Multi-objective management of Glen Canyon Dam release strategies

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Abstract: There are numerous resources that depend on release strategies at Glen Canyon Dam. Since 1996, these strategies have been implemented through direction from the Adaptive Management Program (AMP) based on research, experimental flows, and analyses that examine how resources respond to different strategies. One such analysis, conducted in 2015, assessed the performance of several combinations of all reasonable strategies and recommended a long-term plan that was adopted shortly thereafter. The current management plan incorporates yearly to hourly constraints on releases (operating criteria) and guidance for experimental flows that could benefit resources such as sediment conservation and endangered fish. Some of these experimental flows have been implemented in the past with varying degrees of success. While the recent increased incorporation of experimental flows is a good sign for optimal management of resources, the AMP has occasionally hindered the progress of improving release strategies. Innovative strategies and the creation of more effective implementation pathways will be crucial for solving the water supply issues caused by the current and projected increase in water demand and aridification in the Colorado River Basin.

Keywords: Glen Canyon Dam, reservoir management, Colorado River Basin, Adaptive Management Program, operating criteria, bug flows, high flow experiments.

1. Background

There are enough reservoirs in the Colorado River Basin to store roughly four years' worth of Colorado River flow (Troch et al., 2007). Sitting in the middle of the watershed, Lake Powell has a capacity of about 25 million-acre feet (maf), which is almost half the entire storage in the basin. The lake was created in 1963 by the construction of Glen Canyon Dam. Shortly below the dam, the river enters the Grand Canyon, travels the length of it, and eventually reaches Lake Mead. Therefore, the flow regime through the Grand Canyon depends almost entirely on the release strategy at Glen Canyon Dam. Over the years, the dam has undergone several adaptations of release strategies, but none of the changes were so dramatic as the implementation of Modified Low Fluctuating Flow (MLFF) in the early 1990s.

The MLFF policy came about as a direct result of the 1995 Environmental Impact Statement (EIS) which codified interim guidelines that had been imposed in 1991. Before this time, release strategies were only designed to satisfy water deliveries, maintain flood control space, and maximize hydropower generation

(Feller, 2008). The large daily fluctuations caused by hydropeaking for hydropower were deemed by the EIS to be harmful to the environment downstream; sandbars that provided camping spaces for recreational rafters were being eroded, and populations of endangered fish were in steep decline. Thus, MLFF was adopted to diminish but not eliminate those fluctuations. Despite not completely solving the problems, the policy has shown some promise and is still active today, with some adjustments. To continue working towards release strategies that are optimal for a wide range of resource goals, the EIS also established the adoption of the Adaptive Management Program (AMP).

2. Adaptive Management Program

The AMP was put in place to monitor and assess the effects of dam operations on downstream resources. Comprised of a committee of stakeholders including representatives from federal and state agencies, utilities, Native American Tribes, recreational organizations, and environmental groups, the AMP utilizes research and experimentation, conducted almost exclusively by federal agencies, to decide the best management strategies. Over the years, the AMP has received plenty of criticism. For instance, Feller (2008) points out that the Endangered Species Act was violated by MLFF, which in the 1994 Biological Opinion was assessed to likely jeopardize endangered fish downstream of Glen Canyon Dam. Feller claims the AMP ignored this fact and proceeded with MLFF to achieve a more collaborative solution. Other criticizers of the AMP say that there aren't efficient paths to implement findings from research, and that the AMP's failures are largely due to the absence of concrete objectives (Susskind et al., 2012).

The AMP has incorporated some of the criticisms it has received. In the updated 2016 Record of Decision, there were significantly more explicit considerations for experimental flows. Furthermore, advocates of the AMP point out the plethora of support in the literature for collaborative management, and that frequently there are "surprise" learnings from the experiments that have provided invaluable information to management (Melis et al., 2015). While steps are being taken in the right direction, there is still room for improvement, particularly regarding more efficient implementation of learnings.

3. Major resources downstream of Glen Canyon Dam

The resources that the AMP is intended to manage are numerous and diverse. In addition to the obvious ones like water supply and hydropower, resources such as ecological health, fisheries, recreation, tribal interests, and archeological preservation of important sites can be affected by releases from Glen Canyon Dam (Bunn & Arthington, 2002; Healy et al., 2020; Runge et al., 2015). A few of the major resources and the effect that reservoir releases have on them are described here.

3.1. Water Supply

Allocation of the Colorado River's water has been governed for over a century by various laws, compacts, treaties, and agreements. The most influential document is the Colorado River Compact of 1922 that divided the Colorado River Basin into the upper and lower basins, assigning 7.5 million acre feet (maf) per year to each. Other treaties and decisions include allocations to Mexico (1.5 maf) and Native American Tribes (proportional to the amount of irrigable land on their reservations). Glen Canyon Dam acts as the controller of flow between the basins, storing water for use in the upper basin and making the necessary deliveries downstream to the lower basin and Mexico. Since water supply is largely based on a yearly and monthly quota, there is a lot of freedom when it comes to release strategies on a weekly or daily time frame.

3.2. Fish

There are two main species of fish that are considered in release management decisions: rainbow trout (RBT), and humpback chub (HBC). RBT are an introduced species that is known to harm native HBC, which are endangered. The AMP includes contradictory objectives of both supporting the RBT recreational fishery immediately below Glen Canyon Dam, and supporting the HBC (Melis et al., 2015; Mims & Olden, 2012). Considering the legal priorities that the endangered HBC commands, it is surprising to see the amount of attention given to maintaining the RBT fishery (Runge et al., 2015).

Release strategies can affect these fish in a few ways. RBT prefer the cold, clear releases that usually come from Glen Canyon Dam, and are known to benefit from steadier flows (Melis et al., 2015). This was the case for both high and low flow conditions; the crucial point is that RBT prefer steadier flows, regardless of amplitude. The most important factor for HBC is water temperature; they prefer warmer conditions. This could be achieved by steady low flows, especially during the summer when juveniles are migrating into the Colorado River from the Little Colorado River, but the magnitude would have to be much lower than the experiments done in 2000 and 2012-2013 which did not seem to help or hinder HBC. An alternative for increasing release temperatures would be to engineer new release structures at Glen Canyon Dam that could incorporate warmer water from higher in the reservoir. Melis et al. (2015) identify the issue of supporting HBC as the most important task of the AMP moving forward.

3.3. Recreation, Sediment, and Vegetation

About 27,000 people travel down the Colorado River through the Grand Canyon by boat every year. These boaters camp alongside the river, typically on sandbars. Due to the absence of extreme flood peaks, the impoundment of sediment behind Glen Canyon Dam, and hydropeaking, sandbars in the Grand Canyon were eroding for most of the time since the dam was erected (Hazel Jr. et al., 2006). This was one of the driving forces behind MLFF, and for the implementation of High Flow Experiments (HFEs) to help build sandbars. HFE success is dependent on the duration of high flow and how much available sediment there is, which generally comes from flooding in the two main tributaries (Topping et al., 2019). One of the unexpected potential complications of sandbar building is the establishment of invasive plants on the newly exposed terrain, particularly tamarisk (Ralston, 2010). This dynamic is an example of how resource objectives can quickly become entangled because of tradeoffs, which prompts the need for a systematic way to assess how resources might respond to different release strategies.

4. Decision Analysis

In pursuit of the best long-term management strategy for resources downstream of Glen Canyon dam, the U.S. Department of the Interior and USGS published a comprehensive decision analysis report in 2015 (Runge et al., 2015). The analysis gathered input from 14 stakeholders and even more experts to 1) identify important resources that are affected by reservoir releases, 2) define performance metrics for each resource that can be quantified numerically, 3) develop 19 long term management strategies, and 4) decide how each strategy would affect the performance metrics for each resource. Finally, the results were analyzed and the optimal strategy was suggested.

The 19 long-term management strategies fell into seven main categories (A-G), and primarily consisted of release-based criteria, with some inclusions of non-flow management actions (e.g., mechanical removal of non-native fish). The strategies are listed in Table 1 with their associated resource focuses and some highlights. Strategy “D” was the last strategy to be designed, after all the others were already analyzed, and it was found to perform the best in terms of overall performance amongst all resources. The strategy was officially adopted in 2016 and is described in detail later in this paper.

Table 1: Operating criteria for Glen Canyon Dam.

Plan	Focus	Highlights
A	No-Action	- Continue with current operating procedures
B	Hydropower	- Increase down-ramp rates, possible hydropower improvement flows
C	Multi-objective	- Allowance for more experimental flow events - Smaller range in daily fluctuations (benefits fish and sediment)
D	Multi-objective	- Compromise between C and E
E	Multi-objective	- Allowance for fewer experimental flow events - Smaller range in daily fluctuations (benefits hydropower)
F	Natural Flow	- Zero hydropeaking, allowance for HFEs - Annual releases partially mimic natural flow regime
G	Sediment	- Zero hydropeaking, allowance for HFEs - Monthly volumes somewhat constant

The 2015 report highlights the limitations of the analysis. There are many uncertainties associated with assumptions made, such as how the performance metrics will respond to different flow strategies. For example, in an assessment of resource response to the implementation of MLFF in 1996, assumed performance was correct only about 50% of the time (Lovich & Melis, 2007), suggesting that the accuracy of the 2015 analysis might be similar. Despite these uncertainties, the analysis was instrumental in defining major tradeoffs between management strategies, providing a systematic, collaborative way to decide on a best strategy with the available information, and informing current release strategies at Glen Canyon Dam.

5. Current Release Strategies

5.1. Operational Tiers

The first big-picture release procedures at Glen Canyon Dam are the operational tiers, based on water surface elevations at Lake Powell and Lake Mead, that govern how much water should be released annually. The goal is always to release the amounts allocated by law, but the tiers offer guidance when there is not enough water, or if there is excess (*Record of Decision: Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead*, 2007). The objective of the 2007 Record of Decision is to minimize shortages for both basins. There are four tiers corresponding to four elevations of Lake Powell, defined in Figure 1. Equalization Tier refers to times when Lake Powell is very full, and higher releases may be needed to "equalize" with Lake Mead, thus lowering overall spillage risk. Balancing tiers refer to times when they want to balance the contents of both reservoirs, but either spillage is not as much a risk, or there is so little water in either reservoir that they will continue to try to meet deliveries as best as they can. Yearly releases are further scaled to monthly totals depending on the annual release amount, however this allows for a lot of flexibility in day-to-day operations.

Lake Powell Operational Tiers (subject to April adjustments or mid-year review modifications)		
Lake Powell Elevation (feet)	**Lake Powell Operational Tier**	**Lake Powell Active Storage** (maf)
3,700		24.32
	Equalization Tier equalize, avoid spills or release 8.23 maf	
3,636 – 3,666	- - - - - - - - - - - - - - - - -	15.54 – 19.29
(see table below)	**Upper Elevation Balancing Tier** release 8.23 maf; if Lake Mead < 1,075 feet, balance contents with a min/max release of 7.0 and 9.0 maf	(2008 – 2026)
3,575	- - - - - - - - - - - - - - - - -	9.52
	Mid-Elevation Release Tier release 7.48 maf; if Lake Mead < 1,025 feet, release 8.23 maf	
3,525	- - - - - - - - - - - - - - - - -	5.93
	Lower Elevation Balancing Tier balance contents with a min/max release of 7.0 and 9.5 maf	
3,370		0

Figure 2: Operational tiers at Glen Canyon Dam (2007 Interim Guidelines for Record of Decision).

5.2. Operating Criteria

The following operating criteria were outlined by strategy "D" in the 2015 decision analysis described above. They consist of normal operating criteria, and stipulations for how and when to incorporate experimental flows.

5.2.1. Normal Operating Criteria

The normal operating criteria are shown in Table 2 and were implemented in 2016 by the most recent Record of Decision (ROD) (*Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan Final Environmental Impact Statement*, 2016). They dictate overall maximum and minimum flows, as well as restrictions on daily, hourly, and seasonal releases. In addition to the criteria outlined in the table under normal conditions, there are stipulations that allow for exceedance of the criteria due to experimental releases, emergency operations, and equalization purposes. Examples of emergency operations include if there are infrastructure complications, or extreme hydrologic events necessitating higher or lower releases for safety reasons. Several types of experimental releases are explicitly included in the 2016 ROD, and they are described below.

Table 2: Operating criteria for Glen Canyon Dam.

	Initial (pre-1991)	**Current**
Minimum Release (cfs)	1,000 (winter) 3,000 (summer)	8,000 (7am-7pm) 5,000 (7pm-7am)
Maximum Release (cfs)	31,500	25,000*
Allowable Daily Fluctuations (cfs/24hr)	none	10x monthly volume (Jun-Aug)** 9x monthly volume (Sep-May)** 8,000 maximum
Up-Ramp Rate (cfs/hr)	none	4,000*
Down-Ramp Rate (cfs/hr)	none	2,500*

* Allowed to exceed for experimental releases, emergency operations, and equalization purposes.
** The 10x and 9x multipliers are conversion factors from monthly scheduled release volume (thousand-acre feet) to the daily fluctuation (cfs).

5.2.2. High Flow Experiments (HFEs)

The goals of High Flow Experiments (HFEs) are to promote sandbar growth and support ecological functions downstream of Glen Canyon Dam (Runge et al., 2015). There are three main types of HFEs outlined in the ROD: 1) Spring Sediment-triggered, 2) Fall Sediment-triggered, and 3) Proactive Spring. The sediment-triggered HFEs happen when a threshold amount of sediment available for transport and deposition is determined to exist, generally following flooding in either of the main tributaries, and they can only happen in March- April (spring) or October- November (fall). Proactive spring HFEs can happen between April- June and only during years when the scheduled annual release exceeds 10 maf. There are also limitations on the amount of HFEs between years and within a single year. These have been implemented several times since the mid-1990s and have shown success at building sandbars, however they can have undesirable impacts on fish and vegetation (Melis et al., 2015).

5.2.3. Low Summer Flows

Low summer flows are allowed to be tested beginning Oct 1, 2028. The goal of lowered flows would be to increase water temperatures at the Little Colorado River confluence to benefit juvenile humpback chub. These flows are restricted to July- September and when scheduled annual releases are less than 10 maf. In addition, they can only be utilized if there are no other reasonable alternatives to meet the target temperature at the Little Colorado River confluence (≥ 14 ℃).

5.2.4. Trout Management Flows

The objective of the Trout Management Flows (TMF) is to decrease RBT populations. TMFs function by creating sustained high flow releases, followed by a swift decrease. The hypothesis is that juvenile RBT will seek refuge at higher elevations during the high flows, and then be stranded when the flow decreases rapidly. Up-ramp rates are the same as under normal operations, but the down-ramp rates from peak to low flow are allowed to happen in the span of one hour. TMFs were allowed to be tested as early as October 1, 2017. While there have been studies showing the potential effectiveness of this strategy (Bradford et al., 1995), doubts about its efficacy from scientists and concerns regarding the taking of life without beneficial use from Native American Tribes have kept TMFs from being implemented (*Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan Final Environmental Impact Statement*, 2016).

5.2.5. Macroinvertebrate Production Flows (Bug Flows)

Bug Flows are designed to increase macroinvertebrate populations downstream of Glen Canyon Dam. Macroinvertebrates are the basis of many aquatic food webs, and are regularly used as bioindicators of ecological health (Lenat, 1988). Hydropeaking is known to have severely negative impacts on aquatic insects, the majority of which lay their eggs in shallow water. Because of this, they are particularly susceptible to desiccation when the flow drops; one study showed that survival rate was zero for eggs that were exposed to air for only one hour (Kennedy et al., 2016). To combat desiccation, “bug flows” are characterized by a steady and consistent low flow on weekends as seen in Figure 2. The goal is to make sure that eggs laid in the edges of the river during low weekend flows will remain inundated until they hatch. The range of allowable dates for these flows are between May- August.

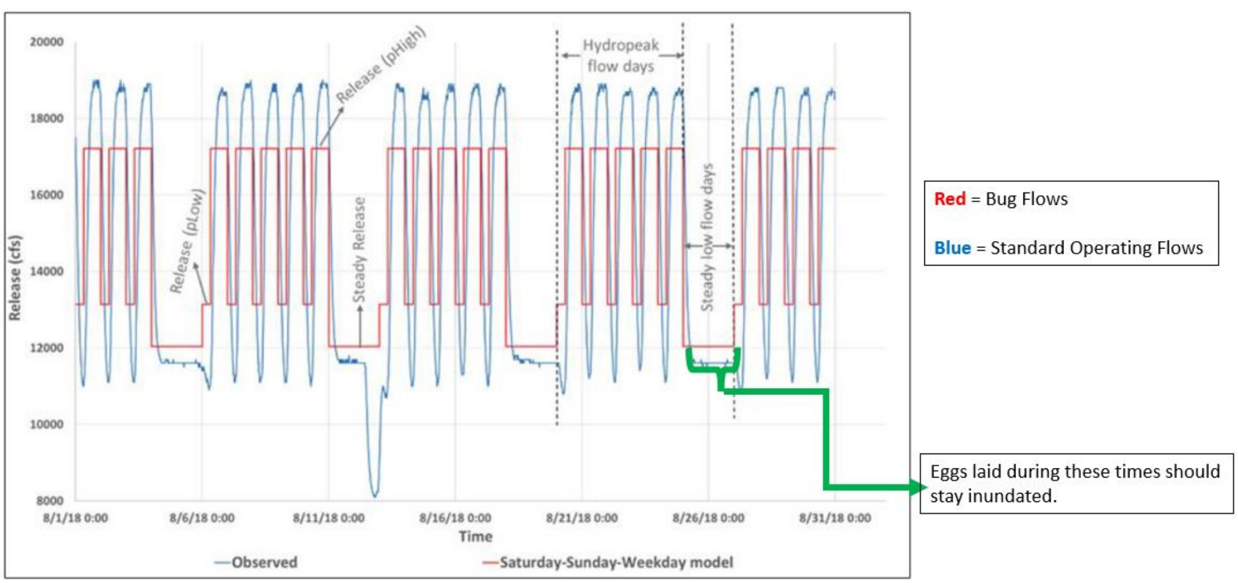

Figure 1: Example of a Bug Flow’s release schedule (Rind & Rosenberg, 2022).

Bug Flows have been implemented four times, in 2018-2020 and 2022. Preliminary results are promising, indicating that caddisflies benefitted strongly and midges to a lesser degree (Ted Kennedy &

Jeff Muehlbauer, 2021); while midges didn't show an increase in population following Bug Flows, their numbers dipped distinctly in 2021 in the absence of such flows. Managers clearly find this management strategy worthwhile. Measured by loss of hydropower revenue, the 2019 and 2020 bug flow events cost $327,000 and $941,000, and the 2022 event was projected to be even more expensive (Ploussard & Veselka, 2022).

6. Conclusion

Release strategies can be tailored to optimize any of the numerous downstream resources; however, due to inherent tradeoffs ,it can be complicated, and likely impossible, to manage them in a way to benefit all resources. A flow strategy that will help one resource, will harm another. One way this problem is dealt with is through legal hierarchy. By law, water supply and supporting endangered species are the two primary objectives when deciding release strategies. All other resources are to be considered secondarily, "only to the extent consistent with the mandatory requirements for water supply and endangered species protection (Feller, 2008)." Despite the explicit wording of this hierarchy, the AMP still makes a great effort to achieve a multi-objective solution. This is largely due to the lack of clear evidence supporting what release strategies would be best for fish (Melis et al., 2015), and a potential over-reliance on collaborative decision making (Feller, 2008). A collaborative, multi-objective approach should always be pursued, so long as federal laws such as the Endangered Species Act are not ignored.

Glen Canyon Dam release management needs to adapt to the combination of climate-driven aridification (Harding et al., 2012) and increased water demand in the Colorado River Basin. Historically low reservoir levels constrain the release strategies that are possible because there is less water to work with. Furthermore, if Lake Powell levels drop below deadpool, releases could stop entirely, creating a major water supply and environmental crisis. At the same time however, lower reservoir levels offer new opportunities for research such as releasing warmer water near the surface. Also, emergencies can act as an impetus to innovation and development of new technologies or infrastructure that can be more effective at handling the difficulties associated with multi-objective management. For that to happen, the AMP will need to be more effective at adapting and implementing new strategies.

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