Reservoir operation on the Colorado River: Goals and policies

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Abstract: Glen Canyon Dam has experienced several experimental reservoir re-operation policies since the implementation of the Glen Canyon Adaptive Management Program (GCDAMP) in 1997. This program defined a framework in which research and monitoring efforts play a key role in: (i) assessing the effect of experimental operating policies; and (2) in revealing new opportunities for developing better river management policies. A new long-term management and experimental plan for Glen Canyon Dam operations, started in 2016 by the U.S. Department of the Interior, provided an opportunity to evaluate management objectives, further identify and estimate key uncertainties about the influence of dam releases, and define additional experiments for learning over the next several decades (2020-2040). A historical overview of tested experimental re-operation policies showed how adaptive learning since 1995 has been a critical input to this long-term planning effort. Embracing test successes and learning opportunities from failures will likely continue the advancement of resource objectives below the dam, and may also promote efficient learning in other complex programs.

Keywords: Glen Canyon Dam, high flow experiments, trout management flows, reservoir re-operation, Colorado River, humpback chub, rainbow trout, macroinvertebrate production flow

1 INTRODUCTION

Water resource systems are managed for multiple and sometimes competing uses, including irrigation, flood control, hydropower, water supply and ecosystems. Human water uses had priority in the past, with reservoir and hydropower operations significantly degrading downstream ecosystems, partly by altering flows and water temperatures upon which aquatic and riparian organism depend. This led to an increased political, legal and management support for aquatic ecosystems and fisheries, in addition to traditional human water uses. These efforts have been intensely and extensively developed in the highly altered and regulated Colorado River, focused on the stretch flowing through the Grand Canyon National Park just downstream Glen Canyon Dam, due to its important ecological value [Melis et al., 2015]. As such, Glen Canyon Dam operations are of great interest for water resource and environmental managers since they define instream conditions (flow and temperature), drivers of habitat quality and characteristics.

Glen Canyon Dam, located at the Utah-Arizona border, forms Lake Powell reservoir which is one of four mainstem water storage units authorized in 1956 under the Colorado River Storage Project (CRSP). With 27 million acre-feet (maf) of storage, it is the second largest reservoir in the US [Melis, 2011]. Since its completion in 1963, fluctuating releases of cold, hypolimnetic water from Lake Powell ($\sim 8°C$) for peak hydroelectric power generation has had a profound impact on the formerly warm, silty Colorado River [Gorman et al., 2005]. Only five of the original eight native fish species remain in the Colorado River and its tributaries within the Grand Canyon [Webb et al., 1999]. Furthermore, sediment dynamics have been greatly disturbed, mainly due to the sediment-free releases from Lake Powell and the suppression of the historic annual floods.

Here, a review of Glen Canyon Dam re-operation strategies is presented. A special focus is given to the ecosystem/hydrology areas intended to be improved, the release pattern proposed to fulfill the environmental objective and the posterior analysis of the actual effects of the re-operating policy on the resources of the Colorado River ecosystem, provided by the monitoring of the field tests.

2 Glen Canyon Dam Adaptive Management Plan (GCDAMP)

The resources of the Colorado River ecosystem are surrounded by significant levels of uncertainty [Webb et al., 1999]. As such, the effect of Glen Canyon dam releases on those resources are bound to an important incertitude [U.S. Department of the Interior, 1996], which must be considered in reservoir re-operating procedures. To this purpose, the Glen Canyon Dam Operations Environmental Impact Assessment stipulated an adaptive management approach, established in 1997 [Melis et al., 2015], named the Glen Canyon Dam Adaptive Management Program (hereafter, GCDAMP). The Program was initiated to work with stakeholder groups to develop management plans for the operation of Lake Powell, to maximize benefits to resource users and aid in the recovery of the ecosystem resources. It defined a framework (Fig. 1) to evaluate the performance of proposed dam operation policies on the Colorado River ecosystem resources by using monitoring and research results. Then, recommendations to the U.S. Department of the Interior are made, based on the results of the assessment [Gloss et al., 2005; Camacho, 2007].

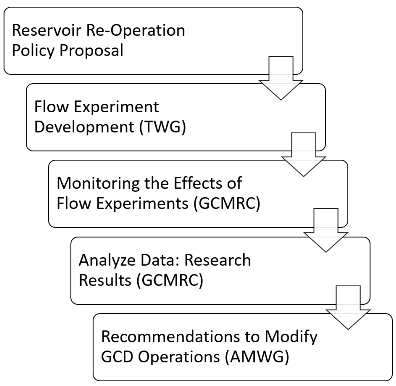

Figure 1. Sketch of the process to implement reservoir re-operation policies under the GCDAMP.

The proposal of new reservoir re-operation policies, including goals and priorities, is submitted by the Adaptive Management Work Group (AMWG). This group contains representation from a variety of stakeholders, since Glen Canyon Dam operations must comply with multiple regulations and laws, e.g. Law of the River, environmental laws, American Indian and Tribal consultation laws. They range from federal and state agencies, Native American Indian Tribes, the Colorado River Basin States, electrical utility consortia, recreational groups, and environmental groups, which have disparate interests in the resource [Feller, 2007]. Then, the Technical Work Group (TWG), comprised of technical representatives of each group represented by AMWG, develops the flow tests to be performed to assess the suitability of the proposed policy. Resource management questions are also proposed by these group to the Grand Canyon Monitoring and Research Center (GCMRC) for the design of the required monitoring and research efforts. The analysis of the monitored data is conducted by the center and supervised by the Science Advisors programs. Finally, the generated research report is provided to the AMWG, which develops the recommendations to the Secretary of the Interior for modifying operating criteria that minimize the conflict between objective functions for each user group [Pine et al., 2009].

3 Experimental Reservoir Re-operation Policies Tests

Several experimental re-operation policies have been tested in Lake Powell since 1991 as a response to the Glen Canyon Dam Operations EIA of 1995 and under the framework of the GCDAMP. These tests have targeted different links of the ecosystem chain, but all were designed as an effort to address three main goals [Melis et al., 2015]: (i) restore historical sediment dynamics in the Grand Canyon; (ii) recover the population of Humpback Chub (*Gila cypha*), an endangered native fish located mainly at the confluence of the Little Colorado River [Gorman et al., 2005]; and (iii) manage trout populations for two different and conflicting objectives, maintaining a healthy recreational fishery at Lees Ferry while limiting their numbers to avoid their migration downstream, where they negatively impact native fishes. A brief review of the tests is given, focusing on (i) the initial hypothesis on the effect of the experiment on the ecosystem; (ii) how the release pattern was changed; and (iii) the final assessment of the experiment from the monitoring and research stages. It must be noted that the tests are presented in a chronological order as shown by Figure 2.

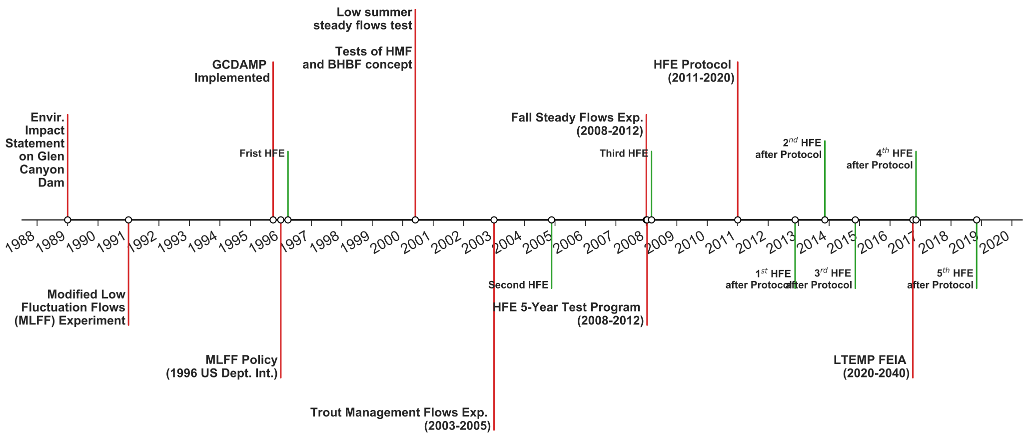

Figure 2. Timeline of experimental re-operation policies tests and occurrence of High Flow Experiments (HFEs).

3.1 Modified Low Fluctuation Flows (MLFF)

They were initially tested from 1991 to 1995 and officially implemented in 1996 (Figure 2). This reservoir re-operating policy focused on improving habitat for native fishes by conserving shoreline sandbars [Gloss et al., 2005]. The measure enhances (i) juvenile habitat by creating and stabilizing backwater areas which provide warmer water than the mainstem [Pine et al., 2009] and (ii) adult habitat by stabilizing mainstem flows [Gloss et al., 2005]. To this purpose, the daily release fluctuations associated with hydropeaking, i.e. high releases through the power plant turbines in order to cover peak energy demands, were greatly reduced, with maximum values as a function of the monthly releases from Lake Powell [Pine et al., 2009]. Fish stranding risk was also reduced by defining a ramp rate threshold, i.e. the releases rate of change per hour, in order to avoid sudden decreases in flow which could affect those individuals rearing in shallower areas. Table 1 summarizes the changes in flow and the defined maximum and minimum flows.

The results of the monitoring and research stages indicated a counterintuitive response of Humpack Chub populations [Pine et al., 2009] since their recruitment did not increase

Table 1. Summary of changes implemented by the Modified Low Fluctuation Flows policy. Source: U.S. Department of the Interior [1996]

Flow Parameter	Unrestricted Fluctuation Flows	Restricted Fluctuation Flows
Minimum releases (cfs)	1,000 Labor Day - Easter 3,000 Easter - Labor Day	8,000 between 7 a.m and 7 p.m 5,000 at night
Maximum releases (cfs)	31,500	25,000 (exceeded during HMFs)
Allowable daily flow fluctuations (cfs/24 hours)	30,500 Labor Day - Easter 28,500 Easter - Labor Day	5,000; 6,000; or 8,000 Depending on monthly releases
Ramp rates (cfs/hour)	Unrestricted	4,000 up; 1,500 down

and may have declined [Coggins Jr, 2008]. The reduction could have been the result of the combination of several factors including hydrology [Valdez and Ryel, 1995], temperature [Coggins Jr, 2008], or parasites [Hoffnagle et al., 2006]. However, there was certainty on the effect of predator increase in the mainstem near to the Little Colorado River (hereafter, LCR), the tributary supporting the most important population of Humpback Chub [Pine et al., 2009]. Within a few years after implementation of MLFF, non-native salmonids (brown and rainbow trout) increased in the tailwater of Glen Canyon Dam Colorado River, possibly due to the improved nearshore habitat from lower fluctuating flows, which forced their dispersal downstream to other mainstem habitats [Gloss et al., 2005]. However, despite initial research not providing enough evidence of a positive effect on native fishes, the re-operating policy was adopted, which created some criticism [Walters et al., 2004]. Rationale of its approval was based on the improved nearshore habitat that would be available when other elements of the ecosystem are targeted [Melis et al., 2015].

3.2 Low Summer Steady Flows (LSSF) Experiment

The Low Summer Steady Flows (LSSF) were tested during 2000 and bracketed by peak powerplant releases in late-May and early-September denoted as Habitat Maintenance Flows (HMFs) (Fig. 3). LSSF were the first seasonally based experiment that focused primarily on biological resources [Ralston, 2011]. LSSF were aimed at improving mainstem spawning success and increasing growth of young native fishes (specially Humpback chub) by providing stable, warm and productive shoreline nursery habitats through reduced and steady releases from GCD during summer [Ralston, 2011]. Figure 3 shows the difference in discharge between a current summer release and the LSSF experiment, in which: (i) daily fluctuations associated to hydropower were suppressed in order to provide the preferred stable nearshore habitat; (ii) low flows (226 m^3/s) were intended to increase mainstem temperatures through radiative forcing, since release temperatures are always defined by the hypolimnion temperature.

It was found that targeted fishes did not respond strongly, either positively or negatively, to flow alterations [Ralston, 2011], even though temperature goals at backwaters were met during daytime (up to 28°C), providing the optimal temperature range for Humpback chub growth and spawning [Webb et al., 1999]. Furthermore, the flow experiment led to costs of $26.4 million to power users (probably the greatest in U.S. history from an environmental science experiment) and enhanced establishment of invasive tamarisk at the shores [Ralston, 2011]. Therefore, this experimental re-operating policy was not incorporated into regular reservoir operation. Several variables might have limited the

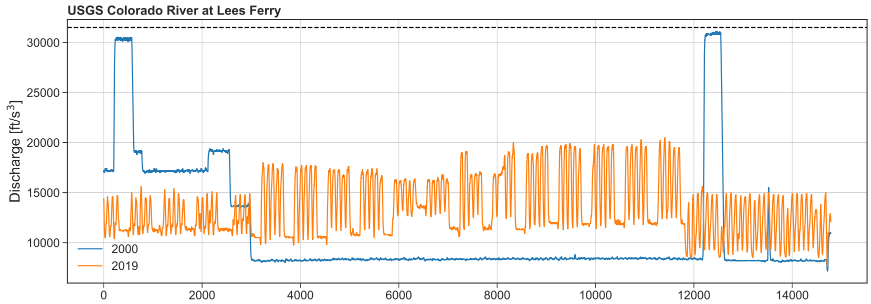

Figure 3. Hourly hydrograph of Glen Canyon Dam releases at Lees Ferry during the Low Summer Steady Flows experiment (blue line) compared with summer releases during 2019 (orange line). The dashed line represents the turbines release capacity.

understanding of the effects of the LSSF hydrograph on young native fish growth and survival. Condensed timelines between planning and implementation (2 months) of the experiment and the time required for logistics, purchasing, and contracting resulted in limited data collection [Ralston, 2011]. Furthermore, the 4-day habitat maintenance flow in September interrupted persistent habitats for YoY (Young-Of-Year) fishes and may have confounded the results. Also, the high abundance of salmonids in the mainstem before the experiment and predation by them may have affected the number and size of native fish that were caught [Ralston, 2011].

3.3 Trout Management Flows (TMF)

Due to the increase in non-native salmonid population at the backwaters of Glen Canyon Dam after the implementation of MLFFs [Pine et al., 2009], active management of their numbers was required to minimize their impact on native populations [Epstein, 2005]. To this purpose the Trout Management Flows (TMF) were designed and tested from 2002 to 2005 during winter, January to March. The experiment consisted of increasing the daily flow fluctuations to 15,000 cfs (5,000 baseflow to 20,000 cfs peak; Figure 4) along with steady flows (5,000 cfs) every Sunday [Epstein, 2005]. The experimental release policy aimed to reduce the recruitment of rainbow trout downstream of Glen Canyon Dam by mimicking the release policy pre-1991, since the non-native salmonid population was unable to be self-sustainable [Epstein, 2005]. During spawning season, trout move to shallower, lower flow areas to construct their redds. Flows during redd building, egg laying and egg hatching must remain at a suitable level to inundate the gravel. Fluctuating flows were meant to disrupt this process. High flows during the day were intended to make trout move into shallower areas to spawn [Korman et al., 2005] and then reduced flows at night would dewater those redds resulting in desiccation of eggs [Davis and Batham, 2003]. Steady low flows during Sundays were intended to prolong atmospheric exposure of redds. The high fluctuations were also designed to reduce the survival of YoY that had already emerged from redds. Higher flows would make trout fry more vulnerable to predation and the rapid lowering of flows would intend to leave them stranded.

TMFs were designed to occur around the peak of trout spawning, but Korman et al. [2005] found that 50-60% of redd excavation actually occurred after March 31st and hence, the flows were released too early. Even so, it was found that 25-40% of all redds constructed before April 1st were lost as an effect of this experiment. Furthermore, over a thousand individuals were estimated to become stranded but only a 7% were found dead [Davis and Batham, 2003]. The much lower mortality and stranded numbers compared with

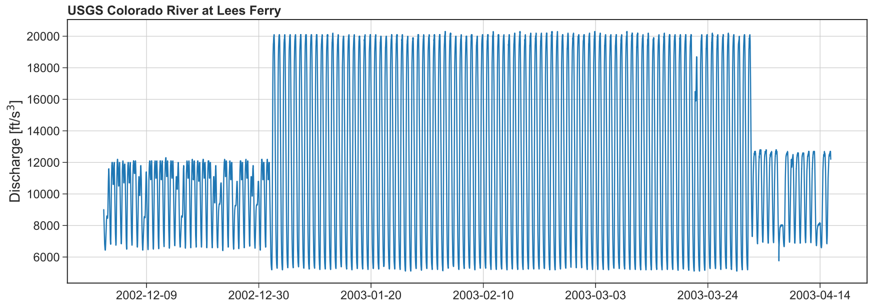

Figure 4. Hourly hydrograph of Glen Canyon Dam releases at Lees Ferry during the Trout Management Flows experiment.

data before the MLFF implementation [Angradi et al., 1992] was associated to the lower ramp rates (i.e. slower decrease in flow rates) and colder temperatures during winter [Epstein, 2005; Korman et al., 2005]. Despite the potential showed by the experiments, it was decided to not implement the re-operating policy, mainly due to the stress induced in other parts of the ecosystem by the highly fluctuating flows [Epstein, 2005].

3.4 Steady Fall Flows Experiment

A 5 year-period (2008-2012) experimental program was approved to provide steady flows in the fall (September and October; Fig. 5) in order to evaluate the ability of such flows to stabilize habitat, i.e. nearshore and backwaters, for juvenile humpback chub [Bureau of Reclamation, 2011]. The steady flows were intended to cause backwater and other nearshore habitats, and nurseries, to become more hydraulically stable, with potentially warmer water temperatures than would exist under regular, fluctuating, MLFF operations. These changes were predicted to help improve conditions for survival and growth of YoY and juvenile humpback chub, by providing more persistent suitable habitat, and increased productivity of macroinvertebrate prey items for use by humpback chub [Bureau of Reclamation, 2011].

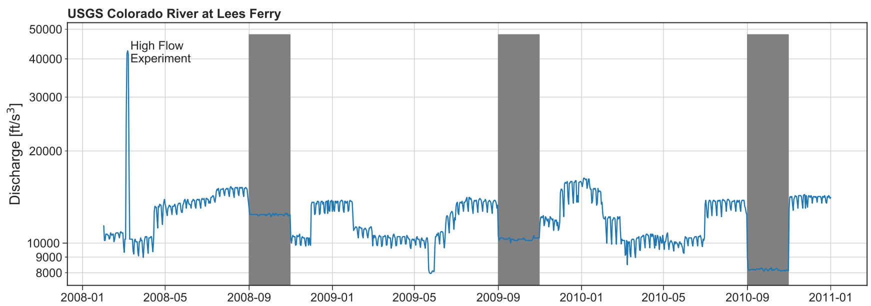

Figure 5. Hourly hydrograph of Glen Canyon Dam releases at Lees Ferry during the Fall Steady Flows experiment. The shadowed area highlights the months of their implementation.

Monitoring and research analysis of the experiment was reported by Dodrill [2012], Finch [2012], Gerig [2012] and Finch et al. [2016]. During the experiment, juvenile humpback chub population showed no relation with the flow regime while apparent survival might have declined during the fall steady flows. Therefore, the data analysis differed from the expectation that steady flows would improve the population of humpack chub by stabilizing available habitats that might allow for lower rearing energy loss and diminishing predation risk. However, several limitations of the experimental design could have contributed to this counterintuitive conclusion [Finch et al., 2016]. Due to the poor results obtained, this re-operation policy was not further implemented or modified.

3.5 High Flow Experiments Protocol

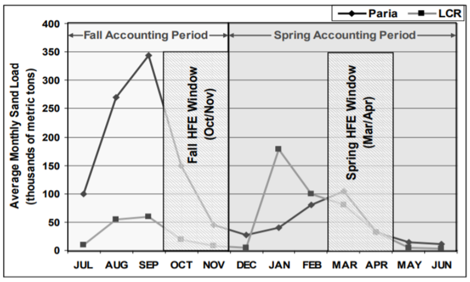

Figure 6. Definition of the two sand accounting periods and the two high-release windows with average sand inputs from Paria and Little Colorado Rivers. Source: Bureau of Reclamation [2011]

The HFE Protocol was adopted in 2011 and exemplifies the strengths of the adaptive management of Glen Canyon dam, since this experimental protocol was built on and developed following the analysis of the series of high flow experimental releases conducted in 1996, 2004 and 2008 [Melis et al., 2015]. The main objective of the protocol was to assess if multiple, sequential and predictable high-flow releases conducted under consistent criteria could better conserve sediment resources, i.e. long term sandbar construction and conservation, while not affecting other parts of the ecosystem [Bureau of Reclamation, 2011]. Therefore, it defined a formal set of rules and procedures to be followed to determine when the high-flows are implemented. Like the 2004 and 2008 HFEs [Topping et al., 2006], they were stipulated to be triggered by existing sand volumes stored in the mainstem from inputs by the Paria and Little Colorado Rivers, related to floods on these systems. These volumes are known from the data acquired from monitoring efforts in both rivers during the accounting periods (Fig. 6). At the beginning of both HFE windows (Fig. 6), sand storage and forecast hydrology are evaluated using a sediment budget model to determine if conditions are suitable for a HFE. If so, flow value and duration is defined using sediment transport modeling, under the premise of selecting the highest flow magnitude possible, to promote sand deposition at higher elevations and generate larger beaches/sandbars, that provide a positive sand balance, i.e. more sand is deposited than eroded away [Bureau of Reclamation, 2011].

Since the implementation, five new HFE have been conducted in Fall 2012, 2013, 2014, 2016 and 2018 (Fig. 2). Hazel et al. [2020] reported some initial conclusions on the impact of these experiments, and hence the HFE Protocol, on sandbars along the Grand Canyon. HFEs since 2012 have resulted in sandbar deposition that offset sandbar erosion that occurs between them. Therefore, the increased frequency ($\sim$ 1/2 yrs, equal to Paria River floods) has been able to maintain sandbars at the majority of the sites, even with an increase in sizes on over 50% of the monitoring sites.

4 Long-Term Experimental and Management Plan (LTEMP)

The LTEMP supposes the next planning step in the adaptive management of Glen Canyon Dam after the exhaustion of the planning period of the 2011 HFE Protocol [Bureau of Reclamation, 2011]. It defines the preferred alternative (Alternative D) for reservoir operation and experimental re-operation policy tests for the 2020-2040 period [US Department of the Interior, 2016]. As such, it is based on the gained knowledge from the previously introduced flow experiments by: (i) implementing those re-operation policies with positive results, i.e. sediment-triggered Fall/Spring HFE as defined by the 2011 HFE Protocol (Section 3.5); (ii) modifying the release patterns of previous tests to correct for unexpected environmental responses, such as the low summer flows (Section 3.2) and a tweak to the Trout Management Flows (TMF; Section 3.3); and (iii) further designing new experimental re-operation policies to target other parts of the ecosystem not considered previously, as the Macroinvertebrate Production Flows (MPF). In this section, a focus is given to the later two, to provide an example of: (a) flow experiments targeting biota different from endangered and non-native fishes and (b) how adaptive management learns from previous efforts to provide an improved and promising re-operating policy.

4.1 Macroinvertebrate Production Flows (MPF)

These experimental releases, also known as the Bugflow Experiment [Ploussard and Veselka, 2019], were implemented May-August in 2018 and 2019. This experimental policy was developed as an answer to Kennedy et al. [2016] findings, which showed that hydropeaking practices affect greatly those aquatic insects in which the adult egg-laying process is located at the river-edges, such as the ecologically important mayflies. These eggs may become dewatered/desiccated if laid during the higher flows of the hydropeaking fluctuation. Therefore, this release pattern could lead to these aquatic insects extirpation from the ecosystem, undermining the Colorado River food webs [Kennedy et al., 2016]. Figure 7 exhibits the change in release decisions proposed, with stable releases during the weekends to a level equal to the minimum discharge during the week. This provides a 2-day window every week during which aquatic insects can lay eggs at river-edges, eliminating the risk of becoming dewatered/desiccated during the week. In order to reduce the economic costs of stopping hydropower operation during weekends, higher fluctuations were authorized during weekdays [Figure 7; Ploussard and Veselka, 2019].

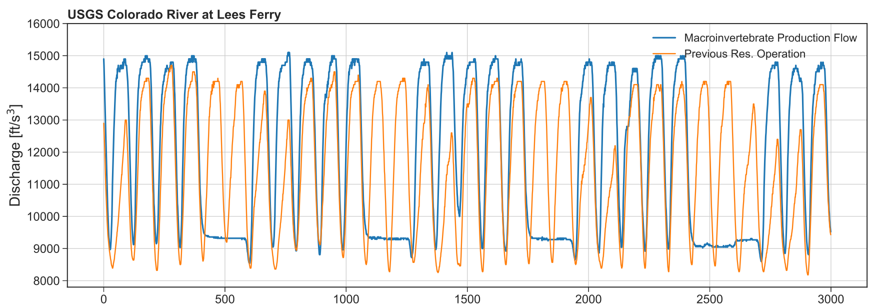

Figure 7. Hourly hydrograph of Glen Canyon Dam releases at Lees Ferry during the Bugflow experiment compared with previous existing releases during several weeks in May-August.

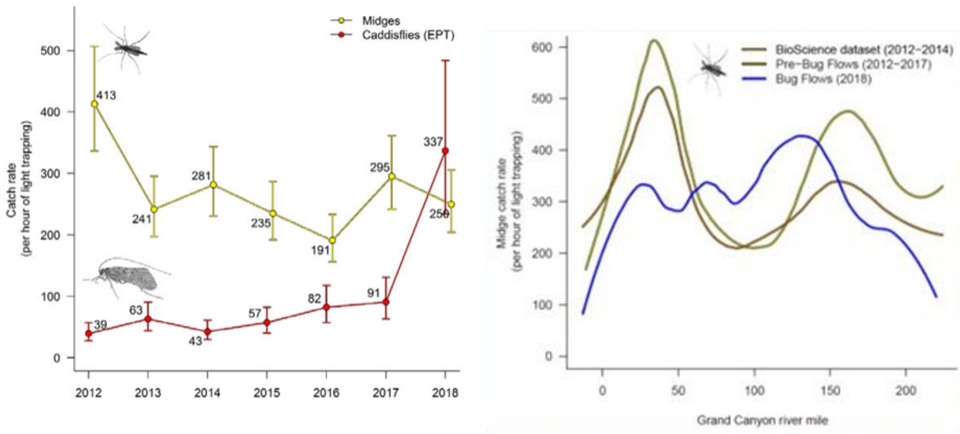

Figure 8. Midges and caddisflies density at Lees Ferry and midges spatial density downstream Glen Canyon Dam. Source: Kennedy and Muehlbauer [2019]

Early monitoring results showed that in 2018, caddisflies, an aquatic insect extremely rare in the Grand Canyon over the past decades, increased nearly four-fold. Furthermore, non-biting midges, a key food source of fish and other wildlife, were almost 800% more abundant during weekends compared to weekdays, but not significantly different than previous years [Kennedy and Muehlbauer, 2019]. However, the midge density spatial pattern became less variable, with higher densities further from the dam, directly affecting greater stretches of the Colorado Rive ecosystem (Figure 8). Since preliminary results showed promising trends, the experiment was repeated in 2019, for which monitoring analysis have not yet been released, and planned for 2020 in order to conduct a robust, 3-year test [Kennedy and Muehlbauer, 2019]. Economically, the suppression of hydropower peaking during weekends and holidays generated a financial cost of approximately $165,000 [Ploussard and Veselka, 2019].

4.2 Trout Management Flows (TMF)

TMFs would be used to control trout recruitment in the Glen Canyon reach to manage the rainbow trout fishery, and to limit emigration of juvenile trout to downstream reaches, particularly to habitat occupied by humpback chub near the confluence of the Little Colorado River [US Department of the Interior, 2016]. Partial success of non-natal salmonids management from flow measures during the 2003-2005 experiment (Section 3.3) led to the consideration and inclusion of new flow management practices to be tested. The proposed TMFs in Alternative D were designed focusing on YoY stranding in shallower areas, observed during the 2003-2005 experiment [Epstein, 2005], rather than the exposure and desiccation of redds, their main previous focus. As such, the proposed experimental flows were developed on the basis of research described in Korman et al. [2005], which concluded that a combination of largely fluctuating flows with high ramping rates are required to maximize YoY trout stranding mortality [Epstein, 2005].

To this purpose, TMFs feature repeated cycles that consist on high flows ($\sim$ 20,000 cfs) sustained for a specific period of time (several days to a week), followed to a sudden drop to a very low flow (e.g. 5,000 to 8,000 cfs), occurring in a single hour span (i.e. ramp rate of 15,000 cfs/hour) and held for less than 12 hours to avoid damage to other parts of the ecosystem [Section 2.2.4.3; US Department of the Interior, 2016]. In this cycle,

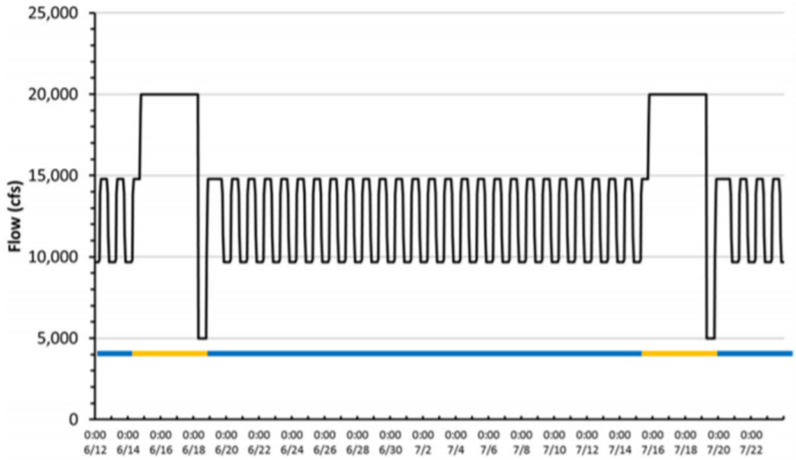

Figure 9. Example of a two-cycle TMF in June and July with normal fluctuating pattern between cycles. Source: US Department of the Interior [2016]

YoY trouts are expected to occupy near-shore habitats during the steady high flows, since observations report that they tend to move towards these areas to avoid predation [McKinney et al., 2001], and then become stranded by the rapid drop on base flow. These cycles will be scheduled for later in the year, with two cycles in June-July (Figure 9), but could be increased based on preliminary results to as many as three per month for May-July. This timing is designed to occur around the peak of YoY population [Korman et al., 2005]. Implementation is triggered by a population of 200,000 YoY that could be modified based on the results of conducted TMF experiments, and if not triggered, scheduled to occur during the first 5 years of the LTEMP timeline [US Department of the Interior, 2016]. No preliminary results are available since no experiment has been conducted yet.

5 Conclusions

The review of the release tests performed at Glen Canyon Dam (Fig. 10) provides a conclusion similar to that of Schmidt et al. [1998], there is no single restoration or rehabilitation strategy that improves the status of every riverine resource, it requires a port-folio of actions targeting each selected resource. This optimal port-folio has been and continues to be developed using the flexible framework in reservoir management defined by GCDAMP, allowing the trial-error process presented in this paper to refine proposed re-operation alternatives and implement satisfactory experimental policies. Despite some criticism for its lack of quantifiable targets [Melis et al., 2015] or for not advancing long-term changes in management in response to learning [Susskind et al., 2012], GCDAMP supposes an important effort to balance human and environmental water uses, giving a very prominent position to science and research in the management process.

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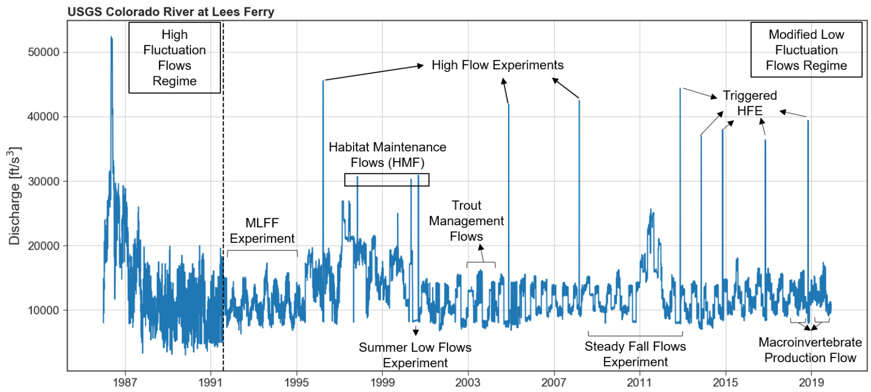

Figure 10. Lees Ferry daily flows and re-operation tests conducted until today.

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