Proposal to Amend the High-Flow Experiment Protocol and Other Considerations

Developed by the Flow Ad Hoc Group, through the Technical Work Group of the Glen Canyon Dam Adaptive Management Program in partnership with the Grand Canyon Monitoring and Research Center and the Bureau of Reclamation.

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Map derived from the GCDAMP Wiki and modified by Mel Fegler, Wyoming State Engineer's Office

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EXECUTIVE SUMMARY
TBD after acceptance of Draft Document

1. INTRODUCTION

High-flow experiments (HFEs) from Glen Canyon Dam (GCD) are part of the Long-Term Experimental Management Plan (LTEMP) to determine whether periodic high releases from GCD can be used to sustainably manage sandbars and shoreline habitats in the Colorado River Ecosystem (CRE) downstream, particularly as Fall and Spring-timed HFEs. The sediment resource goal as defined in the GCD LTEMP is to: "Increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes." Over the past 25 years, scientific information on the use and timing of HFEs has improved understanding of how best to manage tributary-derived sediment supplies below the dam for these purposes. Refined evaluation of opportunities and impediments for HFEs over the past decade under significantly lower Lake Powell reservoir levels warrants review of the HFE implementation protocols. In particular, re-evaluation of the HFE sediment Accounting Period and Implementation Window is indicated as scientifically supportable, to potentially more fully and adaptively achieve the LTEMP goals as they relate to using HFEs.

At the February 15, 2023 Glen Canyon Dam Adaptive Management Program's (GCDAMP) Adaptive Management Work Group (AMWG) meeting, AMWG directed the Technical Work Group (TWG) to review the sediment Accounting Period and provide feedback to the Bureau of Reclamation (Reclamation). Consequently, the TWG charged the Flow Ad Hoc Group (FLAHG) with the following:

> *The FLAHG is charged with working with Grand Canyon Monitoring and Research Center (GCMRC) to draft an outline and a full proposal for amending the HFE protocol. In doing so, the FLAHG should consider the information developed by GCMRC in response to the Secretary's Designee's August 18, 2022 request to evaluate high-flow experiments under low-elevations/low-flows and any other pertinent information to evaluate the accounting window.*
>
> *The proposal should consider the science, approach, and compliance elements that may be needed to make changes to the protocol. An outline of the proposal is requested by the Spring [2023] TWG meeting and the full proposal by the Summer [2023] TWG meeting.*

To meet this charge, the FLAHG developed an outline for the April 2023 TWG meeting. The draft document presented here expands on that outline and provides guidance on how to potentially refine the HFE Implementation Windows and sediment Accounting Periods, as well as other elements of the HFE protocol, such as forecasted inflows, Paria River sand mass balance modeling, and compliance. Also included herein is a consideration of impacts to high-risk non-native fish, hydropower resources, cultural considerations, etc., for future HFEs, especially in relation to sustained low Lake Powell reservoir elevations. The proposed changes identified in this document are based on initial considerations and are subject to change as discussions and review of implications for resources continue.

2. PROBLEM STATEMENT AND OBJECTIVES

Aridification and overallocation of water resources in the western U.S. has led to lower reservoir elevations in Lake Powell. This has resulted in various problems including increased temperatures of water releases, entrainment of warm-water non-native fish, and risks to power production at GCD. These and other problems resulted in the Secretary of the Interior deciding to not implement Fall HFEs in 2015, 2021, and 2022, despite reaching the appropriate input triggers for sediment HFEs. The absence of Spring HFEs during the first 10 years of the HFE protocol, coupled with analyses documenting reduced transport of fine sediments in years with low release volumes and low Lake Powell elevations, have prompted the GCDAMP to reassess the HFE protocol. The objective of this document is to inform decision makers as to whether adjustments in the sediment accounting and HFE implementation procedures are warranted. Provided below is some of the information considered in developing this proposal:

- Data on sediment input and mainstream transport are now monitored with sufficient resolution to predict HFE effects;
- The Fall HFE Implementation Window, October-November, occurs before the spring runoff, therefore extra water released during that time may increase the risk of Lake Powell approaching or falling below minimum power pool elevation;
- A Fall HFE may increase the potential risk of entrainment and dispersal of warm-water non-native fish into the Grand Canyon when reservoir elevations are low (below 3530' +/-), and fish density in the forebay is high. Risk of non-native fish entrainment through the dam is of heightened concern without a fish barrier in place;
- Sandbar volume resulting from Fall HFEs may be largely eroded before the high-use recreation season begins and before the peak season for wind transport;
- Spring HFEs under the existing HFE protocol have been triggered less frequently than predicted in LTEMP;
- High flows historically occurred more frequently during the spring than the fall;
- Spring HFEs may be more reliably planned and implemented than Fall HFEs because the runoff forecast is less uncertain in the spring than the fall;
- Reduced releases from GCD as a result of recent low reservoir elevations has resulted in extended residence time for new sediment supplies in the mainstream channel; and
- Proactive Spring HFEs are limited to years when annual releases are 10.0 million acre-ft (MAF) or greater. These high-volume years are unlikely to occur under low reservoir elevations and recent hydrologic trends, and therefore adjustments to the HFE implementation triggers and duration of proactive Spring HFEs may be warranted. This topic has not been fully discussed within the FLAHG and is not integrated into this document.

If HFEs are infrequently implemented, sandbars will be infrequently rebuilt; and existing sandbar deposits will erode relatively quickly. With more frequent HFEs, sandbars will sustain their size longer and may progressively increase in size (Figure 1). The HFE protocol was designed to test if "sandbar building during HFEs could exceed sandbar erosion between HFEs such that sandbar size can be increased and maintained over several years" (LTEMP ROD page B-19). Modeling indicated Fall HFEs would be triggered in about 77% of the years in the LTEMP period, or 15 in 20 years (LTEMP ROD page B-20). Modeling also indicated that there may be sufficient sediment input for Spring HFEs in about 26% of the years in the LTEMP period, or 5 in 20 years (LTEMP ROD page B-19). Although it was possible for there to be some years with two HFEs (one in fall and one in spring), and some years with no HFEs, the experimental design to test the hypothesis was intended for an average of one sediment-triggered HFE per year to occur.

While this proposed protocol revision is a direct response to the February 15, 2023 AMWG request, the GCDAMP has been considering the feasibility of increased opportunities for Spring HFEs since 2019. The Department of the Interior (DOI) released a Memorandum on August 14, 2019 that states: "*In response to stakeholder input at recent AMWG meetings, the feasibility of conducting Spring High Flow Experiments (HFE), along with modeling for improvements and efficiencies that benefit resources including natural, cultural, recreational, and hydropower should be explored. As a potential starting point, I [Dr. Tim Petty, who was serving as the Secretary's Designee] encourage you to consider opportunities to conduct higher spring releases within power plant capacity, along with Spring HFEs that may be triggered under the current LTEMP Protocol.*"

3. BACKGROUND

System History

Historically, the Colorado River could be characterized as a high-elevation snowpack-driven, bi-modal (meaning large inflows from both spring runoff and monsoonal storms) river system that featured large springtime floods as snowpack melted, transitioning into lower-flow conditions through summer, fall, and winter. Streamflow in the Colorado River between Lake Powell and Lake Mead has been controlled by GCD since March 1963 and operations have largely eliminated snowmelt-driven spring floods and elevated base flows while at the same time, created diurnal flow fluctuations (Topping et al. 2003). Lake Powell traps upstream sediment and associated inputs from Colorado River tributaries downstream of GCD are limited (Topping et al. 2000). This results in clear water releases that may continue downstream long distances (Stevens et al. 1997). One of the most visible impacts of GCD installation was the decline in the number and size of alluvial sandbars (Dolan et al. 1974; Schmidt and Graf 1990). Although narrow strips of fine sediment line the banks throughout much of Grand Canyon, the largest sandbars occur in zones of recirculating flow. These eddies can be dozens of meters wide and hundreds of meters long (Figure 2). Because sandbars are composed of unconsolidated sediment, they inevitably erode through several processes including cutbank retreat, seepage processes, gullying, and wind deflation (Bauer and Schmidt 1993; Budhu and Gobin 1994). Prior to completion of GCD, sediment-rich spring floods replenished sandbars annually. Without those floods, progressive sandbar erosion occurs.

Since 1996, HFEs have been the primary mechanism used by Reclamation to determine if and how the sediment resource goal, now defined in LTEMP, can be achieved. Declining reservoir elevations as well as the interaction among low reservoir conditions and the threats posed by warm-water non-native species have disrupted the frequency of HFE implementation during the LTEMP period. This proposal presents a process for refining the protocol for implementing HFEs, primarily through adjustments of the HFE sediment Accounting Periods and Spring Implementation Window to provide greater opportunity for HFE implementation under varying/uncertain hydrologies, including low reservoir conditions observed in current times.

HFEs have been conducted at GCD on an experimental basis since 1996 in an effort to rebuild sandbars and shoreline habitats with settled sand along the Colorado River in the lower Glen Canyon National Recreation Area and through Grand Canyon National Park. Findings from the initial experimental “controlled floods” resulted in the design of HFEs with the following characteristics: 1) peak magnitude as high as possible within facilities constraints, 2) duration as long as possible without creating a deficit in the available supply of sand, and 3) frequent implementation to offset intervening erosion. These factors are incorporated in the “HFE Protocol” (US Department of the Interior 2016).

Between 2012 and 2018, five HFEs were conducted under the HFE Protocol, all resulting in beneficial sandbar deposition and improved beach quality for camping. Since the last Fall HFE[1] in 2018, sandbars have significantly eroded, and the condition of sandbars have deteriorated.

Continued conditions of low runoff, low reservoir levels, and other resource concerns have created risks that have prevented implementation of HFEs for four consecutive years. Risks identified during the consideration of past HFEs included the concerns of warm-water non-native fish entrainment and dispersal, as well as impacts to hydropower production and water delivery. If reservoir levels do not recover or deteriorate further, such risks are likely to persist. Several of these risks could be alleviated by adjusting the HFE Protocol to allow increased likelihood of triggering HFEs in the spring when hydrologic conditions and reservoir levels are receiving spring runoff.

Declining Reservoir Elevations

The Grand Canyon Protection Act of 1992 directs the Secretary of the Interior to operate GCD “in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established.” The operation and actions of GCD must be fully consistent with and subject to the Law of the River. Declining reservoir elevations have made this dual mandate difficult. For example, if elevations at GCD cannot be maintained above 3490’, the ability to deliver water downstream is affected (or impacted) and there may be implications to critical infrastructure and power grid reliability.

In recent years, releases of lower monthly volumes during the winter have allowed less sediment to be transported downstream. Low reservoir levels and warmer releases have

[1] The last HFE was implemented in Spring 2023, but the most recent Fall HFE was implemented in 2018. Given extraordinary conditions, Reclamation conducted a one-time experimental spring flow in April of 2023 for 72 hours. The results from this experimental flow have not been fully analyzed at the time of this report.

increased the potential for entrainment and downstream distribution of predatory non-native fish. Evaluating these complex trade-offs requires timely and high-quality monitoring data and must allow for continuous informed application of adaptive ecosystem management practices. To better manage sediment in the Colorado River below Glen Canyon Dam, the review of the adequacy of the HFE Implementation Windows and sediment Accounting Periods under low reservoir conditions is warranted.

Current Sandbar Conditions

A total of 10 experimental releases at or above power plant capacity of various durations have been conducted since the first experimental release in 1996. In a recent summary of sandbar monitoring data, Hazel et al. (2022) showed that sand volume increased at 86% of the monitoring sites between 2004 and 2020 due to the seven HFEs that occurred during that period (Figure 3). In contrast, net erosion occurred at 61% of the monitoring sites between 1990 and 2003 – a period that included only one HFE (Hazel et al. 2022).

No HFEs occurred between 2019 and 2022. Since the 2018 HFE, sandbar volume has declined (Figure 4, lower) due to gradual erosion resulting from "normal" GCD operations that would be expected following any individual HFE (Hazel et al. 2010), as well as dramatic episodes of non-GCD related local erosion in 2021 and 2022 during summer thunderstorms[2]. Hillslope runoff during these events resulted in the formation of gullies and deposition of debris on sandbar campsites (Figure 5). Similar damage caused during previous monsoon seasons was repaired by HFEs, which bury debris and fill gullies (Grams et al. 2018).

4. HFE Elements for Consideration

High flow experiments have overall shown trends in sand deposition resulting in the building of sandbars and beaches. High flow releases rebuild sandbars by entraining sediment from the riverbed and redepositing that sediment along the banks and in eddies. Because the locations of eddies are controlled primarily by channel constrictions at tributary debris fans, the zones of deposition are relatively stable and deposition usually occurs on existing sandbars or at the sites of former sandbars that have eroded. HFEs are achieved using GCD power plant capacity releases ($\leq$31,500 cubic feet per second (cfs) with all power generating units and full reservoir conditions) combined with power plant bypass through the "jet tubes" ($\leq$15,000 cfs with all four tubes) not to exceed a total of 45,000 cfs.

Four essential components have been identified for HFEs to be successful in the long-term:

1. Sufficient sand, or sand load, in the mainstream river channel to build sandbars without progressively depleting the sand supply;
2. The sand grain size is sufficiently fine to create conditions of high sand concentration in eddies;

[2] This is supported by observational data presented by Grand Canyon Monitoring and Research Center (GCMRC) staff at the January 2023 Annual Reporting Meeting of the GCDAMP .

3. Sustained flow magnitude is sufficiently high and of sufficient duration to deposit sand at high-elevation sections of sandbars without creating a negative deficit in the sand supply; and
4. HFEs must be frequent enough to offset erosion and to achieve increasing or neutral sandbar size (Wright and Kennedy 2011).

With the exception of the first component, these elements were implemented in the HFE Protocol Environmental Assessment (U.S. Department of the Interior 2012) and were subsequently included in the HFE Protocol in the LTEMP ROD (U.S. Department of the Interior 2016). Background literature and supplemental materials are available in detail within the GCDAMP Wiki HFE Page.

5. Proposed Revisions to the HFE Protocol

The Original 2011 HFE Protocol

The HFE Protocol established release magnitudes for HFEs that could range from 31,500 cfs to 45,000 cfs, and potential durations ranging from one hour to 96 hours (Table 1). The LTEMP extended the duration of Fall HFEs for up to 250 hours (with specifications listed in Table 2) and established a Proactive Spring HFE that could be triggered by an equalization release of ≥10.0 MAF (see Table 2).

The original HFE Protocol was intended to be experimental in nature and was designed to learn how to incorporate high releases into future GCD operations in a manner that effectively conserves sediment and sediment-dependent resources in the long term. The new proposed hypothesis [under the LTEMP] is intended to test if recurring HFEs that provided sandbar building would exceed sandbar erosion in periods between HFEs, such that sandbar size could be maintained and increased over time. The HFE Protocol was originally envisioned to test releases over the 10-year period from 2011-2020. Environmental compliance was later extended for the duration of the LTEMP EIS (2016-2036). The Environmental Assessment for the HFE Protocol can be found on Reclamation's website. Supporting documents and information collected from past HFEs is available at GCDAMP Wiki HFE Page, Reclamation's GCDAMP website, and GCMRC's Sandbar Monitoring site.

Current Sediment Accounting Periods and HFE Implementation Windows

The current HFE Protocol (U.S. Department of the Interior 2016) uses a sediment Accounting Period and Implementation Window which occurs semi-annually (described below; Figure 6). The Accounting Periods are based on the expected timing of sediment delivery and on typical GCD operations. The sediment Accounting Periods are the periods over which sand inputs and exports are measured in order to evaluate whether or not conditions have been met to trigger an HFE. In determining whether or not to conduct an HFE, the Sediment Accounting Model (Wright et al. 2010) is utilized and incorporates monitoring data (reservoir elevations, GCD releases, and sediment) with the goal of maintaining a positive sand mass balance at the end of the Accounting Period. Evaluation of sufficient sediment input to trigger an HFE considers sand input from the Paria River during sediment Accounting Periods to achieve a positive sand mass balance in Marble Canyon with implementation of an HFE.

The current Spring HFE Implementation Window is from March 1 to April 30, with a December 1 through June 30 sediment Accounting Period. The Fall HFE Implementation Window is from October 1 to November 30, with a July 1 through November 30 sediment Accounting Period (Figure 6). Regardless of whether or not an HFE is conducted, the sediment Accounting Periods do not roll-over accumulated sand from the prior Accounting Period in order to trigger a potential HFE during the following Implementation Window (Figure 6). After the Accounting Period is over, the sediment baseline is reset for the next Accounting Period. Only sand received during the current Accounting Period can be included in the model as input sediment to trigger an HFE.

A recent example of needed flexibility in the HFE sediment Accounting Period was encountered in the spring of 2023. During the 2023 spring sediment Accounting Period, much of the sediment remained from the previous Fall Accounting Period due to low annual release volumes and shifted water delivery schedules. Thus, the positive sediment mass balance in Marble Canyon in spring 2023 did not accumulate in the 2023 Spring Accounting Period, but remained from prior Accounting Periods. Given the positive sediment mass balance that persisted into spring 2023, as well as the condition of beaches, the lack of HFEs since 2018, exceptional hydrologic circumstances and the need to release 9.5 MAF in the water year (including the need to release 0.523 MAF of water temporarily held back earlier in the water year), a one-time spring experiment was conducted with the goal of benefitting multiple resources. A Supplemental Information Report was provided by Reclamation.

There are currently four key analysis phases to the HFE modeling component associated with the two sediment budget Accounting Periods and the two HFE Implementation Windows. This process is conducted prior to each HFE Implementation Window and continued throughout the Implementation Window to monitor the potential for considering the implementation of an HFE (LTEMP HFE Protocol, pg C-5). The four key analysis phases are: Phase 1: Fall Accounting Period, Phase 2: October-November HFE Window, Phase 3: Spring Accounting Period, and Phase 4: March-April sediment-triggered HFE Window.

Proposed changes to the modeling component and analysis phases: Revision to Section "1.2 MODELING" of the HFE Protocol

The primary proposed revision to the HFE Protocol involves combining the two sediment Accounting Periods into a single, annual, Accounting Period (Figure 7). The two HFE Implementation Windows, one in the fall and one in the spring, would be preserved with some small modifications. The following is a step-by-step proposed revision of the HFE key analysis components described above and found on page C-5 to C-6 of the LTEMP ROD, with the combination of two of the original phases for a total of three phases. The text that is provided below in *italics* is proposed to replace the text found in the HFE Protocol. Additional non-italicized text is provided for context.

- [Replace paragraph starting with "Phase 1:..." on LTEMP ROD page C-5 with] *Revised Phase 1: Annual Accounting Period. The annual Accounting Period is from July 1 to June*

30. Beginning on July 1 of each year, monitoring data will be used to track the sand storage from Paria River inputs in Marble Canyon.

The revised annual Accounting Period becomes a combination of the Fall and Spring Accounting Periods in the original HFE protocol (Figure 7). The revised annual Accounting Period is extended to one year beginning on July 1 and ending on June 30 of the following year. Beginning on July 1 each year, sediment monitoring data will be used to track the sand storage from Paria River inputs into Marble Canyon. HFEs will be triggered based on maintaining a positive sand mass balance from the start of the Accounting Period to the end of the HFE (not to the end of the sediment Accounting Period as is currently done) using the lower bound of the estimated sand supply.

Resetting the sediment mass balance starting value on an annual basis has some advantages over the current procedures. Any sand that may remain because a Fall HFE was not implemented would also accrue into the sediment mass balance. This situation increases the likelihood of triggering a Spring HFE. This proposed revision does not mean that more than one Fall HFE should be implemented in the Fall Implementation Window or more than one Spring HFE should be implemented in the Spring Implementation Window.

Resetting the sediment account mass balance start value on an annual basis means that any sand that accrued into the balance during the first year, but was not used in that year, is unavailable for use in future years. This potentially abandoned sediment is referred to here as "rollover" sediment.

The FLAHG did not specify how to use rollover sediment because more analyses are needed. However, the FLAHG generally agreed that it was important to consider. The following elements should be considered by Reclamation when considering the impacts of a future contemplated action resulting from this recommendation:

- Element 1: Reclamation should analyze adding rollover sediment from one or more years to the current July 1 starting value if a sediment-triggered HFE was not conducted in the previous annual Accounting Period.
- Element 2: Reclamation should acknowledge that the communication and consultation procedures established in Section 1.4 of the LTEMP ROD will be used to make recommendations on using any available rollover sediment.

- *[Replace paragraph starting with "Phase 2:..." on LTEMP ROD page C-5 with] Revised Phase 2: October-November HFE Implementation Window. Beginning July 1, sand storage and forecast hydrology will be evaluated using the sediment budget model to determine whether conditions are suitable for a Fall HFE or if conditions warrant delaying considerations until Phase 3 (i.e., the Spring HFE Implementation Window). The* *model determines what magnitude and duration of a Fall HFE, if any, would produce a positive sand mass balance at the end of a Fall HFE. If the model produces a positive result, the largest Fall HFE that would result in a positive sand mass balance or delayed consideration of a Spring HFE is forwarded to the decision and implementation component (see below), which also allows for other factors to be considered in the planning process (see Section 1.1). During the decision process, sediment input will continue to be measured, the model will continue to be run and results or output will be forwarded to decision-makers to allow for refinement of the previously recommended magnitude and duration of either a Fall HFE or deferred to a Spring HFE. If the model produces a negative sand mass balance, the model will continue to be rerun using more recent sediment input to determine whether a positive sand mass balance will be reached in time to have a Fall HFE in the release window.*

- *[Replace paragraph starting with "Phase 3:..." and paragraph starting with "Phase 4:..." on LTEMP ROD page C-6 with] Revised Phase 3: March-June sediment-triggered HFE Implementation Window. The evaluation in this phase is the same for the October-November HFE window (see Revised Phase 2) with the model output being forwarded to the decision and implementation component. The model output will be used in the same way as for the October-November determination. The annual Accounting Period will be used to determine if there are suitable conditions to consider implementation of a Spring HFE from March 1 to June 30. Whether or not a Spring HFE is scheduled, sediment inputs will continue to be monitored through the end of the annual Accounting Period. Note that Proactive Spring HFEs (see Section 3.2), which are triggered by water volume and not sediment inputs, could occur in April, May, or June. In addition, Spring HFEs will not be tested in years when there has been an extended-duration Fall HFE earlier in the same water year.*

  Reclamation proposed an action to prevent the establishment of Smallmouth Bass below Glen Canyon Dam in the Glen Canyon Dam/Smallmouth Bass Flow Options Draft Environmental Assessment (Draft EA). However, Reclamation decided to pursue an Environmental Impact Statement based on comments received on the Draft EA. The FLAHG did not resolve a potential future scenario where multiple flow actions (e.g. HFE, Smallmouth Bass flow action) are triggered in the same water year. However, some FLAHG members have already identified impacts to resources that may not be acceptable from their viewpoint. Additional analyses are needed to understand the impacts and tradeoffs of these actions potentially occurring in the same water year. The FLAHG recommends Reclamation analyze such impacts and tradeoffs.

HFE Protocol Revisions in Relation to LTEMP Resource Goals

The objectives of this proposed revision to the HFE protocol (as described above) are to increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow to help attain the resource goals as currently described by the LTEMP. The proposed revisions to the sediment Accounting

Periods and Implementation Windows, and sediment rollover into subsequent HFE Accounting Periods achieves these goals by:

- Expanding opportunities to retain sediment resources in periods where HFEs may provide additional benefits to multiple LTEMP resources while balancing impacts among other resources;
- Implementing and evaluating how HFEs might be conducted during low reservoir conditions;
- Increasing the likelihood that HFEs are implemented with a frequency that is consistent with the original LTEMP experimental design; and
- Adapting the HFE Protocol to continue to test and evaluate the LTEMP hypothesis, including the importance and effectiveness of springtime HFEs, under the new and continuously changing conditions of the Colorado River ecosystem.

To achieve sediment resource objectives intended by LTEMP, it is necessary to amend the modeling component and key analysis phases as described above. Implementation of the proposed HFE protocol revisions will require the continued assessment of sediment input and storage in relation to projected releases, dam maintenance schedules, impacts to other resources, and timing with other experiments. In addition to the consolidation of the sediment Accounting Periods, consideration should be given to extending the Spring HFE Implementation Window such that it would end on June 30, as opposed to April 30. This will increase the likelihood of triggering an HFE by capturing late spring runoff and sediment inputs from the Paria River. The FLAHG encourages analyses of both extending and not extending to June 30 when Reclamation analyzes the impacts of a future contemplated action. Evaluating and documenting this analysis will help determine whether or not HFEs are feasible with consideration to hydropower and other resources during June, and ultimately, will help set expectations and streamline the LTEMP decision framework.

Extending the Spring HFE Implementation Window may provide additional resource benefits, to be tested as part of the HFE hypothesis, such as disrupting Brown Trout and Smallmouth Bass spawning, mimicking historical spring floods, improving the natural processes resource goal, increasing the potential for aeolian transport of fluvial sediment to rebury and protect archaeological sites, and improving the summertime recreation camping experience. The impacts associated with extending (or not) the Implementation Window should be analyzed and more fully considered during an environmental compliance process. The extension of the Spring HFE Implementation Window would provide opportunities for improved understanding of these potential positive or adverse impacts. If the decision to perform a Spring HFE is made later in the Implementation Window due to the proposed extension, there may be potential negative impacts. The later implementation of an HFE may provide less opportunities to shift water volumes between months that are important for hydropower and other resources. The potential positive and negative effects to multiple resources will continue to be considered in the LTEMP decision framework.

6. Spring HFEs and Potential Impacts to Other LTEMP Resources

Overview

The relationships between GCDAMP goals and the role of HFEs is complex, as some resources benefit from HFEs, some remain unaffected, and some are negatively affected (Figure 8). The GCDAMP has acknowledged the potential additional benefits to resources other than sediment through the implementation of Spring HFEs.

Below are the anticipated potential benefits of a Spring HFE, as well as potential adverse impacts to be considered during any process for revising the HFE Protocol. This is not an exhaustive list, and it is anticipated that additional resource impacts will be determined and considered in future analyses. As is the current practice, a number of these potential impacts may already be evaluated through the LTEMP decision framework as part of the normal process to recommend HFEs. Some of these concepts may have greater weight than others, but are listed here for further evaluation:

- Lake Powell reservoir elevations – identification of critical reservoir elevations may change through the post-2026 Colorado River operations development process, therefore no specific elevation is identified here. However, sufficient reservoir elevations will continue to be essential for “normal” operations at GCD, including when an HFE is considered by the LTEMP decision framework. For example, there may be a greater risk of falling below minimum reservoir elevation thresholds (i.e., minimum power pool) during a Fall or Spring HFE that may be triggered prior to spring runoff.
- Non-native warm-water fish – There is likely a greater risk of entrainment and dispersal during a Fall HFE (e.g., Smallmouth Bass, Green Sunfish).
- Fish migration and spawning – The timing of an HFE may provide benefits or adverse impacts based on native and non-native fish life histories (e.g., Humpback Chub, Razorback Sucker, and Flannelmouth Sucker may benefit from a Spring HFE while Brown Trout may benefit from a Fall HFE).
- Improved planning process – A Spring HFE that can utilize fall sediment allows more time to plan for power replacement, potential shifts in monthly water volumes, and monitoring trips.
- Recreation season (April-September) – A Spring HFE is in closer proximity to, and allows more suitable timing, for sandbar persistence during the high-use recreation season. Sandbars deposited by a Fall HFE are subject to erosion at high-priority areas (campsites, etc.) before the arrival of the high-use recreation season.
- Aeolian sand transport – A Spring HFE would coincide with the windy season (April-June) and provide a greater potential for aeolian sand transport.
- Hydropower impacts – Implementing a Fall or Spring HFE during 'peak power months' (i.e., June-August or December-February), could have significant negative impacts on energy grid reliability and replacement power costs. Hydropower impacts, along with other resources, will continue to be considered in the LTEMP decision framework. The following considerations (below) should be included in the NEPA LTEMP SEIS analysis.

- Impacts to hydropower can be reduced by taking water for HFEs from non-peak shoulder months instead of peak power months as described in the HFE Protocol.
- A notice of at least two weeks prior to implementing an experiment that substantially deviates from normal operations is required by Western Area Power Administration (WAPA).
- Advanced decision-making of HFEs has the potential to reduce impacts to hydropower and allows time for resource planning. Making a decision to conduct an HFE at least three months in advance provides the most flexibility for hydropower rate and contract notifications. Establishing reliable protocols allows utilities to accurately assess their 5-year resources planning outlook for construction and acquisition needs.
- Effects analysis of hydropower rate structure changes that have occurred since LTEMP ROD should be included (e.g., WAPA-199).
- Concern about multiple bypass actions in a single Implementation Window.

- Basin Fund impacts – Depending on the timing and duration of an HFE, as well as current power market costs and resource availability, WAPA's assessment of the Basin Fund will be impacted by a multitude of factors. In turn, the status of the Basin Fund has direct implications for funding the statutory obligations assigned to it, which include Reclamation and WAPA operation and maintenance costs, repayment of investment plus interest, irrigation assistance and non-power programs such as the Colorado River Basin Salinity Control Program. Basin Fund levels also have a direct impact on the potential application of a cost recovery charge to Colorado River Storage Project customers.
- Foodbase – A Spring HFE could provide benefits to the natural processes goal. For example, a national synthesis of flow and biological data from over 700 streams and rivers in the lower 48 states found that healthy communities of native aquatic invertebrates and fish were most often present where flood disturbance still occurred, and where flood timing was seasonally appropriate (i.e., similar to the natural condition; Carlisle et al. 2017).
- High-risk non-native fish spawning – Smallmouth Bass spawning occurs when water temperatures rise to 16C (typically June in Lees Ferry). Analysis should include the consideration of an HFE that may also be beneficial in limiting invasive fish spawning where possible to benefit the most resources.
- Cultural Resources – There could be potential adverse impact to cultural sites in Glen Canyon from future HFEs due to erosion, as well as the potential to increase protection and improve the condition of some cultural resources in the Grand Canyon. Tribal engagement is needed to fully assess potential impacts to cultural resources. The assessment of individual effects and their relevance will likely vary by Tribe.
- Riparian vegetation and habitat value – Dispersal and growth of native and non-native (i.e., salt cedar) riparian plant species may vary depending on implementation timing of HFEs. An extended Spring HFE Implementation Window may enhance plant growth with greater habitat value in restoration areas.

- Aquatic vegetation – HFEs are likely beneficial in scouring/impacting undesirable aquatic vegetation, with spring HFEs likely to have longer-lasting effects/benefits compared to fall HFEs (Torn et al. 2010).
- Trout fishery – Although acute disruption of spawning activity and angling opportunities may occur during HFEs, Spring HFEs also have the potential to promote spawning. Rainbow trout typically spawn in the spring and are adapted to spring flood disturbances. Benefits to other resources are likely to indirectly benefit Rainbow Trout in the long-term (e.g., increased foodbase productivity and spawning substrate scouring/cleaning).
- Additional sediment inputs – A Spring HFE could mobilize additional sediment inputs from the Little Colorado River floods that occur in January-March, while large Paria River floods typically occur in August-September.
- Adaptive management – The opportunity to learn from these experiments, including their benefits and impacts, will provide crucial information to inform future recommendations within LTEMP.

FIGURES

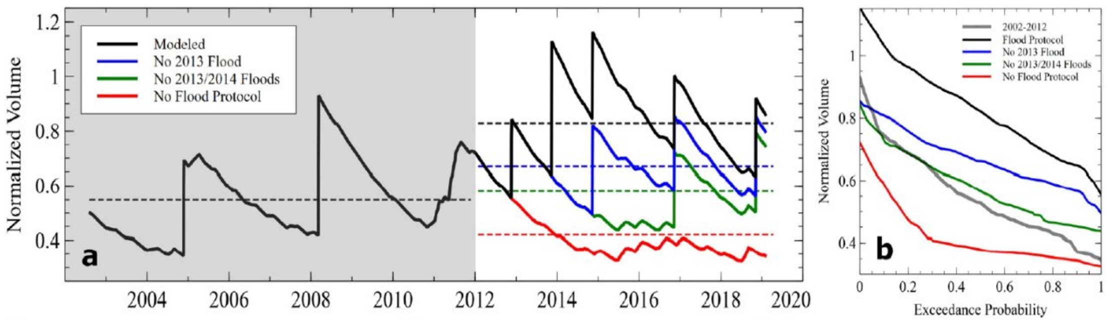


Figure 1. Modeled sandbar volume from 2002 to 2019 showing effects of HFE frequency (a) Time series and (b) exceedance probability of bar volume for different frequencies of controlled floods during the period 2012–2019. From Mueller and Grams (2021).

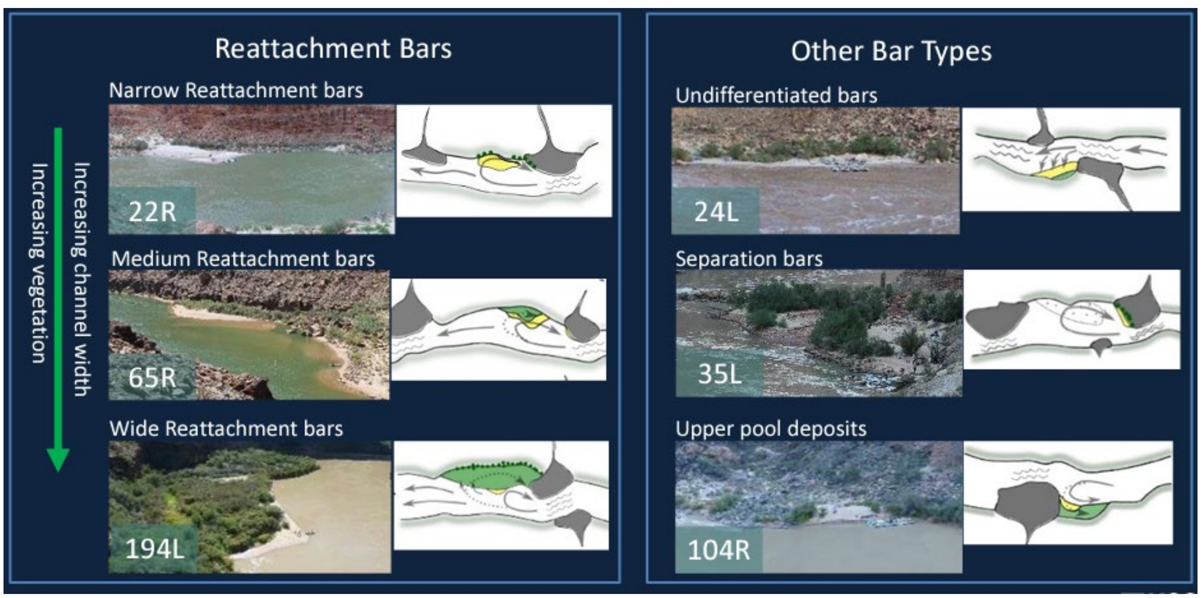
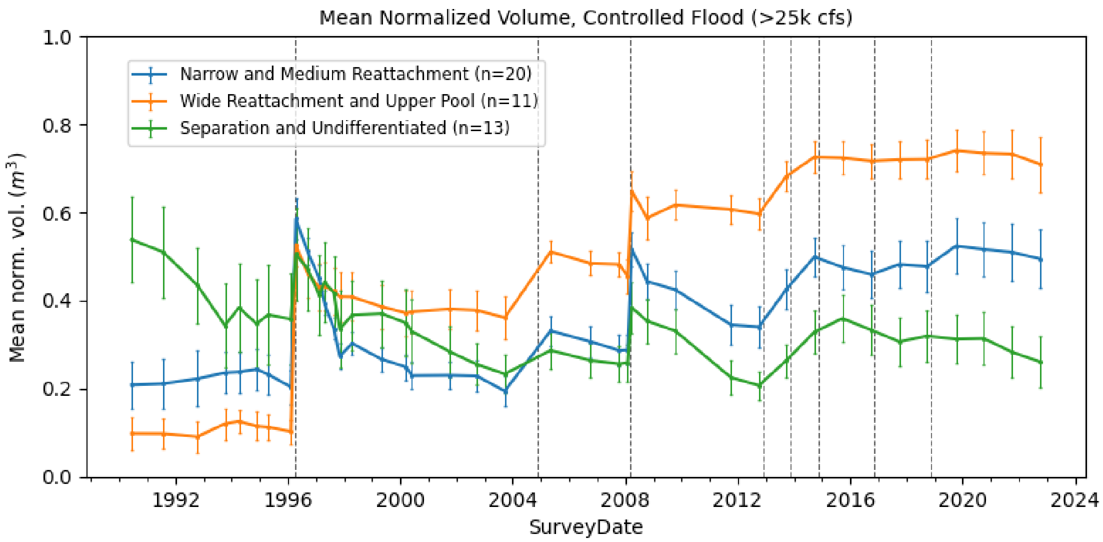


Figure 2. Sandbar types (from Schmidt and Graf 1990 and Mueller et al. 2018).



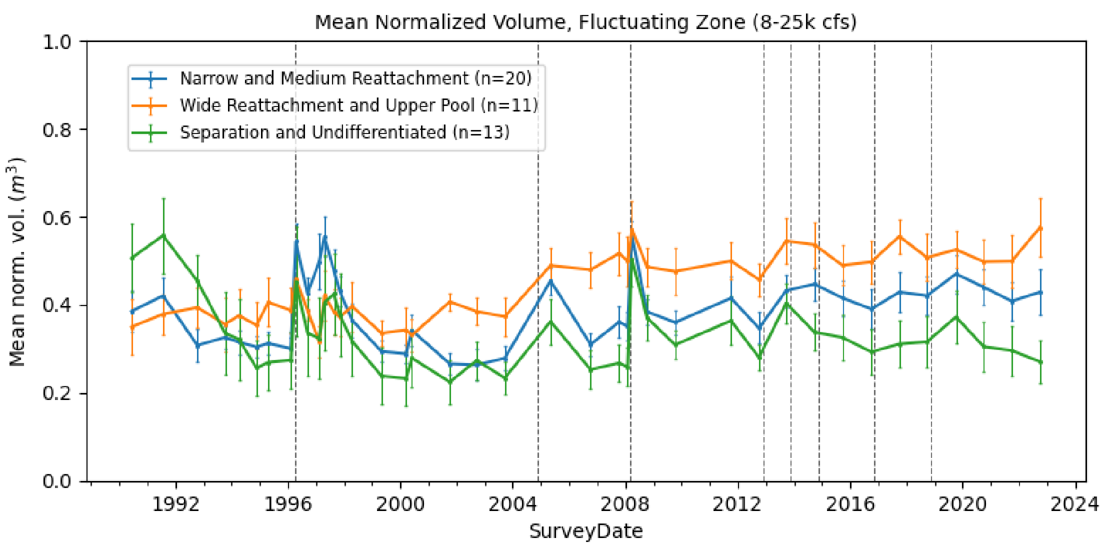


Figure 3. Mean normalized sandbar volumes in narrow-medium reattachment, wide reattachment, and separation or undifferentiated sandbars from 1992-2022 in above-normal-operations elevations (upper graph) versus within-normal-operations elevations (lower graph). Based on Hazel et. al (2022), with figures derived from GCDAMP AMWG February 2023 *Overview of Projects A, B, and L and Evaluation of High-Flow Experiments During Aridification* presentation.

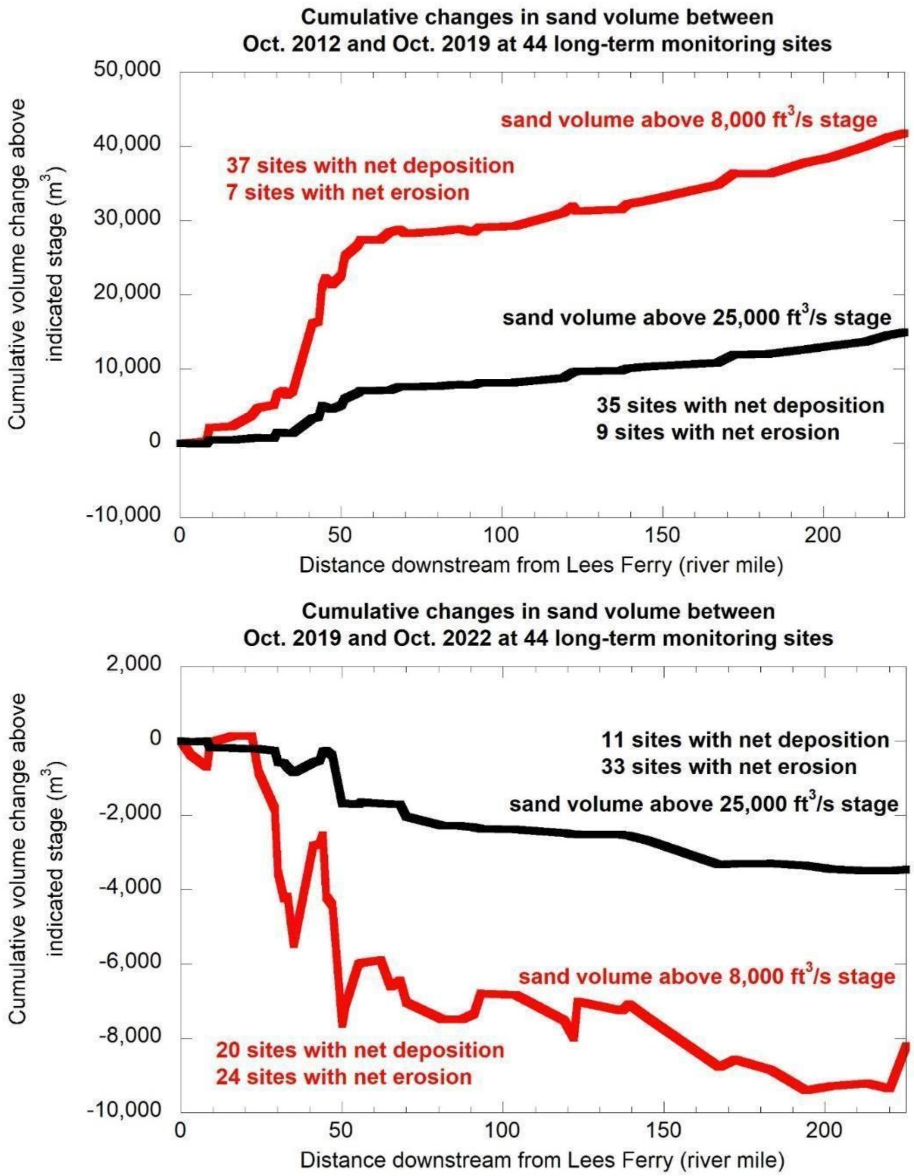


Figure 4. Cumulative changes in sandbar volume between October 2012 and October 2019 (upper graph) and between October 2019 and October 2022 (lower graph) at 44 long-term monitoring sites. Based on Hazel et. al (2022), with figures derived from GCDAMP AMWG February 2023 *Overview of Projects A, B, and L and Evaluation of High-Flow Experiments During Aridification* presentation.

Figure 5. Example of gully erosion at Tatahatso Beach (Colorado River Mile 37L) between October 2020 and October 2022. Photos by P. Grams, USGS.

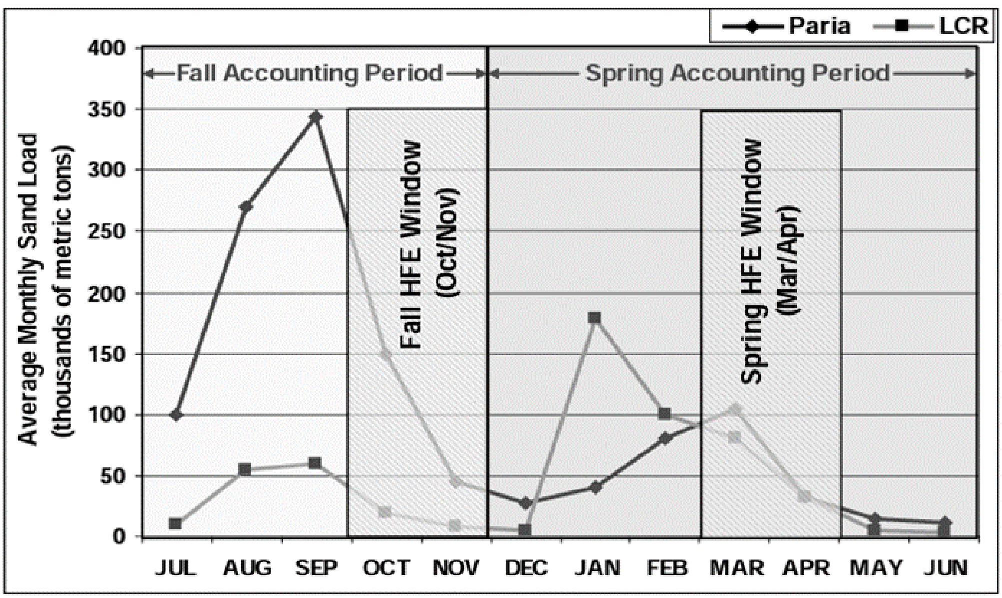


Figure 6. Average monthly sand loads from the Paria River and Little Colorado River showing the existing Fall and Spring HFE Accounting Periods and Implementation Windows defined in the 2011 HFE Protocol.

Post-hoc modeling for HFE implementation using 1-year accounting window

Year*	HFEs triggered and implemented under HFE Protocol and LTEMP EIS			Duration triggered (Oct 15 model run)			Duration triggered (LTEMP accounting)	Duration triggered (Mar 15 model run)	Duration triggered (May 15 model run)		
	Magnitude triggered (cfs)	Magnitude implemented (cfs)	Duration implemented (hours)	Nov HFE (hours)	Apr HFE (hours)	Jun HFE (hours)	Apr HFE (hours)	Apr HFE (hours)	Jun HFE (hours)	"Best" Implementation month***	Choice following proposed decision approach****
2012	45000	44,500	85	144	96	96	0	144	96	Nov & Apr	Nov or Apr
2013	45000	37,000	99	250	250**	250**	0	250	250	Any	Any month**
2014	45000	38,000	104	96	72	72	0	72	72	Nov	Nov
2015			-	48	12	1	0	48	36	Nov and Apr	Nov
2016	45000	36,500	99	36	1	0	0	12	12	Nov	Nov
2017			-	0	0	0	0	0	0		-
2018	45000	39,500	65	48	12	1	0	72	60	Apr	Nov
2019			-	0	0	0	0	0	0		-
2020			-	0	0	0	0	0	0		-
2021	45000		-	192	144**	144**	0	144	144	Nov	Any month**
2022	45000		-	96	96	72	0	96	72	Any	Nov or Apr

Red box = information for October decision   Orange box = updated information for Spring implementation

* Year of beginning of sediment accounting window. Fall HFEs are in same year; Spring HFEs are in following calendar year.

**** Extended-duration with advance warning:**
There are opportunities (Yellow boxes) where it would be possible to test the desired extended duration HFEs with long advance notice. Testing those was part of LTEMP, but they have not been implemented, in part because it's difficult to initiate a major experiment with short notice.

*** Evaluation for best implementation month assumes that all HFEs >= 96 hour duration are equal. That may not be correct and needs to be tested with extended duration HFE.

****** Possible decision approach:**
- If 96-hr or longer is possible in Fall or Spring (based on Oct. prediction), choose implementation month based on other resource considerations.
- If 96-hr or longer is possible in Fall, but less than 96-hr in Spring (based on Oct. prediction), choose Fall unless resource impacts force Spring choice.
- If less than 96-hr is possible in Fall (based on Oct. prediction), choose implementation month based on other resource considerations.

Assumptions:
- All HFEs are 45,000 cfs magnitude
- 4000 cfs/hr ramp up, 2500 cfs/hr ramp down
- mass balance evaluated from July 1 to conclusion of HFE
- used lower bound Paria sand load prediction (10% uncertainty), no inputs after prediction date

Figure 7. Post-hoc modeling for HFE Implementation comparing the current HFE Implementation Window to an annual HFE Implementation Window. Table courtesy Paul Grams, USGS

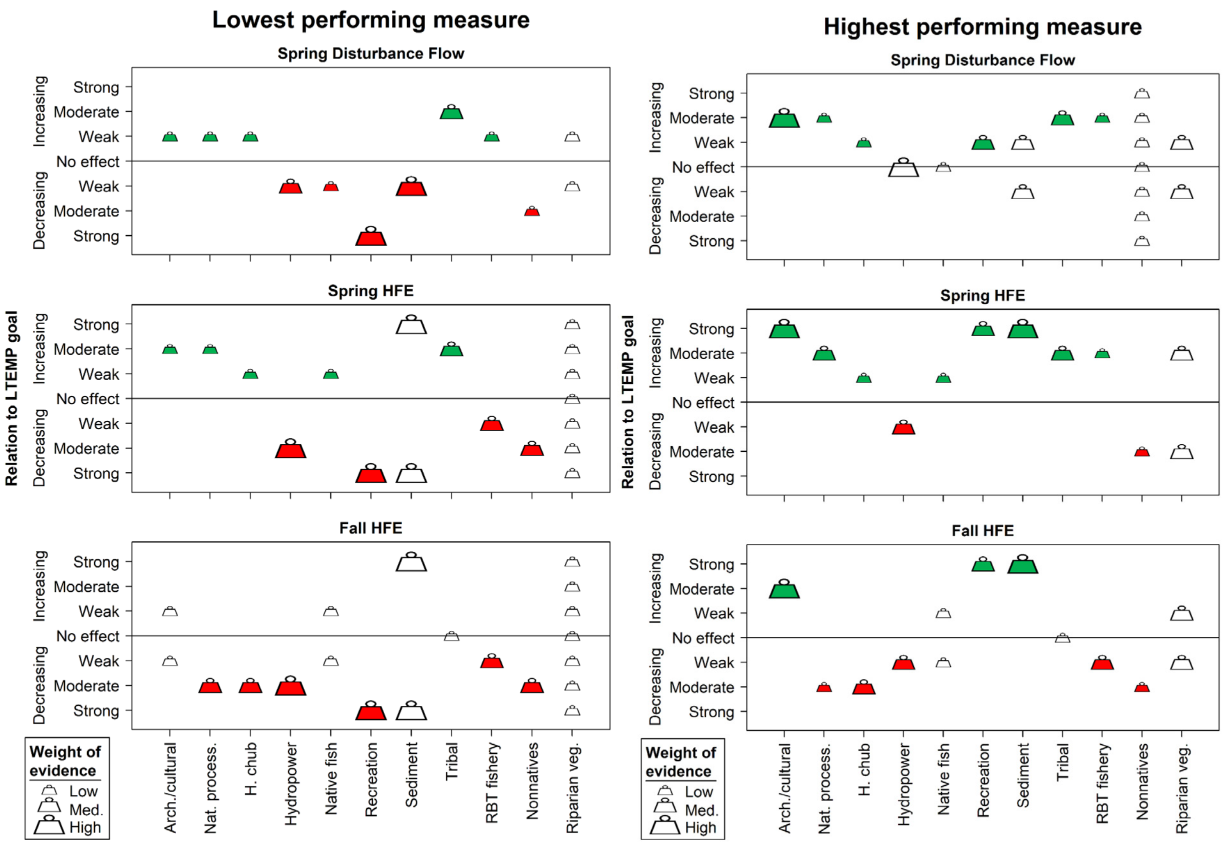


Figure 8. Graphs showing the lowest (left) and highest (right) predicted effects of a Spring Disturbance Flow, a Spring HFE, and a Fall HFE on LTEMP resources, as derived from the Spring Disturbance Flow - Predicted Effects document. Open symbols indicate resources where the direction of effect and/or the strength of the effect was unknown. Low weight of evidence indicates greater levels of critical uncertainty whereas high weight of evidence indicates lower levels of critical uncertainty.

Please note that these graphs do not fully correspond to the ideas proposed in this document, but rather serve as a general guideline for potential effects to various resources and should be considered in further analysis.

TABLES

Table 1. Technical alternatives for 16 different HFE scenarios.

HFE ID	Peak Discharge (cfs)	Duration at Peak (hours)	Volume of water above normal operations (ac-ft)*	Volume of bypass (ac-ft)**
1	45,000	250	756,100	278,900
2	45,000	192	580,700	214,200
3	45,000	144	435,500	160,700
4	45,000	96	290,400	107,100
5	45,000	72	217,800	80,300
6	45,000	60	181,500	66,900
7	45,000	48	145,200	53,600
8	45,000	36	108,900	40,200
9	45,000	24	72,600	26,800
10	45,000	12	36,300	13,400
11	45,000	1	3,000	1,100
12	41,500	1	2,700	800
13	39,000	1	2,500	600
14	36,500	1	2,300	400
15	34,000	1	2,100	200
16	31,500	1	1,900	0

Table 2. HFEs described in LTEMP.

TABLE 4 Implementation Criteria for Experimental Treatments of Alternative D

Experimental Treatment	Trigger[a] and Primary Objective	Replicates	Duration	Annual Implementation Considerations[b]	Long-Term Off-Ramp Conditions[c]	Action if Successful
Sediment-Related Experiments[d]						
Spring HFE up to 45,000 cfs in Mar. or Apr.	Trigger: Sufficient Paria River sediment input in spring accounting period (Dec.–Jun.) to achieve a positive sand mass balance in Marble Canyon with implementation of an HFE Objective: Rebuild sandbars	Not conducted during first 2 years of LTEMP, otherwise implement in each year triggered, dependent on resource condition and response	≤96 hr	Potential short-term unacceptable impacts on resources listed in Section 1.3; unacceptable cumulative effects of sequential HFEs; sediment-triggered spring HFEs will not occur in the same water year as an extended-duration (>96 hr) fall HFE	Sediment-triggered spring HFEs are not effective in building sandbars; or long-term unacceptable adverse impacts on the resources listed in Section 1.3 are observed	Implement as adaptive treatment when triggered and existing resource conditions allow
Proactive spring HFE up to 45,000 cfs (Apr., May, or Jun.)	Trigger: High-volume year with planned equalization releases (≥10 maf) Objective: Protect sand supply from equalization releases	Not conducted during first 2 years of LTEMP, otherwise implement in each year triggered, dependent on resource condition and response	First test 24 hr; subsequent tests could be shorter, but not longer, depending on results of first tests	Potential short-term unacceptable impacts on resources listed in Section 1.3; unacceptable cumulative effects of sequential HFEs; will not be implemented in the same water year as a sediment-triggered spring HFE or extended-duration fall HFE	Proactive spring HFEs are not effective in building sandbars; or long-term unacceptable adverse impacts on the resources listed in Section 1.3 are observed	Implement as adaptive treatment when triggered and existing resource conditions allow
Sediment-Related Experiments (Cont.)						
Fall HFE ≤96 hr up to 45,000 cfs in Oct. or Nov.	Trigger: Sufficient Paria River sediment input in fall accounting period (Jul.–Nov.) to achieve a positive sand mass balance in Marble Canyon with implementation of an HFE Objective: Rebuild sandbars	Implement in each year triggered, dependent on resource condition and response	≤96 hr	Potential short-term unacceptable impacts on resources listed in Section 1.3; unacceptable cumulative effects of sequential HFEs	This type of fall HFE is not effective in building sandbars; or long-term unacceptable adverse impacts on the resources listed in Section 1.3 are observed	Implement as adaptive treatment when triggered and existing resource conditions allow
Fall HFEs longer than 96-hr duration up to 45,000 cfs in Oct. or Nov.	Trigger: Sufficient Paria River sediment input in fall accounting period (Jul.–Nov.) to achieve a positive sand mass balance in Marble Canyon with implementation of an HFE longer than a 96-hr, up to 45,000-cfs flow Objective: Rebuild sandbars	Implement in each year triggered; limited to total of four tests in LTEMP period	Up to 250 hr depending on availability of sand duration of first test not to exceed 192 hr	Potential short-term unacceptable impacts on resources listed in Section 1.3; unacceptable cumulative effects of sequential HFEs	Extended-duration fall HFEs are not effective in building sandbars; resulting sandbars are no bigger than those created by shorter-duration HFEs; or long-term unacceptable adverse impacts on the resources listed in Section 1.3 are observed	Implement as adaptive treatment when triggered and existing resource conditions allow

TABLE 4 (Cont.)

References

Bauer, B. O., & Schmidt, J. C. 1993. Waves and sandbar erosion in the Grand Canyon: Applying coastal theory to a fluvial system. *Annals of the Association of American Geographers*, 83(3), p. 475-497.

Budhu, M., & Gobin, R. 1994. Instability of sandbars in Grand Canyon. *Journal of Hydraulic Engineering*, 120(8), p. 919-933.

Carlisle, D. M., Grantham, T. E., Eng, K., & Wolock, D. M. (2017). Biological relevance of streamflow metrics: Regional and national perspectives. Freshwater Science, 36(4), 927-940.

Dolan, R., Howard, A., & Gallenson, A. 1974. Man's Impact on the Colorado River in the Grand Canyon: The Grand Canyon is being affected both by the vastly changed Colorado River and by the increased presence of man. *American scientist*, *62*(4), p. 392-401.

Grams, P.E., Tusso, R.B., and Buscombe, D. 2018. Automated remote cameras for monitoring alluvial sandbars on the Colorado River in Grand Canyon, Arizona: *U.S. Geological Survey Open-File Report 2018-1019*, 61 p. https://doi.org/10.3133/ofr20181019.

Hazel, J.E., Jr., Grams, P.E., Schmidt, J.C., and Kaplinski, M. 2010. Sandbar response following the 2008 high-flow experiment on the Colorado River in Marble and Grand Canyons: U.S. Geological Survey Scientific Investigations Report 2010-5015, p. 52 p., http://pubs.usgs.gov/sir/2010/5015.

Hazel Jr, J.E., Kaplinski, M.A., Hamill, D., Buscombe, D., Mueller, E.R., Ross, R.P., Kohl, K. and Grams, P.E., 2022. *Multi-decadal sandbar response to flow management downstream from a large dam—The Glen Canyon Dam on the Colorado River in Marble and Grand Canyons, Arizona* (No. 1873). US Geological Survey. https://doi.org/10.3133/pp1873

Mueller, E. R., Grams, P. E., Hazel Jr, J. E., & Schmidt, J. C. 2018. Variability in eddy sandbar dynamics during two decades of controlled flooding of the Colorado River in the Grand Canyon. *Sedimentary Geology*, *363*, p. 181-199.

Mueller, E.R., and Grams, P.E. 2021. A morphodynamic model to evaluate long-term sandbar rebuilding using controlled floods in the Grand Canyon: *Geophysical Research Letters*, v. 48, p. 1–10. http://doi.org/10.1029/2021GL093007.

Schmidt, J. C., & Graf, J. B. 1990. *Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona* (No. 1493). US Government Printing Office.

Stevens, L. E., Shannon, J. P., & Blinn, D. W. 1997. Colorado River benthic ecology in Grand Canyon, Arizona, USA: dam, tributary and geomorphological influences. Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management, 13(2), 129-149.

Topping, D.J., Rubin, D.M., and Vierra, L.E. Jr. 2000. Colorado River sediment transport 1. Natural sediment supply limitation and the influence of Glen Canyon Dam: *Water Resources Research*, v. 36, p. 515–542. https://doi.org/10.1029/1999WR900285.

Topping, David J., John C. Schmidt, and L. E. Vierra Jr. *Computation and analysis of the instantaneous-discharge record for the Colorado River at Lees Ferry, Arizona—May 8, 1921, through September 30, 2000*. No. 1677. US Geological Survey, 2003.

Torn, Kaire, Georg Martin, Jonne Kotta, and Maarit Kupp. "Effects of different types of mechanical disturbances on a charophyte dominated macrophyte community." Estuarine, coastal and shelf science 87, no. 1 (2010): 27-32.

U.S. Department of the Interior. 2012. Colorado River Basin Water Supply and Demand Study. Bureau of Reclamation. https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/studyrpt.html

U.S. Department of the Interior. 2016. Glen Canyon Dam Long-term Experimental and Management Plan Environmental Impact Statement. Salt Lake City, UT: Bureau of Reclamation, Upper Colorado Region; Lakewood, CO: National Park Service, Intermountain Region. http://ltempeis.anl.gov.

Wright, S. A., Topping, D. J., Rubin, D. M., & Melis, T. S. (2010). An approach for modeling sediment budgets in supply-limited rivers. *Water Resources Research*, *46*(W10538), 1–18. https://doi.org/10.1029/2009WR008600

Wright, Scott A., and Theodore A. Kennedy. "Science-based strategies for future high-flow experiments at Glen Canyon Dam." *Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona. US Geological Survey Circular* 1366.147 (2011): 127-147.