, and after the 1996 MLFF. Photos are taken at Eminence Break (Wright, et al. 2005).

Figure 6 Before and after photos of the 1996, 2004, and 2008 HFEs at river mile 22. The sandbar is getting progressively larger over time. Photo from Schmidt and Grams 2011.

Table 1 A comparison of the March 1996, November 2004, and March 2008 HFEs. Information derived from Melis, et al. 2010; Melis and Ralston 2011; Schmit and Schmidt 2011.

	March 1996	**November 2004**	**March 2008**
Peak cfs	7 days @ 45,000 cfs	60 hours @ 41,700 cfs	60 hours @ 42,800 cfs
What changed		Shorter duration, timed with tributary inputs	Relatively similar methods, unusually high sand 2006 and 2007
Results	(+) Sandbars were built! (-) Sandbars were higher; not wider (-) Sandbars eroded quickly	(+) Sandbars increase in area and volume	(+) Sandbars increase in area and volume
Lessons learned	• High flows can build sandbars • Sandbars erode within a few days • 1996 EIS was wrong • Sand supply was from lower portions of existing sandbars	• Timed HFEs are effective at increasing area and volume of sandbars	• Reconfirmed that timed HFEs are most effective at increasing area and volume of sandbars
Proposed changes	Time HFEs with tributary inputs	Continue with timed HFEs	Continue with timed HFEs
Additional considerations	• Sand inputs were low this year • EIS based on lack of data		• Sand inputs were unusually high in 2006 and 2007

Climate Change Implications

Although several lessons have been learned from past HFEs, there is still a high level of uncertainty surrounding HFEs that has limited the ability to produce a long-term solution to sandbar maintenance. Managers still do not fully understand stream dynamics, including understanding when sand inputs will occur, how often they will occur, and how much sand will be produced (Wright and Kennedy 2011). Additionally, climate change is a major source of uncertainty for future water availability. Most evidence suggests that climate change will decrease overall water availability through changes in precipitation patterns, temperature increases, and future droughts in the Colorado River Basin (Udall and Overpeck 2017, Milhous 2005). HFEs are dependent on water supply for sediment availability and transport, so it can be assumed that HFEs will be sensitive to changes in water availability. Therefore, it is important to consider predictions of climate change patterns to understand how future HFEs may change in their effectiveness and timing.

Precipitation

Precipitation from storms is considered a major contributor to lower basin runoff because it is at a relatively lower elevation and is relatively hotter. The upper basin, by contrast, is at a higher elevation and is more heavily influenced by snowmelt runoff in the main steam of the Colorado River (National Research Council 2007). Since the lower basin is reliant on precipitation for tributary runoff, it is important to understand what future precipitation patterns are predicted. However, future precipitation patterns demonstrate the most inconclusive patterns under climate change projections. The Colorado River Basin naturally experiences high variability in precipitation, and significant trends in precipitation patterns have not been exhibited in the last 110 years (National Research Council 2007). Some studies suggest that precipitation is expected to increase by 2.1% in the upper basin and decrease by 1.6% in the lower basin by 2050 (Bureau of Reclamation 2011), but most do not see a conclusive pattern (Fig. 7) (National Research Council 2007). Furthermore, there is no conclusive information on how decreased precipitation will affect flows or sediment transport in the Grand Canyon. While some studies have found no significant relationship exhibited between changes in precipitation and sediment transport (Milhous 2005), other studies suggest that sediment transport capacity will be negatively affected by decreased water availability (Bureau of Reclamation 2019).

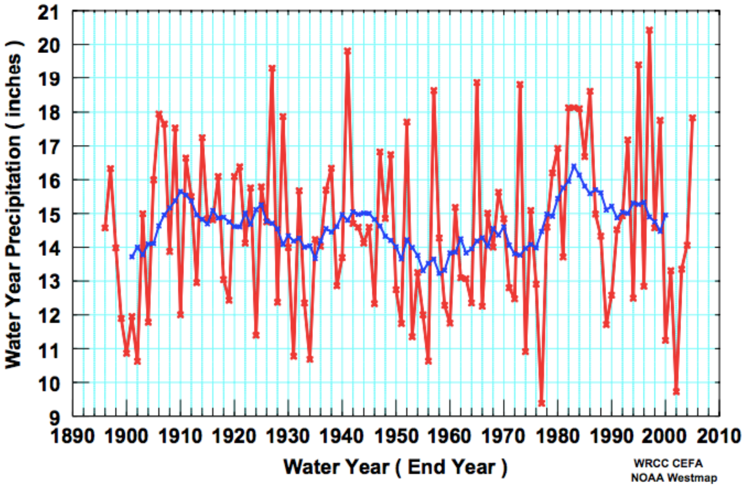

Figure 7 "Annual precipitation for the Colorado River basin above Lees Ferry, 1895-2005" (National Resource Council 2007). No clear patterns are exhibited in the last 110 years.

Temperature

The last 100 years have demonstrated a steady increase in temperature, and temperatures are expected to continue to increase throughout the entire Colorado River Basin (National Research Council 2007, Bureau of Reclamation 2011). Warmer temperatures can negatively affect water availability through faster evaporation rates, shifts in precipitation patterns, shifts in snowmelt patterns, and less overall snow availability (National Research Council 2007). Furthermore, each of these scenarios under higher temperatures will likely have a cascading effect on the stream system. For instance, higher temperatures may lead to more evaporation in reservoirs and streams, which may decrease overall storage and surface water availability, and decrease tributary runoff.

Higher temperatures may also cause a shift in seasonal runoff patterns. Harmer temperatures will likely cause less snowfall at higher elevations, which will increase overall albedo and decrease the ability of the surface to reflect heat, which will increase the ability of the ground to absorb heat and accelerate the rate at which snow melts. This process may lead to earlier snowmelt, which may shift patterns of the main Colorado River's runoff and flooding from spring to winter (National Research Council 2007).

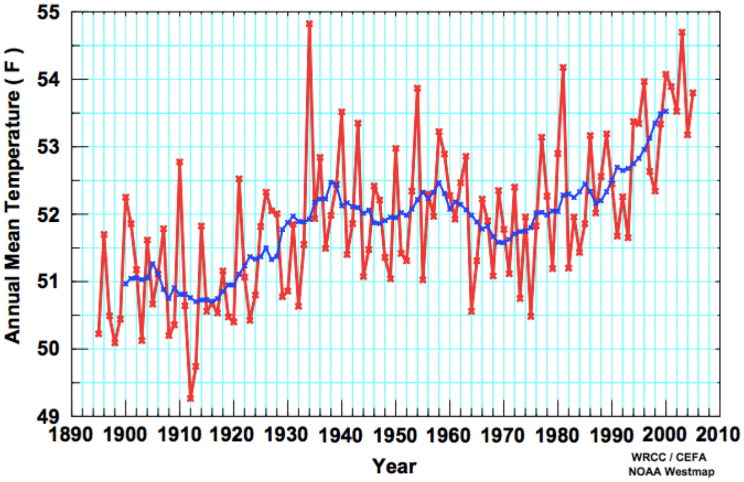

Figure 8 "Annual average surface air temperature for [the] entire Colorado River basin, 1895-2005" (National Research Council 2007).

Drought

Droughts are anticipated to get longer and more intense with climate change. Although precipitation and temperature have variable projections, records show that more prolonged and hotter droughts have occurred more frequently in the past several decades. There is even potential risk of megadroughts, which are multi-decadal droughts that would severely decrease overall water availability to the region (Udall and Overpeck 2017). Even under the former scenario, prolonged droughts are projected to decrease overall water availability and lead to decreases in reservoir storage and surface water availability due to increased evaporation rates, less frequent precipitation, and decreased runoff.

Although there is still a high amount of uncertainty with climate change, the predictions for precipitation, temperature, and drought all seem to point towards an overall hotter and drier climate in the Colorado River Basin. While more localized regions of the basin will likely exhibit different patterns, there appears to be consistency in decreased runoff and flow in the basin. Some predict average annual runoff to decrease by 8.5% by 2050 (Bureau of Reclamation 2011) and others predict flow decreases between 5 and 45% by 2050 (Belnap and Campbell 2011). Because the HFEs are dependent on flows for sediment transport, it seems reasonable to assume that climate change will have a negative impact on HFEs and on sandbar formation. Decreased water availability might decrease runoff and flows, which may therefore decrease the potential for sediment transport, and decrease the effectiveness of HFEs on sandbar formation.

Additionally, changes in precipitation patterns may change the timing of HFEs. Lower basin tributary flooding in the Paria and Little Colorado are more heavily influenced by precipitation events, and have appeared to consistently occur in the winter and the summer. Although future precipitation patterns are the most unpredictable, patterns are expected to shift which will likely change the timing of tributary flooding, and therefore change the timing of HFEs. The Bureau of Reclamation believes that HFEs are expected to occur more frequently in the fall than the spring, due to some predictions of decreased spring precipitation (Bureau of Reclamation 2019).

Conclusion

There is currently no long-term solution to sandbar sustainability, and managers are continuously faced with the uncertainty of understanding physical stream processes and climate change. The HFEs in 1996, 2004, and 2008 were able to teach Glen Canyon Dam managers the importance of timed, repeated floods for sandbar maintenance, but there is still a high amount of uncertainty surrounding HFEs especially under climate change projections. There is inconclusive evidence on how precipitation, temperature, and drought changes will affect water availability. However, there seems to be a strong prediction of overall decreased water availability in the future. While there are other factors that influence the success of HFE on sandbar formation, it can be inferred that future changes in water availability alone will likely have an impact on the effectiveness and timing of HFEs. Furthermore, anticipated population growth will likely exacerbate some of the climate change impacts. Increased population may lead to more greenhouse gas emissions that contribute to climate change, and higher need for water may create a gap between supply and demand. All of these projections are still unpredictable, and with this much uncertainty it is important for managers to continue to maintain a flexible and adaptive management approach. It is necessary for managers to continue to monitor, evaluate, and adjust HFEs to improve strategies. The Glen Canyon Dam Adaptive Management Program will therefore need to maintain flexible, adaptive management to maximize economic and environmental goals for the wildlife and people of the Lower Colorado River Basin.

References

1. Belnap J and Campbell DH. (2011). Effects of climate change and land use on water resources in the Upper Colorado River Basin. United States Geological Survey. Retrieved from https://permanent.access.gpo.gov/gpo20877/FS10-3123.pdf
2. Bureau of Reclamation. (2011). Retrieved from https://www.usbr.gov/climate/secure/docs/2011secure/factsheets/coloradobasinfactsheet.pdf
3. Bureau of Reclamation. (2019). Glen Canyon Dam High Flow Experimental Release. Retrieved from https://www.usbr.gov/uc/rm/gcdHFE/index.html
4. Bureau of Reclamation. (2019). Glen Canyon Unit. Retrieved from https://www.usbr.gov/uc/rm/crsp/gc/
5. Department of the Interior. (2016). Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan Environmental Impact Statement. Retrieved from http://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf
6. Gao Y, Vano JA, Zhu C, Lettenmaier DP. (2011). Evaluating climate change over the Colorado River basin using regional climate models. *Journal of Geophysical Research,* Vol. 116, D13104. DOI: 10.10.1029/2010JD015278
7. Martinez EL and Babbitt B. (1996). Record of Decision Operation of Glen Canyon Dam Final Environmental Impact Statement. Retrieved from https://www.usbr.gov/uc/envdocs/rod/Oct1996_OperationGCD_ROD.pdf
8. Melis TS, Walters CJ, Korman J. (2015). Surprise and opportunity for learning in Grand Canyon: the Glen Canyon Dam Adaptive management Program. *Ecology and Society*: 20(3): 22
9. Melis TS and Ralston BE. (2011). Three experimental high-flow releases from Glen Canyon Dam, Arizona – Effects on the downstream Colorado River ecosystem. *US Geological Survey*.
10. Melis TS, Topping DJ, Grams PE, Rubin DM, Wright SA, Draut AE, Hazel JE Jr., Ralston BE, Kennedy TA, Rosi-Marshall E, Korman J, Hilwig KD, Schmit LA. (2010). 2008 High Flow Experiment at the Glen Canyon Dam benefits Colorado River resources in Grand Canyon National Park. USGS. 2010. Retrieved from https://pubs.usgs.gov/fs/2010/3009/fs2010-3009.pdf
11. Milhous RT. 2005. Climate change and changes in sediment transport capacity in the Colorado Plateau, USA. *Sediment Budgets 2*. Retrieved from https://iahs.info/uploads/dms/13077.39%20271-278%20Foz%20S12-23%20Milhous.pdf
12. Mueller ER, Grams PE, Hazel JE, Schmidt J. (2016). Variability of eddy sandbar response during two decades of controlled flooding along the Colorado River in the Grand Canyon. *Sedimentary Geology*: 363(2018): 181-199.
13. National Research Council. (1999). Downstream: Adaptive management of Glen Canyon Dam and the Colorado River ecosystem. Washington, DC: The National Academies Press. https://doi.org/10.17226/9590
14. National Research Council. (2007). Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability. Washington, DC: The National Academies Press. https://doi.org/10.17226/11857.

15. Schmidt JC and Grams PE. (2011). The high flows – Physical science results. Melis TS. Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from the Glen Canyon Dam, Arizona. (pp. 53-92).
16. Schmidt JC and Grams PE. (2011). Understanding physical processes of the Colorado River. Melis TS. Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from the Glen Canyon Dam, Arizona. (pp. 17-52).
17. Schmit LM and Schmidt JC. (2011). Introduction and overview. Melis TS. Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from the Glen Canyon Dam, Arizona. (pp. 1-16).
18. Wright KK, Baxter CV, Li JL. (2005). Restricted hyporheic exchange in an alluvial river system: implications for theory and management. *Journal of the North American Benthological Society*: 24: 447–60.
19. Wright SA and Kennedy TA. (2011). Science-based strategies for future High-Flow Experiments at Glen Canyon Dam. Melis TS. Effects of Three High-Flow Experiments on the Colorado River Ecosystem Downstream from the Glen Canyon Dam, Arizona. (pp. 127-147).
20. Udall B and Overpeck J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*: 53(3): 2404-2418. https://doi.org/10.1002/2016WR019638