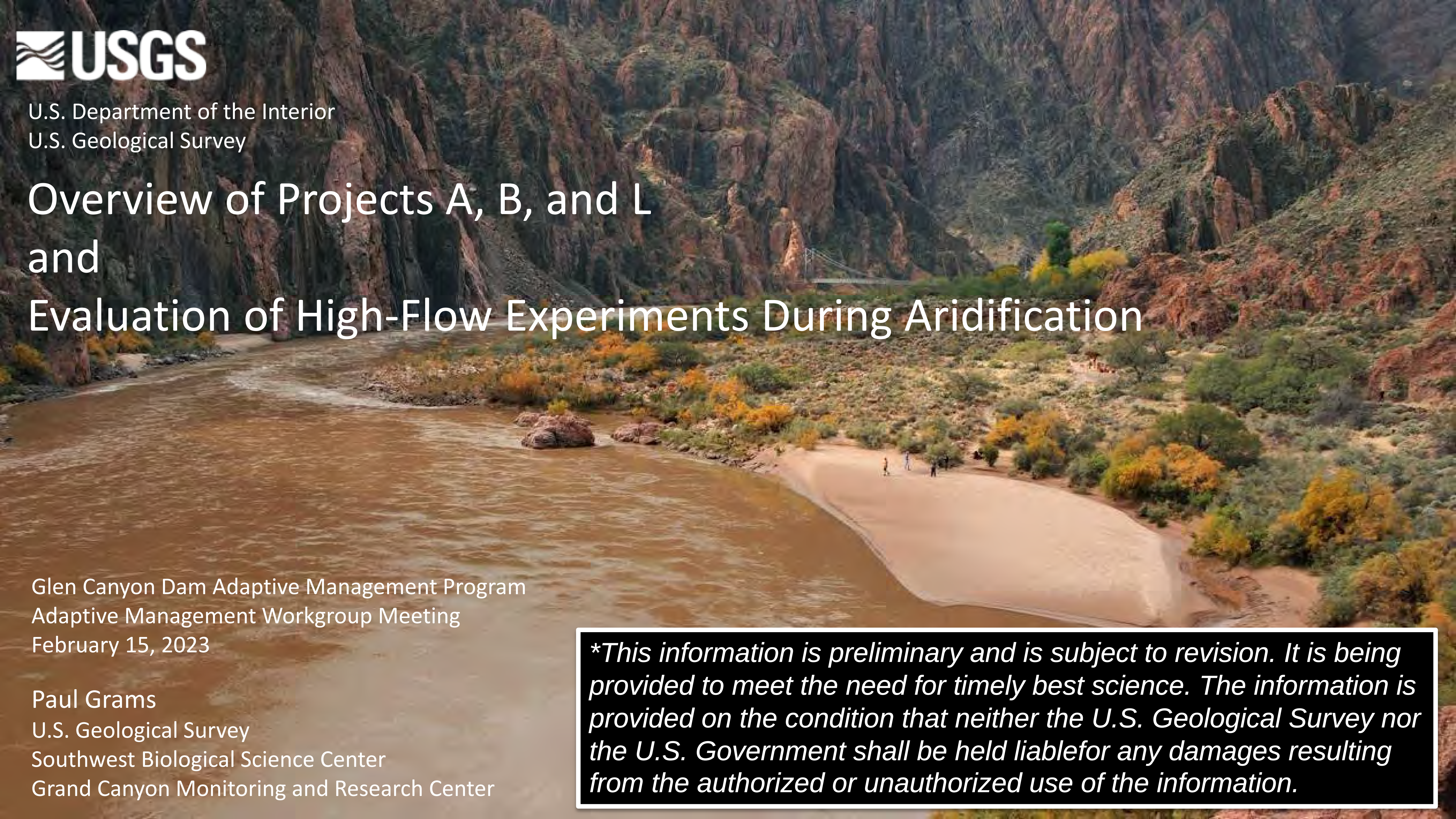

U.S. Department of the Interior
U.S. Geological Survey

Overview of Projects A, B, and L and Evaluation of High-Flow Experiments During Aridification

Glen Canyon Dam Adaptive Management Program
Adaptive Management Workgroup Meeting
February 15, 2023

Paul Grams
U.S. Geological Survey
Southwest Biological Science Center
Grand Canyon Monitoring and Research Center

Acknowledgements

Project A: Streamflow, Water Quality, and Sediment Transport
David Topping, Ron Griffiths, David Dean, Nick Voichick, Joel Unema

Project B: Sandbars and Sediment Storage
Paul Grams, Katie Chapman, Matt Kaplinski, Keith Kohl, Gerard Salter, Shannon Sartain, and Robert Tusso

Project L: Remote Sensing
Joel Sankey, Laura Durning, Nathaniel Bransky, Lori Pigue

GIS and website support:
Thomas Gushue, Caitlin Andrews, Joe Thomas, and Erica Byerley

Collaborators and field assistants:
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photo: Jeff Behan

NORTHERN ARIZONA UNIVERSITY

GRAND CANYON RIVER GUIDES

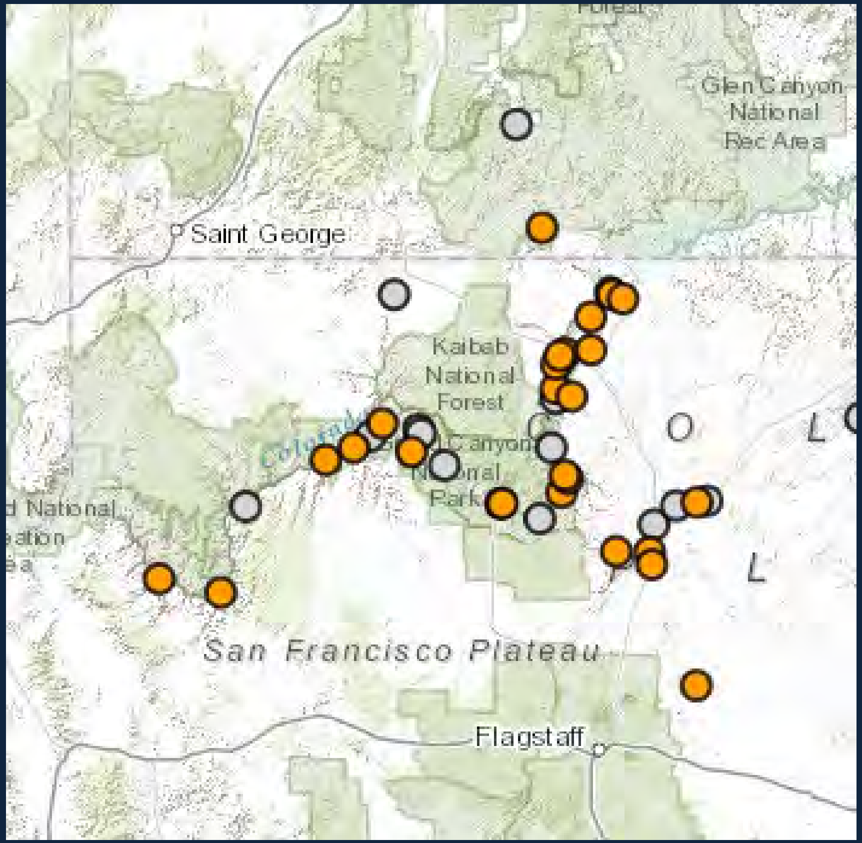
USGS

Project A: Streamflow, Water Quality, and Sediment Transport and Budgeting in the Colorado River Ecosystem

We collect, post, and analyze the following data at stations located through the Colorado River Ecosystem, including key tributaries…

- Element 1: Stream gaging
  - Stage
  - Discharge
- Element 2: Water quality
  - Water temperature
  - Salinity (specific conductance)
  - Turbidity
  - Dissolved Oxygen
- Element 3: Sediment transport and budgeting
  - Suspended- and bed-sediment data
  - Sediment loads (silt and clay loads and sand loads)
  - User-interactive sand budgets in 6 reaches from Lees Ferry to Lake Mead

– User-interactive tools for visualizing all parameters
www.gcmrc.gov/discharge_qw_sediment/



Project A data collection stations

Almost all other projects funded by the Glen Canyon Dam Adaptive Management Program (GCDAMP) use these data, and data from this project informs 10 LTEMP goals

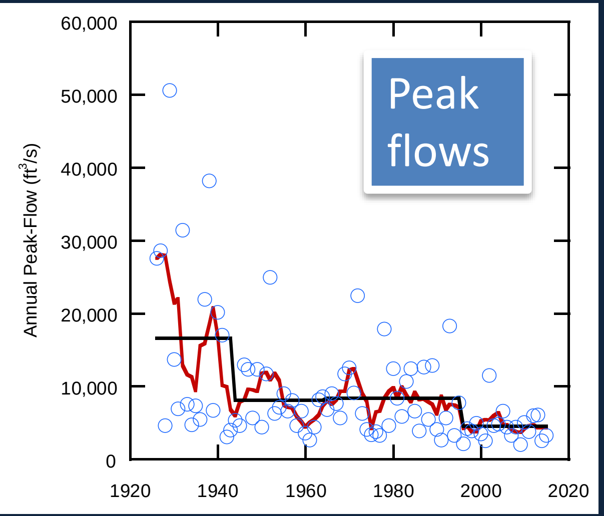
Funding: GCDAMP provided $1.15 million during FY 2022

Project A: Physical changes in Moenkopi Wash and the Little Colorado River (ARM talk by David Dean)

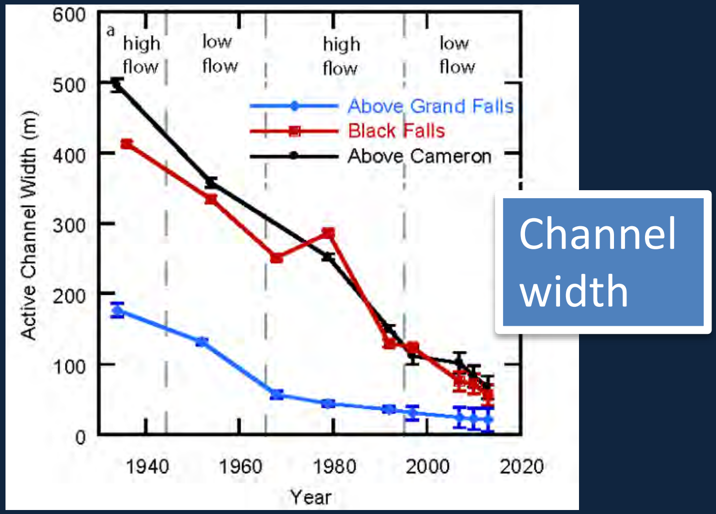
- Decrease in peak flows (1920s to present)
- Decrease in channel width (and channel conveyance)
- Increase in riparian vegetation

→ Lower magnitude floods and less disturbance to LCR in Grand Canyon

→ Decreased sediment supply to Colorado River in Grand Canyon



Dean and Topping, 2019, GSA Bulletin



Dean and Topping, 2019, GSA Bulletin

Dean and Topping, 2019, GSA Bulletin

Project B: Sandbar and Sediment Storage Monitoring and Research

- Project Objectives
  - Monitor the effects of High Flow Experiments and intervening operations on sandbars and sand storage
  - Investigate and model the interactions between dam operations, sand transport, and eddy sandbar dynamics
- Project Elements
  - **B.1 Sandbar Monitoring** (ARM talks by Katie Chapman and David Topping and ARM poster by Bob Tusso)
  - **B.2 Long-term trends in sediment storage** (ARM poster by Matt Kaplinski on Columbine Reach surveys in Western Grand Canyon for Project O.2)
  - **B.3 Control Network and Survey Support** (ARM talk on river profile by Shannon Sartain)
  - **B.5 Fine Sediment and Sandbar Modeling** (ARM poster by Gerard Salter)
- GCDAMP FY2022 Funding: $994,345
- Cooperators: Northern Arizona University, Grand Canyon River Guides, Southern Utah University

USGS

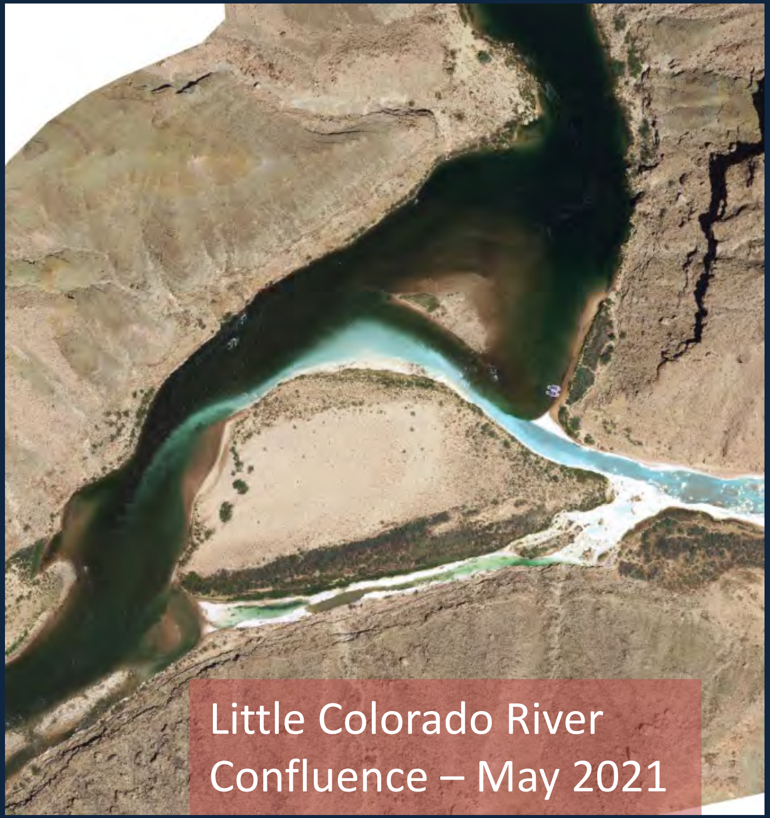
Project L – Remote Sensing Overflight (ARM talk by Joel Sankey)

Budget (FY21, FY22, FY23): $892k, $284k, $316k

Science Question:

- How has landcover in the Colorado River Ecosystem (CRe) changed as a result of dam operations?

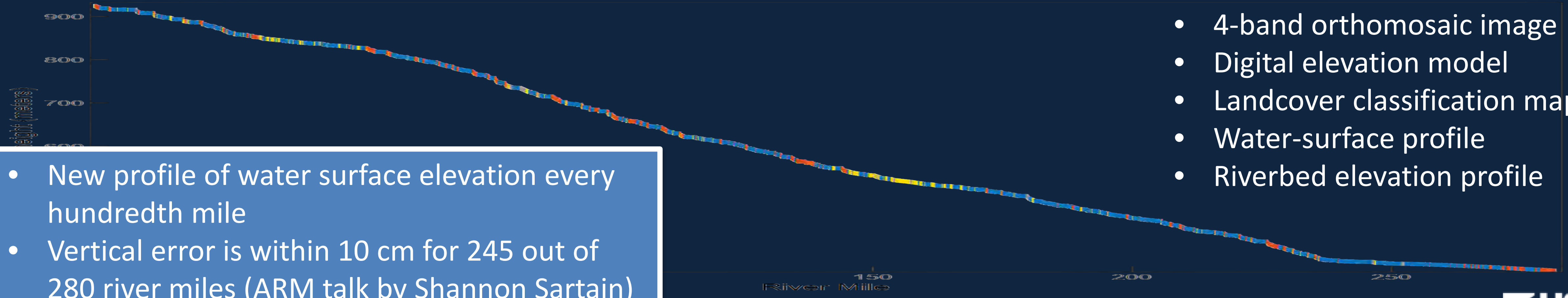
- 2021: Dataset collected
- 2022: Delivery of preliminary to GCMRC, QA/QC, and delivery of revised data
- 2023: Publication of final datasets and data analysis (Unpublished datasets are being used for science projects and river logistics at GCMRC and NPS)



Little Colorado River Confluence – May 2021

Data and Information Products:

- 4-band orthomosaic image
- Digital elevation model
- Landcover classification maps
- Water-surface profile
- Riverbed elevation profile



- New profile of water surface elevation every hundredth mile
- Vertical error is within 10 cm for 245 out of 280 river miles (ARM talk by Shannon Sartain)

Preliminary data – do not cite

USGS

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

Status of Sand Mass Balance and Sandbars

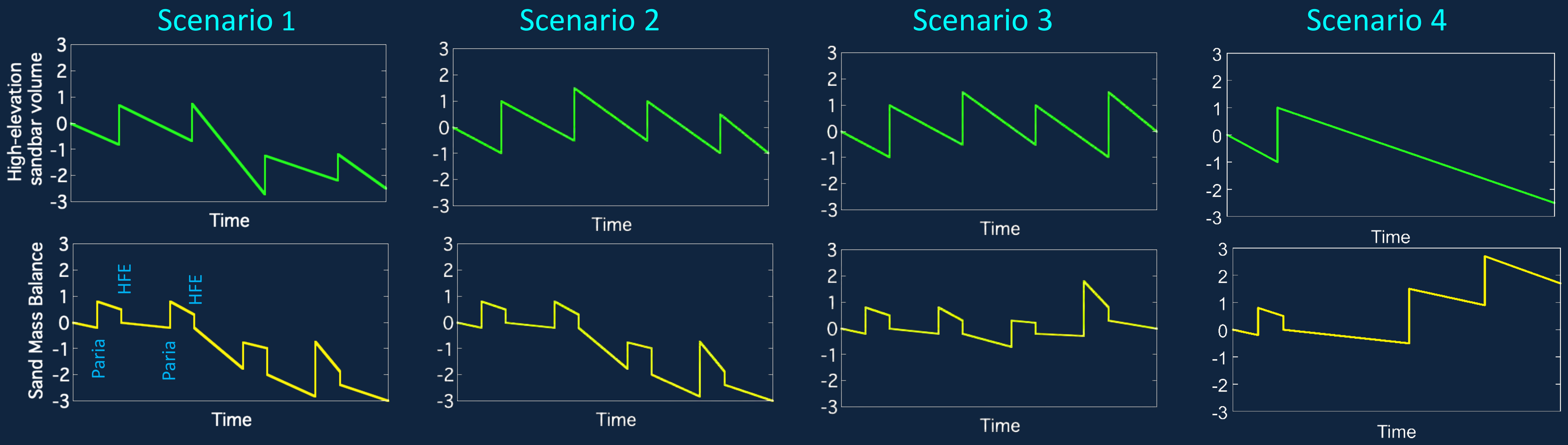
Glen Canyon Dam Adaptive Management Program
Annual Reporting Meeting
January 25, 2023

Summary of ARM presentations by:
David Topping, Robert Tusso, and Katie Chapman

U.S. Geological Survey
Southwest Biological Science Center
Grand Canyon Monitoring and Research Center


(photo by L. Manone)

Sustainable management of sand under the LTEMP sediment goal requires neutral to positive trends in both the sand mass balance (i.e., the bank account) and the high-elevation sandbar volume (i.e., expenditures) over decades



Not sustainable
Sandbars eroding and storage decline
"Not enough Sand"

Not sustainable
Bank account mined to deposit sandbars
"Living on credit"

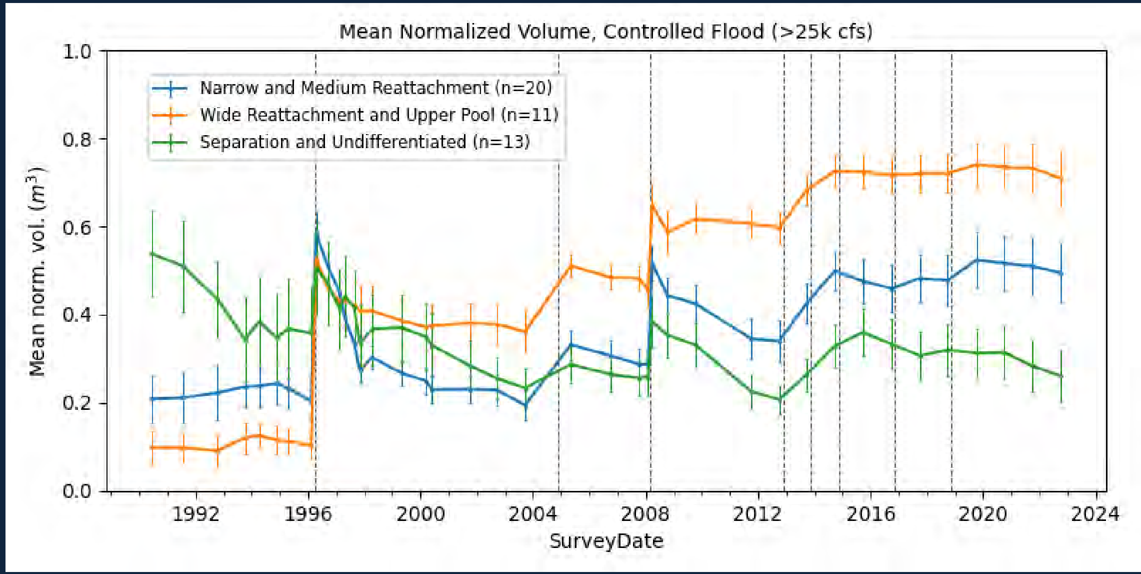
Sustainable
Sandbars and storage are maintained
"Living within your means"

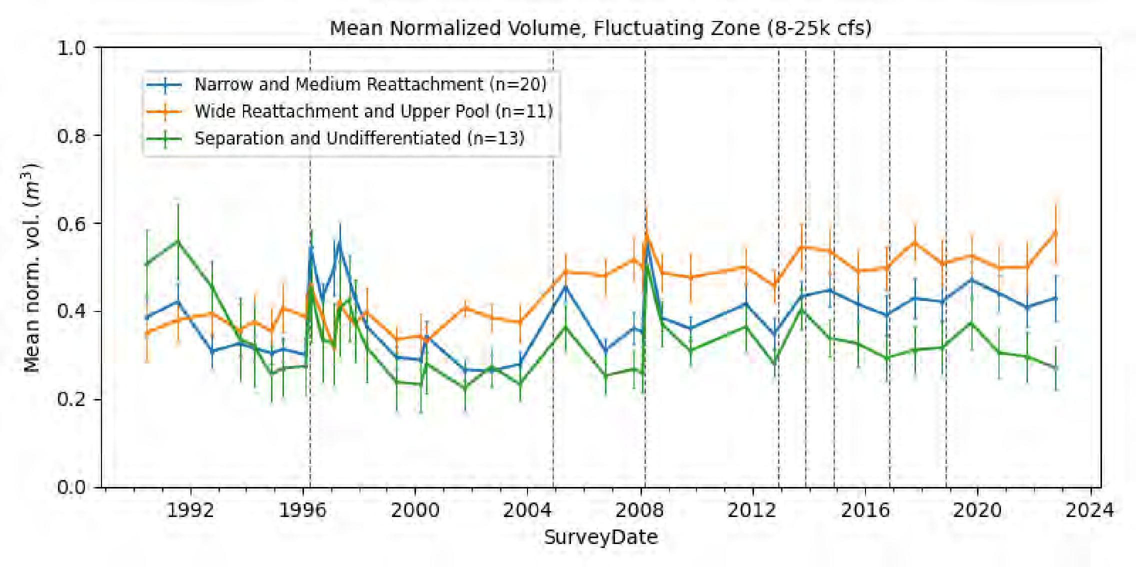
Not Meeting Goals
Sandbars erode while storage increases
"Abandonment of the experimental design"

Preliminary results, subject to review, do not cite

USGS

Long-term trends: 1990 to 2022 (the details)





High Elevation Sand

- All types increase with HFEs
- All types decrease without HFEs
- Reattachment bars and upper pool bars have increased since 1990
- Separation and Undifferentiated bars have decreased since 1990
- since 2012: All sizes of reattachment and upper pool bars have more deposition during HFEs, retain sand better during interim flows

>> Response shows potential for increasing long term sand storage in high-elevation zone.

Lower Elevation Sand (affected by daily flows):

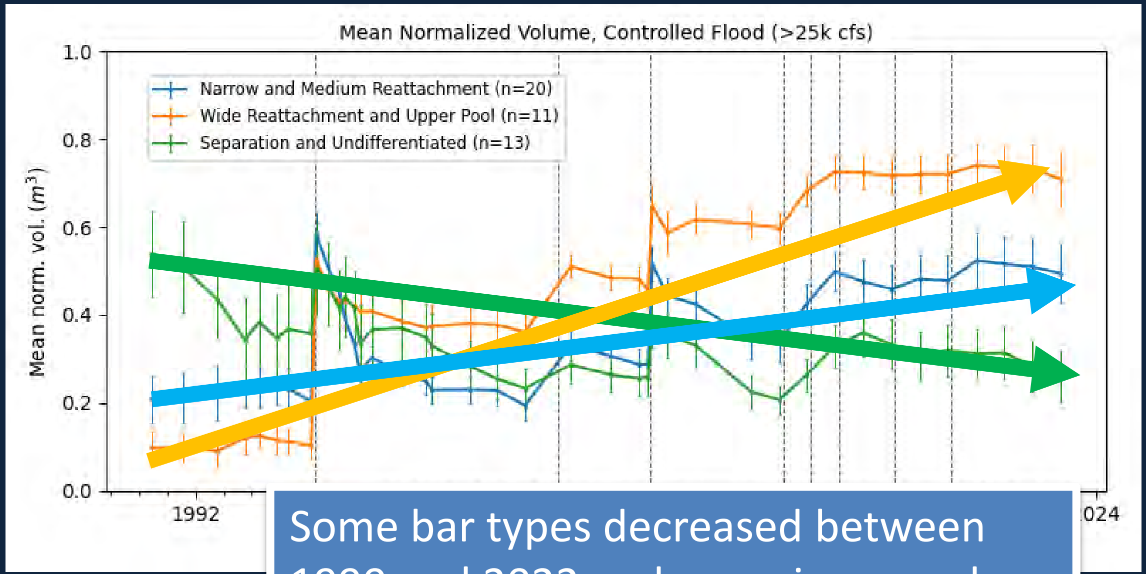
- Greater variability than higher elevation zone
- Reattachment bars and upper pool bars have increased since 1990
- Separation and Undifferentiated bars have decreased since 1990

>> Response shows less potential for increasing long term sand storage in fluctuating zone.

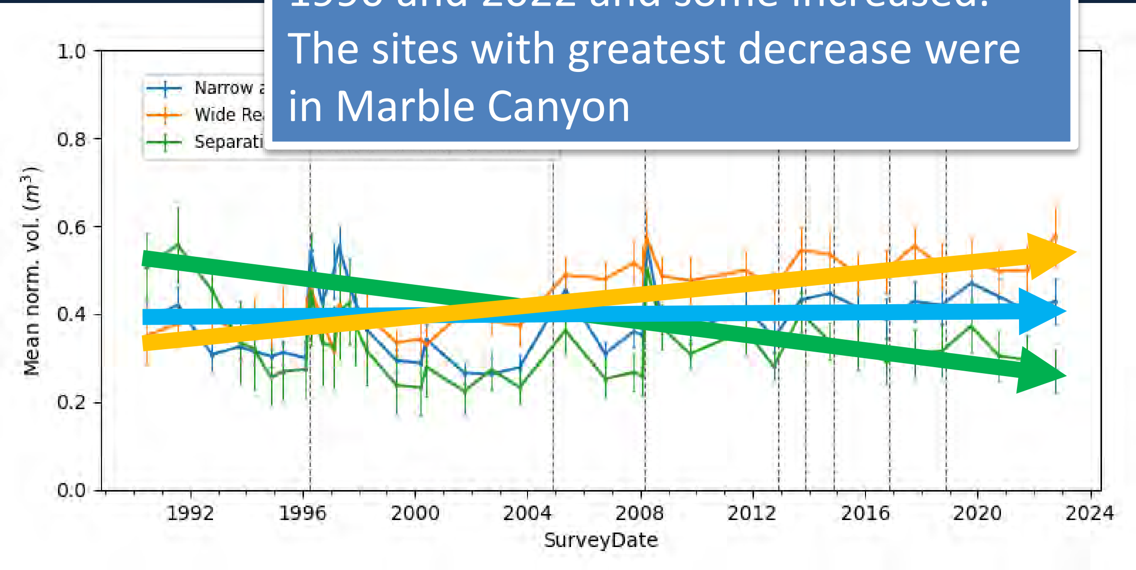
Data from: www.gcmrc.gov/discharge_qw_sediment/ and www.usgs.gov/apps/sandbar/

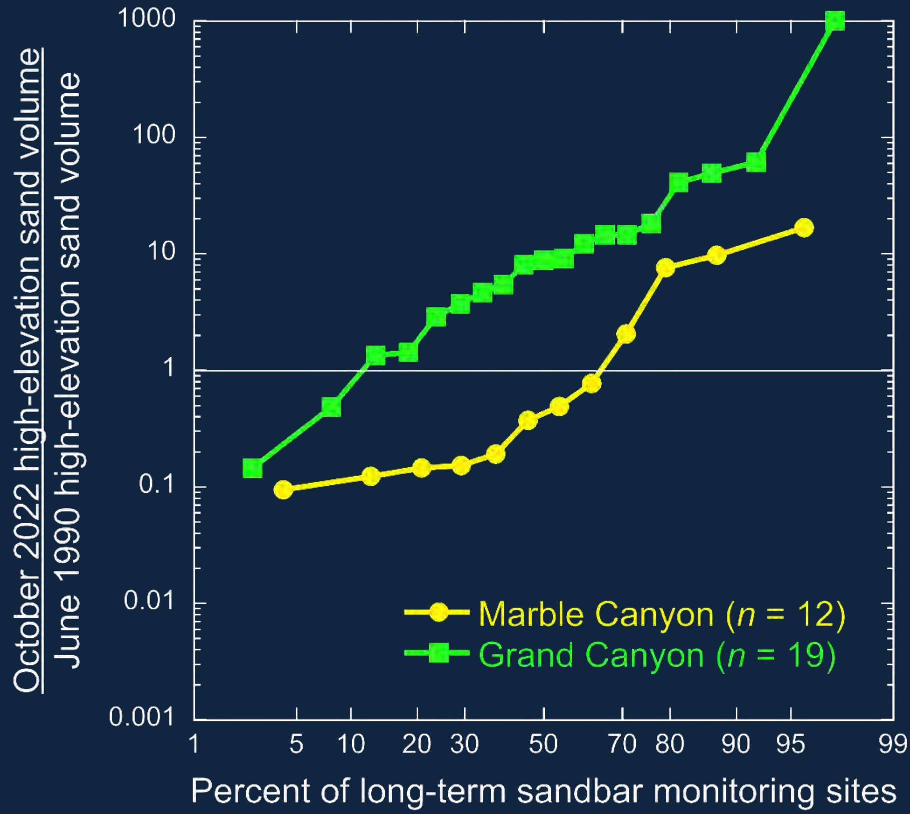
Preliminary results, subject to review, do not cite

Long-term trends: 1990 to 2022 (the details)



Some bar types decreased between 1990 and 2022 and some increased. The sites with greatest decrease were in Marble Canyon





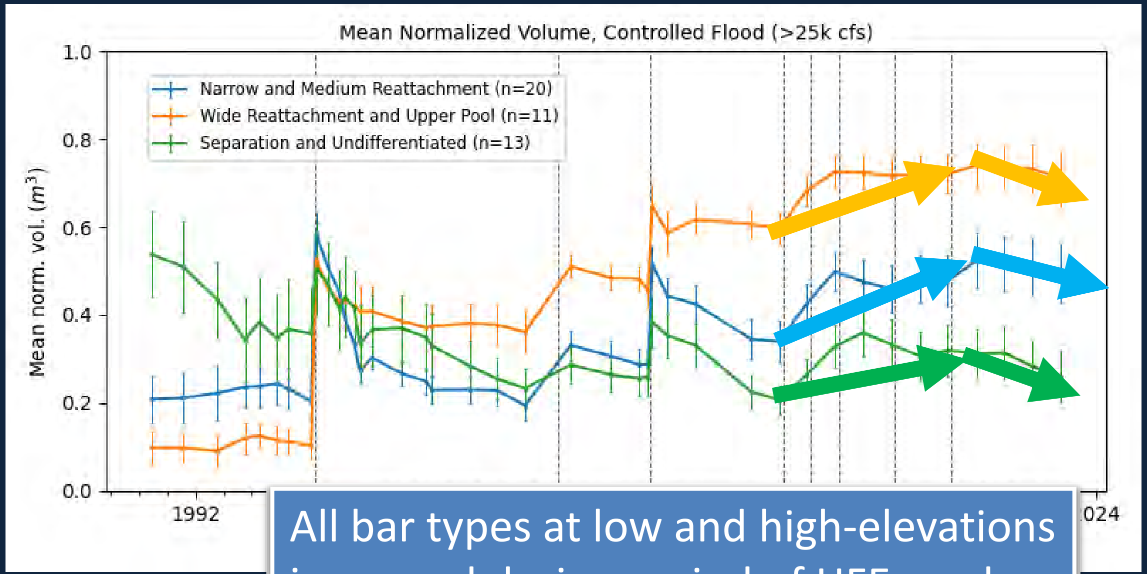
Marble Canyon: 67% of long-term sites decreased from 1990 to 2022.
Grand Canyon: only 11% of long-term sites decreased 1990 to 2022

Data from: www.gcmrc.gov/discharge_qw_sediment/ and www.usgs.gov/apps/sandbar/

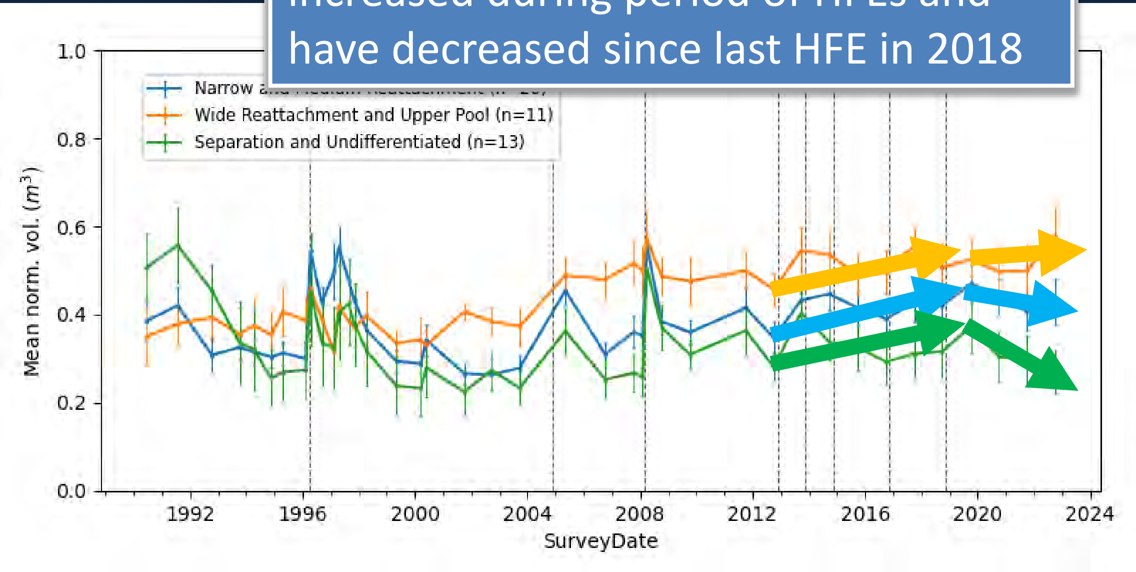
Preliminary results, subject to review, do not cite

USGS

Long-term trends: 1990 to 2022 (the details)



All bar types at low and high-elevations increased during period of HFEs and have decreased since last HFE in 2018



<u>High Elevation Sand</u>

- All types increase with HFEs
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- Reattachment bars and upper pool bars have increased since 1990
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<u>Lower Elevation Sand (affected by daily flows):</u>

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- Separation and Undifferentiated bars have decreased since 1990

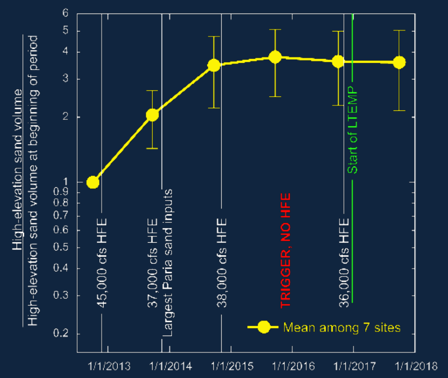
>> Response shows less potential for increasing long term sand storage in fluctuating zone.

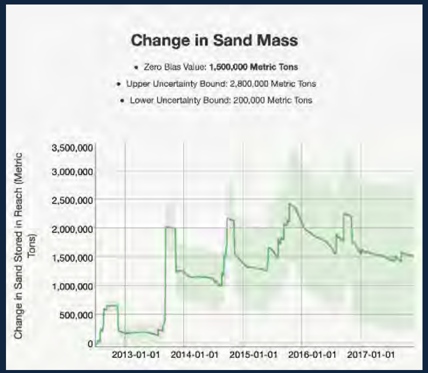
Data from: www.gcmrc.gov/discharge_qw_sediment/ and www.usgs.gov/apps/sandbar/

Preliminary results, subject to review, do not cite

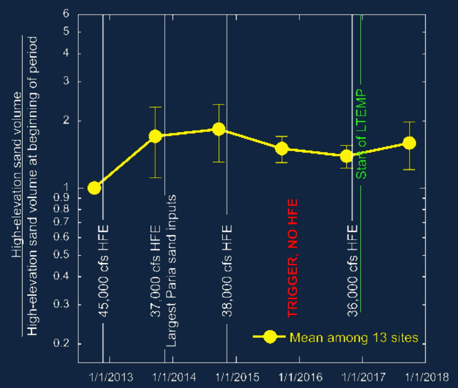
Four out of the five segments met the criteria for “sustainable” or “possibly sustainable” in the 2012 to 2018 period when HFEs were implemented

RM 0-30

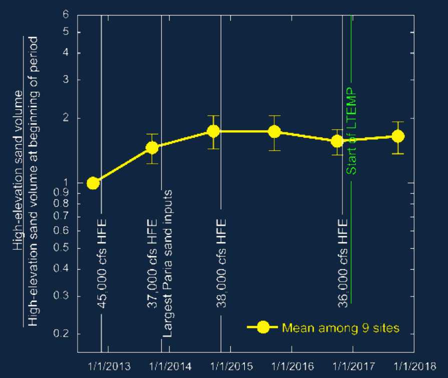


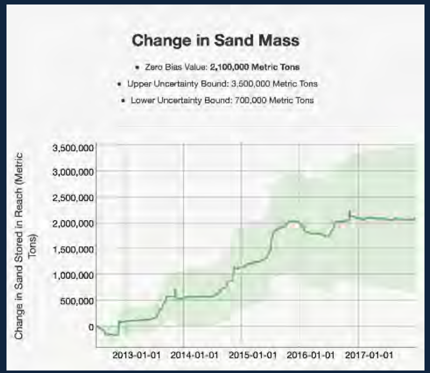


RM 30-60

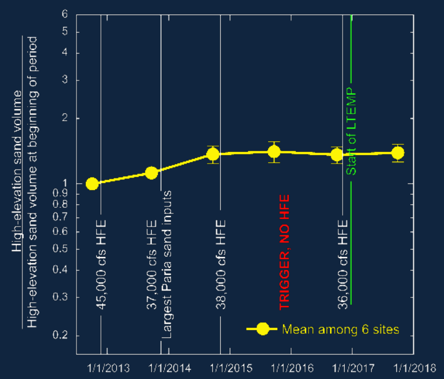


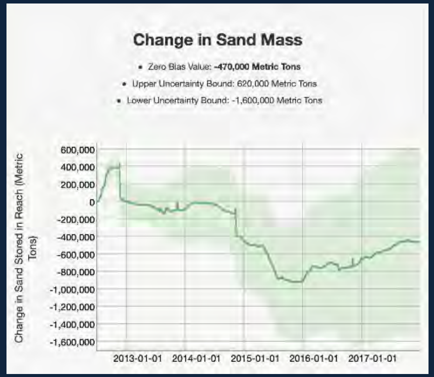
RM 87-166



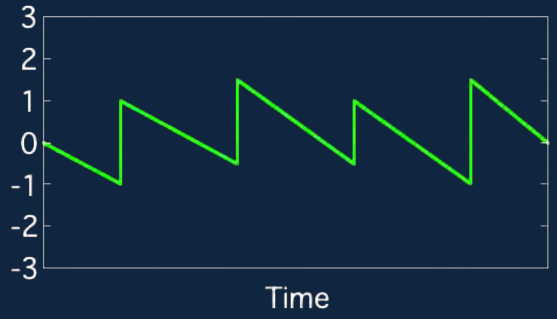


RM 166-225





Scenario 3



Sustainable
“Living within your means”

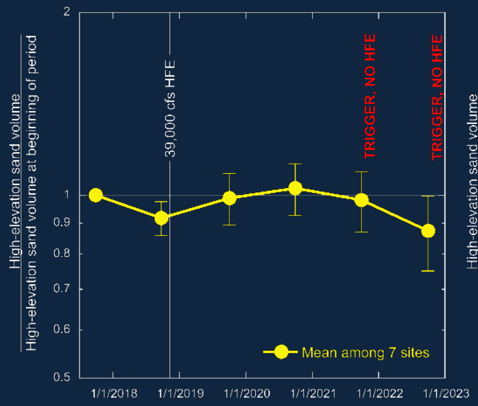
Deposition on high-elevation sandbars while sand is maintained or accumulates in channel = sustainable sand management

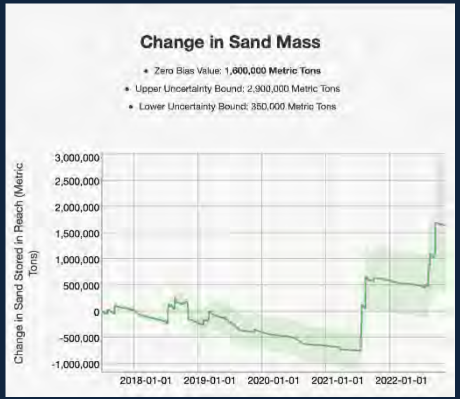
Data from: www.gcmrc.gov/discharge_qw_sediment/ and www.usgs.gov/apps/sandbar/

Preliminary results, subject to review, do not cite

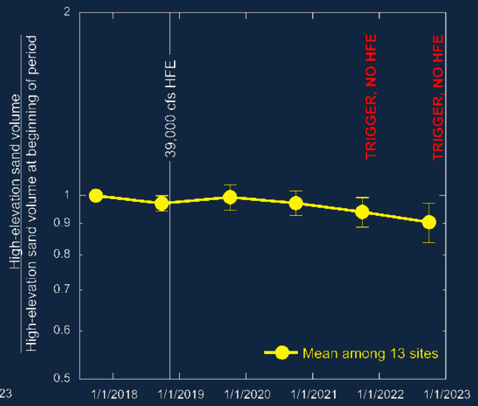
In four out of the five segments sandbars eroded while sand mass in the channel increased during 2019 to 2022 period without HFEs

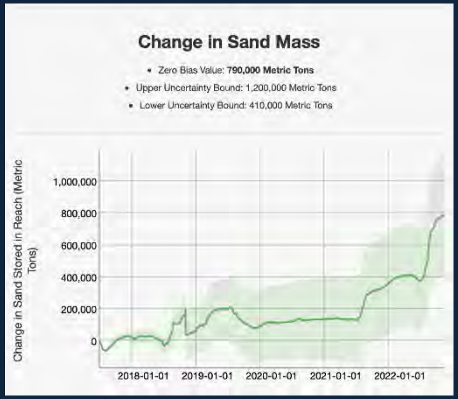
RM 0-30



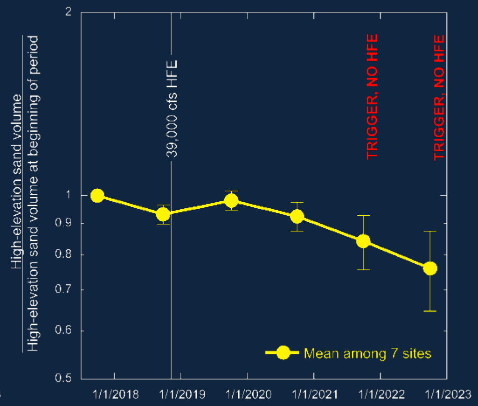


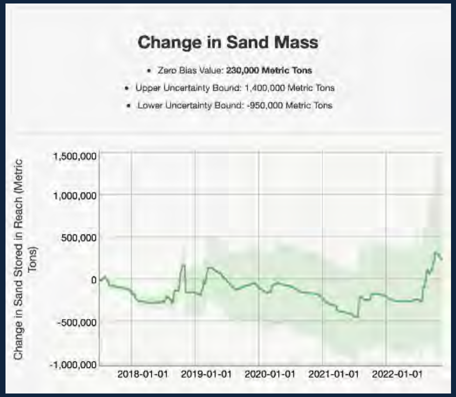
RM 30-60



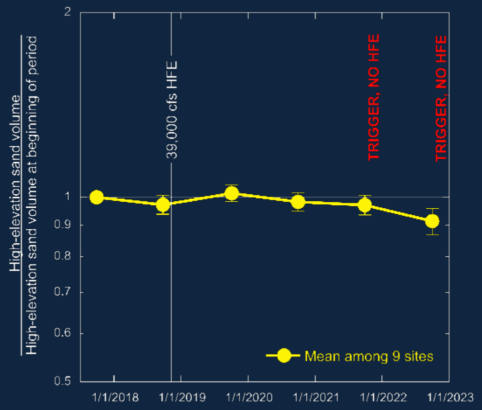


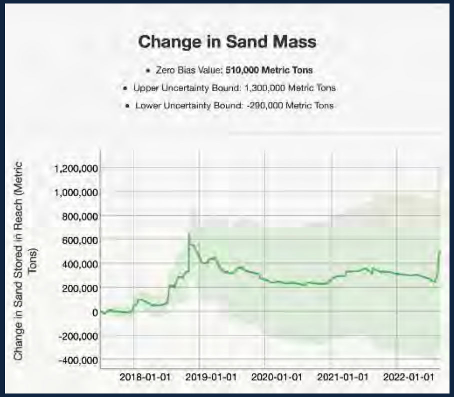
RM 60-87



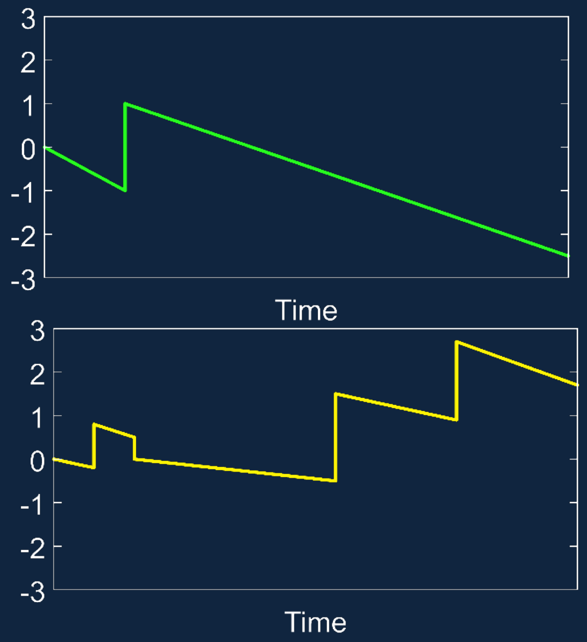


RM 87-166





Scenario 4



Sandbar Erosion
“Abandonment of the experimental design”

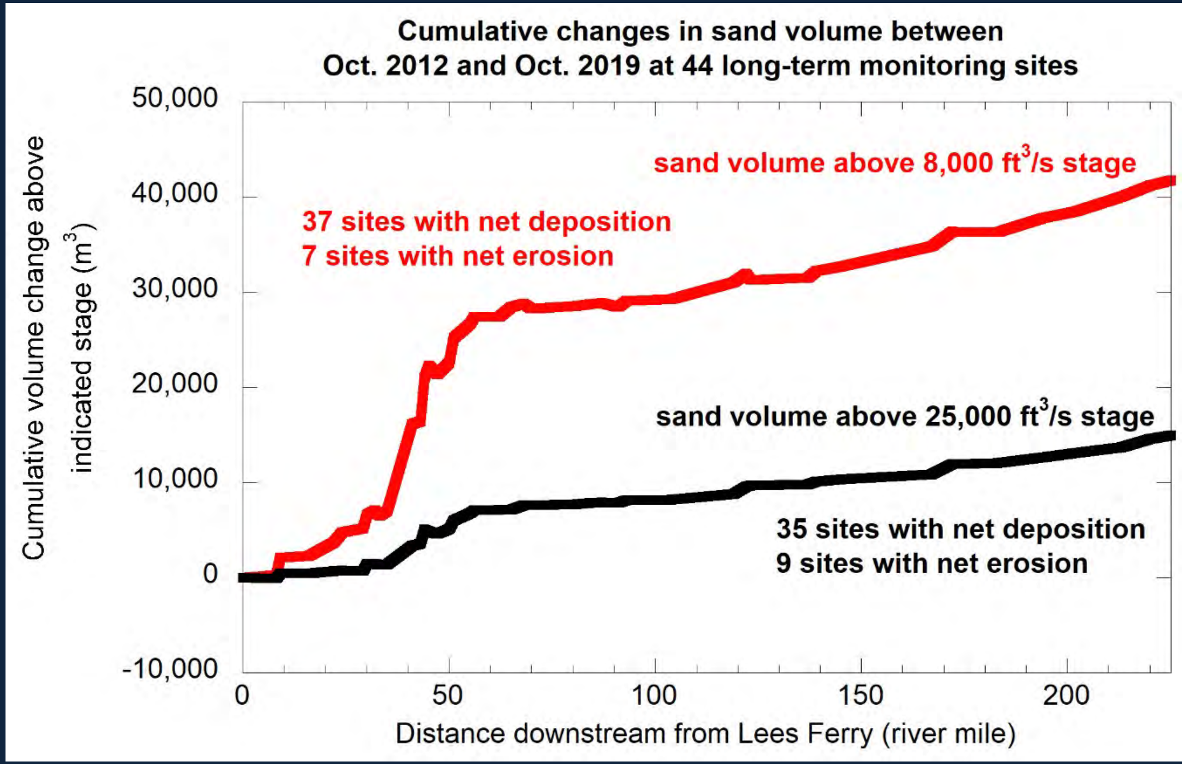
Erosion of high-elevation sandbars while sand accumulates in channel = missed opportunities to rebuild sandbars

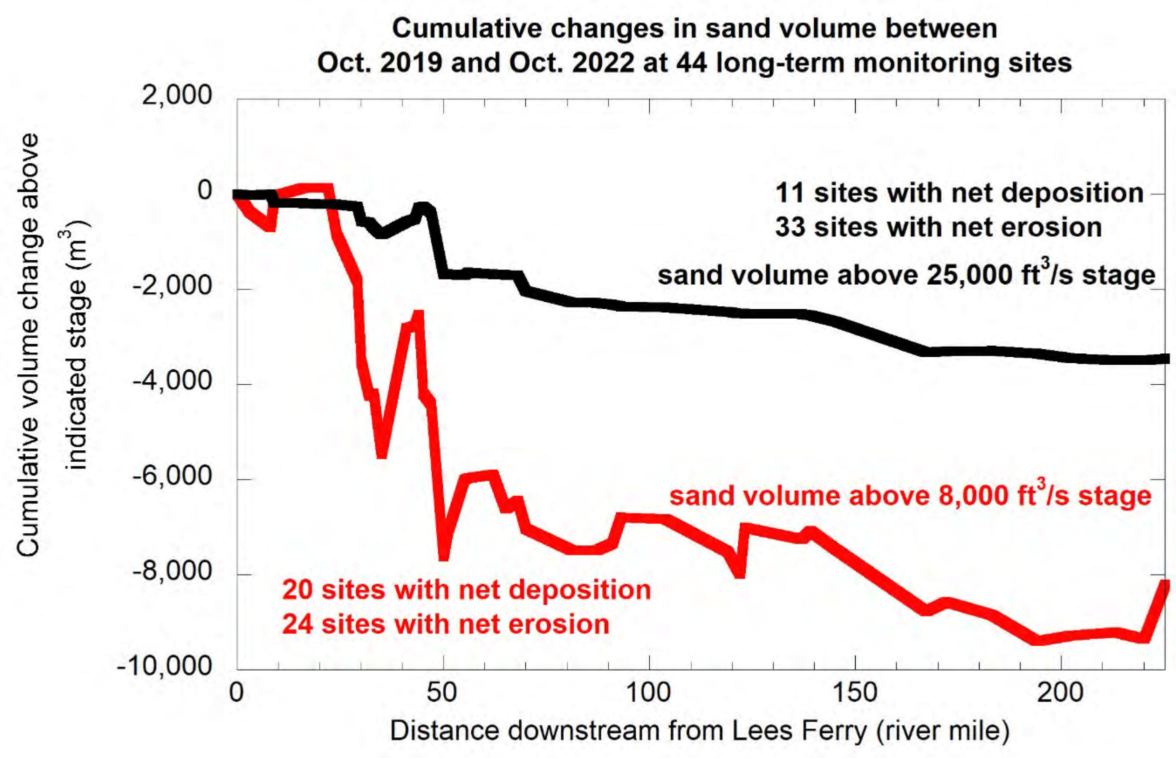
Data from: www.gcmrc.gov/discharge_qw_sediment/ and www.usgs.gov/apps/sandbar/

Preliminary results, subject to review, do not cite

USGS

Sandbar volume change: 2012 to 2022 (the bottom line)





Dominated by deposition during period of five HFEs (2012 to 2019)

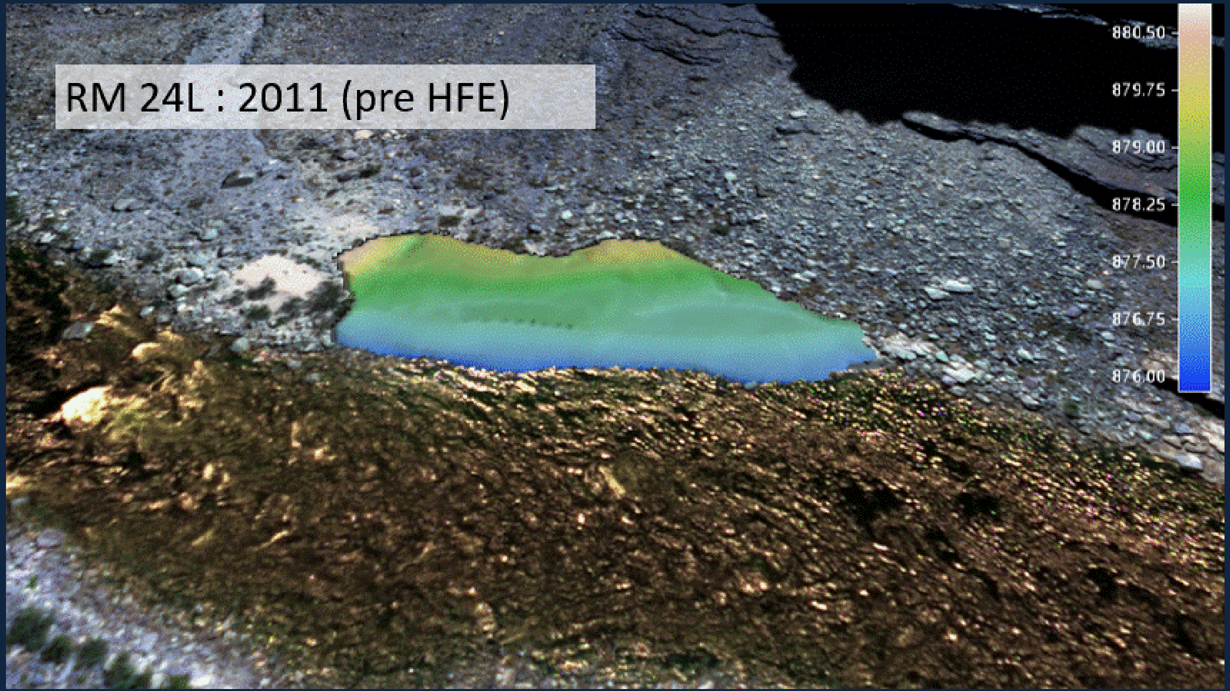
Dominated by erosion during period without HFEs (2019 to 2022)

Data from: www.gcmrc.gov/discharge_qw_sediment/ and www.usgs.gov/apps/sandbar/

Preliminary results, subject to review, do not cite

USGS

RM 24L (Lone Cedar Beach) 2011-2022



2011-2022: Gully erosion and filling by HFEs

RM 32R (South Canyon)

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

Evaluation of High-Flow Experiments During Aridification

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

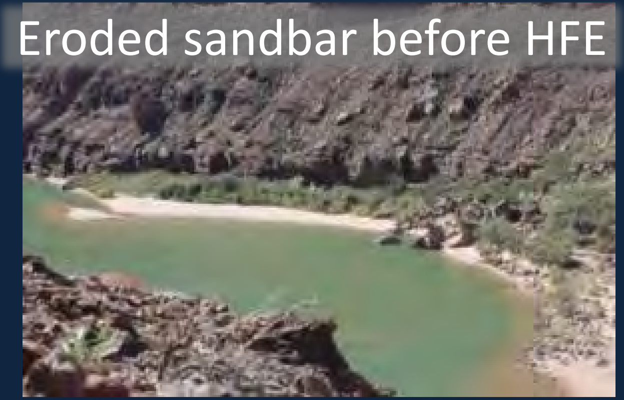
Lake Powell at 3526 ft in December 2022 (photo by P. Grams)

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

Paul Grams
U.S. Geological Survey
Southwest Biological Science Center
Grand Canyon Monitoring and Research Center

Purpose of HFEs in LTEMP ROD

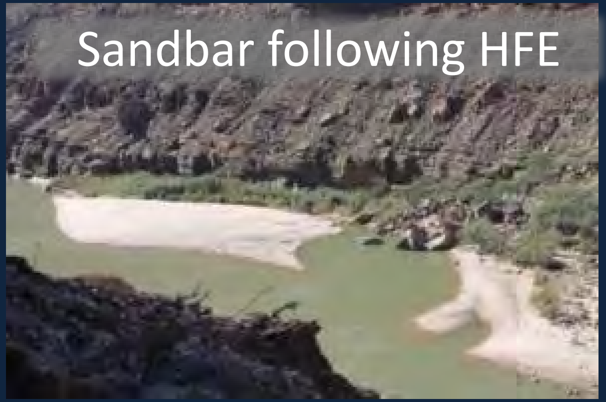
- The purpose of HFEs is to address the LTEMP sediment goal:
  - “Increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes.”
- Sandbars erode by dam operations and other processes
- HFEs have functioned as intended by the HFE Protocol and LTEMP EIS to rebuild sandbars



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 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?

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 with volumes needed for HFEs added

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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
December	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
January										
February										
March										
April										
May										
June										
July										
August										
September										

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 yet know the snowpack and runoff?

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

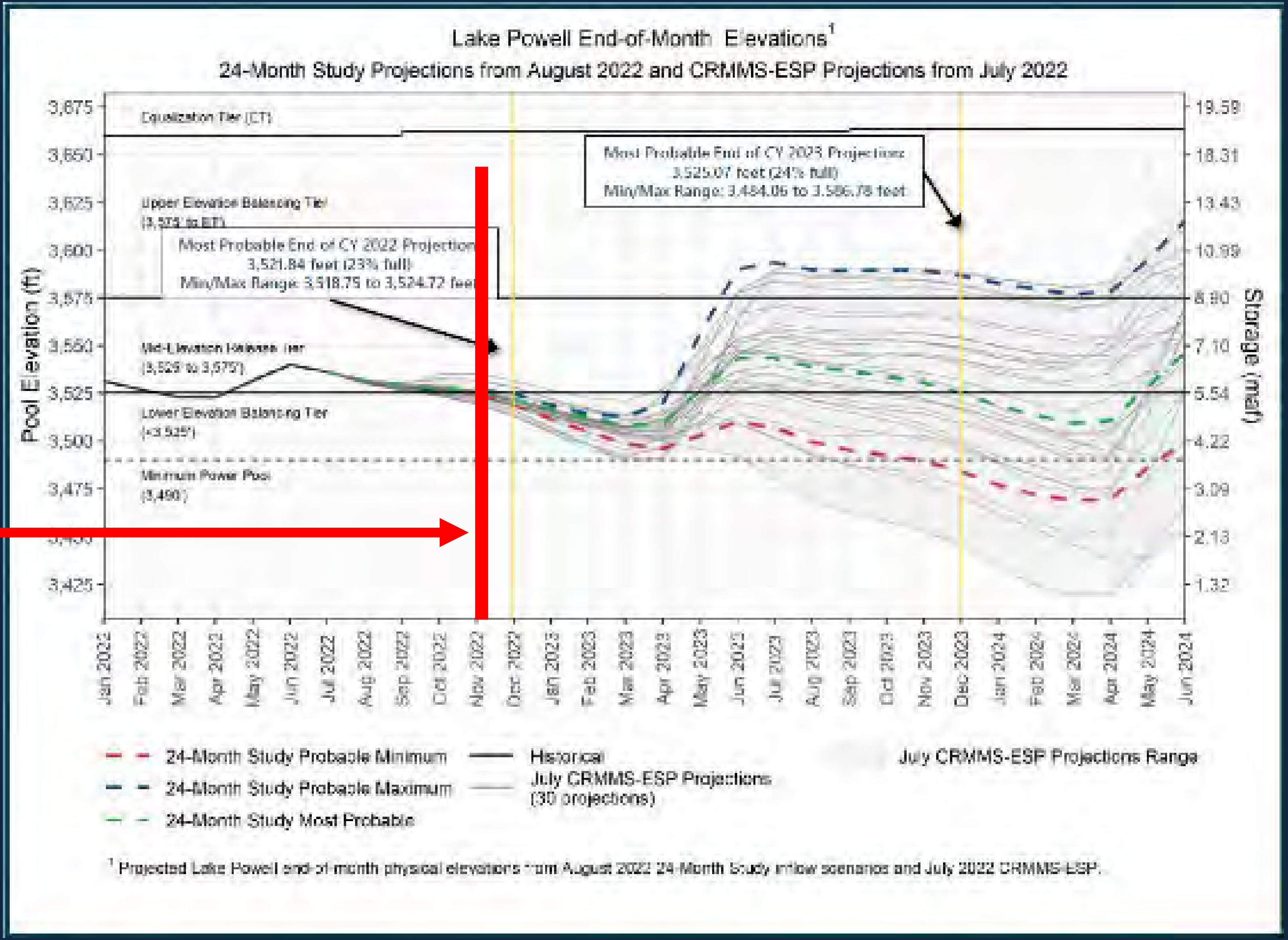
HFE ID	Peak Discharge (cfs)	Duration at Peak (hours)	Volume of water needed (ac-ft)*
1	45,000	250	756,100
2	45,000	192	580,700
3	45,000	144	435,500
4	45,000	96	290,400
5	45,000	72	217,800
6	45,000	60	181,500
7	45,000	48	145,200
8	45,000	36	108,900
9	45,000	24	72,600
10	45,000	12	36,300
11	45,000	1	3,000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

- 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.

Table in LTEMP does not include HFE volumes

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



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

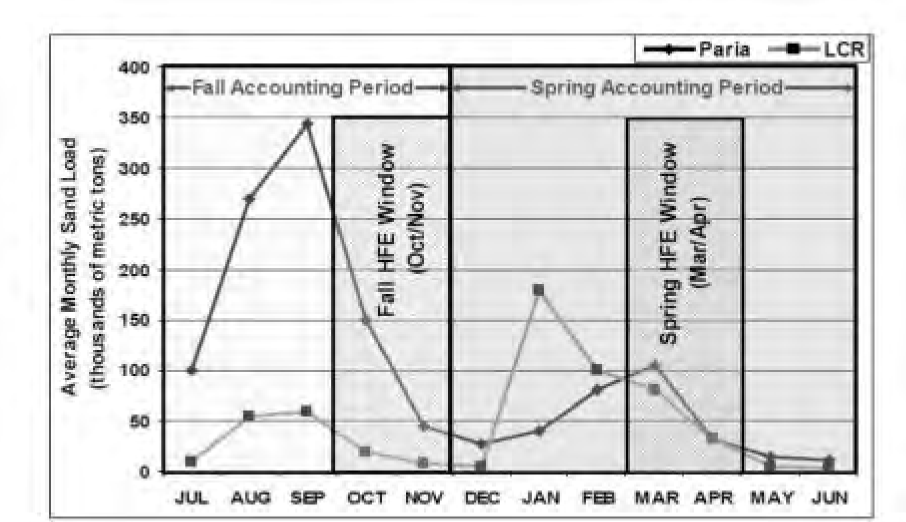
- In LTEMP, the HFE process was guided by the assumption that sediment availability was the critical limiting factor in HFE implementation: **water availability was assumed**.
- For low-reservoir conditions, water availability is an additional constraint to factor in the decision process.

Why have HFEs been implemented in Fall?

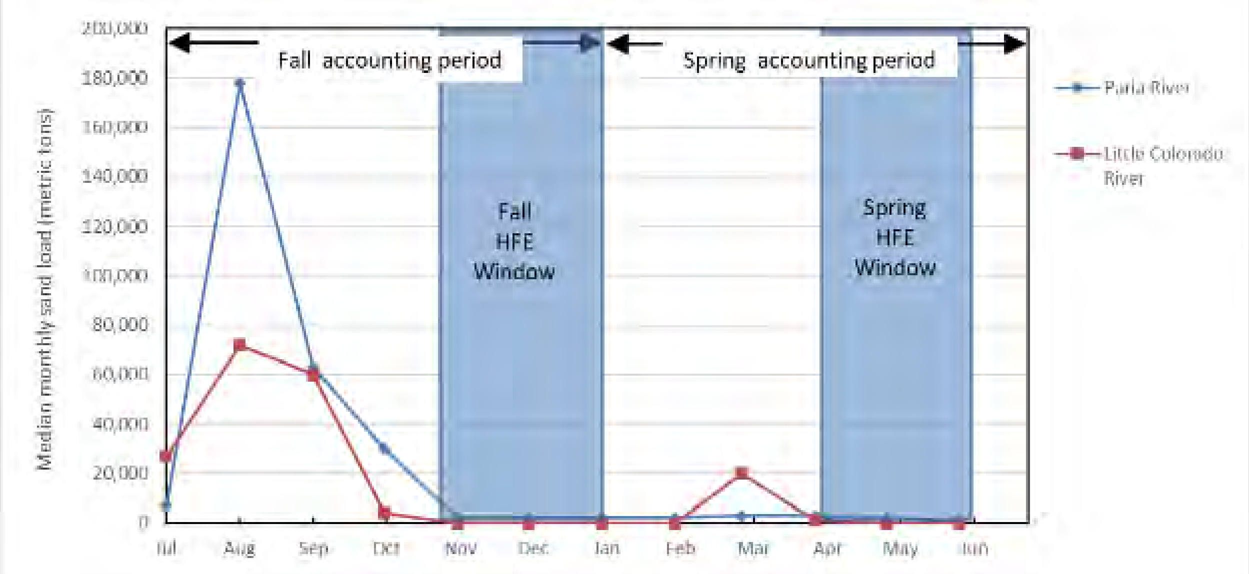
- Sediment concentrations and deposition rates will be greatest when the sand supply in the channel is greatest and is the finest grain size
  - These conditions are highest soon after a series of tributary floods and then decrease
  - If dam releases are relatively high during the winter, there can 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



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

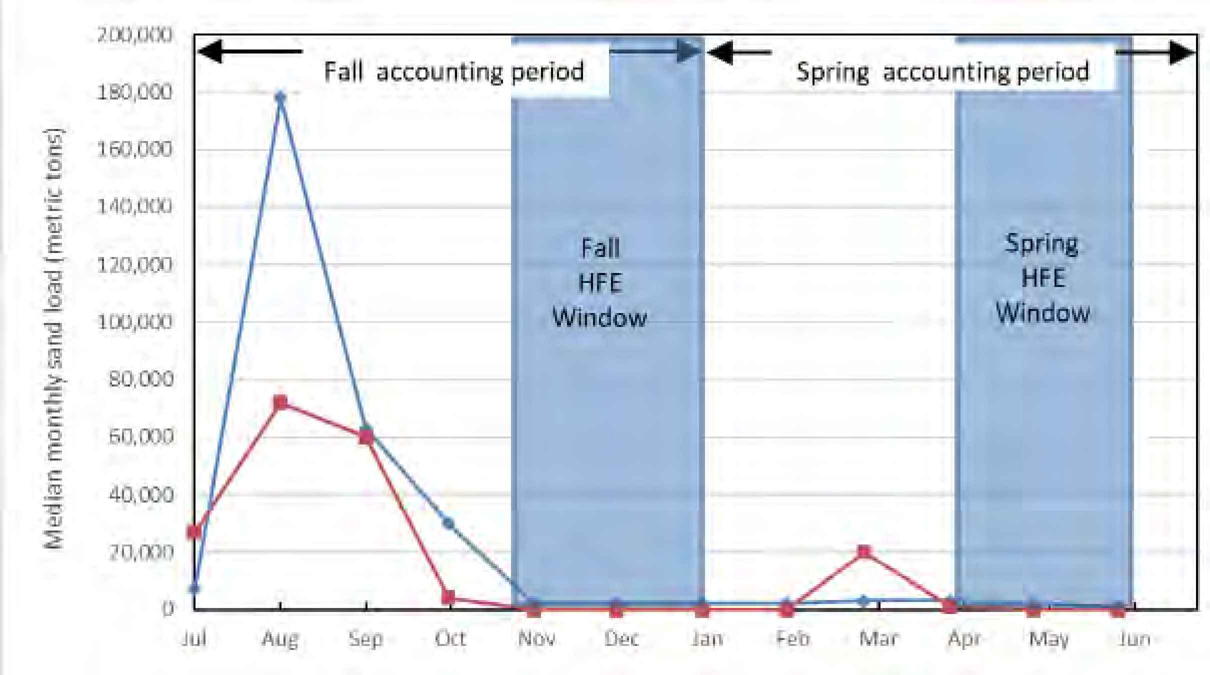
Low-water HFE Protocol Step 1

- 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

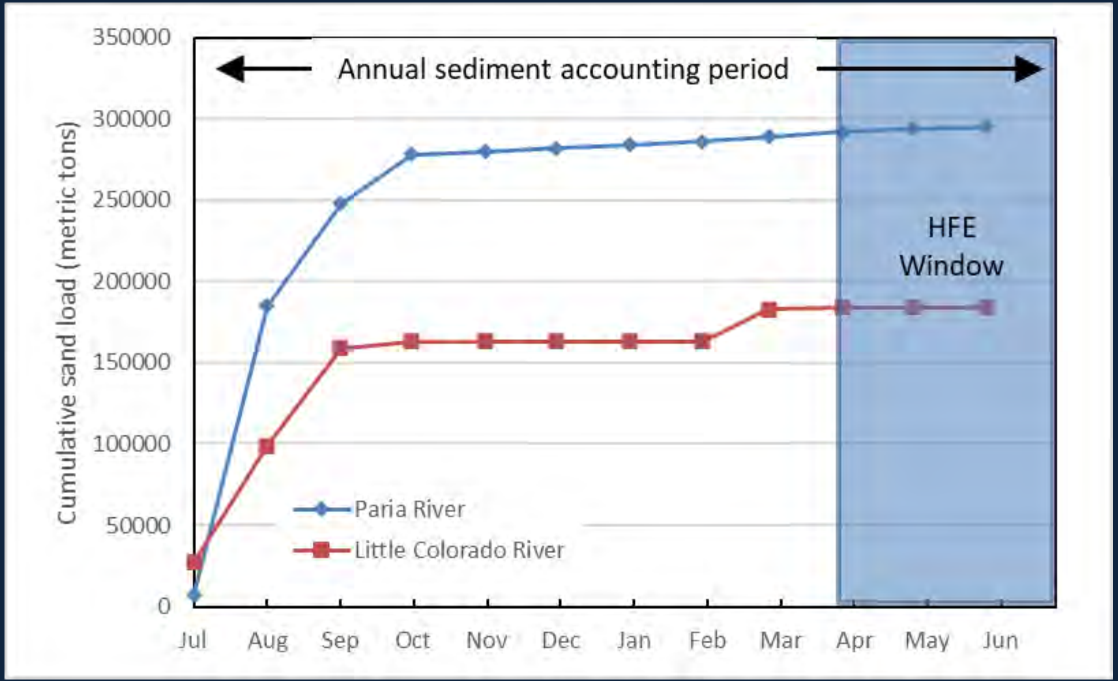
LTEMP sediment accounting



Optimizes to implement HFE as soon after Paria sediment inputs as possible.

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

Low-reservoir sediment accounting

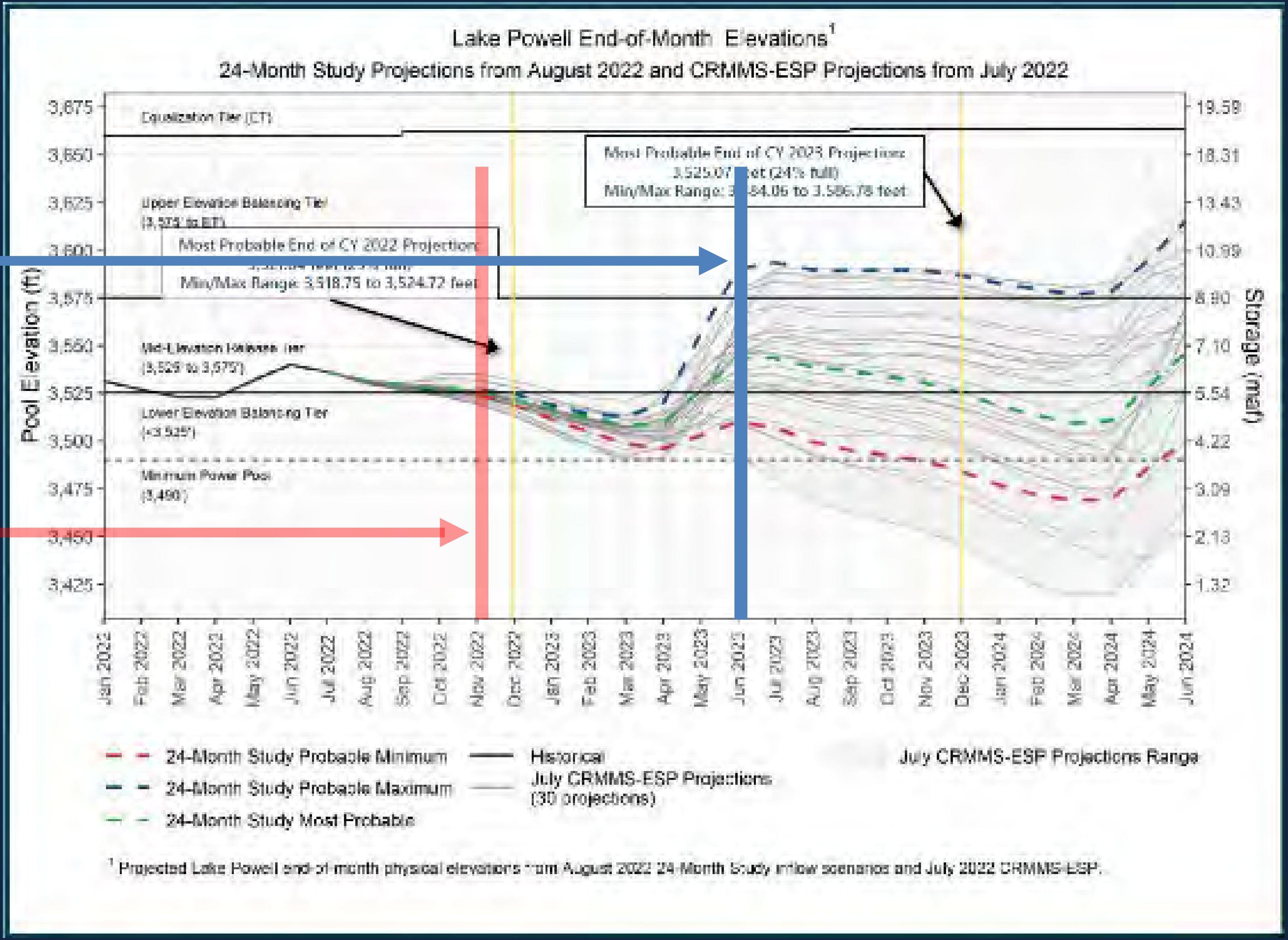


Optimizes to implement HFE following accumulation of both Paria and LCR inputs.

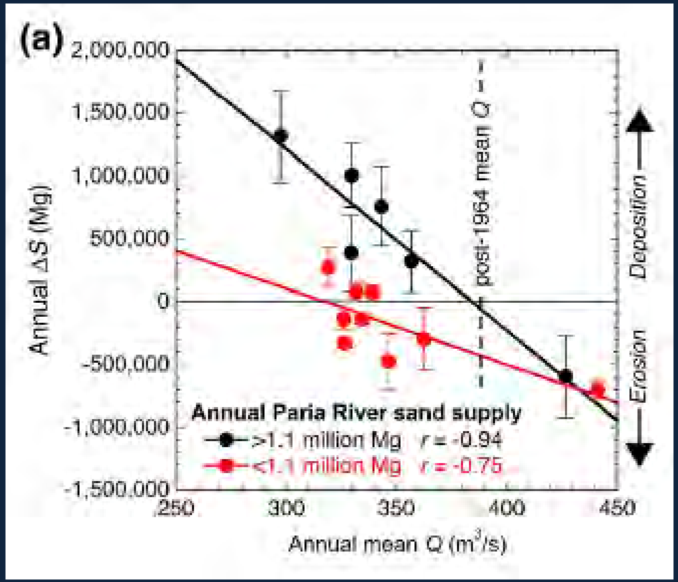
- **Will only work when winter releases are low.**

June HFEs would occur after reservoir elevations have increased with runoff

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



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)

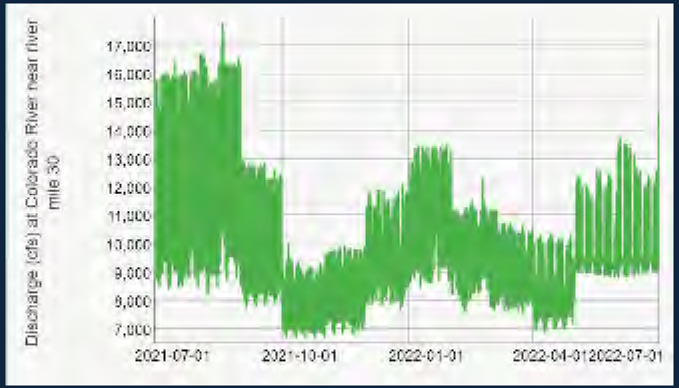
LTEMP Accounting

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

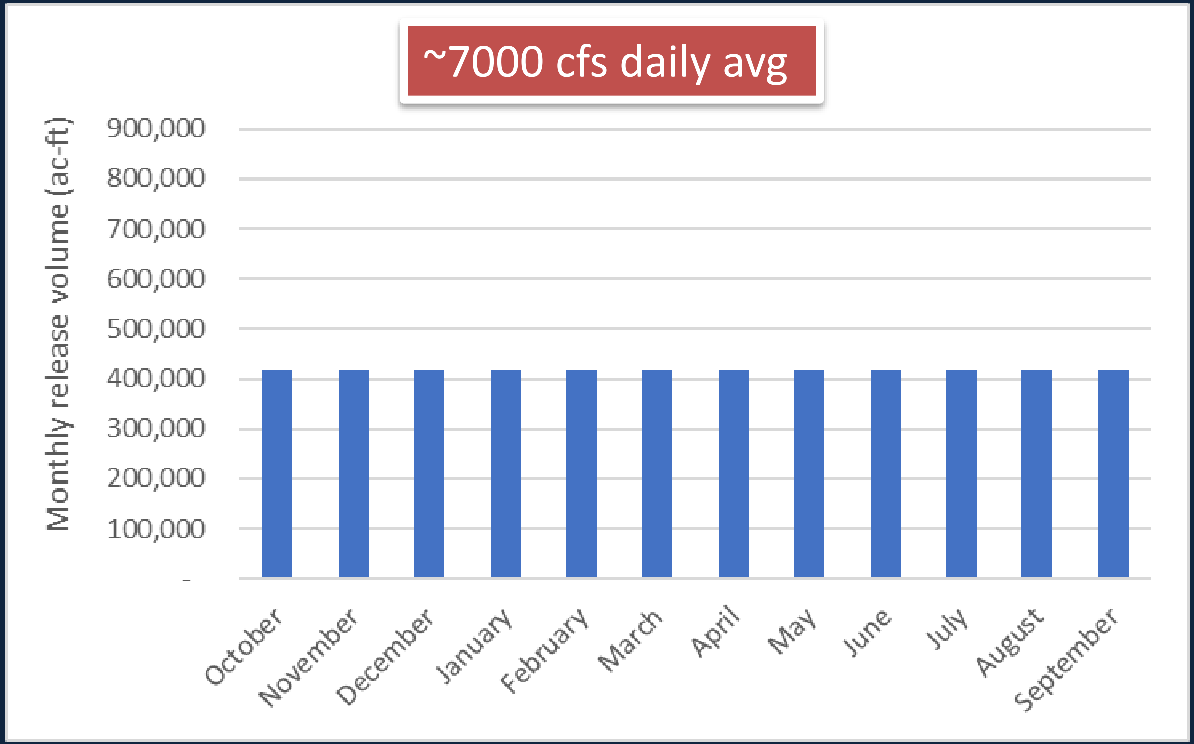
2021-2022 (Powell at and below 3550 ft)
- ~ 1,400,000 metric tons accumulation
- ~ 8 million acre-ft annual volume
- Most sand retainied through following spring

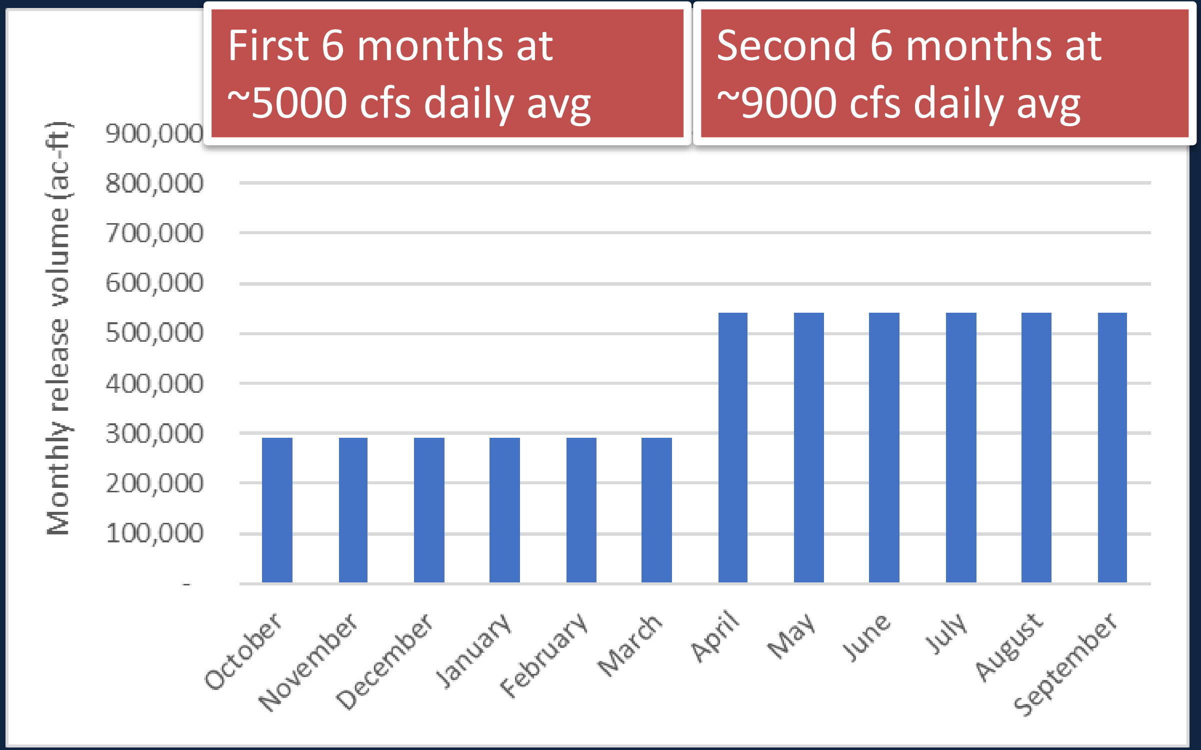


HFE could be implemented in either fall or spring because sand is retained

Low-water HFE Protocol Step 2

Annual volume = 5 maf

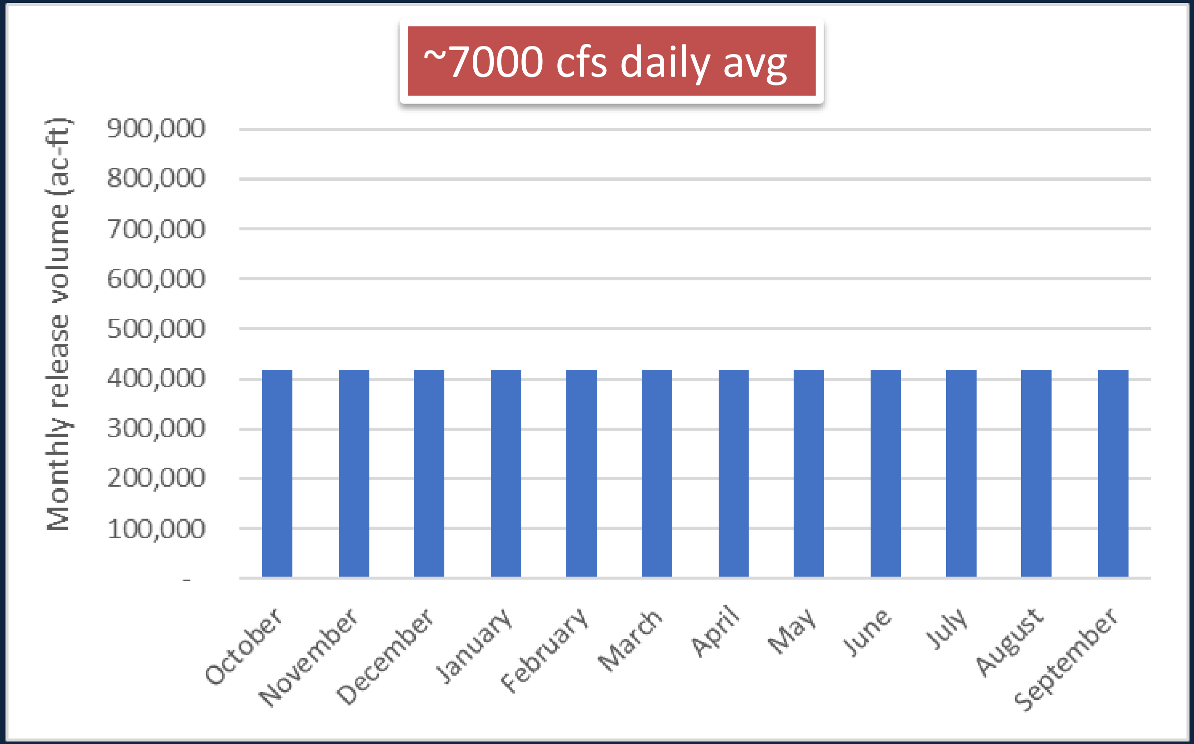


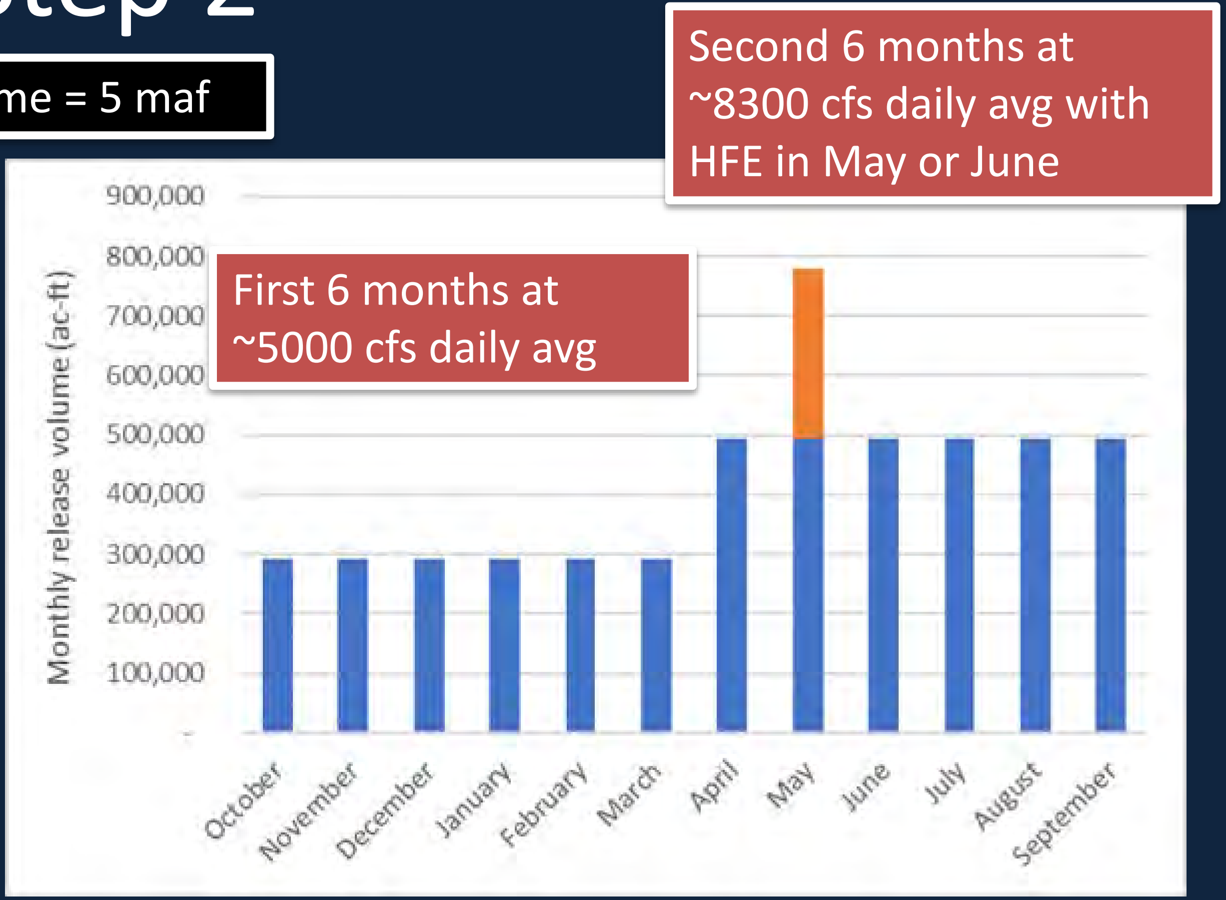


Beginning the water year with lower releases protects Lake Powell elevations in winter and allows higher flows in spring/summer.

Low-water HFE Protocol Step 2

Annual volume = 5 maf

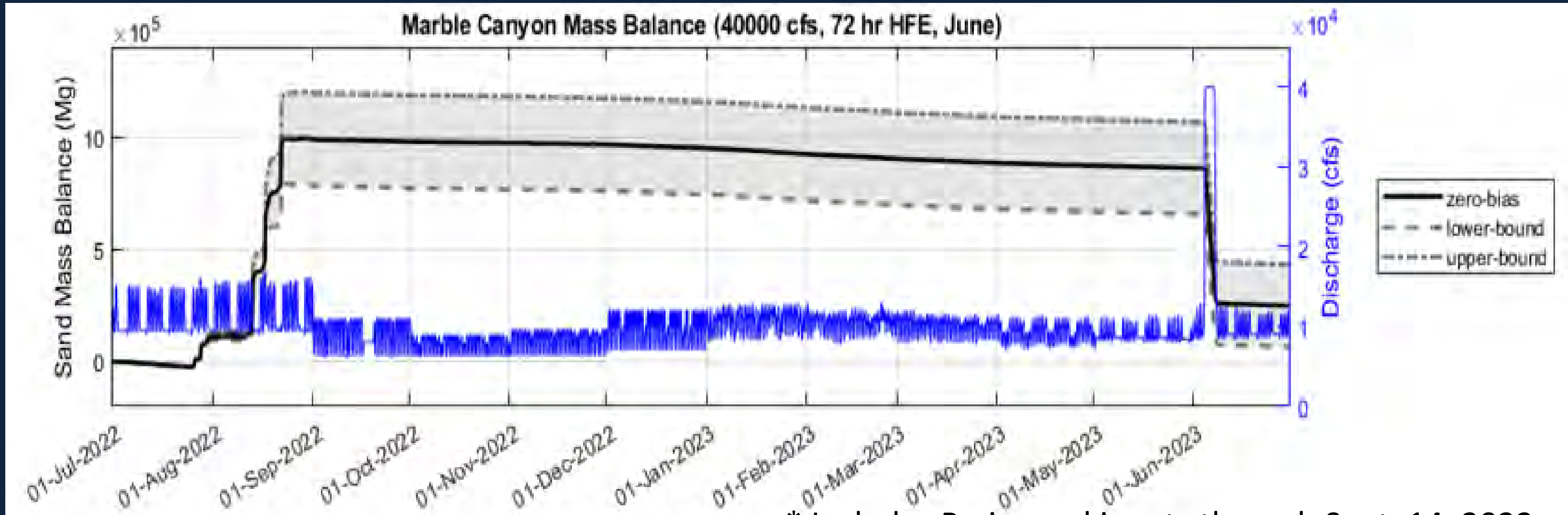




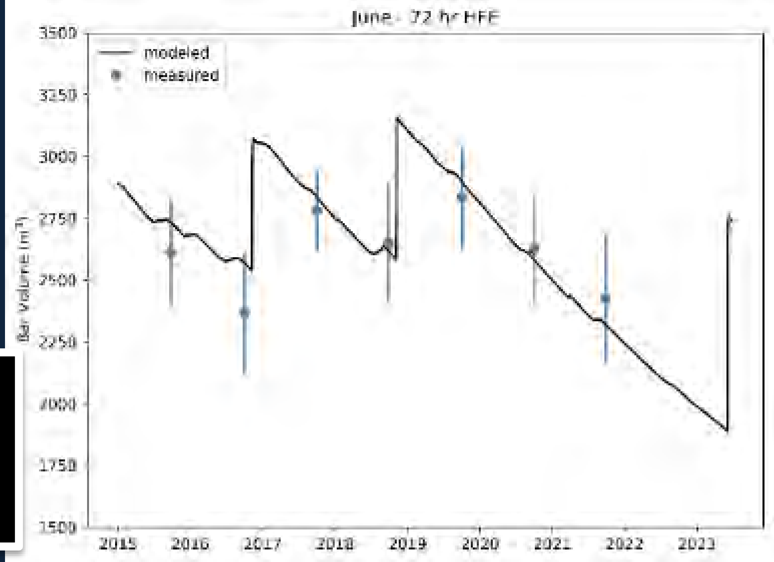
If sediment trigger is reached, slight redistribution of monthly volumes in summer allows for May or June HFE.

Conditions for potential Spring/Summer 2023 HFE

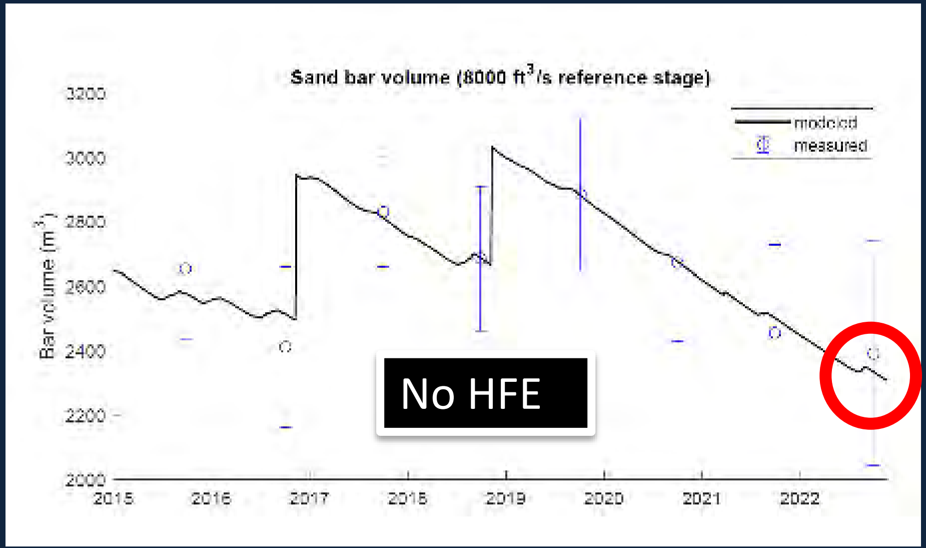
Current sediment conditions support a high flow of up to 40,000 to 45,000 cfs and up to 72 hours anytime between fall 2022 and summer 2023.



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

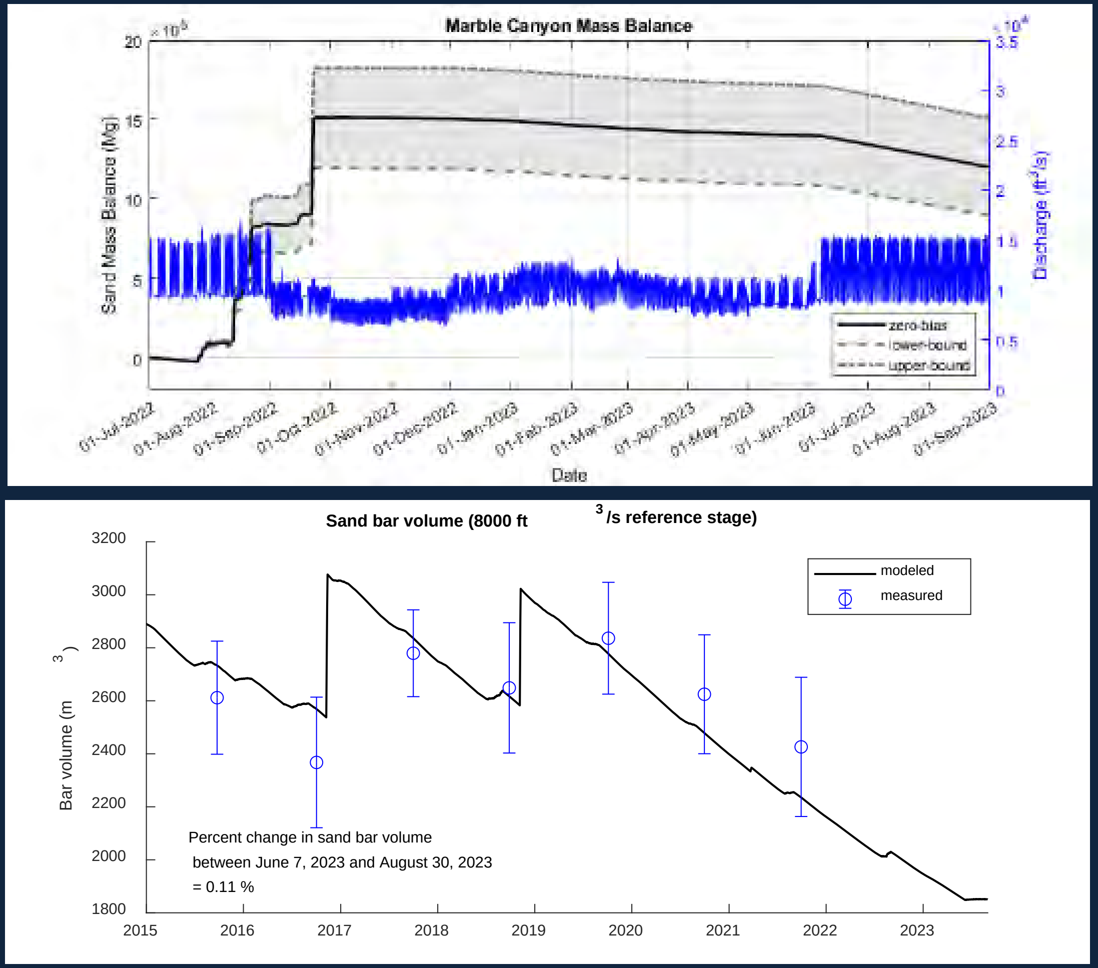


Predicted sandbar response to potential June 2023 HFE of 40,000 cfs for 72 hr

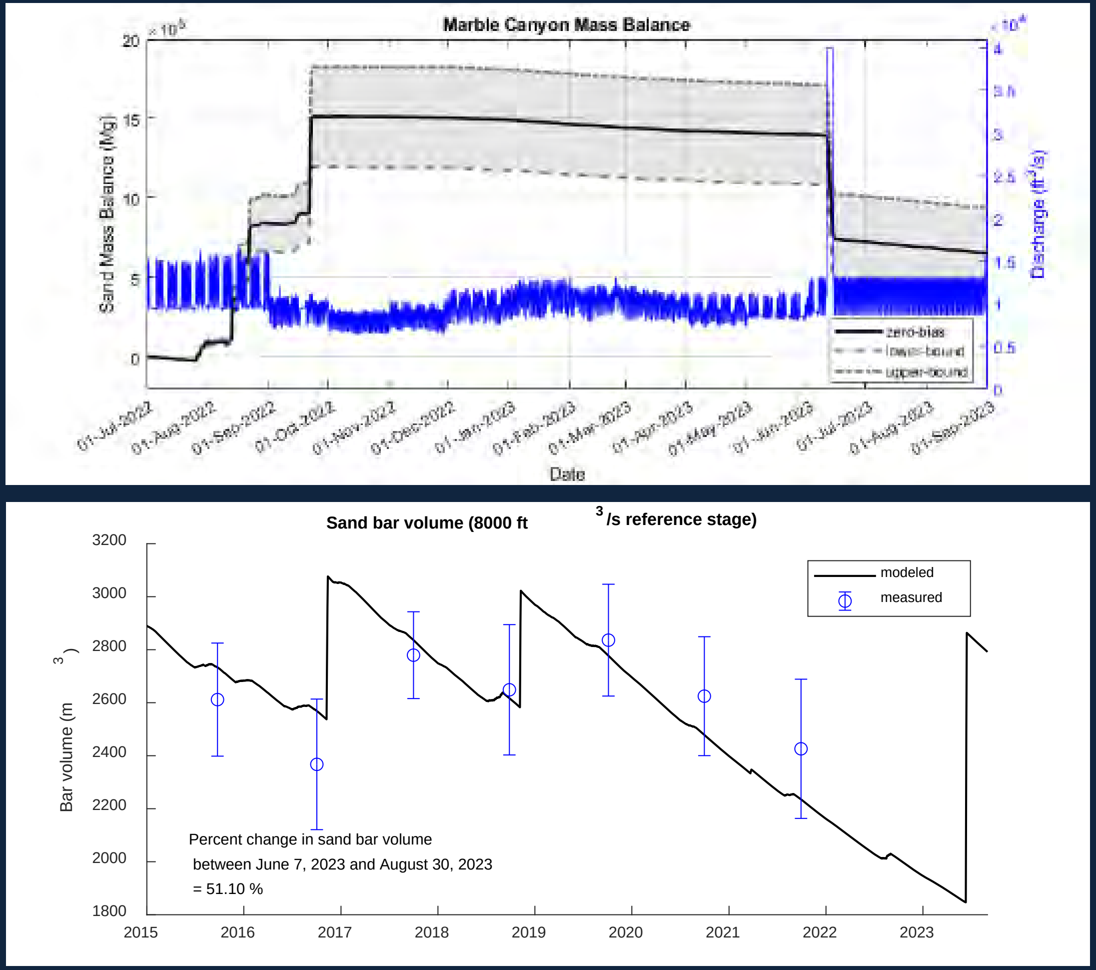


Preliminary model results. Do not cite.

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

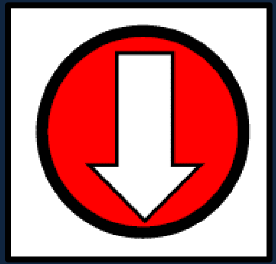


Predicted sand mass balance and sandbar response for small mouth bass control with 72-hr 40,000 ft^3/s flow spike.

Preliminary model results. Do not cite.

USGS

Project A & 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 sandbars 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).
- Current Status:
  - 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 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.

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

- HFEs functioned to rebuild sandbars when implemented
- Sandbars have eroded since implementation of last HFE in 2018
- 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.

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/