# *Environmental Flow Regime Management in the Grand Canyon*

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**Abstract:** Glen Canyon Dam was originally constructed to meet water supply obligations under the Colorado River Compact and to generate hydropower. Construction and operation of the dam has created significant impacts to the natural flow regime of the Colorado River through the Grand Canyon. These impacts have negatively affected the downstream aquatic habitat and native species. In response to these effects, an adaptive management program was implemented to couple science and management objectives of the dam. As part of the program, several flow experiments have been completed with mixed results. Success of the flow experiments is often hindered by the geomorphic conditions in the Grand Canyon and the need to meet the dam's original objectives, water supply and hydropower. Nonetheless, hope remains that the adaptive management program is producing strategies to improve habitat and ecosystem processes in the Grand Canyon.

## 1. Glen Canyon Dam

Glen Canyon Dam impounds the Colorado River just 15 miles upstream from the border of Grand Canyon National Park. Originally authorized as part of the Colorado River Storage Project Act of 1956, the dam began to fill Lake Powell in January 1963, although the dam was not completely finished until September 1966. The original objectives of the dam were largely two-fold. First was to regulate the flow of the Colorado for flood control and water supply purposes. The location of Glen Canyon is located at the hydrologic breakpoint between the upper basin (Colorado, Wyoming, Utah, New Mexico) and lower basin states (Nevada, Arizona, California) of the Colorado River Compact. As such, it provides an effective means for the upper basin states to meet their 8.23 million acre-feet water delivery obligation to the lower states and Mexico. Secondly, Glen Canyon produces an average of 4,717 gigawatt-hours per year of electricity through its hydropower penstocks (USBR, 2016a). The dam is essentially a "cash-register", as hydropower revenues are used to pay for annual dam operation and maintenance costs, the Glen Canyon Dan Adaptive Management Program (GCDAMP), and other Bureau of Reclamation expenses (Ladson, 2002).

However, as has been seen in other rivers throughout the world, release schedules from the dam have created a flow regime that differs from the pre-dam natural flow regime. Post-dam flows through the Grand Canyon differ significantly in their timing and magnitude, temperature and chemistry, and sediment and nutrient loads (Sabo, 2012). The changes to the flow regime have negatively impacted aquatic habitats and ecological processes in the Grand Canyon, to which native species are adapted. Consequently, three native fish species have gone extinct and several other species are endangered or threatened (Rice, 2013).

As societal concern for the environment and the scientific understanding of aquatic and riparian flow demands increased, calls came for better environmental management of dam releases from Glen Canyon. However, the Bureau of Reclamation was unable to alter dam operations without congressional authorization. This changed with passage of the

1992 Grand Canyon Protection Act and implementation of the Glen Canyon Adaptive Management Program (AMP), which added environmental and cultural objectives to the dam's operational objectives. Over the last 20 years a number of release experiments have been implemented as part of the AMP. The goal of the flow experiments has largely been to provide flow processes that benefit native species and ecosystems, along with cultural and recreational objectives. However, meeting the flow demands of the diverse group of basin stakeholders is difficult. Potential environmentally focused experiments and management actions are often limited by the dam's other operating objectives, and success is complicated by the current geomorphic and biologic conditions in the Grand Canyon. Nonetheless, much has been learned from the Adaptive Management Program's implementation of environmental flow regime management in the Grand Canyon (Melis, 2015).

## 2. The Flow Regime of the Colorado River through the Grand Canyon

Glen Canyon Dam has broadly impacted the natural flow regime of the Colorado through the Grand Canyon. In particular, changes to the flow timing and magnitude, sediment levels, and water temperatures have been dramatic. The impacts brought by these changes have acted to significantly alter habitat availability, the aquatic food web, and native species reproduction, while also improving conditions for many non-native species (Sabo, 2012).

Before construction of the dam, the Colorado's flow regime had a predictable snowmelt dominated spring flood and smaller summer and fall monsoonal floods. The dam has effectively eliminated the seasonal long-duration flood flows, and now produces a nearly constant flow regime. Post-dam winter, late summer, and fall flows are also considerably higher than what would occur in the pre-dam "low flow" periods. Figure 1 demonstrates this clearly with the mean daily flow at Lees Ferry for pre-dam and post-dam conditions.

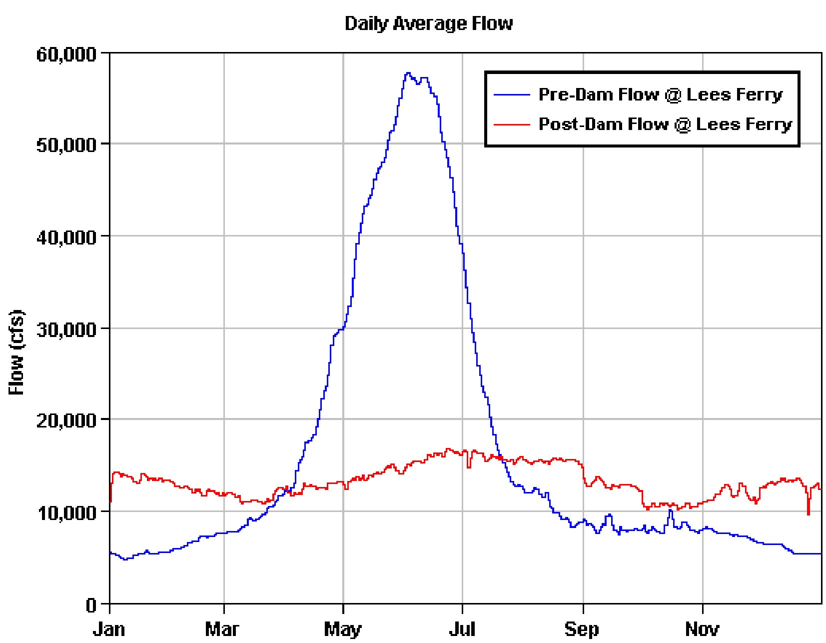


**Figure 1. Pre- and Post-Dam Mean Daily Flow at Lees Ferry**

Historically, floods of nearly 60,000 cfs would occur every year and flows of 120,000 cfs would occur on average every 6 years. The dam's regulation of large flows has limited floods to only a handful of years (1965, 1983, 1984, 1985, and 1986). These "floods" were the result of flood control operations, and only in 1983 and 1984 did they last for extended periods (30+ days). The lack of flood flows eliminates the ecological benefits of overbank flooding and floodplain inundation. Furthermore, the "flat-lining" of the annual flow hydrograph increases the frequency of moderate flows through the canyon.

Dam releases are also subject to large daily fluctuations due to a process known as "hydropeaking". Hydropeaking involves making larger dam releases when the price of electricity is largest (during the day), to maximize revenue from hydropower generation. Hydropeaking is particularly impactful to riparian zones, and has affected the reproduction and habitat of many native macro-invertebrates (Kennedy, 2016).

Sediment levels in the Colorado through the Grand Canyon go hand-in-hand with flow magnitudes. Historically the main stem of the Colorado River carried more than 30,000,000 tons of sediment annually through the Grand Canyon. Floods were the driver of sediment transport and deposition in the Grand Canyon (Rice, 2013). Pre-dam sediment flux consisted of about 78% by volume from the mainstem Colorado and about 15% from the Little Colorado and Paria Rivers (Melis, 2011). Today these ratios have switched, as Glen Canyon Dam blocks about 90% of the sediment that reaches the dam. The Colorado through the Grand Canyon is now in a sediment deficit, which limits the natural maintenance and construction of sandbars. The current annual release pattern of mostly moderate flows further acts to increase erosion and sandbar degradation (Lovich, 2007). Sandbars are an important part of the Grand Canyon ecosystem, as they provide beneficial habitat for native species by creating backwater areas with calmer and warmer water. Sandbars also provide suitable camping and recreation spots for rafters and hikers. The reduced sediment levels also create clearer, or less 'turbid' water. The clearer water benefits non-native fish, such as trout, which hunt by sight, and is detrimental to native fish, such as the humpback chub, which use the turbid conditions to find refuge (Rice, 2013).

Normal dam releases are made through the hydropower penstocks, which draw water from the bottom of Lake Powell to maximize hydropower output. Water at such depths is cold year-round, which produces water temperatures at Lees Ferry between 7-12° C, depending on the time of the year and the water elevation of Lake Powell (Lovich, 2007). This is a stark contrast from historic conditions, where pre-dam water temperatures varied between 0-30°C through the year. Although water temperatures do warm about 1°C for every 30 miles downstream from Glen Canyon, dam releases keep the system in a perpetual spring-like temperature regime (USBR, 2016a). The cooler water temperatures limit spawning and rearing conditions for many native fishes (including humpback chub), while improving conditions for many non-natives.

The environmental impacts of the dam were noted as early as the 1970s. At the time, the Bureau of Reclamation was unable, and perhaps unwilling, to change dam operations to mitigate the negative environmental effects. Changes to the operational objectives of the dam could not be made without congressional approval. Approval finally was given though the Grand Canyon Protection Act (GCPA) of 1992. The Act requires the Bureau to operate Glen Canyon Dam "so as to mitigate the adverse impacts on the natural and cultural resources of the Grand Canyon". The Act also recommended that an "adaptive management program" be implemented to allow for ecosystem studies and to guide operational decisions that satisfy all objectives (Meretsky, 2000). The AMP allows for scientific observation of flow and operational tests to determine the effects of different operating policies and their impacts on the ecosystems of the Grand Canyon (Sabo, 2012).

To comply with the GCPA and the AMP, in 1996 the Bureau adopted a modified low fluctuating flow (MLFF) policy to guide release decisions from Glen Canyon Dam. The main components of the MLFF are high flow experiments (HFEs) and implementation of a threshold on the daily fluctuation and ramping rates of hydropower releases (Rice, 2013). Whenever changes to MLFF operations are considered, a number of stakeholders (federal agencies, power generators, recreational users, environmental organizations, Native American tribes) must be consulted. It is extremely difficult, if not impossible, to satisfy all stakeholder demands, and often the planning process is cumbersome and slow (Camacho, 2010). The MLFF structure maintains focus on all of the dam's operating objectives, particularly water supply and hydropower, which has the potential to prohibit ideas for more dynamic flow experiments. Nonetheless, the MLFF policy has been an integral part of the AMP, and has provided engineers, scientists, and dam managers with a path forward to test ideas and operational policies to improve ecosystem health in the Grand Canyon.

### 3. Flow Experiments and Water Management

Adaptive management and the MLFF have allowed for a number of different flow experiments to be completed over the last 20 years. The most notable and most publicized experiments have been the HFEs, but several other interesting tests have occurred. Table 1 summarizes the major flow experiments since 1996 and some of their results (Meretsky, 2000), (Rice, 2013), (Melis, 2011), (Melis, 2015), (Ladson, 2002).

| Flow | Timing | Results |
|---|---|---|
| **High Flow Experiments** | Spring 1996 | - 45,000 cfs for 7 days<br>- Improved understanding of sediment transport, water movement, and ecosystem processes<br>- Little actual sediment transport and redeposition; mostly geomorphical shifting<br>- Non-native vegetation was buried, not scoured |
| | Fall 2004 | - Peak 41,700 cfs for 60 hrs; total 3.8 days.<br>- Slower flow ramp-up than Spring 1996; Benefits to trout |
| | Spring 2008 | - Peak 42,800 cfs for 60 hrs; total 3.6 days.<br>- Expansion of sandbars and backwater habitat<br>- Realization that HFEs need to be more frequent and better timed with sediment inputs<br>- Increased trout population |
| | Fall 2012 | - 42,300 cfs for 24 hrs; total 3.8 days |
| | Fall 2013 | - 37,000 cfs for 4 days; total 5.2 days; timed with tributary inputs<br>- Low steady flows (5000-8000 cfs) before and after<br>- Sandbar stabilization |
| | Fall 2014 | - 37,500 cfs for 96 hrs; total 5.3 days; timed with tributary inputs |

| | | |
|---|---|---|
| | | - Low steady flows (5000-8000 cfs) before and after<br>- Sandbar stabilization; control of trout; benefits to humpback chub |
| | Fall 2016 | - 36,000 cfs for 96 hrs; total 5.3 days; specific controlled ramping rates; timed with tributary inputs<br>- Results to be determined |
| **Habitat Maintenance Flows** | Fall 1997 | - Pulse release to activate and deposit sediment from tributary inputs<br>- Sandbar / backwater rebuilding |
| | Spring / Fall 2000 | - Pulse flows before and after summer steady flows<br>- Improved trout habitat; buried, not scoured riparian vegetation |
| **Steady Low-Flows** | Summer 2000 | - Flows steady at 8000 cfs for 3 months in between pulse flows to simulate natural flow pattern for benefit of native fish<br>- Increased water temperatures, especially near-shore and backwater. Stabilized sandbars, benefited native fishes, but need additional sand input |
| | Fall 2008-2012 | - Need additional and better timed HFEs to optimize sediment transport and deposition<br>- Created more erosion |
| **Trout Management Flows** | 2003-2005 | - 2x increase in daily fluctuations to limit trout egg viability. Largely successful. |

**Table 1. Major Flow Experiments from Glen Canyon Since 1996**

Results from each experiment have been mixed, with some surprises and disappointments related to effects on humpback chub and trout populations. In particular, sediment has shown to behave much differently than initially expected. The persistence of moderate flows in the post-dam flow regime slowly erodes sandbar and channel sediment, while the primary goal of the HFEs was to activate sediment to rebuild and maintain sandbars for ecosystem and recreational benefits. In some cases this has been achieved, but it's now realized that maintain current conditions, HFEs need to occur at least annually, and must be well timed with large sediment inputs from the major tributaries (Melis, 2015). Furthermore, while the goal of rebuilding and maintaining sandbars has been for environmental and cultural reasons, the sandbars created provide minimal ecosystem habitat and a largely for the benefit of rafters and backpackers (Rice, 2013).

Perhaps the greatest surprise has been the failure of some experiments that tested more "natural" flow processes, such as lower steady flows and even the HFEs. Geomorphic conditions in the river are now so different from pre-dam conditions that attempts to mimic natural processes fail. The reduced occurrence of high flow events limit the ecological benefits of floodplain inundation as HFEs do not match historic floods in timing, magnitude, or duration. Even if a natural flood could be simulated, the sediment deficit in the Grand Canyon would limit the sediment related geomorphic impacts (Rice, 2013).

It's worth noting that the HFEs result in the loss of several million dollars of hydropower revenue. However, there is practically little effect on water supply, as the water released during the experiments still counts towards the lower basin water supply allocation requirements. Flow experiments have and continue to be limited by the need to minimize impacts to water supply and hydropower objectives, and many have argued that these objectives still reign supreme over "natural and cultural" objectives (Camacho, 2010). Nonetheless, results and conclusions from all of the past flow experiments have provided insight into how to improve management given the physical and political management constraints. The results of past experiments have informed the newest management plan for Glen Canyon Dam, the LTEMP.

## 4. Current Policy and Future Possibilities of Grand Canyon Flows

In December 2016, the environmental impact statement for the Long-Term Experimental and Management Plan (LTEMP) was finally approved, which set in place the current management strategy for Glen Canyon Dam operations. The LTEMP provides a 20-year framework to continue the AMP per the objectives specified in the GCPA. The new plan sought to address a number of objectives, most notably: continued loss of sandbars/backwater, humpback chub populations, non-native fish populations and ranges, riparian vegetation management, and hydropower. As such, seven different dam management strategies were considered that addressed each of these objectives, while still meeting the multi-objective management requirements of the GCPA. The seven alternatives and a brief summary are discussed in Table 2 (USBR, 2016a).

| Alternative | Summary as Compared to Current Management Plan |
|---|---|
| A | Current management protocol. One annual HFE between 31.5-45 kcfs. Daily fluctuation limited by monthly pattern. Minimum flow 8 kcfs from 7am-7pm & 5 kcfs from 7pm-7am. Mechanical trout/invasive vegetation removal |
| B | Increase hydropower performance (allow greater daily fluctuation). Use non-flow actions & experiments to address sediment and species objectives. |
| C | Resource condition dependent release decisions. More seasonal release patterns with less daily fluctuation, while minimizing effects to hydropower. |
| D (chosen) | Increased frequency of HFEs triggered by sediment inputs, comparable daily fluctuations, but reduced ramping rates. Lower summer flows, but comparable monthly pattern. Trout and macro-invertebrate flows. |
| E | Only Fall HFE. Focus management on humpback chub, but improve hydropower releases. Lower summer/fall flows, but increased daily fluctuations. Other flow actions triggered by resource conditions. |
| F | Natural flow pattern to limit sediment transport and allow for increased summer water temperatures. No within-day release fluctuations. |
| G | Maximize conservation of sediment. Steady release pattern year-round to maintain and increase sandbar size and formation. Condition dependent flows in spring and early summer (HFEs). |

**Table 2. Alternatives of the 2016 LTEMP (USBR, 2016b)**

Of the various solutions assessed in the LTEMP, Alternative D was recommended and ultimately chosen. Alternative D does not offer a drastic departure from the current management plan (Alternative A), but allows for additional flow experiments and further limits on daily fluctuations. Alternative D allows for both spring and fall HFEs, although spring HFEs can only occur if an HFE did not occur the previous fall. The plan also allows for up to 4 extended Fall HFEs (up to 250 hours long) over the next 20 years. Trout management flows will again be tested, and a test of constant weekend flows (no hydropeaking) will be implemented to benefit macro invertebrate populations. The last flow experiment to be included allows for steady summer flows to be tested in the 2nd 10-year period. These flows will limit daily fluctuations to just 2,000 cfs, but can only be implemented if water temperatures at Lee's Ferry will reach 14° C. Additional mechanical trout removal and riparian vegetation treatments will continue to be implemented where beneficial.

Alternative D offers a continued step forward in the AMP process, and should continue to build off the lessons and successes of past experiments (USBR, 2016b). It demonstrates the benefits of the flexible protocol allowed by the AMP, shows how the lessons and successes of past experiments are used to inform future operations, and how scientists and mangers are attempting to manage to current geomorphic conditions in the Grand Canyon. Nonetheless, several other opportunities exist to restore some of the natural flow regime to the Colorado in the Grand Canyon that would have minimal impacts on the water supply, hydropower, and other cultural objectives of Glen Canyon Dam. Installation of a temperature control device or selective release mechanism has been proposed. Such a device would allow power plant managers to withdraw water from different lake elevations to produce releases of a specific temperature. Warmer temperatures would likely benefit native fishes, although there is some concern that without other control measures, warmer releases could benefit non-natives as well (Rice, 2013). An additional proposal includes construction of a slurry pipeline from the bottom of the dam to augment sediment supply downstream of the dam. Both proposals are costly, but would allow dam releases to simulate a more natural flow regime, while minimizing impacts to other management objectives.

Other proposals such as Fill Mead First (releases to maximize storage and hydropower of Lake Mead before Lake Powell), Grand Canyon First (scaled flow releases to completely mimic natural flow regime, including natural flood events), and Decommission Glen Canyon (operate Glen Canyon as run-of river dam; the dam would only act in the event of major flood control) are currently not considered because they do not allow the Bureau to meet the congressionally-mandated objectives of water supply, hydropower, and the natural and cultural resources of the Grand Canyon (USBR, 2016b). Furthermore, without the required sediment supply, any flow regime that attempted to mimic a more natural pattern would likely result in additional sandbar erosion and improved non-native fish habitat (Melis, 2015).

## 5. Conclusion

Glen Canyon Dam was primarily built to meet the water supply allocation requirements of the Colorado River Compact and to produce hydropower. Although dam operations are now managed with the environmental and cultural objectives of the downstream system in mind, the original objectives remain just as important. The dam has drastically altered the downstream environmental conditions, such that natural flow processes do not provide the same geomorphic and ecological benefits that they would have in pre-dam conditions. Scientists and engineers are still learning how to achieve natural flow processes given the limitations imposed by the dam's operational objectives and the altered environment of the Colorado through the Grand Canyon.

The AMP has served as a useful tool to work under these environmental and political conditions. AMP has allowed for responses to ecosystem uncertainties and has provided valuable ecological information, while limiting impacts to hydropower and water supply objectives. Nonetheless, without significant changes to sediment levels, the temperature regime, and the flow regime, the Colorado River's ecosystem through the Grand Canyon will likely be locked in the perpetual management of competing interests.

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