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

Project B Overview and Evaluation of High-Flow Experiments During Aridification

Glen Canyon Dam Adaptive Management Program
Annual Reporting Meeting
January 25, 2023

Paul Grams
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Southwest Biological Science Center
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Acknowledgements

Project B personnel:

Paul Grams, Katie Chapman, Matt Kaplinski, Keith Kohl, Gerard Salter, Shannon Sartain, and Robert Tusso

GIS and website support:

Thomas Gushue, Caitlin Andrews, and Erica Byerley

Collaborators and field assistants:

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photo: Geoff Gourley

photo: Jeff Behan

photo: Geoff Gourley

NORTHERN ARIZONA UNIVERSITY

GRAND CANYON RIVER GUIDES

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Project B: Sandbar and Sediment Storage Monitoring and Research

- Project Elements
  - B.1 Sandbar Monitoring
  - B.2 Bathymetric and topographic mapping for monitoring long-term trends in sediment storage
  - B.3 Control Network and Survey Support
  - FY 2021 involvement in other projects:
    - O.2 (sediment dynamics in Western Grand Canyon)
    - L (overflight remote sensing)
- Project Objectives
  - track the effects of individual High Flow Experiments (HFEs) on sandbars
  - monitor the cumulative effect of successive HFEs and intervening operations on sandbars and sand conservation
  - investigate the interactions between dam operations, sand transport, and eddy sandbar dynamics
- GCDAMP FY2022 Funding: $994,345
- Cooperators: Northern Arizona University, Grand Canyon River Guides, Southern Utah University

Project B: AMP goals addressed and information provided

- LTEMP goal:
  - "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."
- Question from HFE Protocol:
  - "Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years?"
- Project B address these questions by two related monitoring efforts:
  - Annual sandbar and campsite monitoring (sandbar surveys and daily photographs)
    - Annual assessment of the effects of HFEs and other dam operations on selected sandbars and campsites.
    - Assessment of immediate response to HFEs by network of remote time-lapse cameras
  - Periodic channel mapping (Combined topographic and bathymetric mapping)
    - Evaluation of LTEMP performance by measuring long-term trends in sand area, volume, and distribution from a large sample of sandbars.
    - Measurement of long-term trends in sand storage on the riverbed.

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Project B: Publications (2022)

- Hazel, J. E., Jr., Kaplinski, M. A., Hamill, D., Buscombe, D., Mueller, E. R., Ross, R. P., Kohl, K., & 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, 104 p, https://doi.org/10.3133/pp1873.
- Kaplinski, M., Hazel, J. E. J., Grams, P. E., Gushue, T., Buscombe, D. D., & Kohl, K. (2022). Channel mapping of the Colorado River from Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona. U.S. Geological Survey Open-File Report 2022-1057. https://doi.org/10.3133/ofr20221057.
- Kaplinski, M., Hazel, J.E. Jr, Grams, P.E., Gushue, T., Buscombe, D.D., and Kohl, K., 2022, Channel mapping Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona - Data: U.S. Geological Survey data release, https://doi.org/10.5066/P98GFP93.

Data and web applications

- Images from remote camera monitoring of sandbars: https://grandcanyon.usgs.gov/gisapps/sandbarphotoviewer/RemoteCameraTimeSeries.html
- Images from GCRG adopt-a-beach program: https://grandcanyon.usgs.gov/gisapps/adopt-a-beach/index.html
- Data from long-term sandbar monitoring sites: https://www.usgs.gov/apps/sandbar/

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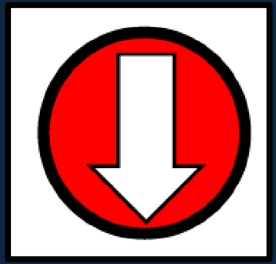
Project B: Key findings with respect to LTEMP Goals and Knowledge Assessment

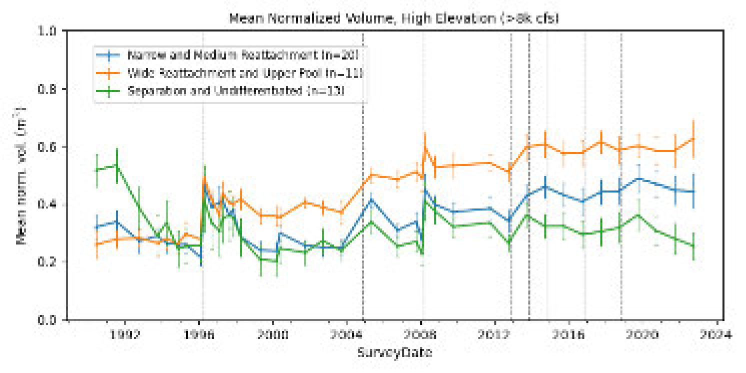


- LTEMP goal:
  - "Increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes."
- Assessment:
  - Although specific targets for sanbars are not defined, each HFE has resulted in deposition demonstrating that the general objective of retaining and/or increasing sand volume above the 8000 cfs stage can be achieved when sand inputs occur and HFEs are implemented (2012-2018).
- Prognosis:
  - Deposition at sandbars is likely stage-limited (bars not likely to get larger without larger HFEs)
  - Sandbar volume increased and maintained from 2011 to 2018 when dam releases were relatively low and sand inputs from Paria River average or above and HFEs were implemented.
  - Since 2019, sandbar volume has decreased for most bar types because monsoon failure (2019, 2020) and low reservoir levels (2021, 2022) prevented HFE implementation for 4 consecutive years.

Status: Significant concern because sandbars are eroding and not being rebuilt by HFEs.

Trend: decreasing because bars have eroded since last HFE in 2018

Confidence: high, because the monitoring is robust.



Preliminary results, subject to review, do not cite

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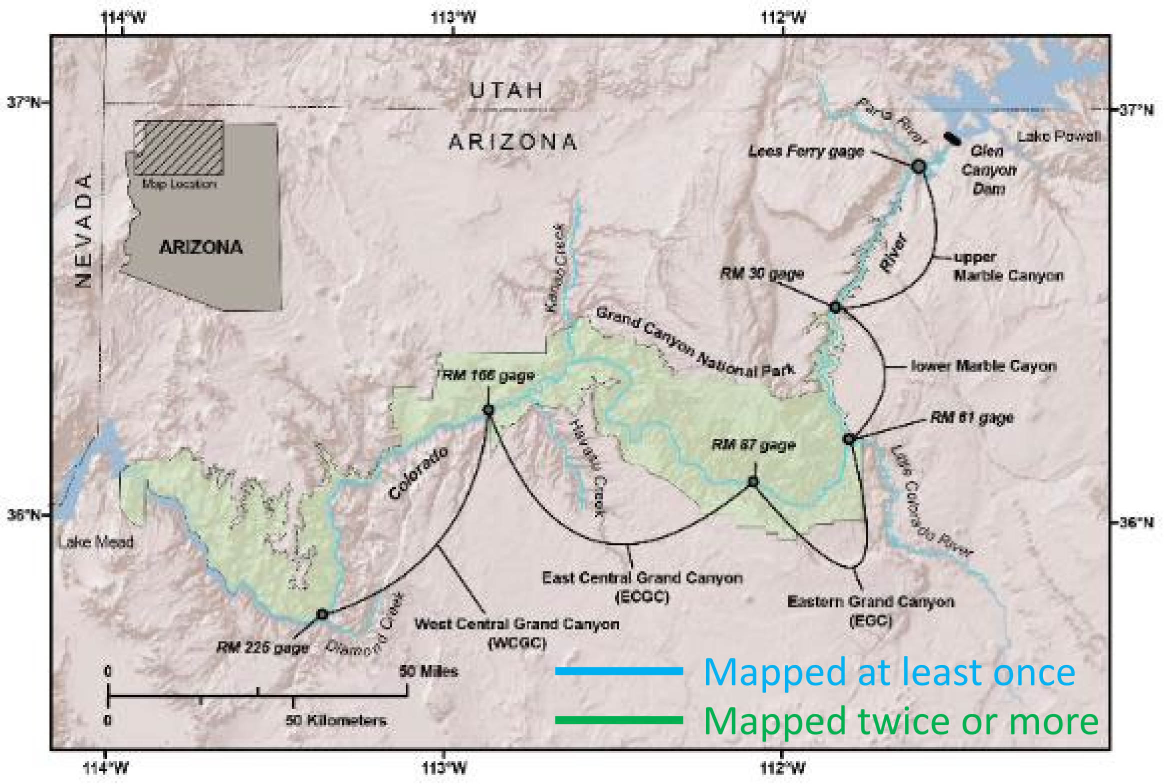
Short update on Project B.2 (Channel Mapping for Sandbar and Sand Storage Change)

- Mapped Lower Marble Canyon and Eastern Grand Canyon (60 river miles) in 2019
- Working on report that will provide a ~10-year status update on performance of HFE protocol by:
  - Evaluating the effects of HFEs on more than 100 sandbars throughout LMC and EGC (compared to the 20 measured annually in this reach)
  - Showing where sand eroded or deposited on the riverbed
  - Verifying the sand mass balance measured in Project A
- *In April 2022, we completed the first channel mapping survey of RM 87 to RM 166, resulting in a complete basemap for all reaches from the dam to Diamond Creek*



Segment (river miles)	Completed Maps
Glen Canyon (-15 to 0)	2014
Upper Marble Canyon (0 to 30)	2013, 2016
Lower Marble Canyon (30 to 61)	2009, 2012, 2019
Eastern Grand Canyon (61 to 87)	2011, 2014, 2019
East Central Grand Canyon (87 to 166)	2022
West Central Grand Canyon (166 to 225)	2017
Western Grand Canyon (225 to 280)	*

* A 2-mile study reach has been mapped for project O.2.

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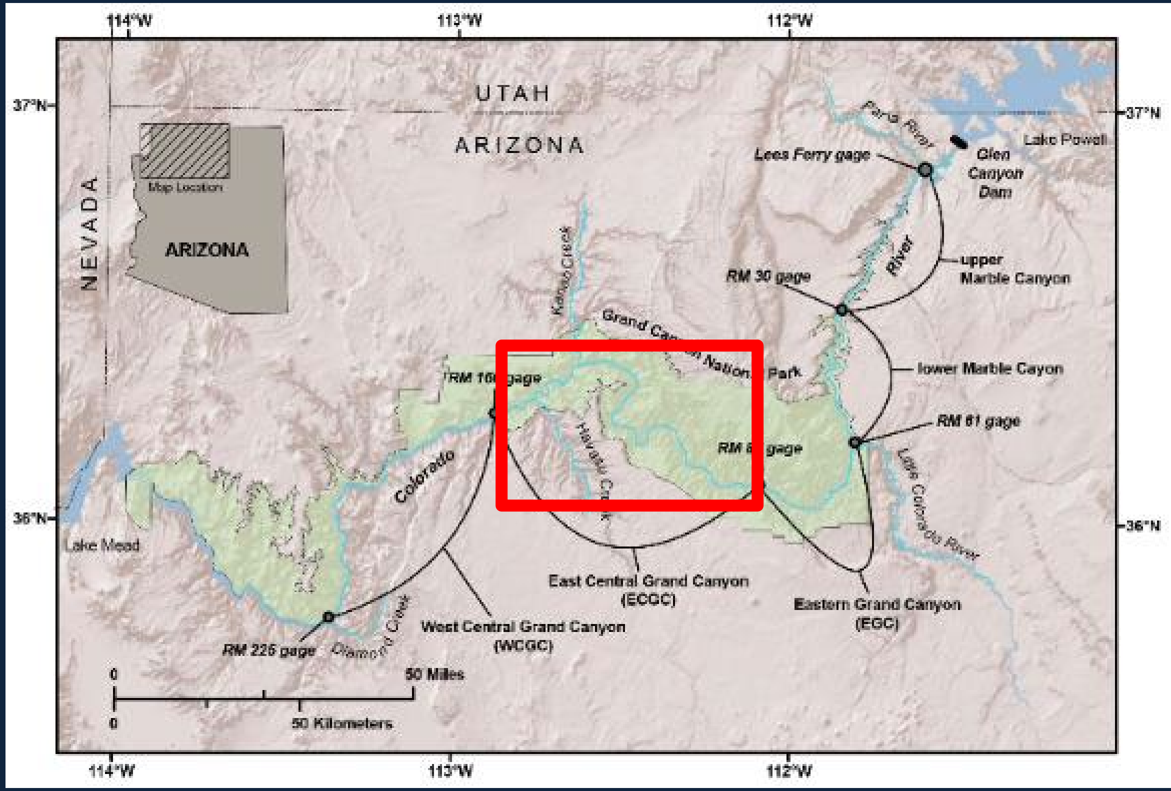
April 2022 Mapping of RM 87 to 166

- 64 topographic surveys of sandbars
- 165 bathymetric surveys
- 18,677 measurements of bed grain size at 409 sample locations



Other Project B Activities

- Control network and survey support
- Water-surface and bed profile collected during 2021 overflight (see upcoming talk by Shannon Sartain)
- Sandbar monitoring (see upcoming talk by Katie Chapman and poster by Bob Tusso)
- Sediment and sandbar modeling for HFE planning
- Work on new fine sediment model (see poster by Gerard Salter)
- Processing of “Columbine Reach” surveys (see poster by Matt Kaplinski)

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Evaluation of High-Flow Experiments During Aridification


Sandbar after November 2013 HFE (photo by M. Collier)


Lake Powell at 3526 ft in December 2022 (photo by P. Grams)

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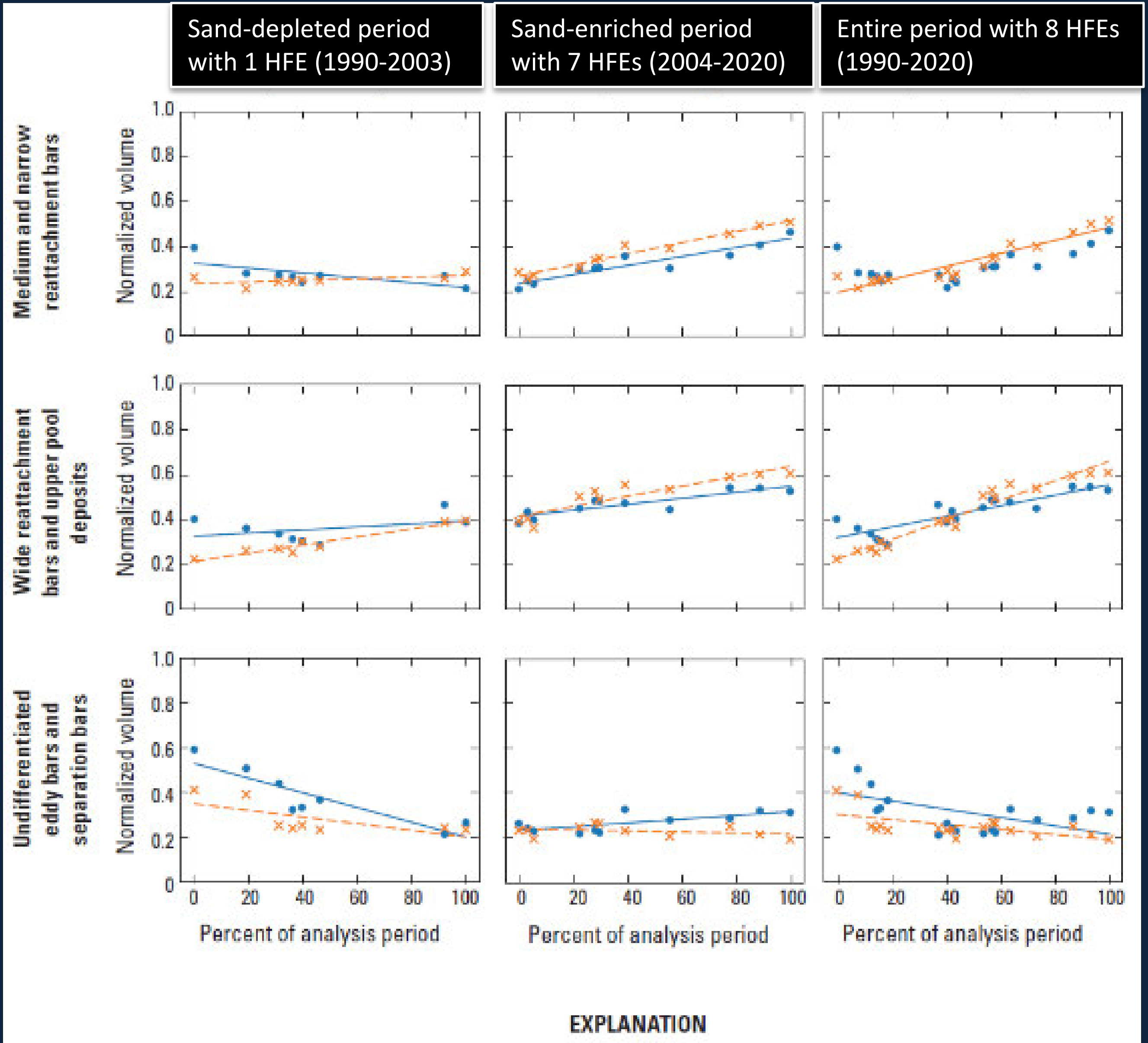
Purpose of HFEs in LTEMP ROD

- The purpose of HFEs is to address the LTEMP sediment goal:
  - "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 other 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.

When implemented, HFEs have functioned as intended by the HFE Protocol and LTEMP EIS to address the LTEMP sediment goal

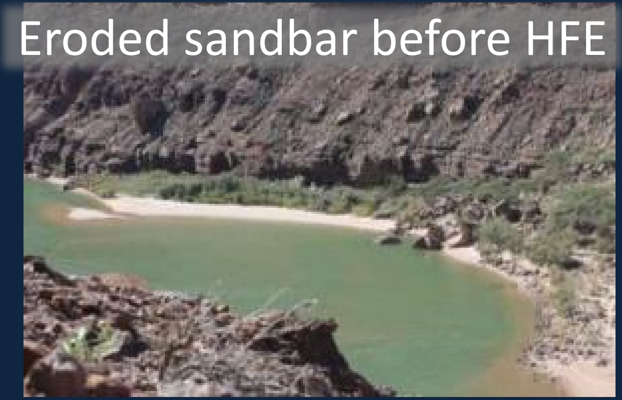


Hazel and others (2022)

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)



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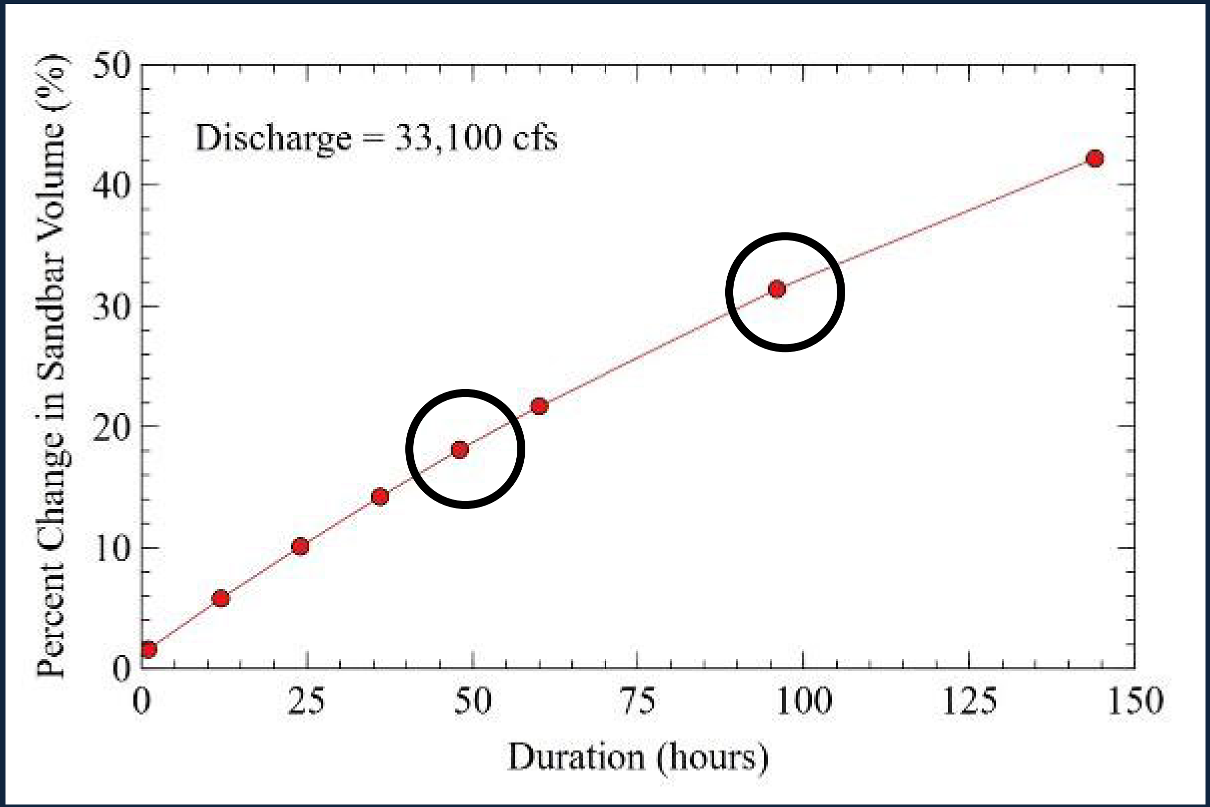
HFE magnitude, duration, and frequency all affect response and are not interchangeable

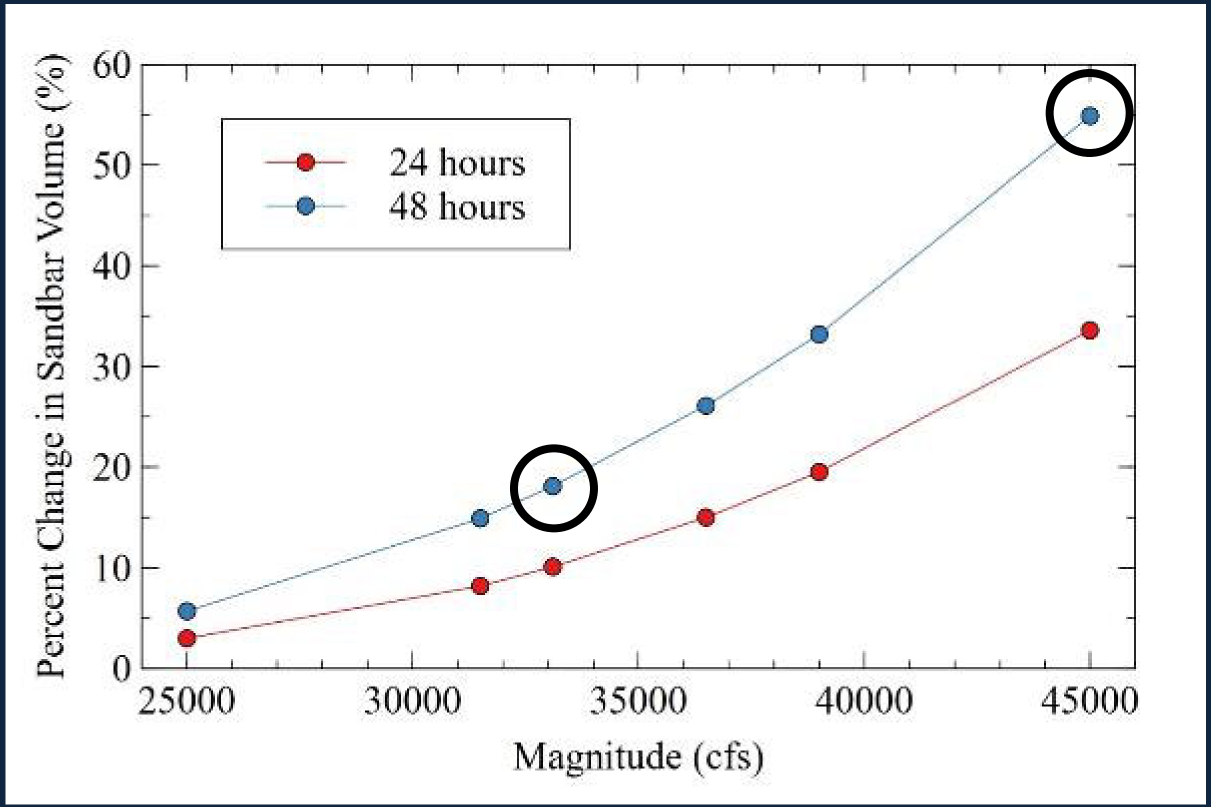
- **Magnitude** has strongest control over deposition because it controls potential deposit size by inundating more area. We have very high confidence in this physical control on bar deposition based on observations and modeling results dating back to the 1996 HFE (Hazel and others, 2022)
  - *Low magnitude (~30,000 cfs) are much less effective than ~40,000 cfs, but still result in sandbar deposition.*
- **Duration** is secondary to frequency, 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 (Wiele and others, 1999).
- **Frequency** is important because repeat HFEs are needed to rebuild the deposits that inevitably erode between HFEs (Hazel and others, 2022)

Following the HFE Protocol to maximize magnitude first, then duration, and implement as frequently as conditions allow is the only way to test the LTEMP hypotheses and possibly achieve the LTEMP sediment goals.

- What adjustments must be made to follow these guidelines under conditions of low runoff and low Lake Powell Elevations?

Predicted changes in sandbar volume as functions of HFE duration and Magnitude





48-hr HFE predicted to be about half as effective as a standard 96-hr HFE. 24-HFE about one-third as effective.

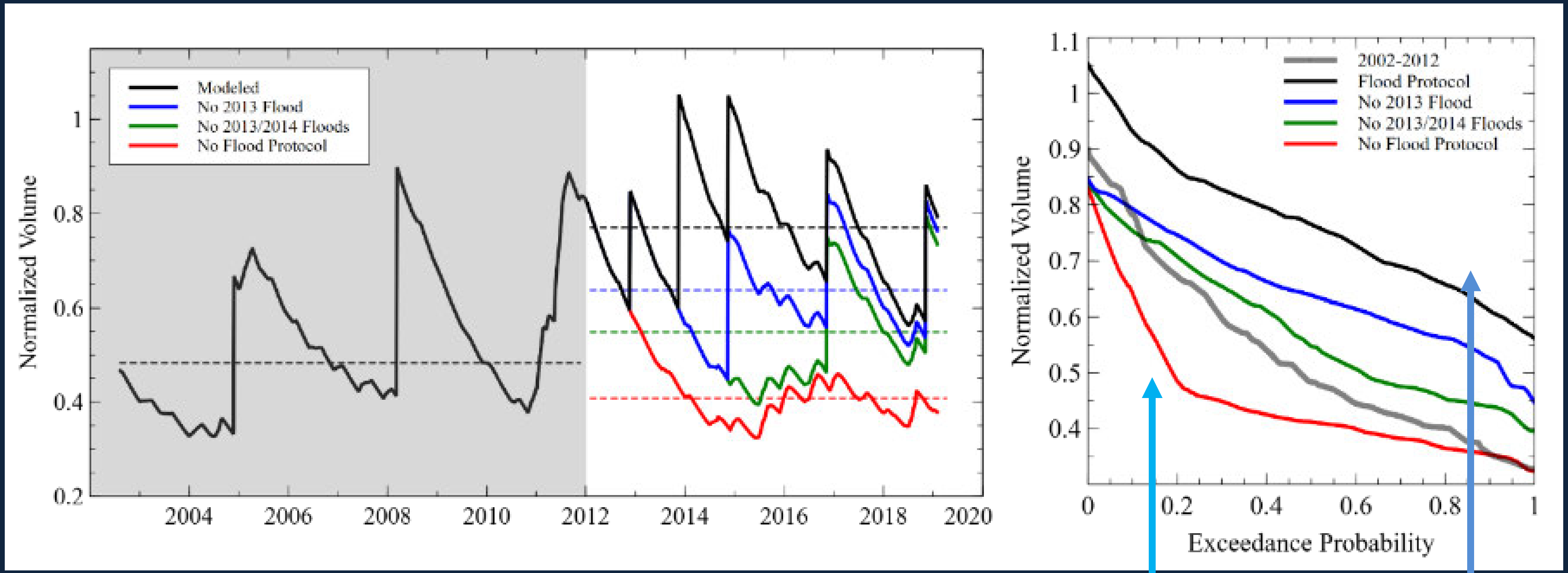
33,100 cfs HFE predicted to be about one-third as effective as 45,000 cfs HFE.

*Predictions from Mueller and Grams (2021) sandbar model using observed flow and sediment inputs through 9/14/2022.

Importance of HFE Frequency

Model simulations reducing the number of HFEs

Proportion of time sandbars are larger during HFE protocol.



Fewer HFEs = reduced sandbar size

Without protocol, sandbars are that large only 20% of the time.

Over the period of the protocol, sandbars are at least 70% of maximum observed size for 80% of the time.

Mueller and Grams (2021)

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HFE Optimization

"How do we optimize HFEs for the current low flow and low Lake Powell reservoir elevations and minimize the impacts to hydropower?"

HFE impacts:

- Bypass of hydroelectric turbines
  - All HFEs require bypass
  - These impacts were analyzed in LTEMP
  - *Impacts to hydropower could be reduced by ensuring that all hydropower units are available for any potential HFE implementation window.*
- Lake Powell Elevations
  - **HFEs do not impact annual release volumes or Lake Powell elevations on annual scale.**
  - HFEs may require reallocation of monthly release volumes, and therefore, *may temporarily affect Lake Powell elevations*

Impacts on Lake Powell elevations can be mitigated by changing the timing of HFE implementation.

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

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

- October and November are the lowest volume months.
- LTEMP recognizes that water may need to be allocated from other months.
- But that can increase the risk of Lake Powell elevations becoming critically low in the winter months.

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 in LTEMP does not include HFE volumes

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

TABLE 3 Monthly Release Volumes under Alternative D

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May	550	599	632							
June	577	628	663							
July	652	709	749							
August	696	758	800							
September	522	568	600							

How do we reallocate 300k ac-ft of water to a 500k ac-ft month in the fall when Lake Powell is approaching minimum power pool and we don't know what the winter will bring?

- October and November are
- LTEMP recognizes that wat
  months.
- But that can increase the risk of Lake Powell elevations becoming critically low in the winter months.

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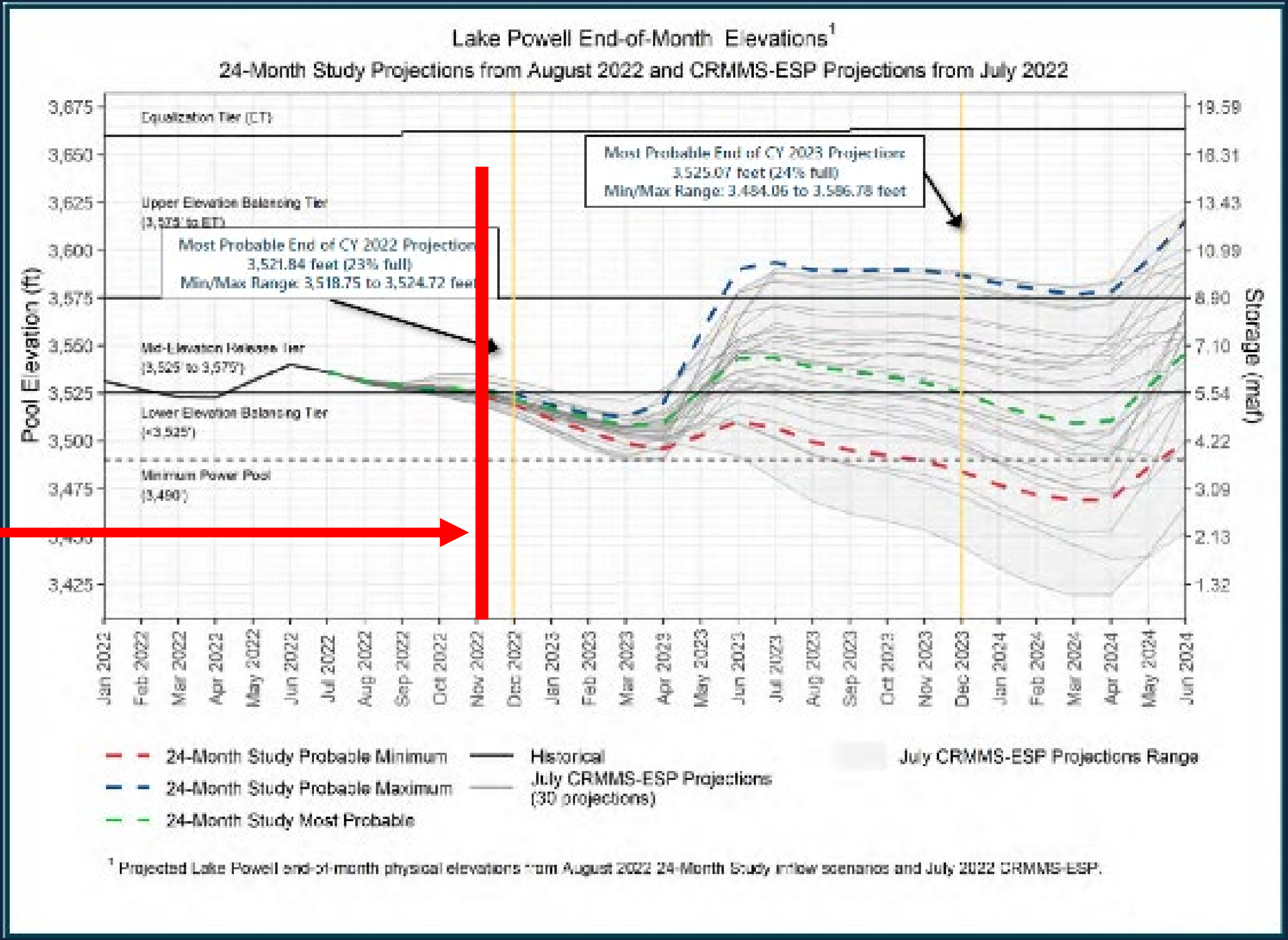
16	31,500	1	1,900

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

Table in LTEMP does not include HFE volumes

November HFEs occur just before the period of year with lowest reservoir elevations



https://www.usbr.gov/uc/water/crsp/studies/index.html

LTEMP works to implement HFEs when annual volumes are "normal" and Lake Powell elevations are "non-critical"

- All but one of the HFEs have been implemented when annual volume was 8.6 maf or greater
  - The 2014 HFE was implemented in a year with a 7.6 maf volume, but reservoir levels were still above 3600 feet
- LTEMP HFE triggering makes fall HFEs more likely
  - Although the LTEMP analysis predicted Spring HFEs would occur in about 5 out of 20 years, none have been triggered in the 10 years of the HFE protocol.
- But when Lake Powell is low, reallocation of water to the fall months has been deemed too risky by the majority of the HFE Technical Team

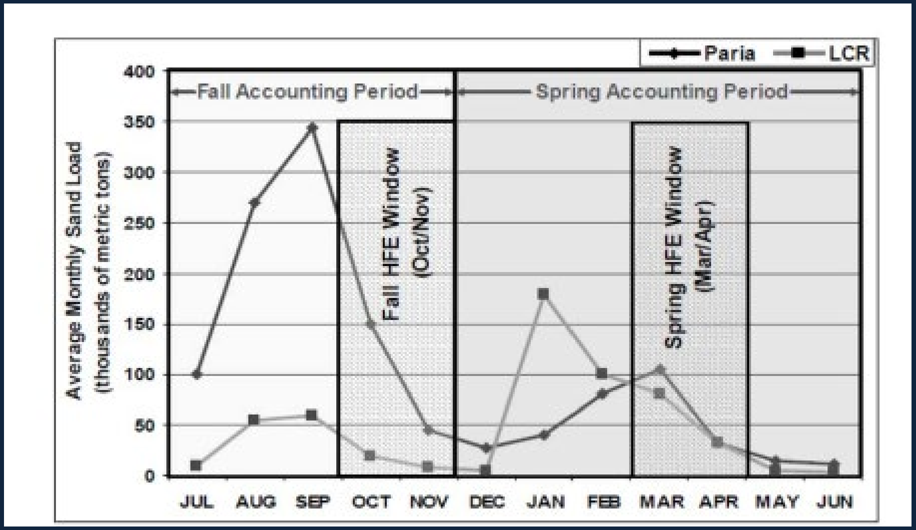
- In LTEMP, the HFE process was guided by the assumption that sediment availability was the critical limiting factor in HFE implementation: **water availability was assumed**.
- For low-reservoir conditions, water availability is an additional constraint to factor in the decision process.

Why have HFEs been implemented in Fall?

- Sediment concentrations and deposition rates will be greatest when the sand supply in the channel is greatest and is the finest grain size
  - These conditions are highest soon after a series of tributary floods and then decrease
  - If dam releases are relatively high during the winter, there can be much less sand and coarser sand by spring
  - But if dam releases are relatively low during the winter, more of the fine sand will remain available
  - The HFE Protocol was designed to guard against losing the sand over the winter but did not include provisions for allowing use of the sand if it persisted over the winter.

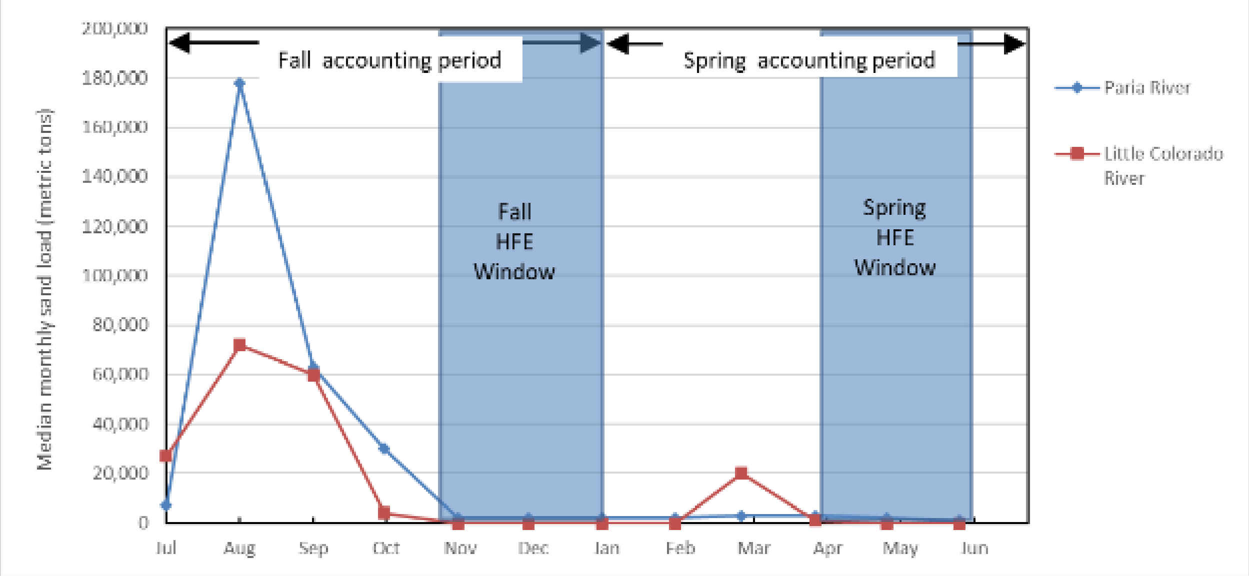
LTEMP sediment accounting optimizes to implement HFE as soon after Paria sediment inputs as possible.

- Important when winter releases are high.



Paria and LCR average monthly sand loads used in HFE Protocol and LTEMP

https://ltempeis.anl.gov/



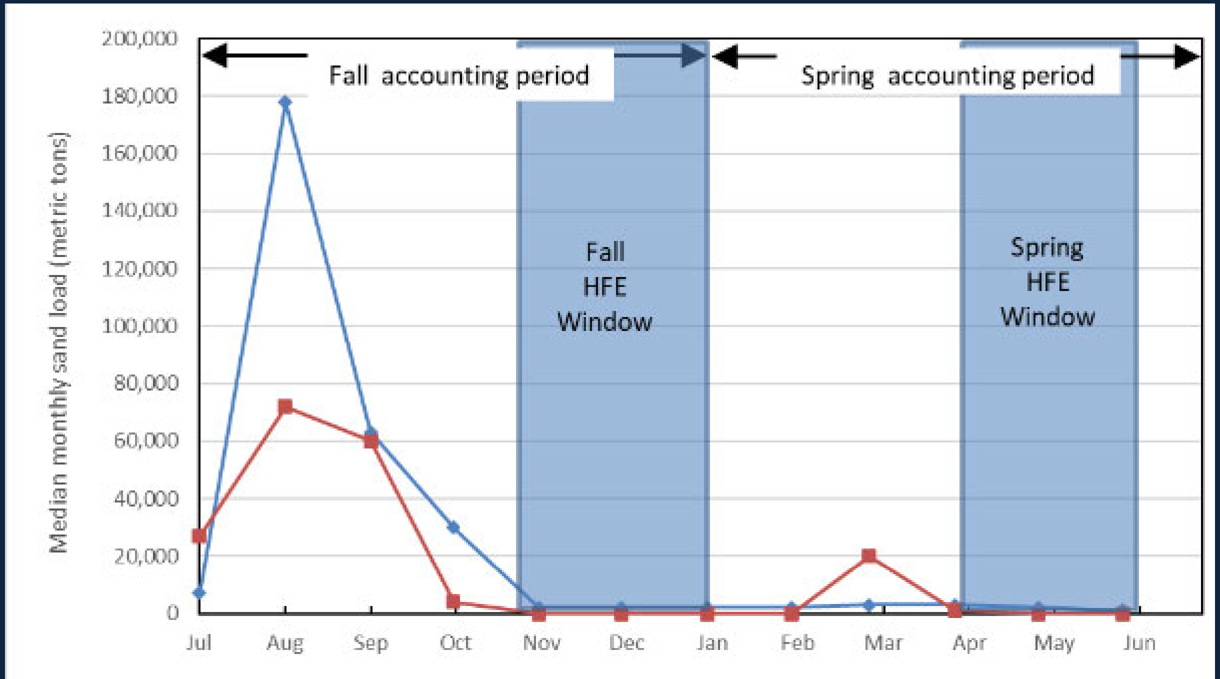
Paria and LCR median monthly sand loads for 1998-2017 (Topping et al., 2021)

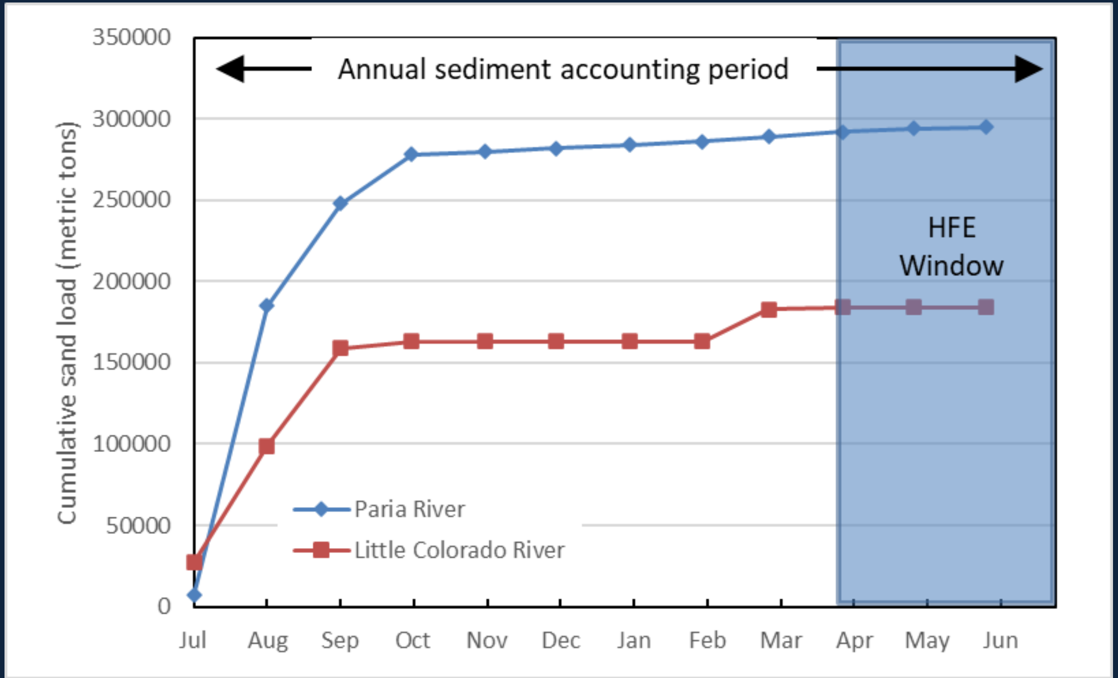
Low-water HFE Protocol Step 1

- Revise the sediment accounting window to run a full 12 months, starting and ending July 1 every year.
  - This adjustment would allow HFE implementation when water availability is known (spring) using sediment from previous summer/fall
  - This adjustment to the protocol is scientifically justified because low-water conditions allow greater sediment retention over the winter than was anticipated for LTEMP flows above 8.2 million ac-ft.
  - By limiting HFEs to one per sediment year, this would not increase the number of HFEs anticipated in the LTEMP ROD.

The LTEMP modeling analysis anticipated 15 fall HFEs and another 5 to 7 spring HFEs in the 20-year period. Six years into LTEMP, three fall HFEs and zero spring HFEs have been triggered and only one fall HFE implemented.

Revised sediment accounting periods





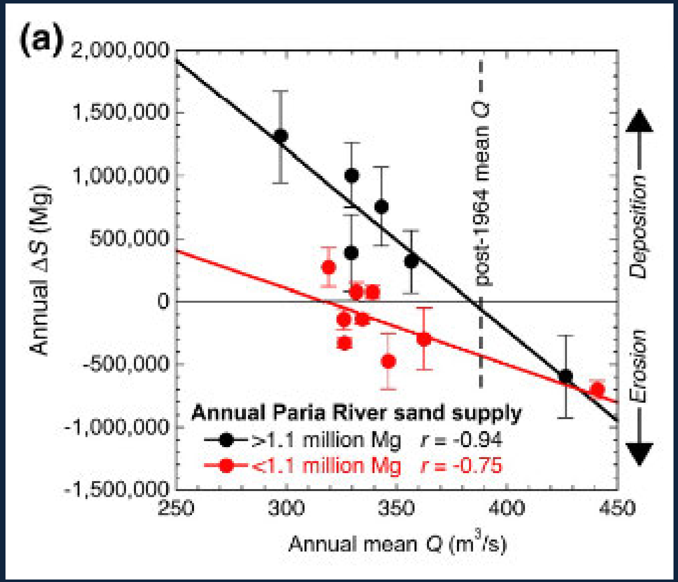
LTEMP sediment accounting optimizes to implement HFE as soon after Paria sediment inputs as possible.

- **Important when winter releases are high.**

Low-water sediment accounting optimizes to implement HFE following accumulation of both Paria and LCR inputs.

- **Will only work when winter releases are low.**

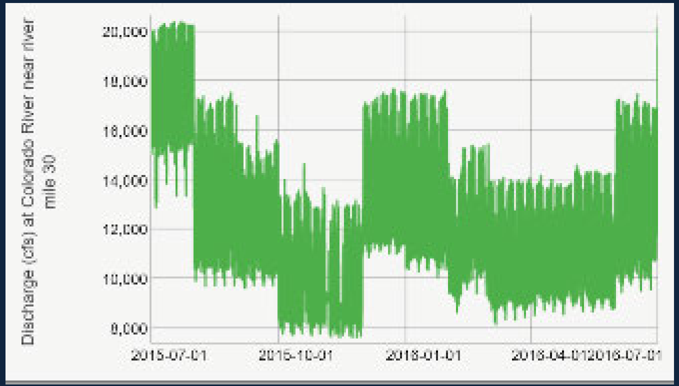
Example mass balance for Upper Marble Canyon



- Switch from "two-period" to "annual" sediment accounting when annual release volumes are less than 8.2 maf (~11,300 cfs average flow) (Topping et al., 2021)

LTEMP Accounting

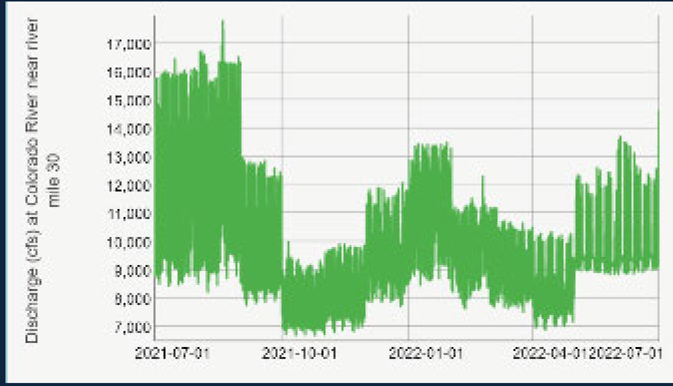
2015-2016 (Powell above 3600 ft)
- ~ 800,000 metric tons accumulation
- ~ 9 million acre-ft annual volume
- Most sand eroded by following spring



Important to implement HFE in fall before sand is exported.

Revised Accounting

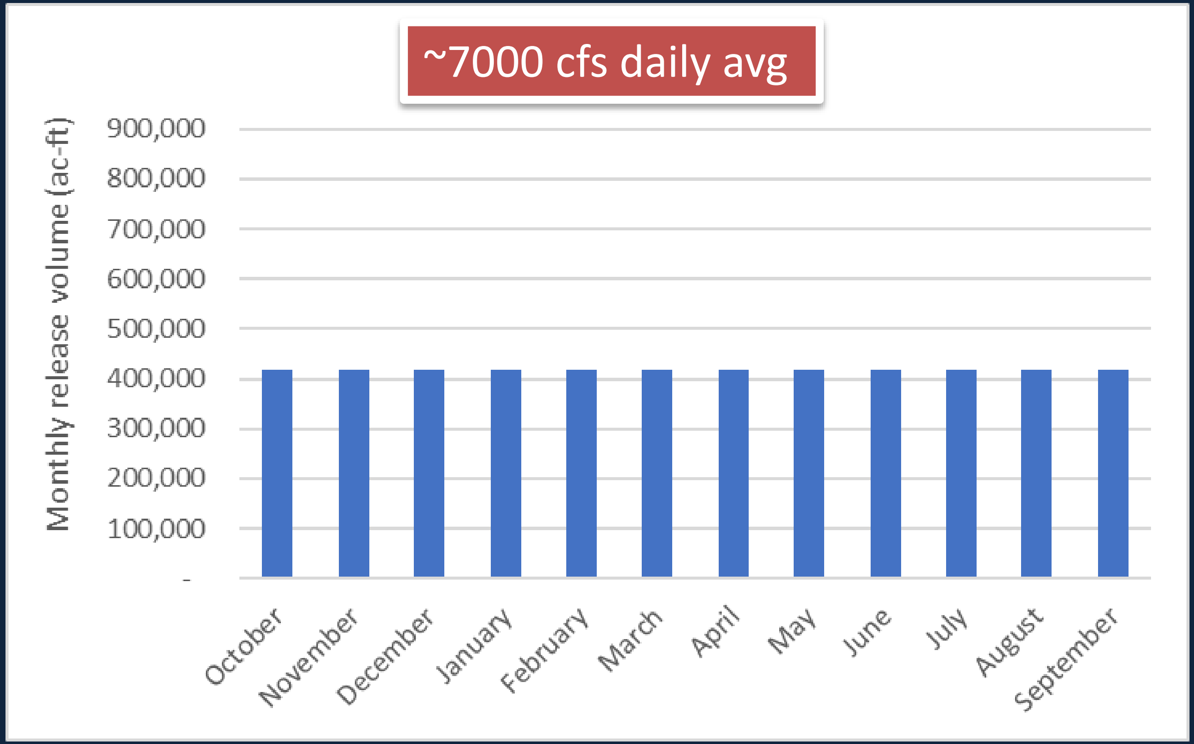
2021-2022 (Powell at and below 3550 ft)
- ~ 1,400,000 metric tons accumulation
- ~ 8 million acre-ft annual volume
- Most sand retainied through following spring

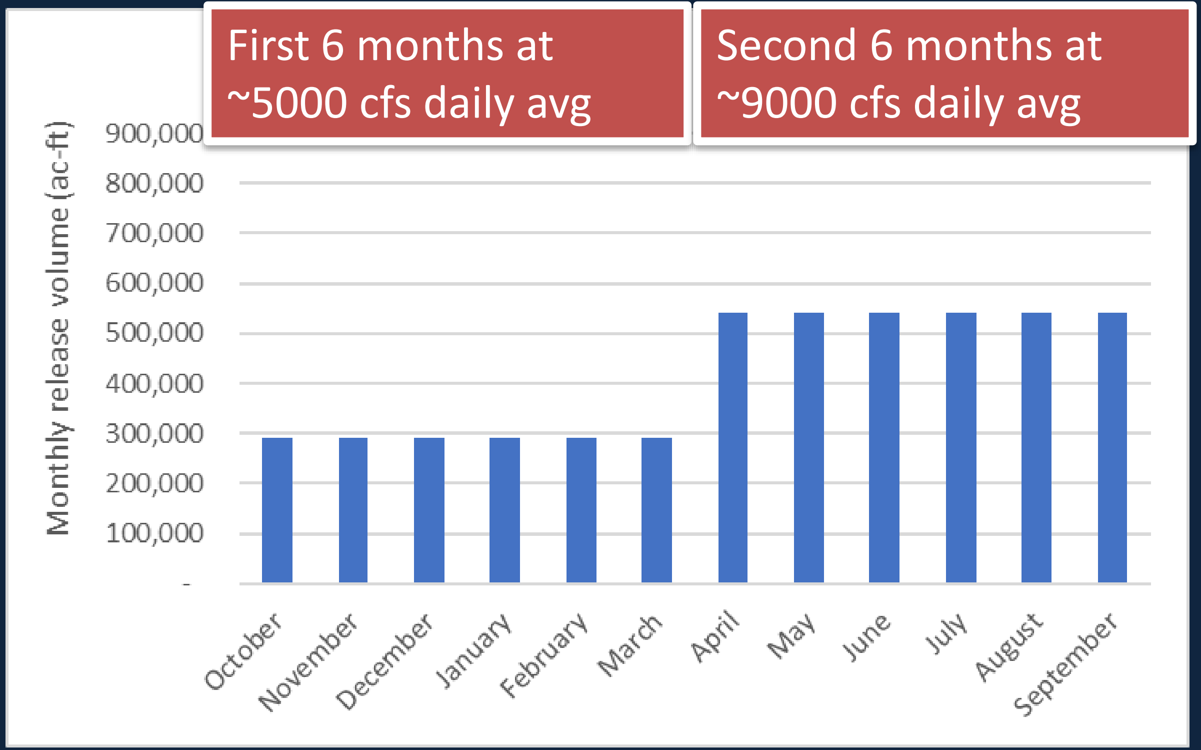


HFE could be implemented in either fall or spring because sand is retained

Low-water HFE Protocol Step 2

Annual volume = 5 maf





Adding variability pretects Lake Powell elevations in winter and allows higher flows in spring/summer.

Low-water HFE Protocol Step 2

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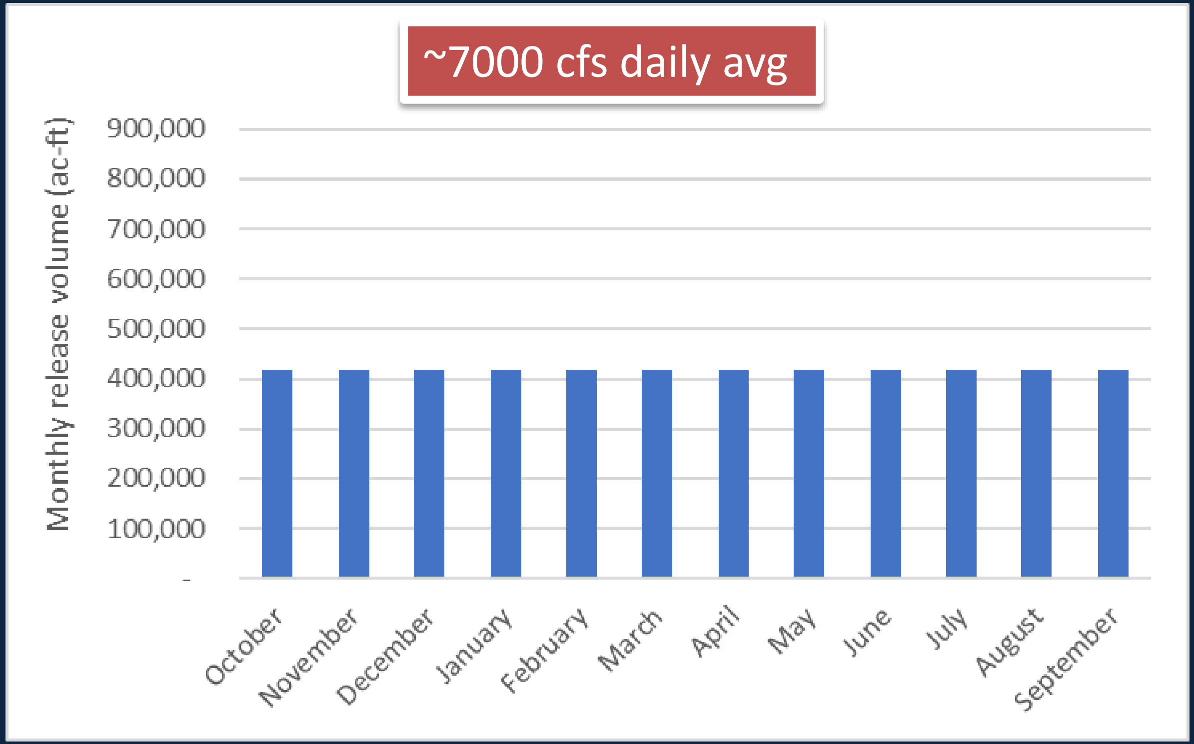
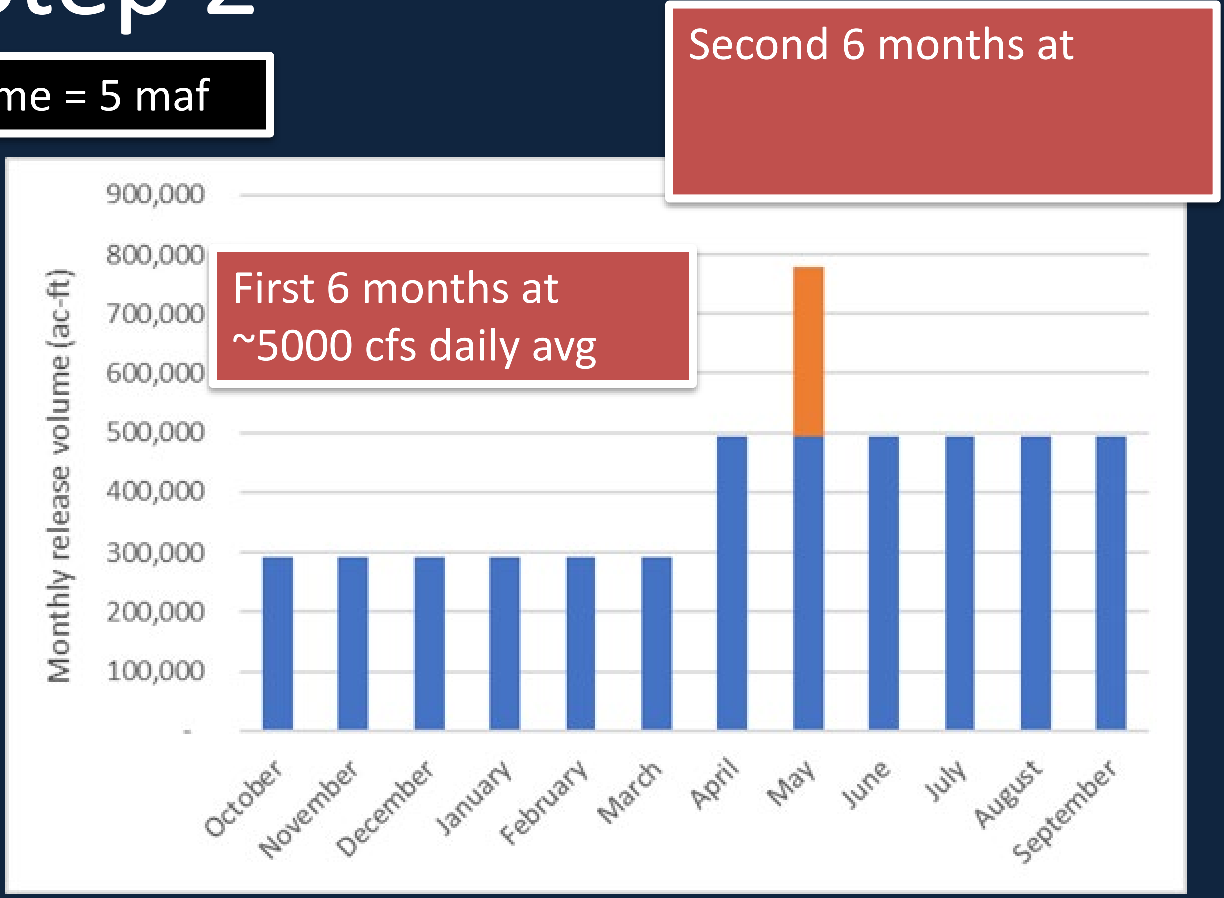
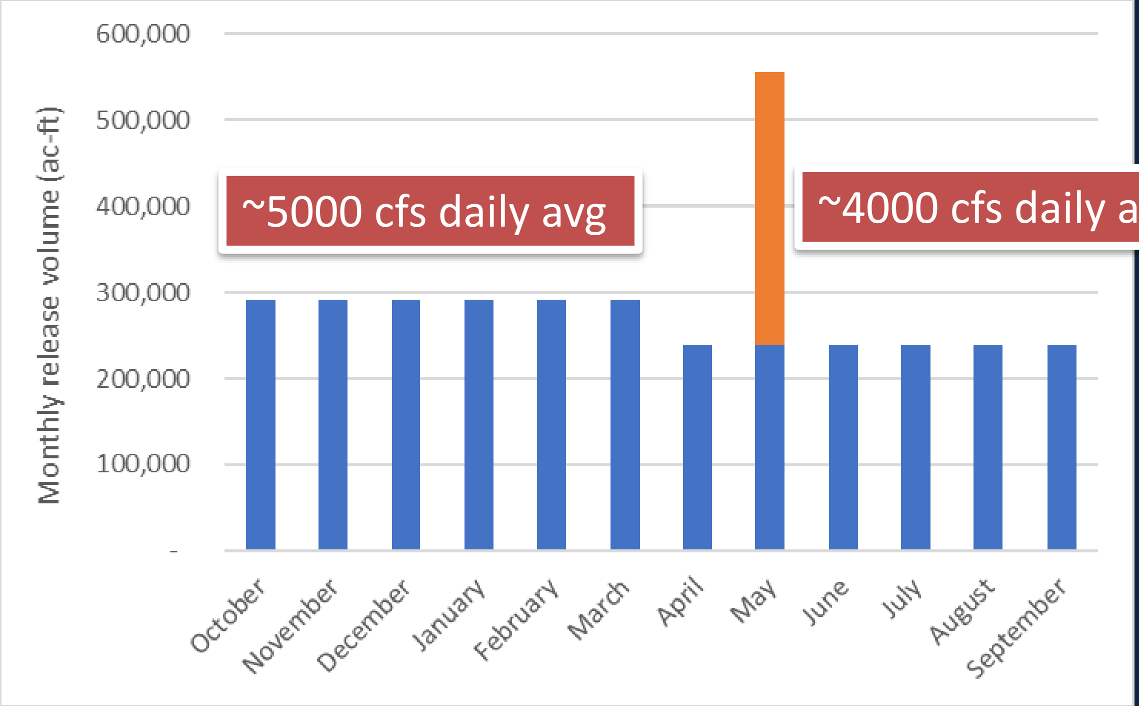




Adding variability pretects Lake Powell elevations in winter and allows higher flows in spring/summer and HFE.

Low-water HFE Protocol Step 2

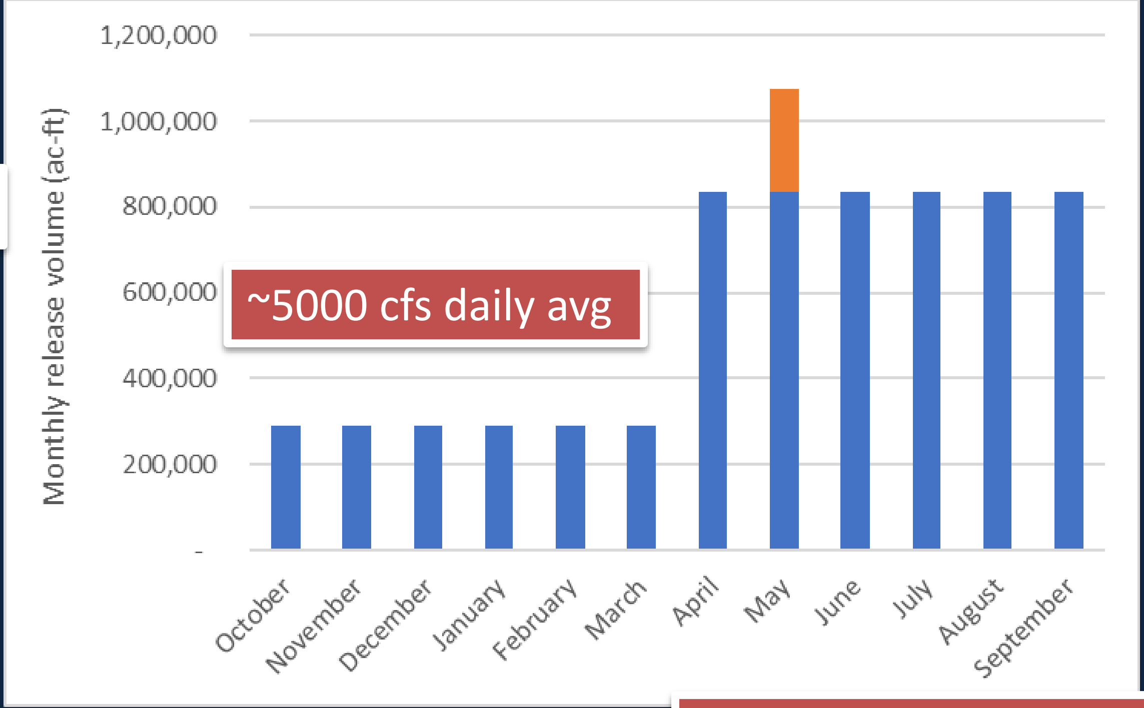
5 maf variable pattern revised to 3.5 maf



~5000 cfs daily avg

~4000 cfs daily avg

5 maf variable pattern revised to 7 maf

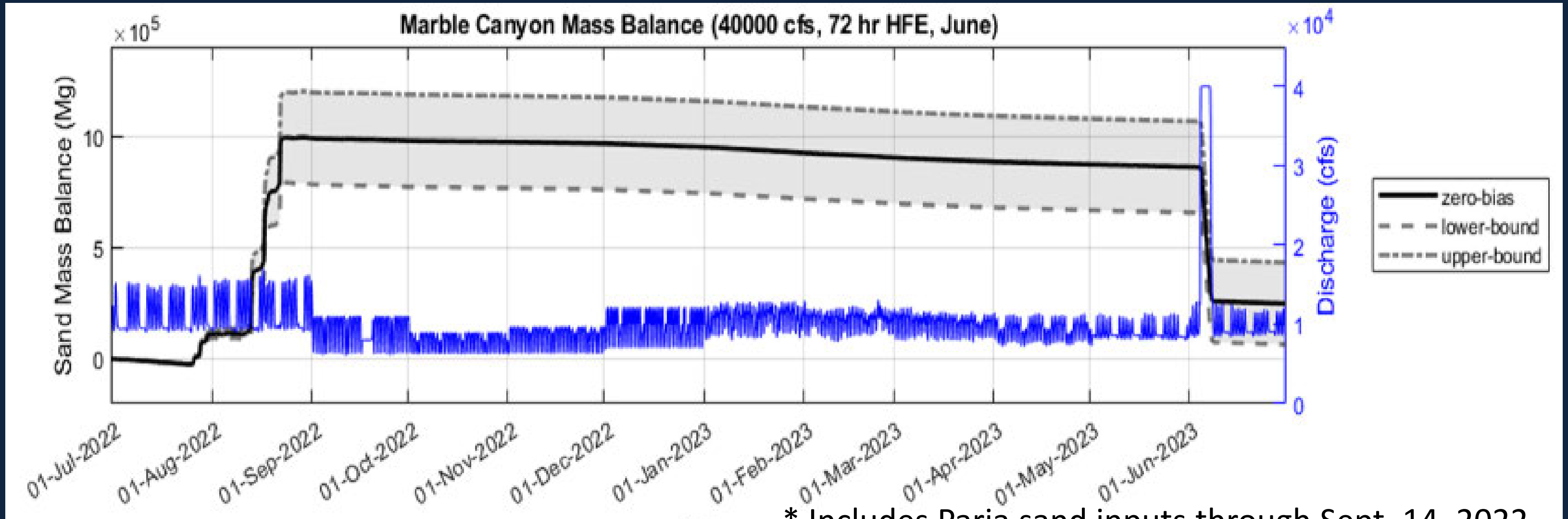


~5000 cfs daily avg

Second 6 months at ~8300 cfs daily avg with HFE in May or June

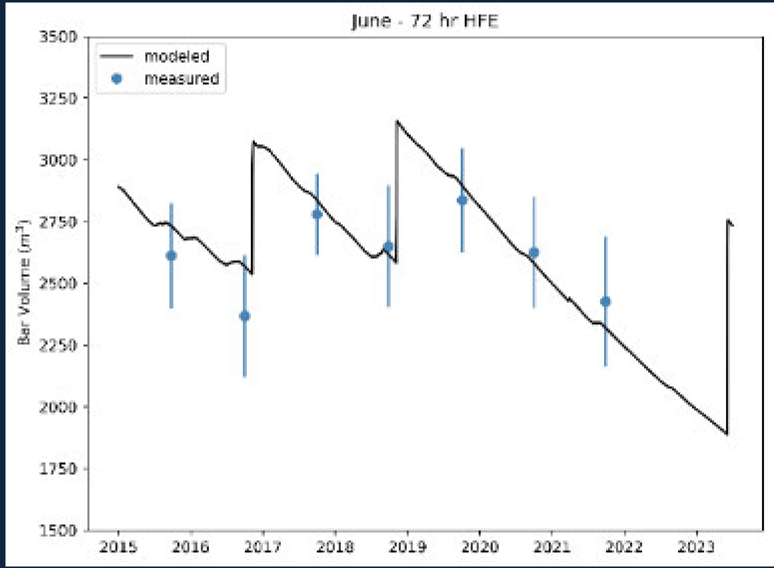
Conditions for potential Spring/Summer 2023 HFE

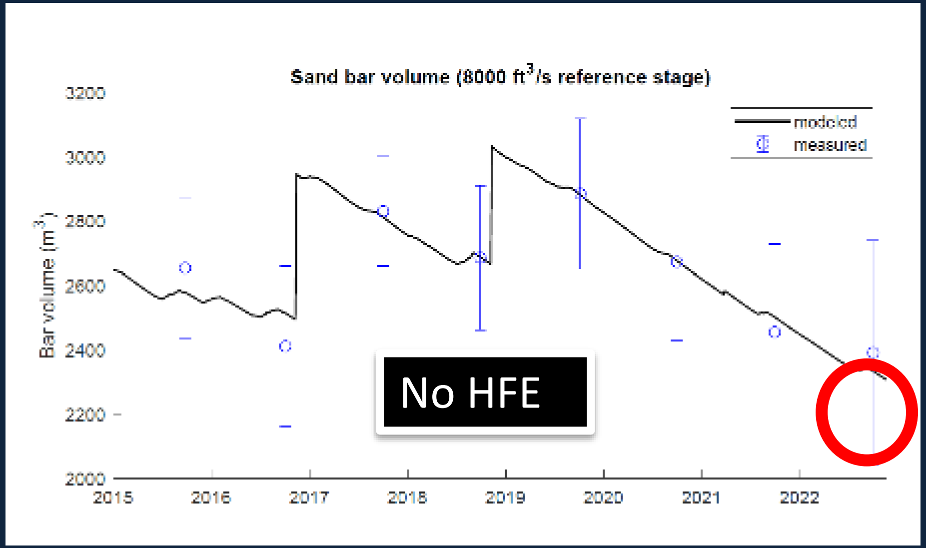
Current sediment conditions support a high flow of up to 40,000 to 45,000 cfs and up to 72 hours anytime between fall 2022 and summer 2023.



* Includes Paria sand inputs through Sept. 14, 2022.

Predicted sandbar response to potential June 2023 HFE of 40,000 cfs for 72 hr



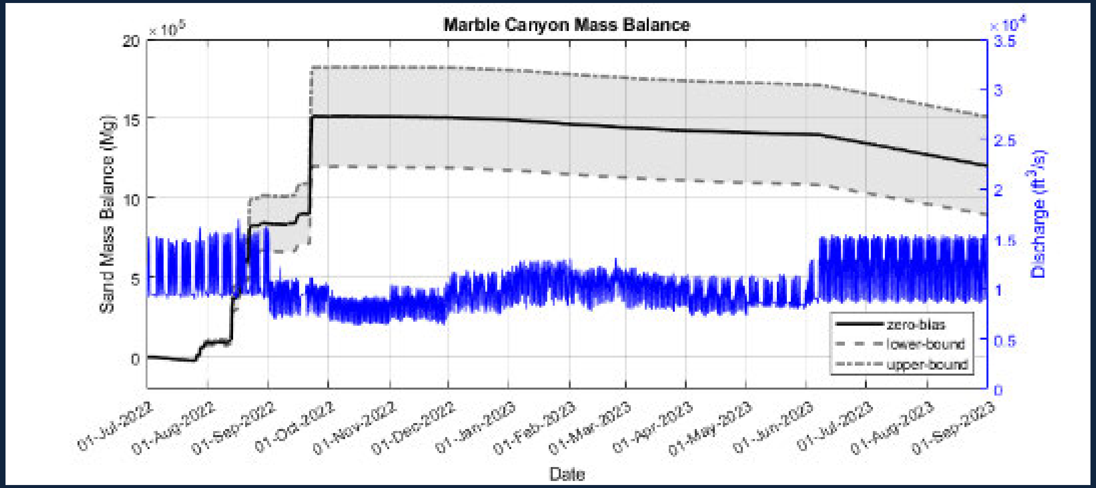


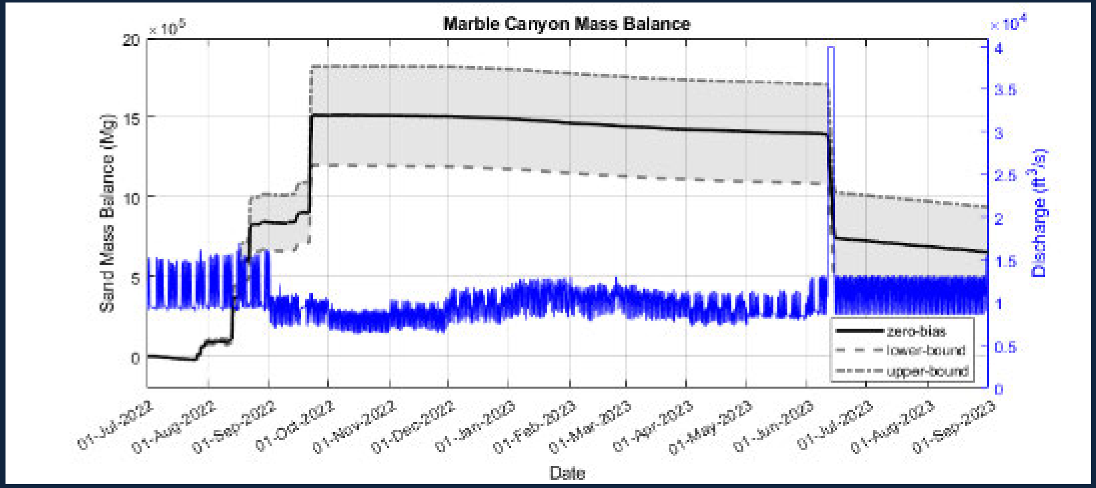
*Predictions from Mueller and Grams (2021) sandbar model using observed flow and sediment inputs through 9/14/2022.

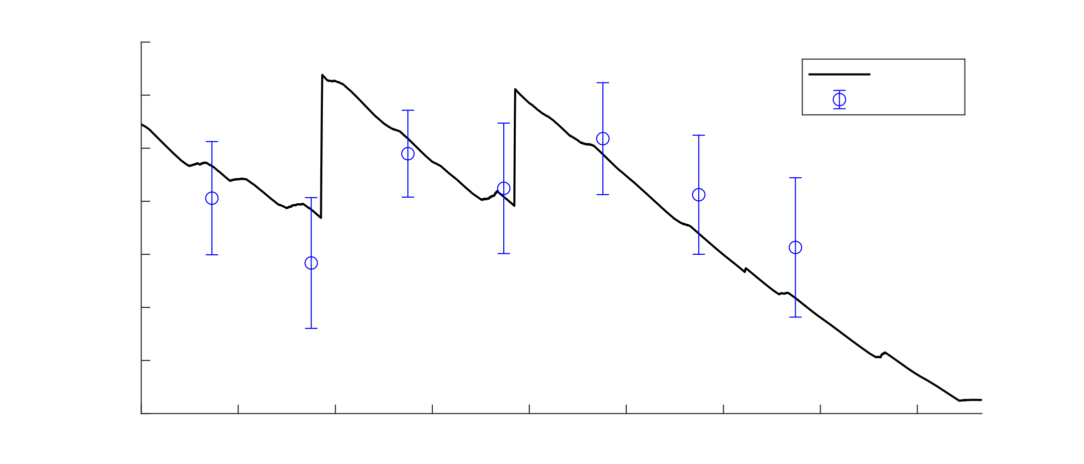
Preliminary model results. Do not cite.

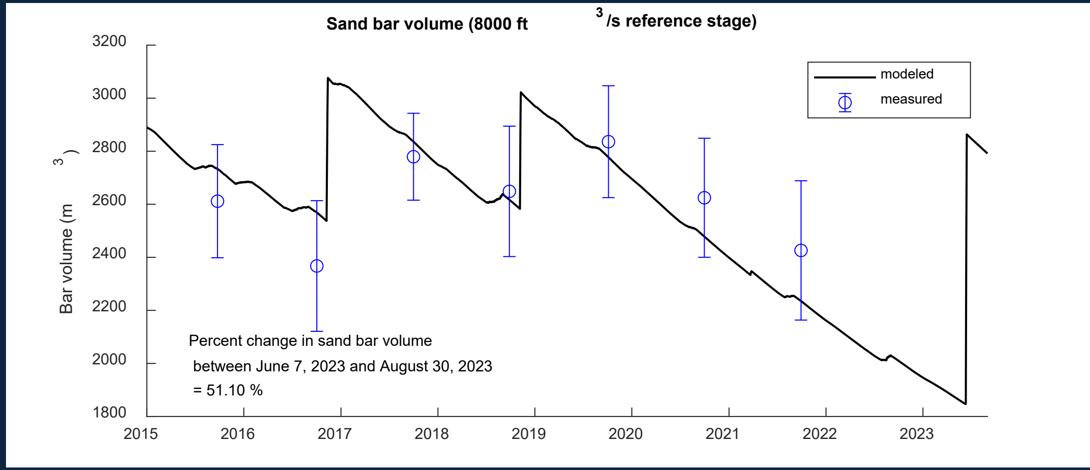
USGS

Spring HFE for sediment consistent with spike flows for SMB control









Predicted sand mass balance and sandbar response for small mouth bass control options without flow spikes

Predicted sand mass balance and sandbar response for small mouth bass control with 72-hr 40,000 ft^3/s flow spike.

*Predictions from Mueller and Grams (2021) sandbar model using observed flow and sediment inputs through 9/14/2022.

Preliminary model results. Do not cite.

USGS

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

- LTEMP ROD intended frequent HFEs for sediment goals.
- HFEs are not being implemented because sediment triggering criteria is incompatible with need to prevent Lake Powell storage from "bottoming out" in late winter.
- Two-part solution:
  - Adjust sediment accounting window to allow sediment-triggered HFEs in spring/summer
  - Plan distribution of monthly volumes such that water is available for HFE regardless of annual volume.
- Resource benefits
  - Sediment enriched HFEs for sandbar building
  - Spring high flows for other resources (e.g. small mouth bass control)
  - Highest monthly volumes (relatively) in summer for recreation and power generation
  - Maximum protection for Lake Powell elevations

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.
- Wright, S.A., Topping, D.J., Rubin, D.M., and Melis, T.S., 2010, An approach for modeling sediment budgets in supply-limited rivers: Water Resources Research, v. 46, p. 1–18, doi:10.1029/2009WR008600.
- U.S. Department of the Interior, 2016, Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan Final Environmental Impact Statement, https://ltempeis.anl.gov/