U.S. Department of the Interior
U.S. Geological Survey

Evaluation of High-Flow Experiments under conditions of low flows and low reservoir elevations

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How can HFEs be optimized for the current low flow and low Lake Powell reservoir elevation conditions?

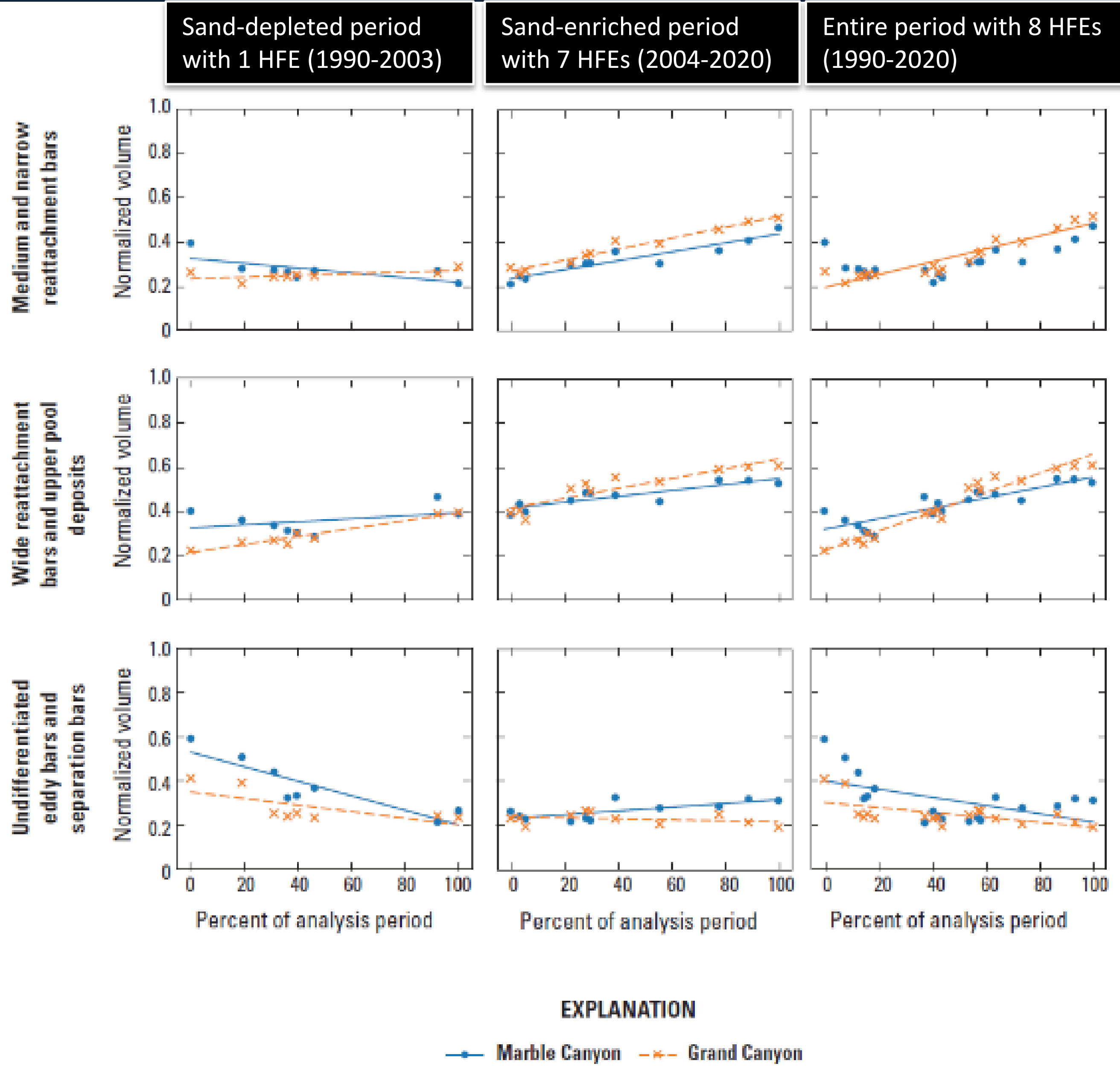
Questions from GCDAMP Secretary Designee Pullan (paraphrased):

- HFE frequency and magnitude
  - *Is it better to have fewer high-magnitude HFEs or more frequent low-magnitude HFEs?*
  - *What are minimal frequency, flow, and duration that would be effective?*
- *Are there other alternatives for meeting the objectives of HFEs?*
- *How do we design HFEs to minimize impacts to hydropower?*

Purpose of HFEs in LTEMP ROD

- The purpose of HFEs is to address the LTEMP sediment goal, which 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."
- The fine-sediment deposits (sandbars) erode by dam operations and natural processes such as hillslope runoff from monsoon rains
- HFEs are the only mechanism that has produced widespread re-distribution of sediment from the riverbed to the sandbars above base flow elevations.

HFEs have functioned as intended by the HFE Protocol and LTEMP EIS



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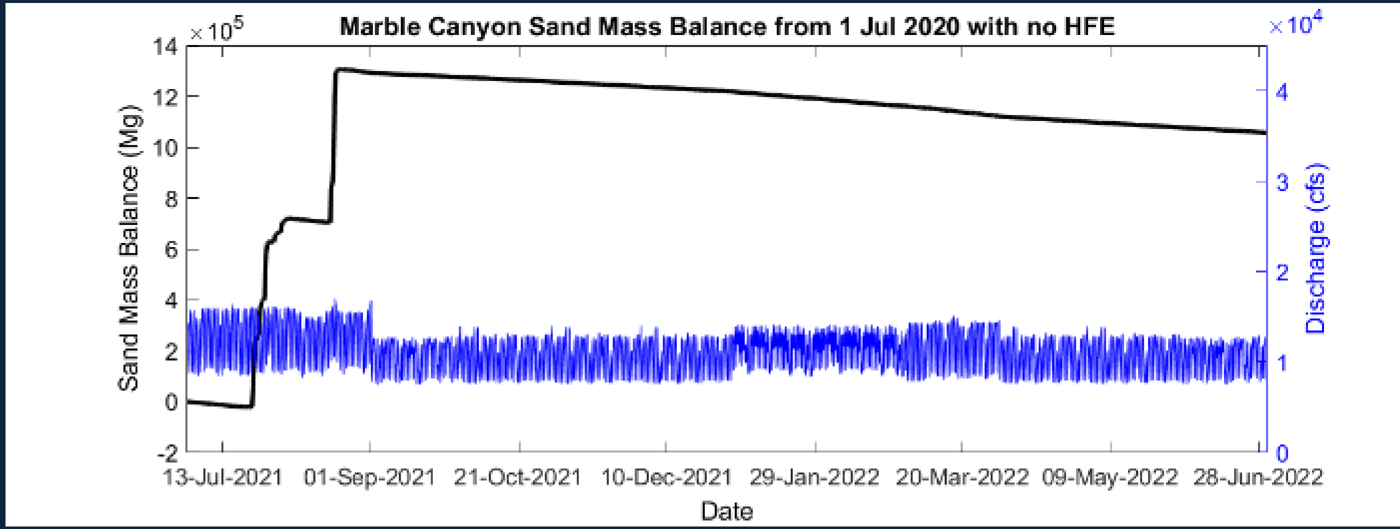
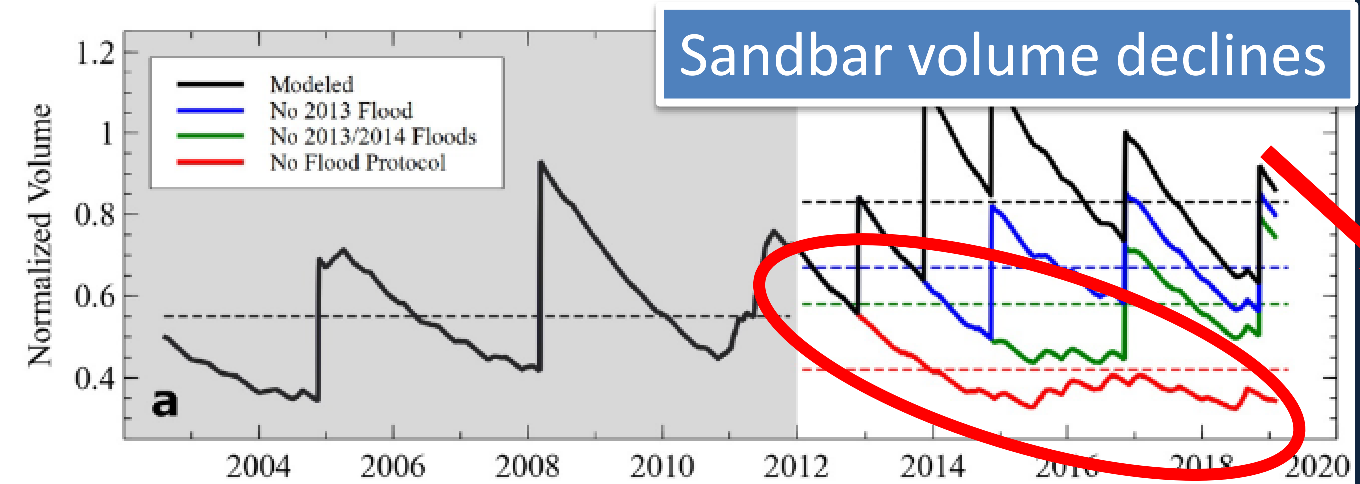
Without HFEs, sand remains on bed and sandbars erode and sand volumes above baseflow decline



Sand remains on riverbed in Marble Canyon



Sandbar volume declines

Eroded bars are not rebuilt

Mueller and Grams (2021)

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Three Key Ingredients for Successful HFEs:

1. There is sufficient sand in the system to build sandbars without causing net erosion.
   - Addressed in HFE Protocol by using sediment model to design HFE.
2. Sand grain size is sufficiently fine to create conditions of high sand concentration in eddies.
   - Addressed in HFE Protocol by using sediment model to design HFE.
3. HFE magnitude is high enough to deposit sand at the high-elevation parts of sandbars and campsites.
   - Addressed in HFE Protocol by step-down approach to find the largest HFE that can be implemented for the available sand supply (consistent with 1 and 2, above).

These guidelines are embedded in the LTEMP ROD and are based on observations from first three HFEs (1996, 2004, and 2008) and verified by observations from recent HFEs (2012, 2013, 2014, 2016, and 2018)

HFE frequency, magnitude, and duration

- HFE magnitude has strongest control over deposition because it controls potential deposit size by inundating more area. We have very high confidence in this physical control on bar deposition based on observations and modeling results dating back to the 1996 HFE.
  - Low magnitude (~30,000 cfs) are much less effective than ~40,000 cfs, but still result in sandbar deposition.
- Duration is secondary, but also important because time is needed for sand concentrations to increase and for sand to be redistributed within eddies. Duration is hypothesized to control the number and distribution of sites that benefit.
- Frequency is important because repeat HFEs are needed to rebuild the deposits that inevitably erode between HFEs.
- The HFE Protocol was designed to optimize HFE hydrographs based on this knowledge by maximizing magnitude first, then duration

→ HFE Magnitude, Duration, and Frequency are not interchangeable

The HFE Protocol was designed to optimize HFEs based on this knowledge by maximizing magnitude first, then duration, and implementing as frequently as conditions allow.

Hazel and others (2022), Wiele and others (1999)

HFE frequency, magnitude, and duration

The HFE Protocol says do HFEs of the highest magnitude possible, longest duration possible, and as frequently as sediment conditions allow.

- Is it better to have fewer high-magnitude HFEs or more frequent low-magnitude HFEs?
  - Low-magnitude HFEs *of any frequency* are not a substitute for higher-magnitude HFEs.
  - Observations indicate that bars erode substantially when HFEs are ~4 years or more apart.
  - We expect very little or no additional benefit to doing HFEs more frequently than annually. But *if there is enough sediment*, multiple HFEs per year may be okay.
  - “optimal” frequency is probably every 1 to 3 years under enriched sediment.

  → High-magnitude HFEs every 1 to 3 years is likely better than more frequent smaller HFEs

HFE frequency, magnitude, and duration

The HFE Protocol says do HFEs of the highest magnitude possible, longest duration possible, and as frequently as sediment conditions allow.

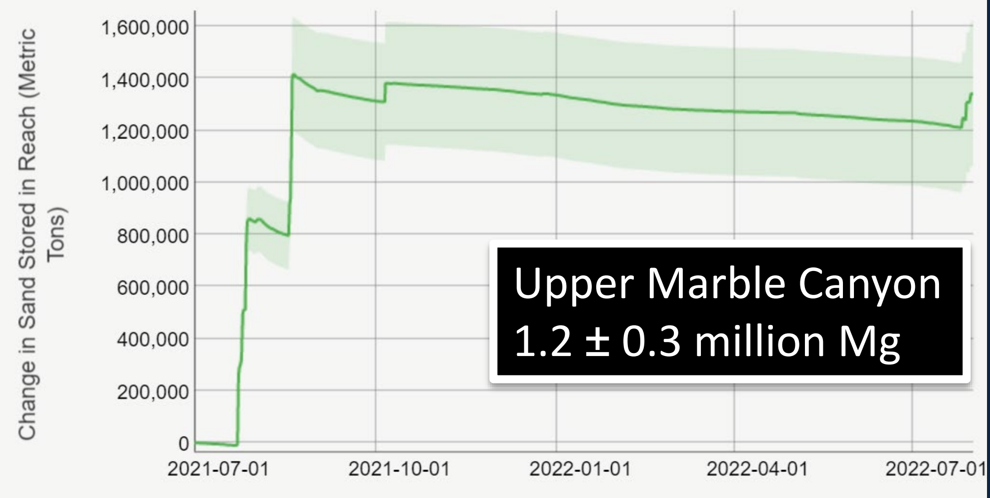
- What are minimal frequency, flow, and duration that would be effective?
  - We know HFEs of ~36,000 cfs and as short as ~60 hours have been effective.
  - The HFE Protocol allows for HFEs as low as 31,500 cfs for as short as 1 hour. These have not yet been tested under sediment-enriched conditions.
  - → These lower magnitude and duration HFEs are worth testing when larger HFEs are not possible, but they will be less effective than larger HFEs.
  - → If following the HFE Protocol (highest magnitude and duration possible under enriched conditions), frequencies of 1 to 3 years probably maintains sandbars.
  - → If all three variables are set to the minimum allowed in the HFE Protocol for every HFE, sandbars are likely to decline in size.

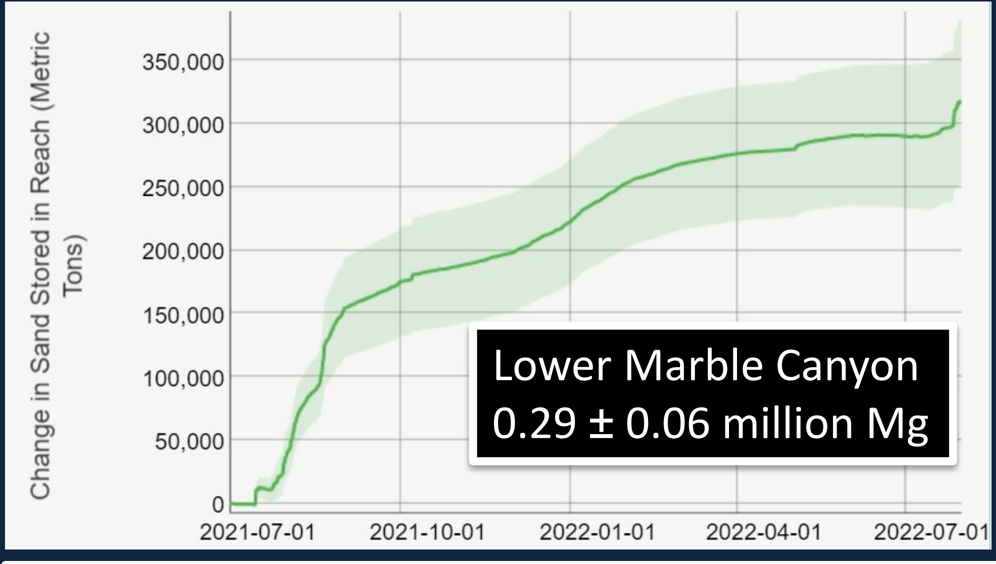
Are there other alternatives for meeting the objectives of HFEs?

- Some improvements in sandbar and campsite quality may be achieved by vegetation removal, which is being implemented at selected sites. Expansion of this effort might be considered as a mitigation to reduced frequency/magnitude of HFEs.

HFE Optimization

- The purpose of the HFE "sediment accumulation periods" and "implementation windows" was to make the most efficient use of scarce sediment during periods when sediment inputs might be low and release volumes might result in net sand export
- Large 2021 inputs from Paria River combined with relatively low dam releases has resulted in accumulation of sand in Marble Canyon





While these conditions persist, a sediment-enriched HFE could be conducted any time of year, using the sand routing model and flexible accounting windows to ensure sediment conservation

Mable Canyon (RM 30 to 61) mass balance for sediment year 2021 (7/1/2021 – 6/30/2022) was **positive 1.5 ± 0.3 million Mg**

Provisional data downloaded from: https://www.gcmrc.gov/discharge_qw_sediment

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HFE Optimization

The question posed by the Secretary's Designee was "How do we time and design HFEs to minimize the hydropower impacts?"

Two different categories of impacts:

- Impacts to Lake Powell reservoir levels (by causing shifts in monthly volumes, HFEs can affect the risk of dropping below minimum power pool)
  - *We can evaluate and potentially mitigate this risk by considering HFEs of different volumes and optimizing the reallocation of the monthly volumes*
- Impacts to hydropower production/revenues
  - This impact is more complicated to evaluate and requires a trade-off analysis
  - Minimizing impacts to reservoir levels may result in a lower volume of bypass which should reduce impact to hydropower production
  - *Impacts to hydropower could be further reduced by ensuring that all hydropower units are available for any potential HFE implementation window.*

Example Scenario A: Conduct Fall HFE without affecting Lake Powell elevations

Given the maximum possible HFE discharge magnitude in November 2022 is 33,100 cfs, what is the maximum duration that could be implemented without needing to reduce releases in any month other than November?

HFE Duration (hours)	Mean daily discharge required before and after HFE to achieve 500 kaf November monthly volume (cfs)	Difference from planned mean daily discharge for 500 kaf November monthly volume (cfs)	Is this change consistent with daily min/max flows allowed in LTEMP EIS?
96	4603	-3800	No – below allowed minimum flows
48	6639	-1764	Yes
36	7103	-1300	Yes
24	7551	-852	Yes
12	7984	-419	Yes
1	8368	-35	Yes

- A Fall HFE of up to 33,100 cfs and up to 48 hours duration would have no impact to Lake Powell reservoir elevations after Nov. 30, 2022

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- A Fall HFE of up to 33,100 cfs and up to 48 hours duration would have no impact to Lake Powell reservoir elevations after Nov. 30, 2022

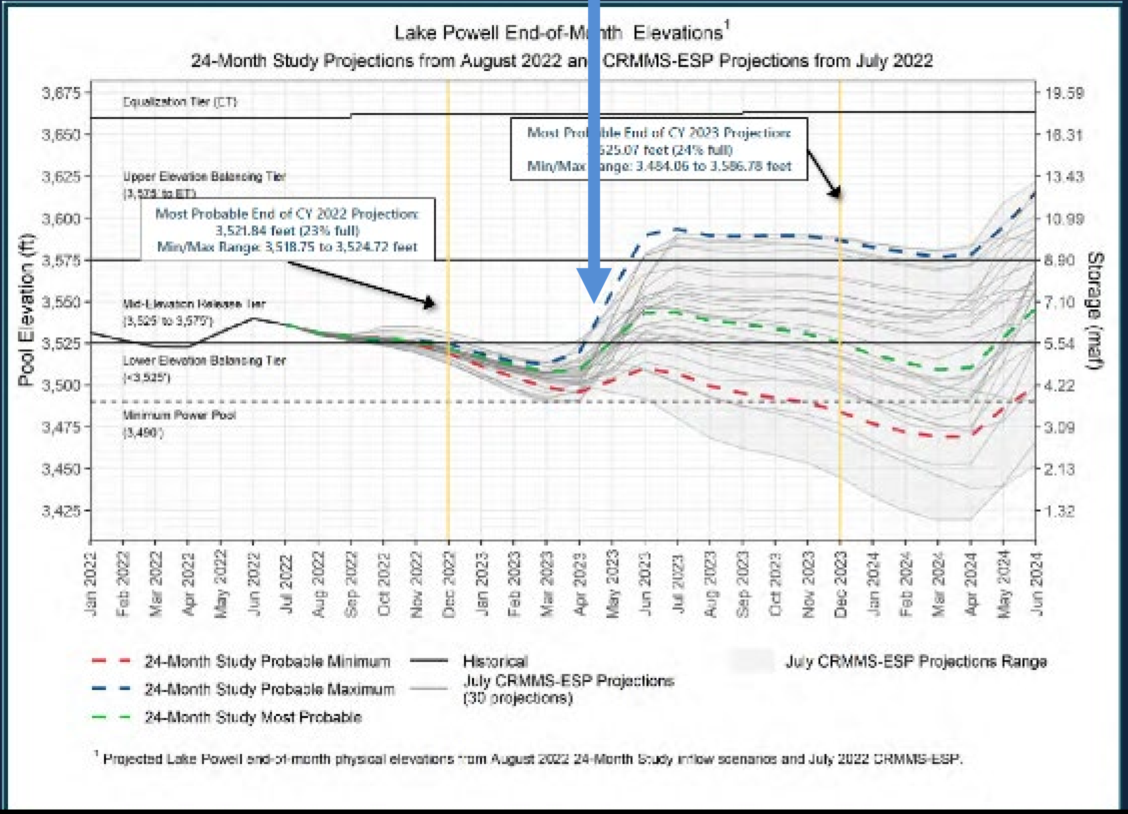
It would likely be possible to accommodate up to a 96-hour HFE by extending the adjustment to December (moving some water from the planned 600 kaf December into November)

Example Scenario B: Conduct HFE in April implementation window when snowmelt runoff volumes can be predicted

- Follow HFE Protocol for HFE design but with expanded accounting window that would include entire sediment year (July 1 through June of following year)
- Add hydrologic constraints – such as requiring that the HFE be conducted without increasing the risk of reservoir elevations dropping below a specified threshold (e.g. 3490 or 3525).
- Use of the LTEMP Spring implementation window and limiting the number of Spring HFEs to the frequency anticipated by the LTEMP analysis may simplify additional compliance

Sediment conditions would have permitted implementing an HFE in Spring 2022 under this scenario. We will evaluate this scenario for 2022-2023 with the flow, sediment, and sandbar models.

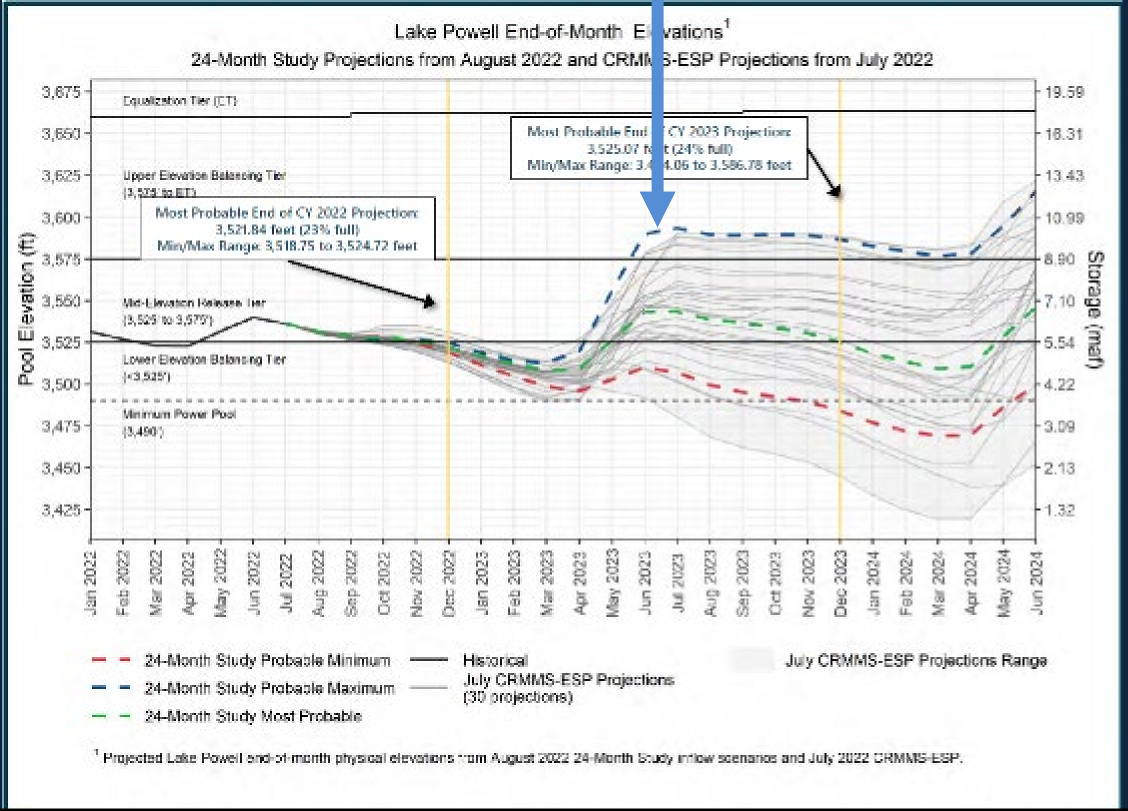
April HFE with no increased risk to cause low Lake Powell elevations



Example Scenario C: Conduct HFE in May, June, or July to maximize benefit to other resources

- Follow HFE Protocol for HFE design but with expanded accounting window that would include entire sediment year (July 1 through June of following year)
- Add hydrologic constraints – such as requiring that the HFE be conducted without increasing the risk of reservoir elevations dropping below a specified threshold (e.g. 3490 or 3525).
- Design HFE to meet other resource objectives (e.g. small mouth bass control and/or aquatic production).

Late Spring or Summer HFE with no increased risk to cause low Lake Powell elevations and other resource benefits



Sediment conditions would have permitted implementing an HFE in 2022 under this scenario. We will evaluate this scenario for 2022-2023 with the flow, sediment, and sandbar models.

Conclusions: HFEs under conditions of low flows and low reservoir elevations

- Owing to low flows, a sediment-enriched HFE could likely be conducted at any time of year. The LTEMP accounting periods and implementation windows were designed to minimize the risk of progressive sediment depletion, which is unlikely to occur under the conditions of aridification.
- The LTEMP provides an optimization scheme that is consistent with the best science: prioritize HFE magnitude, then duration, and implement as frequently as sediment conditions allow.
- By adding some hydrologic criteria/constraints, HFEs could be implemented that follow the intent of LTEMP for sediment but do not add to the risk of Lake Powell elevations dropping below specified thresholds:
  - Reduce HFE magnitude and duration for a fall HFE such that all monthly volumes can follow the planned 24-month study.
  - Implement HFE in spring when inflows can be reliably forecasted and other resources may benefit.
  - Implement HFE in late spring or summer when inflows have been realized and other resources may benefit.

LTEMP is the guide to use for designing HFE magnitude, duration, and frequency. But low flow/reservoir conditions mean we can have more flexibility with HFE timing and LTEMP does not provide guidance for adjusting monthly volumes to accommodate HFEs.

LTEMP provides specific procedures for designing HFEs and specifies monthly flow volumes based on annual release volume

List of HFEs Available for Sediment-Triggered Experiments (fall, extended-duration fall and spring) in LTEMP ROD

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

* Amount of water above assumed base operation volume for 500 kaf/month (8400 cfs mean daily flow)

TABLE 3 Monthly Release Volumes under Alternative D

	Monthly Release Volume (thousand ac-ft)[a]									
Total Annual	7,000	7,480	8,230	9,000	9,500	10,500	11,000	12,000	13,000	13,000
October	480	480	643	643	643	643	643	643	643	643
November	500	500	642	642	642	642	642	642	642	642
December	600	600	716	716	716	716	716	716	716	716
January	664	723	763	857	919	1,041	1,102	1,225	1,347	1,470
February	587	639	675	758	813	921	975	1,083	1,192	1,300
March	620	675	713	801	858	973	1,030	1,144	1,259	1,373
April	552	601	635	713	764	866	917	1,019	1,121	1,223
May	550	599	632	710	761	862	913	1,014	1,116	1,217
June	577	628	663	745	798	905	958	1,064	1,171	1,277
July	652	709	749	842	902	1,022	1,082	1,202	1,322	1,443
August	696	758	800	899	963	1,091	1,156	1,284	1,413	1,537
September	522	568	600	674	722	819	867	963	1,059	1,160

LTEMP recognizes that implementation of an HFE "may require reallocating water from other months in order to maintain flows above the required minimum (i.e., 5,000 to 8,000 cfs)," but does not provide specific guidance for how to do so.

Observations and modeling that demonstrate the role of HFE Magnitude, duration, and frequency

References

- Hazel, J.E., Jr., 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: U.S. Geological Survey Professional Paper 1873, https://doi.org/10.3133/pp1873
- 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, no. 9, e2021GL093007, https://doi.org/10.1029/2021GL093007.
- Wiele, S.M., Andrews, E.D., and Griffin, E.R., 1999, The effect of sand concentration on depositional rate, magnitude, and location in the Colorado River below the Little Colorado River, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 131–145.

Sandbar response to HFE magnitude

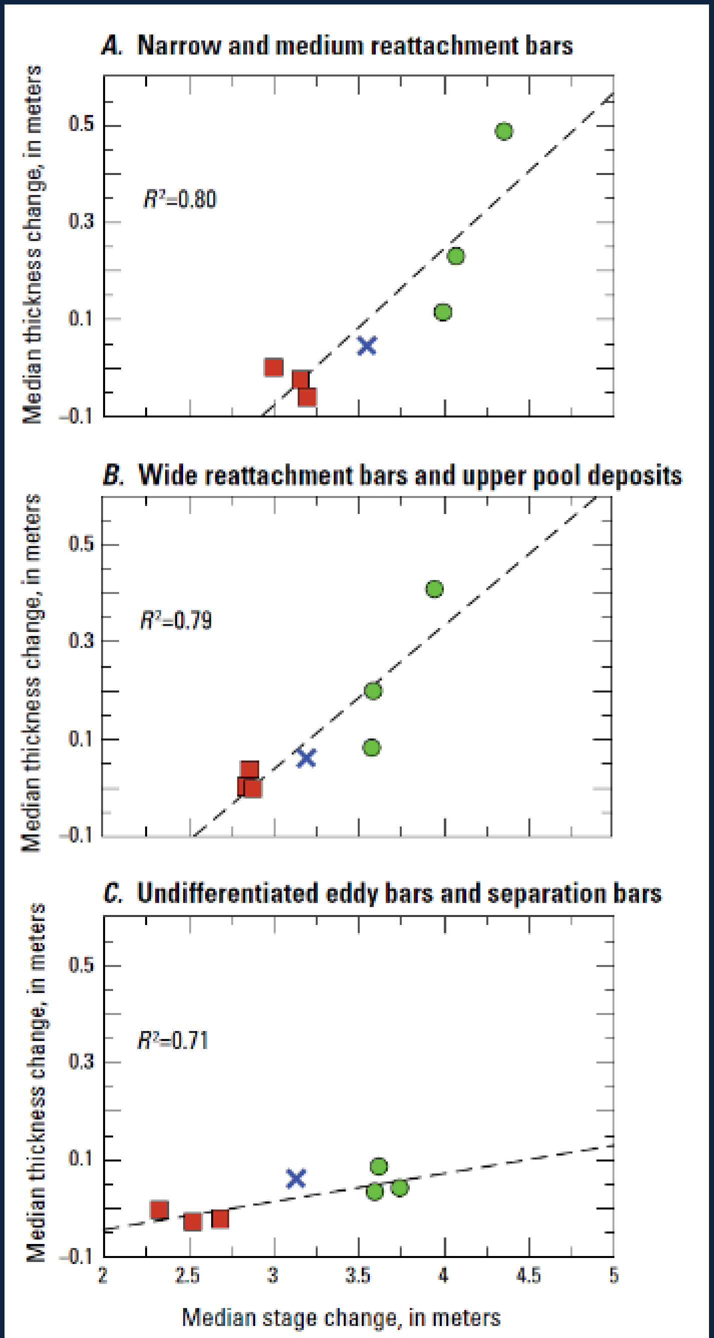
Hypothesis: higher HFEs inundate the bars at greater depth and result in larger deposits

Data: Compared HFEs (1996, 2004, and 2008) with powerplant capacity “habitat maintenance flows” (HMFs) conducted in 1997 and 2000.

HFEs of ~40,000 cfs or larger have been more effective than ~30,000 cfs releases

EXPLANATION

- High-flow experiments **(>40,000 cfs)**
- Habitat maintenance flows **(~ 30,000 cfs)**
- Median value for the 1993 Little Colorado River floods



Hazel and others (2022)

USGS

Recently completed sandbar model to evaluate scenarios

Key Points:

- A simple morphodynamic model using sub-daily flow and sediment concentration data predicts decadal changes in average sandbar volume
- The model optimizes an erosion rate parameter and eddy exchange coefficient and is relatively insensitive to the calibration data
- Post-hoc modeling demonstrates the importance of flood frequency and sand concentration for increasing average sandbar volume

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Geophysical Research Letters

A Morphodynamic Model to Evaluate Long-Term Sandbar Rebuilding Using Controlled Floods in the Grand Canyon

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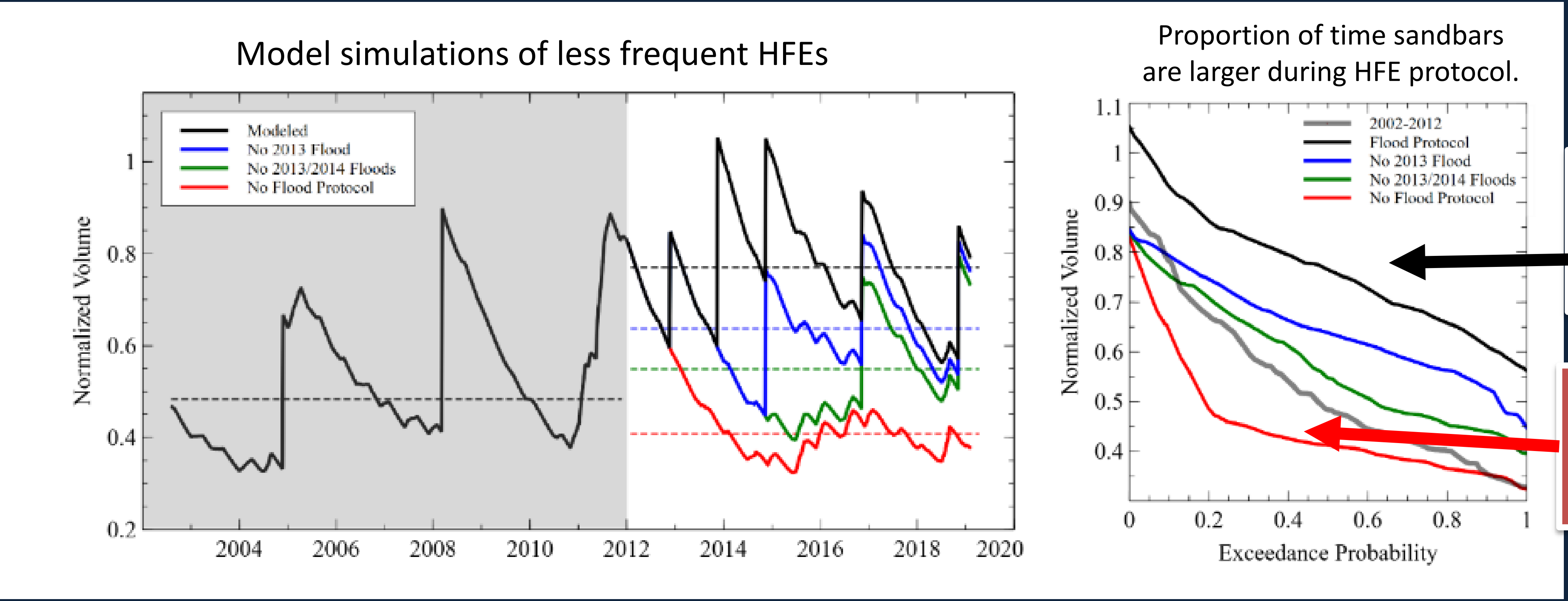
Abstract Controlled floods released from dams have become a common restoration strategy in river systems worldwide. Here we present a morphodynamic model of sandbar volume change for a subset of sandbars of the Colorado River in Grand Canyon National Park, where controlled floods are part of a management strategy focused on sandbar maintenance. We simulate sandbars as a triangular wedge, where deposition and erosion are modeled using physically based approaches that are driven by nearly continuous observations of flow and suspended sand concentration. We optimize an eddy exchange coefficient and erosion rate parameter by comparing model predictions to measured bar volumes. The model captures most of the variability in observed volume changes, and demonstrates the importance of flood frequency and sand concentration on average bar size. The model is easily implemented and adaptable, providing a means for predicting the future behavior of sandbars under a variety of streamflow and sediment supply scenarios.

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL093007

Post-hoc Controlled Flood Scenario Modeling: HFE Frequency



During the HFE protocol, sandbars were relatively larger for a greater proportion of time.

With decreasing frequency of HFEs, sandbars spend more time in eroded conditions

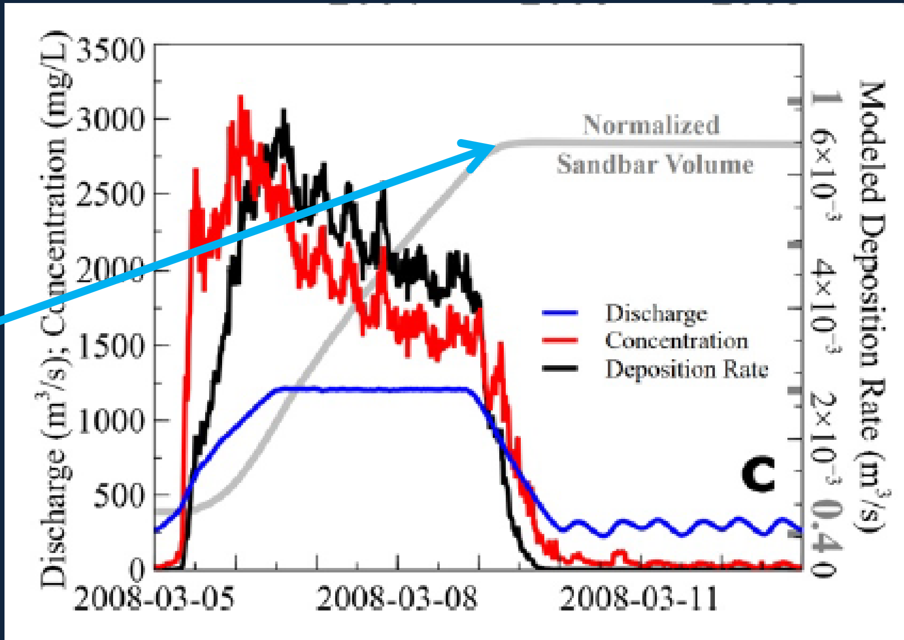
Fewer HFEs = reduced sandbar size

Mueller and Grams (2021)

USGS

Post-hoc Controlled Flood Scenario Modeling:
HFE duration and magnitude

Pattern of 2008 HFE (~45,000 cfs for ~90 hours)



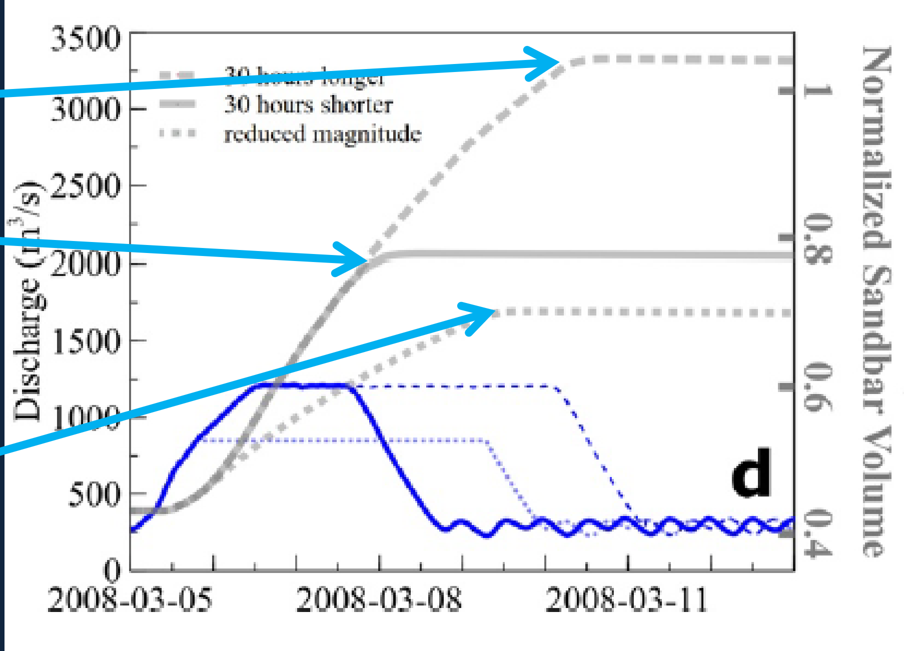
One-third change in duration changes predicted bar volume by ~15%

30 hours longer → 15% more sandbar volume

30 hours shorter → 15% less sandbar volume

One-third change in magnitude changes predicted bar volume by ~40%

One-third magnitude (30,000 cfs instead of 45,000 cfs) → 40% less sandbar volume



Mueller and Grams (2021)