Responses of fish to high flow experiments in the Grand Canyon

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Summary

Organisms found within streams and rivers often rely on seasonal flooding activities for nutrients, habitat creation, and increased turbidity. Dams present an opportunity to examine the effects on organisms in response to decreased seasonal flooding. Here, I will focus on the Glen Canyon Dam found in the Grand Canyon. Of particular concern downstream of the dam are endangered native fish species that also interact with non-native fish. Recently, High Flow Experiments have been used as an attempt to restore natural flooding to the area. The primary objective of the flow experiments is to increase sandbar size downstream of the dam. In addition, the experiments have had mixed results with non-native fish increasing in population size after the events. Native fish have seen declines after some of these flood experiments. This has largely been attributed to increased predation from non-native fish and decreased water temperatures. Separating direct versus indirect effects of these experiments and other management tactics is difficult. Managers will need to continue examining the effect of such flood experiments on native fish. In addition, managers may need to adjust the timing or magnitude of flood experiments to reduce adverse effects on native fish.

Keywords: high flow experiment, Grand Canyon, adaptive management, Humpback chub

Introduction

Streams and rivers are dynamic landscapes for the organisms that live within them (Poff et al. 2016). This is exemplified with seasonal flooding events that occur in many river systems. During these events, a number of river processes are affected, which can in turn affect the species living there. For instance, seasonal flooding can increase sedimentation, alter water flow, create new habitat, and deliver nutrients downstream (Poff et al. 2016). These processes can in turn affect various species and ecosystem level processes. For instance, increased nutrient load can increase primary productivity that can then support more consumers. Native species found in these rivers have evolved to handle natural flooding events. Adaptations can include the use of different sensory organs for hunting, streamlined body-shapes, and life history events (e.g. reproduction) timed to take advantage of flooding events (U.S. Fish and Wildlife 2017). In addition, long lifespans and breeding more than once can act as a way for organisms to handle variability in environmental conditions from year to year (Lawson et al. 2015).

Man-made dams present an opportunity to examine the effects of reduced, or absent, seasonal flooding events. Globally, around 58,000 dams are used to regulate water flow for a variety of reasons (Poff et al. 2016). Dams can be important for flood management, storing water, generating hydropower, and creating recreational opportunities (Poff et al. 2016). In addition, these dams can have a number of effects on ecosystems downstream by fragmenting habitat and altering natural river flows. Dams can be particularly harmful to nearby fish populations. Dams can alter seasonal flows which affects water temperature, sediment and nutrient delivery downstream, and the availability of habitat. Often these changes can benefit non-native fish while adversely affecting native fish species evolved for seasonal flooding ecosystem (Yard et al. 2011).

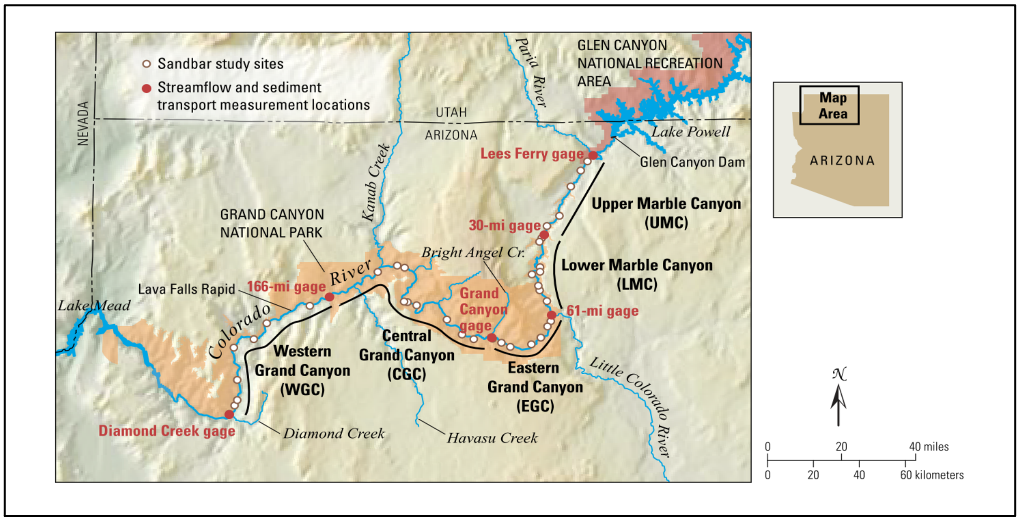

Figure 1: Map of the Grand Canyon, from Schmit & Schmidt 2011

For example, suspended sediment can be important to protect certain species from sight-adapted predators (Yard et al. 2011). There are numerous other factors that can directly or indirectly affect fish, including changes to their prey community, effects on other interacting species, and harvesting by humans—all of which may be affected by the presence of a dam. Therefore, important consideration should be made regarding the multiple objectives of dams.

Grand Canyon

The focus of this paper will be on the Glen Canyon Dam on the Colorado River northeast of the Grand Canyon (Schmit & Schmidt (2011), Fig. 1). The dam was completed in 1963, creating the Lake Powell reservoir (Melis 2011; Schmit & Schmidt 2011). The dam was originally constructed to store water and generate hydropower in response to growing human populations nearby. Prior to the building of the dam, it was not unusual to have flooding events that moved water at 120,000 cubic feet per second (Fig. 2). Most of these flooding events occurred in spring or summer after snowmelt. Consequently, the flooding events transported a lot of sedimentation downstream. The sedimentation helped maintain large sand and gravel bars downstream. These large sandbars create habitat for terrestrial organisms and allow for backwater areas (i.e. areas of reduced flow) that are used by some aquatic species. Backwater areas allow for pockets of lower water flow and can sometimes serve as a refuge from predators (Dodrill et al. 2016). In addition, large flood events scoured river banks and removed vegetation (Cross et al. 2011). These events can also important for fish egg laying. First, fish require beds of heavier gravel in the river to lay their eggs in; the types of gravels required are held back by the dam. And second, silt can deposit within the space between river bed gravel (i.e. the hyporheic zone). With no large flooding events to remove this silt, fish cannot lay their eggs; therefore, a suite of environmental conditions must be met for suitable spawning habitat (Yao et al. 2015).

The dam has greatly reduced seasonal flooding activity, decreased water temperatures, and decreased water turbidity (Schmidt & Grams 2011). There is still some variation in flooding activity, but no where near pre-dam levels (Fig. 2). In addition, water temperatures have decreased as water that moves through the dam is drawn from the bottom of Lake Powell. Sedimentation is also blocked by the dam, creating clear waters just below. This has greatly altered natural river hydrology. Altered river hydrology has, in turn, affected ecosystems downstream of the dam (Kennedy & Ralston 2011). Although the dam has effects on a number of species, I will focus on native and non-native fish in this report.

Fish of the Grand Canyon

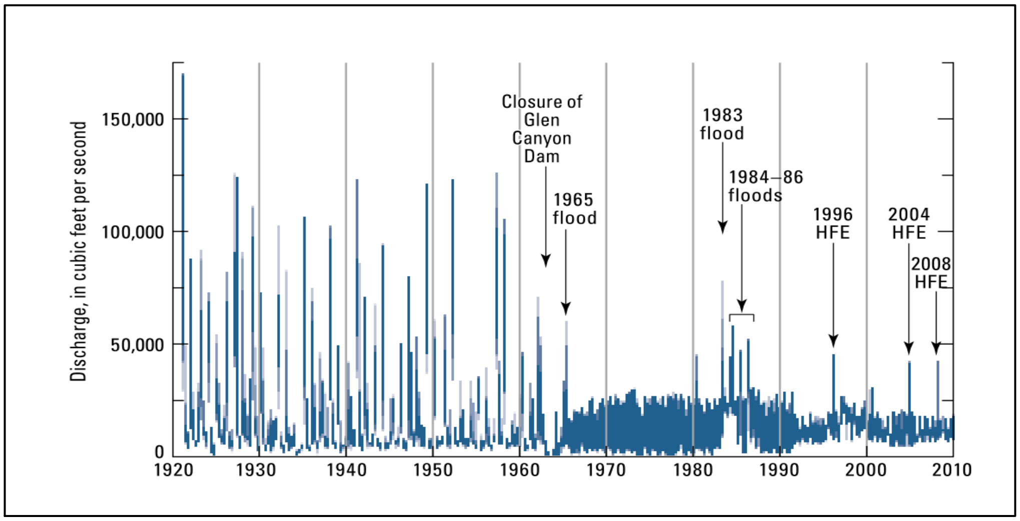

Figure 2: Historical discharge amount on the Colorado River. Timing of dam construction and recent high flow experiments are also denoted. Taken from Melis et al. 2011

There are eight species of native fish found in the Grand Canyon. Since the Glen Canyon dam was built, four of these species have been listed as endangered: the Humpback chub, bonytail chub, razorback sucker, and Colorado pikeminnow (U.S. Fish and Wildlife 2017). However, only the Humpback chub and razorback sucker are still found in the Grand Canyon. Native Grand Canyon fish evolved in warmer and more turbid water than that currently downstream of the dam. There are particular concerns regarding the Humpback chub as only six populations of the species remain in the Colorado River basin (U.S. Fish and Wildlife 2017). These populations have generally continued to decline since the species was originally listed as endangered in 1967. The razorback sucker was listed as endangered federally starting in 1991. There are no established populations of the razorback sucker remaining in the Grand Canyon. However, some young individuals were found in 2014, giving biologists hope that a population could re-establish (U.S. Fish and Wildlife 2017). Each of these endangered species has formal recovery plans. However, none of them appear close to being downgraded or delisted from the endangered species list (U.S. Fish and Wildlife 2017). There are several actions currently being taken to recover at least the Humpback chub populations including:

- managers monitor population numbers throughout the Grand Canyon
- non-native fish removals (Yard et al. 2011)
- habitat restoration efforts
- water flow management from the Glen Canyon Dam

There are around 13 species of non-native fish in the Grand Canyon as well. The most prominent of which is the rainbow trout (*Oncorhynchus mykiss*), which provides an important sport fishery near Lee's Ferry (U.S. Fish and Wildlife 2017). Many of these non-native fish species thrive in cold and clear water, the exact conditions created by the Glen Canyon Dam. Some limited removal efforts of rainbow trout have occurred in the past, but these have not been consistent (Yard et al. 2011).

Rainbow trout and other non-native fish compete with native fish for resources. In addition, rainbow trout are known predators of juveniles of native fish species (Yard et al. 2011; Dodrill et al. 2016). Rainbow trout are sight-predators meaning they need clear water to find their prey. Given the clear waters below the Glen Canyon dam, juvenile native fish are more susceptible to predation pressures (Kennedy2011; Dodrill et al. 2016). Combined with other stressors (e.g. modified temperature and flow regimes), the pressures imposed on native fish by rainbow trout make interpretation of population trends over time more difficult (Fig. 4).

High flow experiments

Grand Canyon managers have to balance many objectives when considering any changes to their efforts. These objectives include hydropower production, native fish recovery, sport fishery development, recreation activities, and cultural resources (Melis 2011). However, it is not always clear ahead of time how a particular management action will affect each objectives. For these reasons, an adaptive management approach was established in the Grand Canyon (Melis et al. 2016). As part of the Grand Canyon Adaptive Management program, management agencies are supposed to monitor and experiment with new management strategies (Melis et al. 2015). This allows for a more dynamic management strategy that can evolve over time as managers learn from past efforts.

One major area of concern is the lack of natural, seasonal flooding that has occurred since the Glen Canyon dam was completed (Fig. 2). Although "seasonal flooding" may still occur, it is only around one-tenth historical records (Fig. 2). In response, managers have used High Flow Experiments (HFEs) to try and simulate natural flooding events (U.S. Bureau of Reclamation 2011). A HFE is a short-term release of water (usually between 3-7 days) from the Glen Canyon Dam. Through this process managers release on the order of 40,000 cubic feet per second (Melis 2011). Importantly, a HFE releases not only water, but they can also move sedimentation from tributaries downstream. In fact, increasing sedimentation in order to increase sandbar size below the dam is the primary objective of the HFEs. Improving the health of aquatic ecosystems is only a secondary objective (U.S. Bureau of Reclamation 2011).

Accidental flooding occurred between 1983 and 1986 (Fig. 2). The first intentional HFEs occurred in 1996 and 2004 (Melis 2011). Both of these had the primary objective to rebuild sandbars. Therefore, neither focused particular scientific effort towards better understanding the HFE's effect on aquatic organisms (Melis 2011). Both of these experiments showed potential for rebuilding of sandbars downstream. I will focus here on more recent HFEs that explicitly examined effects on both native and non-native fish populations.

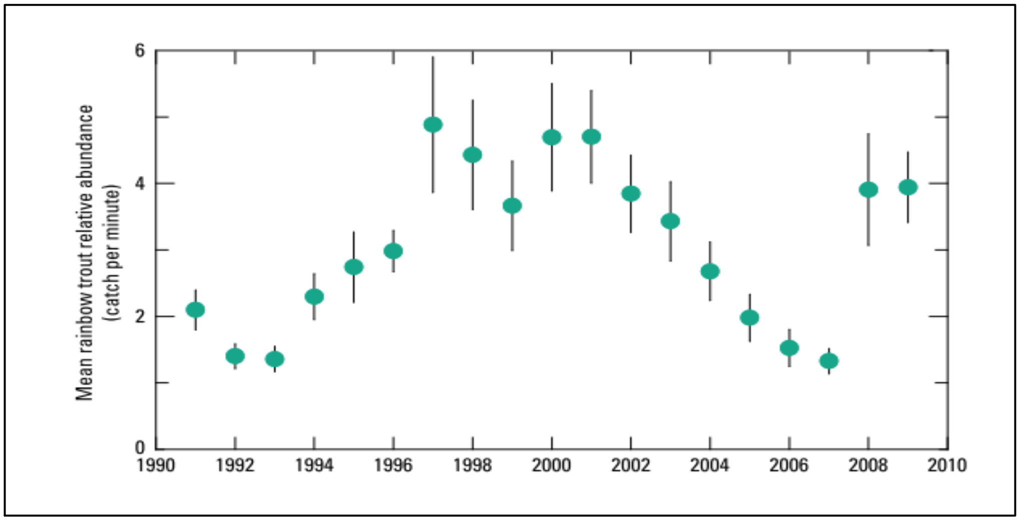

Figure 3: Catch per minute for rainbow trout over time within the Grand Canyon. Taken from Kennedy & Balston 2011.

The High Flow Experiment in 2008 is perhaps the best studied example in the Grand Canyon (Kennedy & Ralston 2011). A great deal of effort when into the planning of the experiment and evaluating its impacts of increased flow and sedimentation. Again, the primary objective of the 2008 HFE was to increase the size of sandbars downstream of the Glen Canyon dam. However, more emphasis was also placed on secondary objectives like aquatic ecosystem health, protecting cultural resources, and improving recreational activities (Kennedy & Ralston 2011). Here, I focus on the non-native rainbow trout and the native, endangered Humpback chub.

After the 2008 HFE, rainbow trout catch increased over 800 percent (Fig. 3). Generally, rainbow trout populations increased throughout the Grand Canyon, but the largest increases were just below the Glen Canyon dam (Korman2011; Kennedy & Ralston 2011). This was largely attributed to better habitat quality for juvenile rainbow trout. Following the HFE, survival rates of juvenile rainbow trout were around four times higher than expected (Korman2011; Kennedy & Ralston 2011). The increased survival rates may have resulted from increases in aquatic insect populations or improved habitat conditions (Kennedy & Ralston 2011). It is important to note that the 2008 HFE occurred in spring, which likely contributed to the beneficial effects on rainbow trout. Subsequent modeling studies have confirmed that HFEs should improve juvenile rainbow trout habitat quality (Yao et al. 2017). Importantly, this modeling work also demonstrated that different life stages may be affected by different aspects of the HFE. For example, juvenile rainbow trout are strongly affected by water depth, but spawning rainbow trout were affected by bed elevation (Yard et al. 2011). Modeling efforts can also explore how different attributes (e.g. duration, timing, or magnitude) of HFEs may affect fish populations (Yao et al. 2015).

The 2008 HFE was predicted to either have a positive or no effect on Humpback chub. This was hypothesized as the flow could create backwater habitat behind sandbars which could be used by Humpback chub (Melis 2011). However, the HFEs could also drop water temperatures or increase flow velocity potentially killing fish. Kennedy & Ralston (2011) argue that it is difficult to understand how the 2008 HFE affected Humpback chub. There are a number of indirect and direct factors that can drive Humpback chub populations, making inference difficult (see Fig. 4 and Cross et al. (2011)). Further, the long lifespans of Humpback chub indicate a number of years sampling post-HFE is needed. In addition to the processes described in Fig. 4, other management actions (e.g. non-native fish removals) will also affect interpretation of HFEs. Unfortunately, Kennedy & Ralston (2011) do not present strong evidence either way regarding the Humpback chub in the Grand Canyon. Kennedy & Ralston (2011) argue that, although there may be effects on the Humpback chub, the effects are probably not long-lasting.

Recent high flow experiments

In response to prior high flow experiments the Bureau of Reclamation designed and has implemented a new protocol from 2011 to 2020 (U.S. Bureau of Reclamation 2011). Unlike past work, the plan explicitly acknowledges the primary risks to Humpback chub resulting from a HFE including:

1) displacement of young fish downstream
2) short-term reduction in habitat availability
3) short-term reduction in food supply, but potential long-term increases
4) increased predation rates with larger rainbow trout populations

However, the report concludes that “these effects are not expected to be of sufficient magnitude to negatively impact the overall population of Humpback chub”.

The 2011 to 2020 HFE protocol is different from past flow experiments. It has the goal of conducting more frequent, possibly twice a year, releases in order to increase sandbar size (U.S. Bureau of Reclamation 2011). Sandbars tend to decay quickly, so the hope is that more frequent releases will help maintain their size. It is not known how native fish may respond to more frequent releases. Further, the specific timing of releases may be important with spring releases potentially more harmful to Humpback chub (U.S. Bureau of Reclamation 2011). Given that Humpback chub evolved in an environment with spring flooding, we might expect spring HFEs would be beneficial. However, it appears that the spring flow experiments are particularly effective at increasing the survival rates of young non-native trout—indirectly harming Humpback chub (Kennedy & Ralston 2011). This again highlights the difficulty of separating direct and indirect effects on native fish.

Since 2011, HFEs have been conducted 2012, 2013, 2014, and 2016. Unlike past HFEs these have the potential to interact with one another depending on their frequency and magnitude. In other words, HFEs are not independent of one another. The new HFE plan has also proposed conducting larger flow experiments (U.S. Bureau of Reclamation 2011). Unfortunately, and perhaps surprisingly, analyses of more recent HFEs (since 2011) have either not been conducted or are not accessible online. I was not able to obtain raw monitoring data online despite extensive searches.

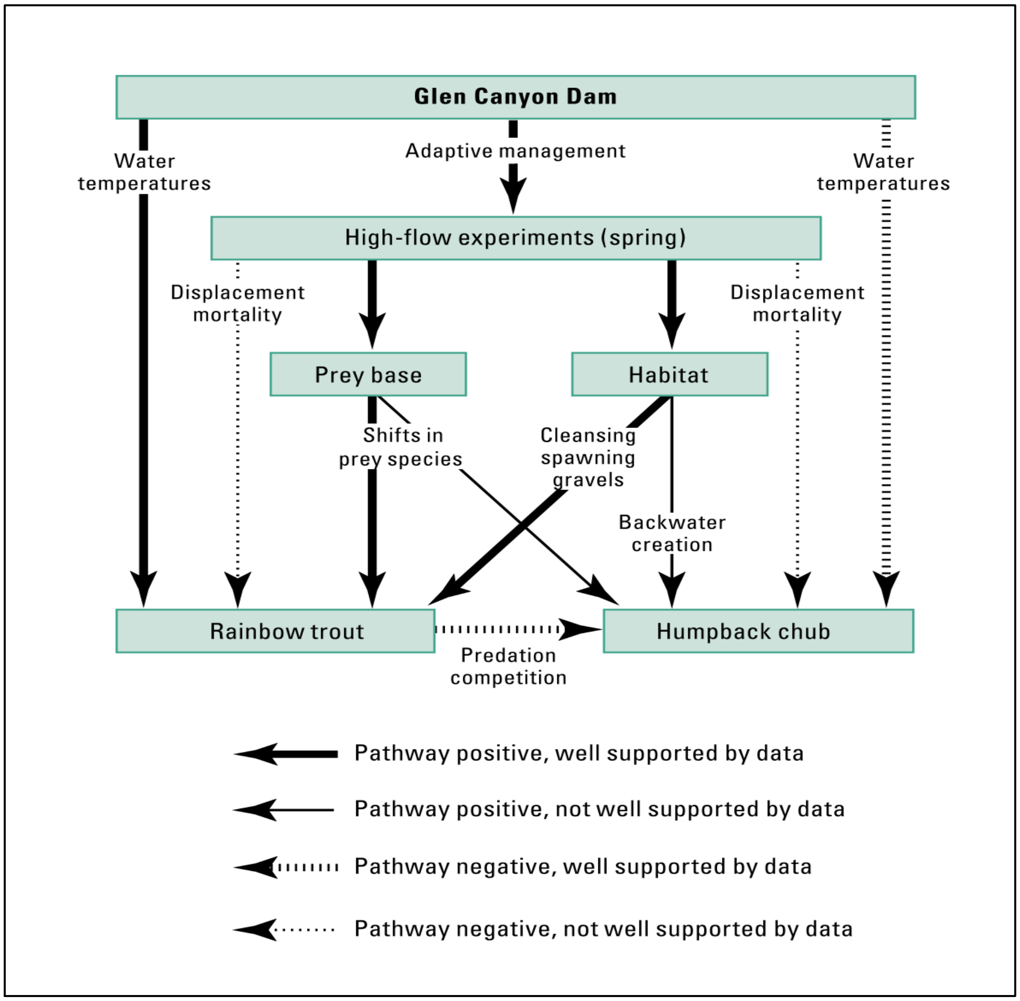

Figure 4: Flowchart of how both a high flow experiment and other natural and human pressures may affect both native and non-native fish. The chart also illustrates which processes are well understood. Taken from Kennedy & Balston 2011.

Flow experiments at other dams

High flow experiments have also been used in other places to restore natural flooding events. Olden et al. (2014) reviewed 113 flow experiments in 20 different countries, including those described in the Grand Canyon. They stressed the importance of clear objectives for HFEs: "When clear objectives were articulated prior to conducting flow experiments (i.e. objectives that included an explicit statement of expectations and/or hypotheses), experiments were twice as likely to achieve their stated objectives as compared to flow experiments without clearly articulated objectives". The objectives for the Glen Canyon HFEs are clear with respect to sandbar rebuilding, but less clear for native fish recovery plans.

In looking to the future, Olden et al. (2014) stress the need to experiment with different types of HFEs. They found that most flow experiments (around 80%) focused on discrete flooding events. They contrast this to actually restoring a flow regime resembling natural flows. Importantly, around three-quarters of flow experiments explicitly recorded abiotic and biotic responses. In addition, HFE rarely manipulate temperature profiles. Olden et al. (2014) argue that future HFEs should manipulate flow types and temperature, especially if an objective is related to ecological processes.

Decision analysis of flow experiments

In order to determine when and if a high flow experiment should be used, a proper decision analysis has to be developed. Essentially, this would break down how a particular high flow experiment would affect the numerous objectives within the Grand Canyon. A decision analysis would use simulation-based models to understand how a high flow experiment may affect processes directly and indirectly (Alexander et al. 2006; Yao et al. 2015). The difficulty is in building and parameterizing such a model, even if the model is greatly simplified (White et al. 2014). For fish alone, you would need to understand all the processes in Fig. 4 and how they specifically affect longterm population dynamics of fish. This is complicated by factors like environmental variability which makes it difficult to predict how a high flow experiment may affect fish in any particular year. For instance, Alexander et al. (2006) describes a decision analysis for using flow experiments to manage mountain whitefish (*Prosopium williamsoni*) in the Columbia River. In order to determine the optimal amount of water to release, they had to build a model combining both fish ecology and river hydrology. They had to run a number of simulations to account for the great uncertainty in these models. With a better understanding of key abiotic and biotic processes within the Grand Canyon, a detailed decision analysis could be conducted before any high flow experiment (Alexander et al. 2006).

Future recommendations and need for research

Grand Canyon managers appear committed to high flow experiments at least until 2020 (U.S. Bureau of Reclamation 2011). Depending on specific sediment and water levels, these experiments will continue every one or two years. The primary purpose of these experiments is to rebuild sandbars downstream of the Glen Canyon Dam. Native wildlife are only of secondary concern. However, under the Endangered Species Protection act, managers must consider the needs of federally-listed species like the Humpback chub. This is also enshrined in 1992 Grand Canyon Management Act (U.S. Bureau of Reclamation 2011). A careful balance between objectives will need to be considered.

In 2020, managers will reassess how high flow experiments are carried out. Research efforts will continue to evaluate their effect both on abiotic and biotic factors. This is important as each high flow experiment costs between $3-4 million dollars (Olden et al. 2014). Before 2020, it is critical to better understand their effects on native wildlife. Unfortunately, the effects of these flows on species like the endangered Humpback chub are not well-established. Initial evidence, however, suggests that Humpback chub, and other native species, may be adversely affected by the experimental flows. The Grand Canyon Adaptive Management program allows managers to "learn by doing" (Melis et al. 2016). The high flow experiments might be a useful component of a manager's toolbox—more research is needed to determine their effect on the many objectives within the Grand Canyon (Melis et al. 2016). As Melis et al. (2016) point out, we have a better understanding of HFE effects on some processes (e.g. sandbar rebuilding) versus effects on wildlife (e.g. endangered species recovery). Moving forward, managers will need to continue experimenting with different management practices. For instance, different flow regimes (e.g. hydropeaking) may have different effects on wildlife (Finch et al. 2015; Melis et al. 2016). Furthermore, different management practices may need to be tried in concert with one another (e.g. altering water temperature and performing non-native fish removals). With more key dam processes determined, formal decision analyses can be used for more formal management decisions (Alexander et al. 2006). These types of formal decision analyses will also have to take into account the role of previously unobserved environmental conditions driven by climate change (Melis et al. 2016).

Deputy Commissioner for Operations Lowell Pimley and other managers of the dam remain optimistic: "Dams have impacts, but as we have learned over the last 50 years, we can operate Glen Canyon Dam in ways that both meet our demands for water and hydropower, but also achieve our goals for natural resources and recreation".

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