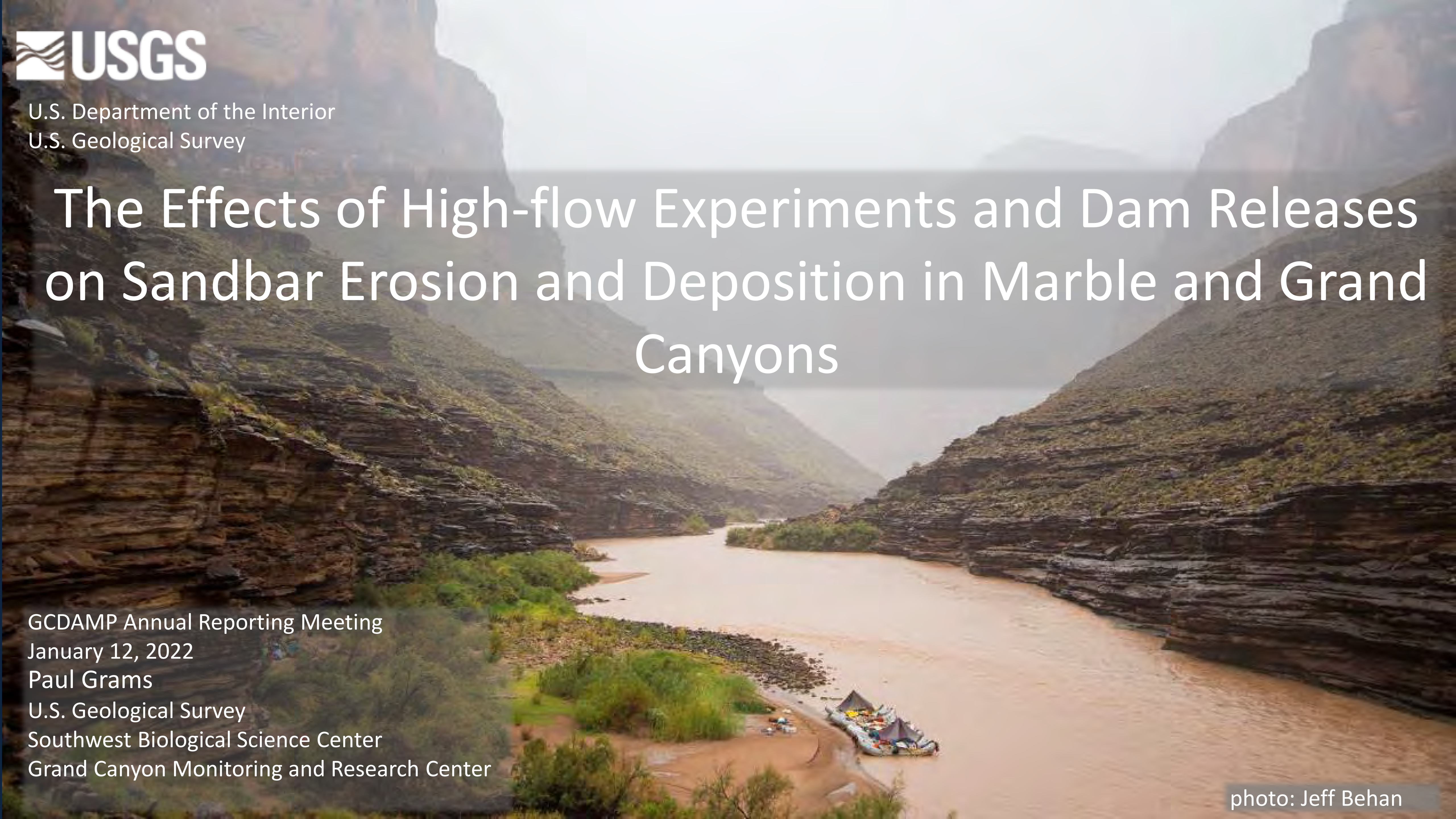

U.S. Department of the Interior
U.S. Geological Survey

The Effects of High-flow Experiments and Dam Releases on Sandbar Erosion and Deposition in Marble and Grand Canyons

GCDAMP Annual Reporting Meeting
January 12, 2022

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

photo: Jeff Behan

Acknowledgements

Project B personnel:

Matt Kaplinski, Joseph Hazel, Katie Chapman, Robert Tusso, Keith Kohl, Thomas Gushue, James Hensleigh, Shanon Sartain, and Caitlin Andrews

Collaborators and field assistants:

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photo: Geoff Gourley

photo: Jeff Behan

photo: Geoff Gourley

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GRAND CANYON RIVER GUIDES

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Moving on…

Joe Hazel retired in June 2021 after 30+ years at Northern Arizona University and as a cooperator with Reclamation and USGS on sandbar and sediment-related projects in Grand Canyon

joseph.hazel@nau.edu

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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 FY2021 Funding: $865,635
- Cooperators: Northern Arizona University, Grand Canyon River Guides, Southern Utah University

Project B: Publications (2021)

- Alvarez, L.V., and Grams, P.E., 2021, An eddy-resolving numerical model to study turbulent flow, sediment, and bed evolution using detached eddy simulation in a lateral separation zone at the field-scale: Journal of Geophysical Research: Earth Surface, v. 126, no. 10, e2021JF006149, https://doi.org/10.1029/2021JF006149.
- Durning, L.E., Sankey, J.B., Yackulic, C.B., Grams, P.E., Butterfield, B.J. and Sankey, T.T, 2021, Hydrologic and geomorphic effects on riparian plant species occurrence and encroachment—Remote sensing of 360 km of the Colorado River in Grand Canyon: Ecohydrology, e2344, https://doi.org/10.1002/eco.2344.
- 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.
- Sabol, T.A., Griffiths, R.E., Topping, D.J., Mueller, E.R., Tusso, R.B., and Hazel, J.E., Jr., 2021, Strandlines from large floods on the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey Scientific Investigations Report 2021-5048, 41 p., https://doi.org/10.3133/sir20215048.
- Unema, J.A., Topping, D.J., Kohl, K.A., Pillow, M.J., and Caster, J.J., 2021, Historical floods and geomorphic change in the lower Little Colorado River during the late 19th to early 21st centuries: U.S. Geological Survey Scientific Investigations Report 2021–5049, 34 p., https://doi.org/10.3133/sir20215049

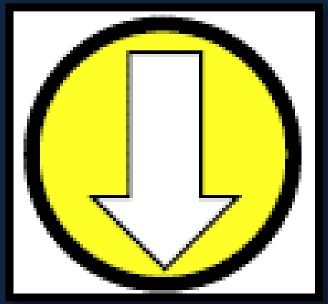
Data and web applications

- Grams, P.E., Alvarez, L., Kaplinski, M., and Wright, S., 2021, Repeat measurements of bathymetry, streamflow velocity and sediment concentration made during a high flow experiment on the Colorado River in Grand Canyon, March 2008: U.S. Geological Survey data release, https://doi.org/10.5066/P9O00Z44
- Grams, P.E., Hazel, J.E., Jr., Kaplinski, M., Ross, R.P., Hamill, D., Hensleigh, J., and Gushue, T., 2020, Long-term sandbar monitoring data along the Colorado River in Marble and Grand Canyons, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/P93F8JJK
- Sabol, T.A., Griffiths, R.E., Topping, D.J., Mueller, E.R., Tusso, R.B., and Hazel, Jr., J.E., 2021, Surveyed peak-stage elevations, coordinates, and indicator data of strandlines from large floods on the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey data release, https://doi.org/10.5066/P9GIQ9ZN

- 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/

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 (2012-2020).
- 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) prevented HFE implementation for 3 consecutive years.



Status: moderate concern because sandbars are decreasing, but still larger than before start of HFE protocol and sediment supply is good

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

Confidence: high, because the monitoring is robust.

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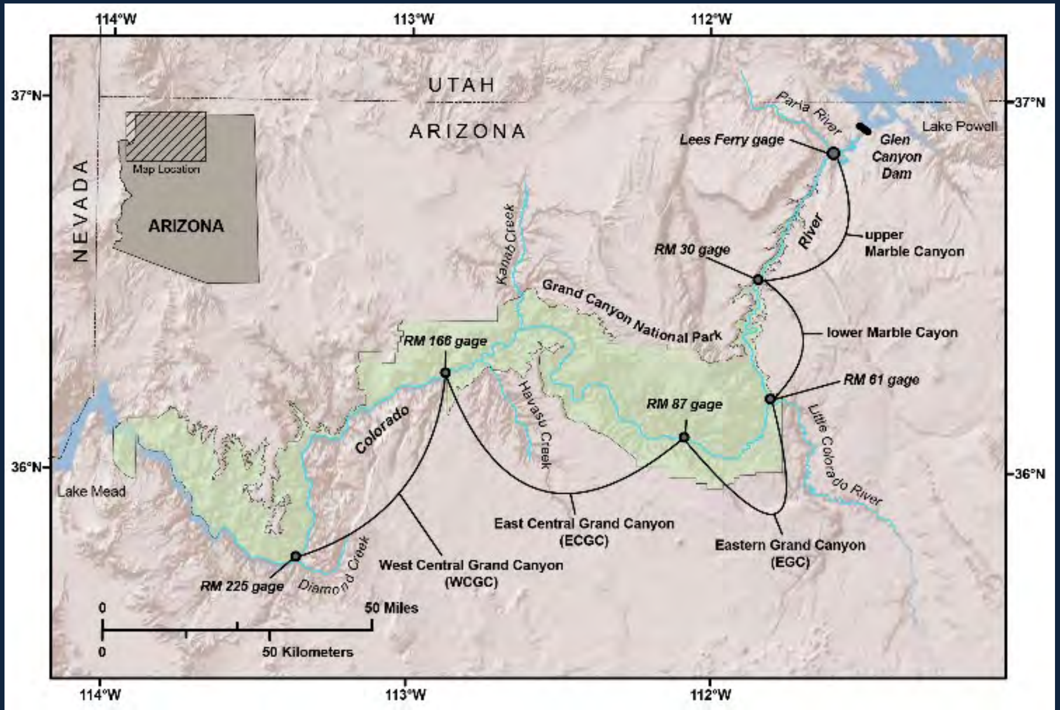
Short update on Project B.2 (Channel Mapping for Sandbar and Sand Storage Change)

- Mapped Lower Marble Canyon and Eastern Grand Canyon (60 river miles) in 2019
- Data processing is complete but final analysis and reporting has been delayed by covid-related staffing issues in 2020 and lots of field work (overflight and SDF) in 2021.
- Will be reporting in future meetings this year or at next ARM
- These data 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
- *This April we will conduct 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*

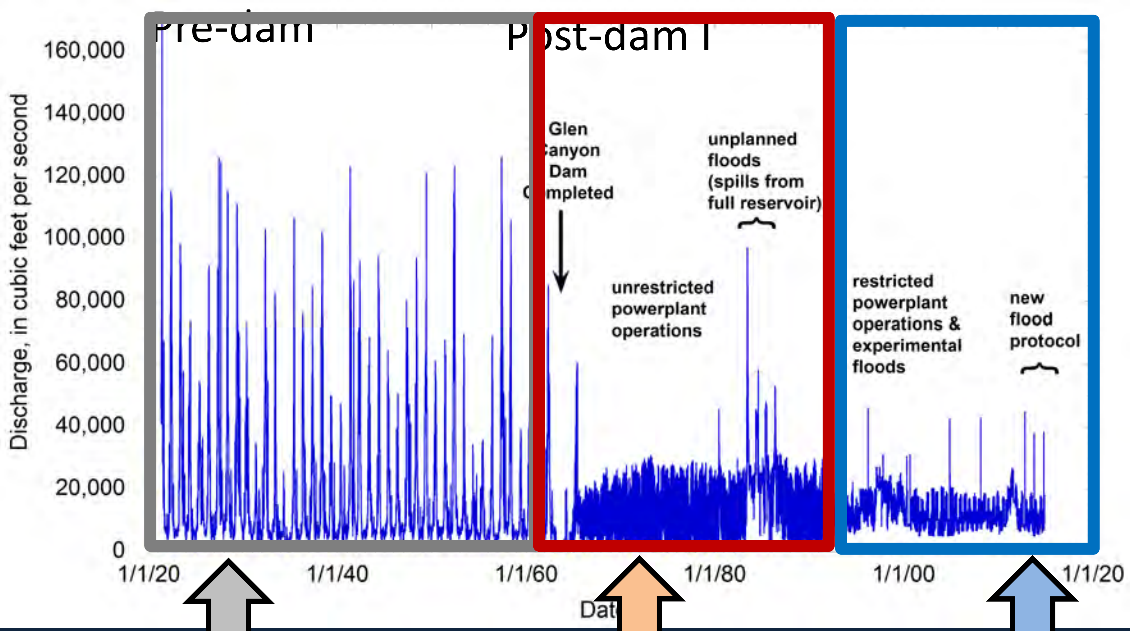


Segment (river miles)	Completed Maps
Glen Canyon (-15 to 0)	2014
Upper Marble Canyon (0 to 30)	2013, 2016
Lower Marble Canyon (30 to 61)	2009, 2012, 2019
Eastern Grand Canyon (61 to 87)	2011, 2014, 2019
East Central Grand Canyon (87 to 166)	2022
West Central Grand Canyon (166 to 225)	2017
Western Grand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

* A 2-mile study reach has been mapped for project O.2. There are no current plans to map the rest of the reach.

Pre-dam flows, dam operations, high flows, and sandbars

Three major periods of flows and dam operations



HFE-related Science and Management Questions:

- With frequent HFEs, will sandbars increase in size and abundance?
- Will frequent HFEs cause sand supply in channel to decrease and exacerbate sediment deficit?

Pre-dam:

- Annual floods
- Abundant sand supply
- Large sandbars

Post-dam I:

- Daily small floods
- Limited sand supply
- Eroding sandbars
- Unplanned floods (spills)

Post-dam II:

- Restricted hydropower operations
- **High Flow Experiments (HFEs)**
  - triggered by sand supply from Paria River

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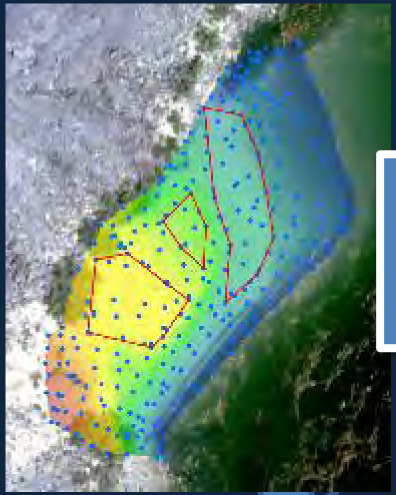
Sandbar monitoring data

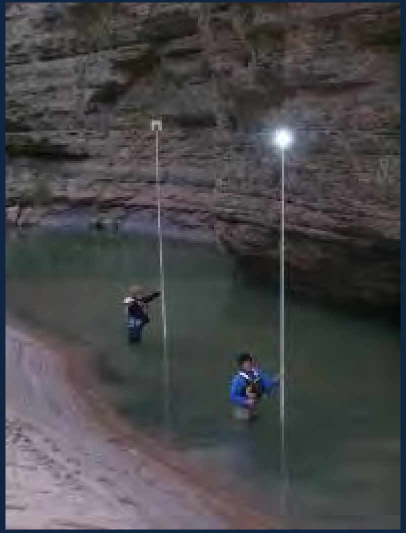


21st century data processing and analysis

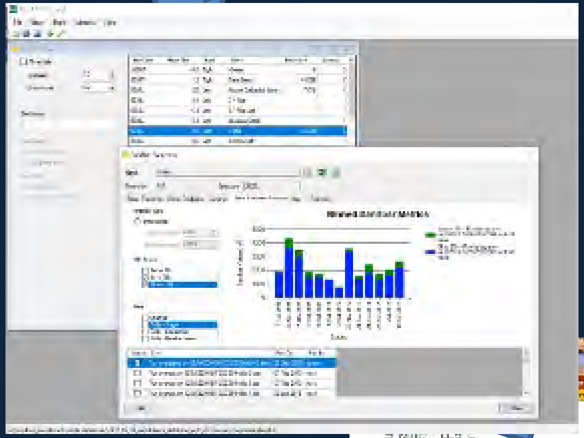
Topographic surfaces modeled in survey software

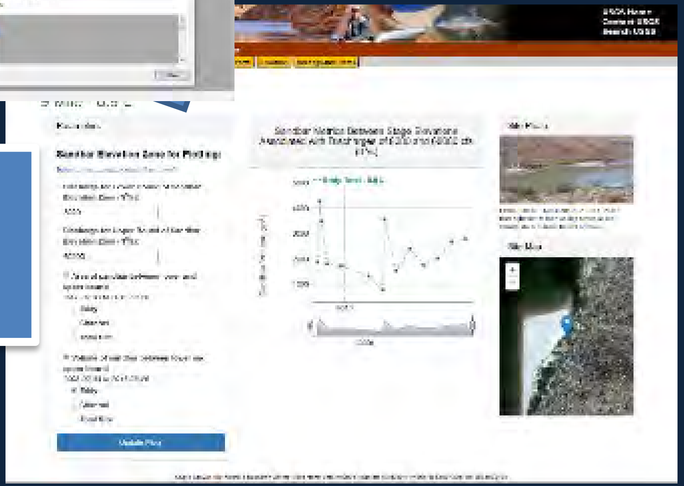
Data collection: old school total station and survey rod

Allows data collection down to 8,000 cfs stage and in dense vegetation. Neither of which can be done reliably with modern methods (lidar etc.)



Data processed and analyzed in sql database

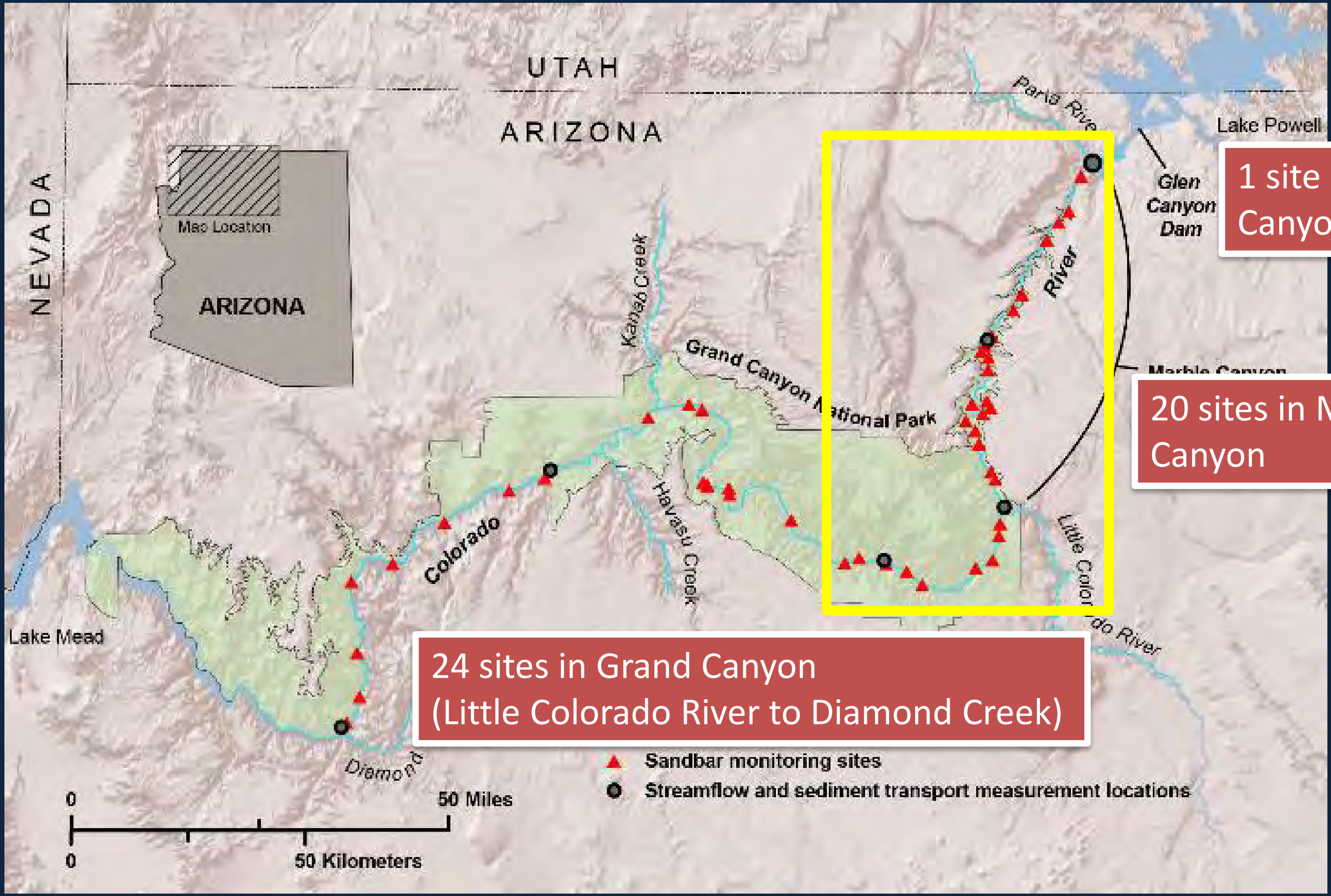




Data served in sandbar web application

www.gcmrc.gov/sandbar OR www.usgs.gov/apps/sandbar

Sandbar monitoring study sites



Monitoring Data

- 45 sites currently monitored
- 32 monitored since 1990
- Data collected annually in October
- 42 of the sites instrumented with remote cameras

*Only reporting on first 28 sites (RM 0 to 93) today.

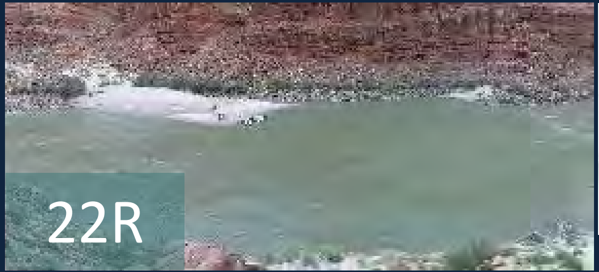
Sandbar monitoring site types

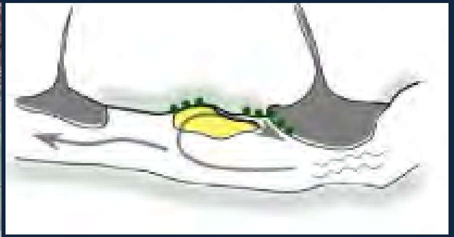
Reattachment Bars

Increasing vegetation

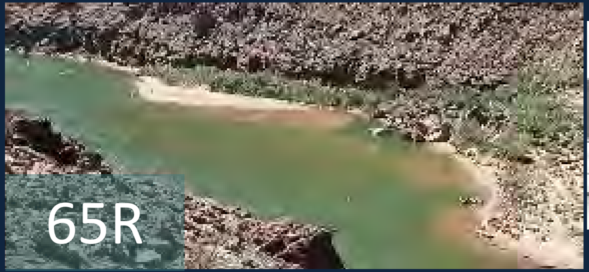
Increasing channel width

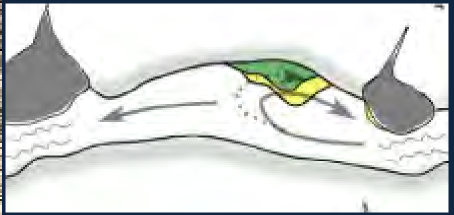
Narrow Reattachment bars





Medium Reattachment bars

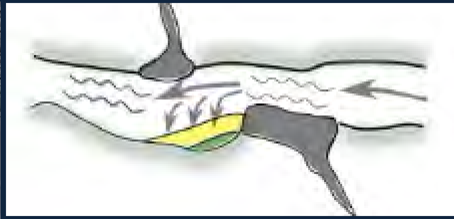




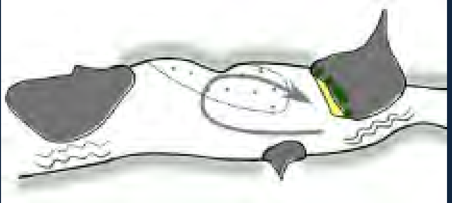
Wide Reattachment bars

Other Bar Types

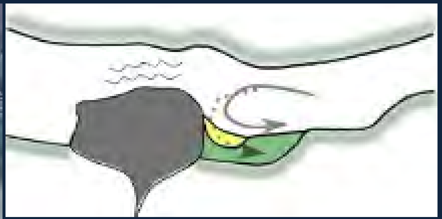
Undifferentiated bars



Separation bars



Upper pool deposits



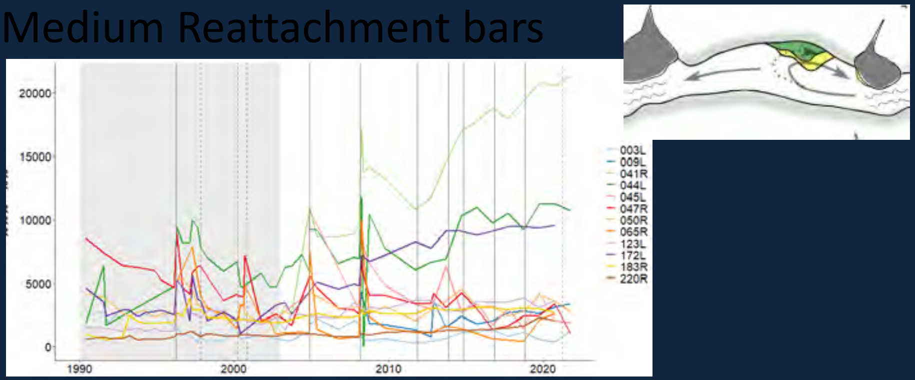
Mueller and others (2018)

USGS

Sandbar monitoring results: Sites between RM 0 and RM 93*

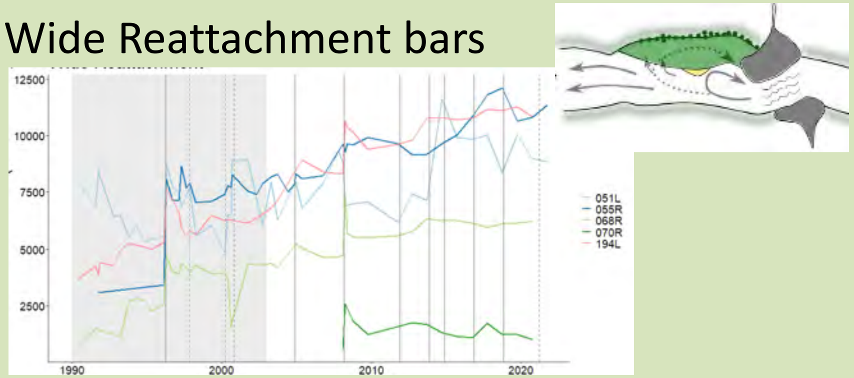
Narrow Reattachment bars

Medium Reattachment bars

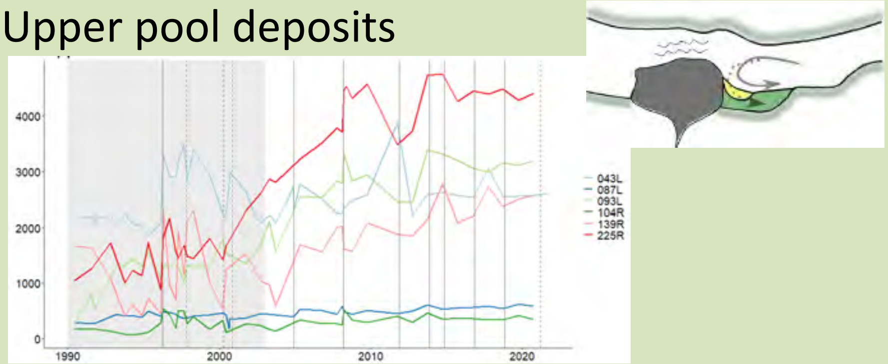


- Most response to HFEs.
- Moderate vegetation expansion.
- Common campsites.
- Net decrease 2020 to 2021

Wide Reattachment bars

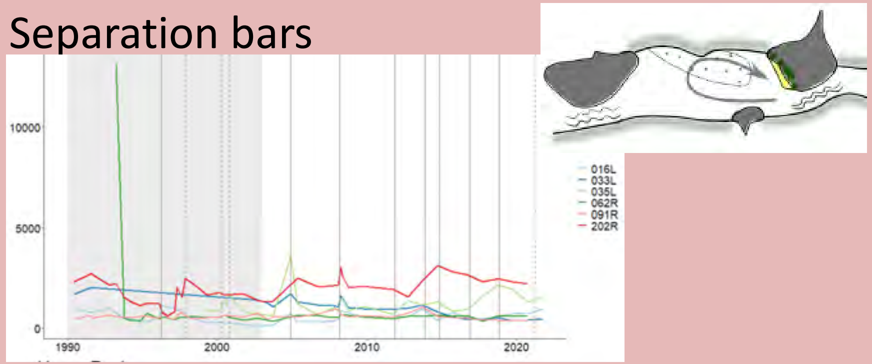


Upper pool deposits

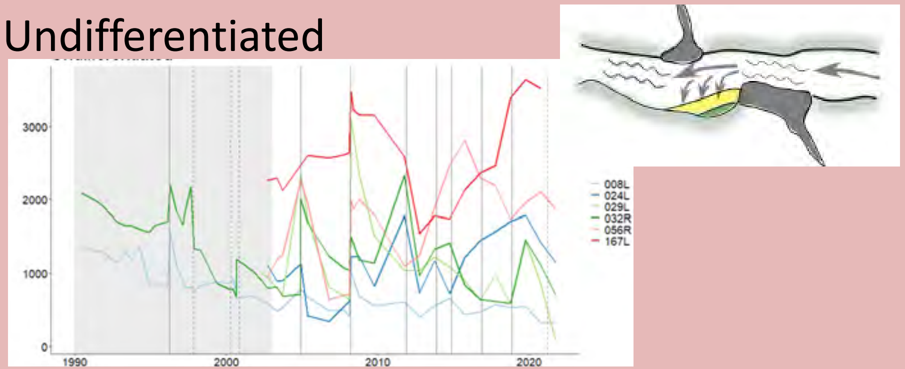


- Least responsive to HFEs.
- Heavy vegetation expansion.
- Less common campsites.
- Net increase 2020 to 2021.

Separation bars



Undifferentiated



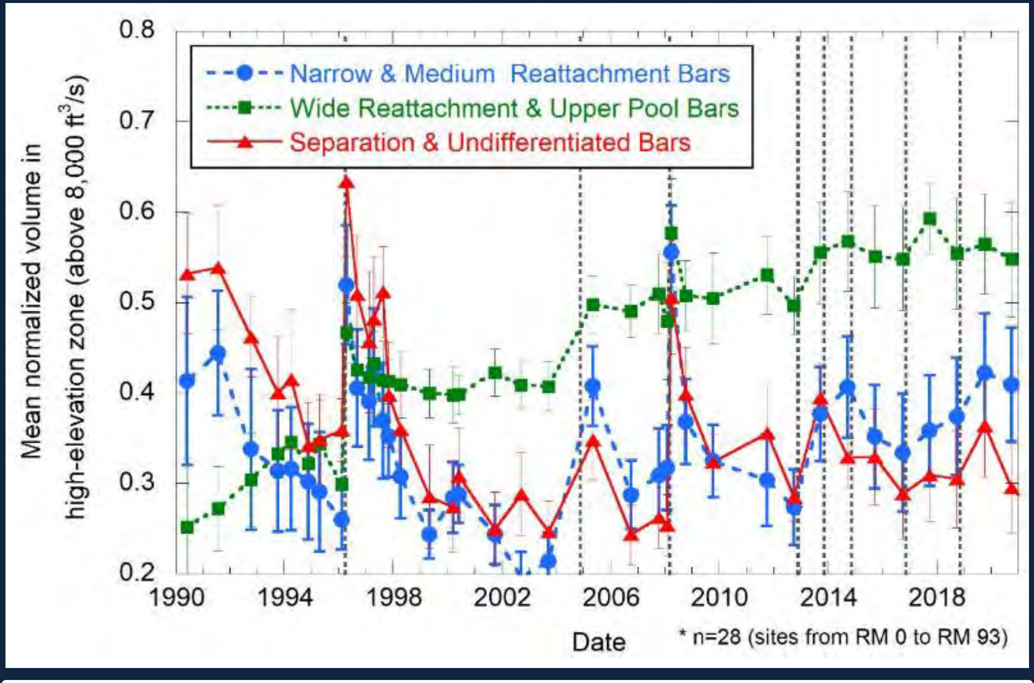
- Variable response to HFEs.
- Moderate vegetation expansion.
- Common campsites.
- Net decrease 2020 to 2021.

*2021 data processed for 28 out of 44 sites

Preliminary results, subject to review, do not cite

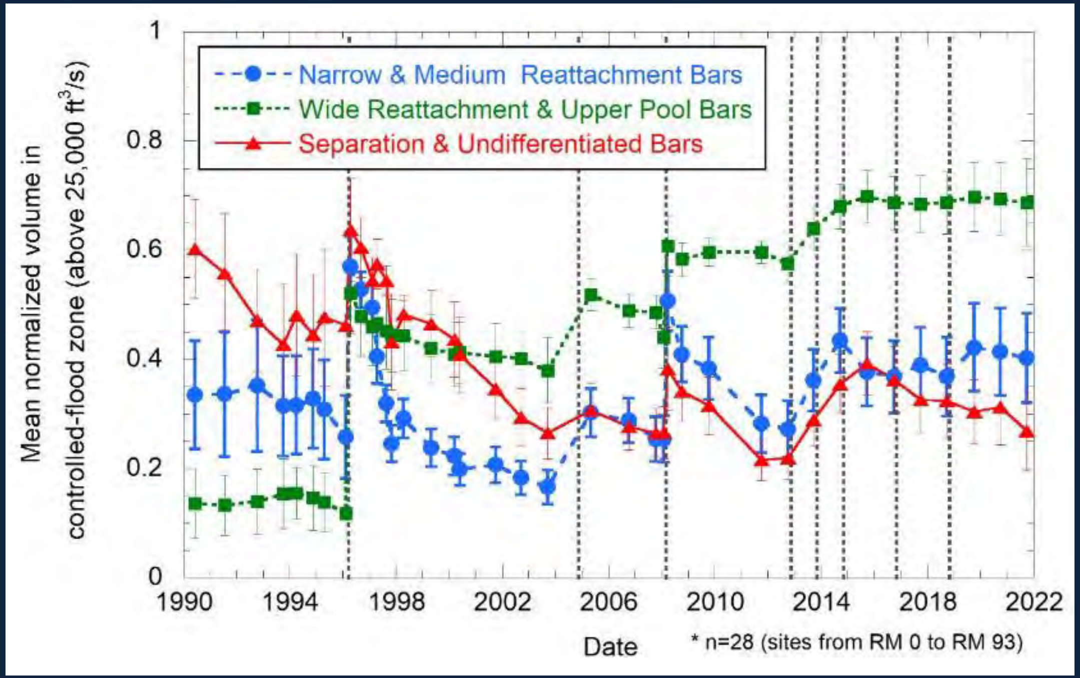
Sandbar monitoring results by bar type: 1990 to 2021

All sand above 8,000 ft³/s stage (includes fluctuating zone intermittently available for camping)



- 2020 to 2021 decrease in all types.
- Largest decrease in Separation and Undifferentiated bars.

Only sand above 25,000 ft³/s stage (always usable for camping)



- 2020 to 2021 decrease Narrow & Medium Reattachment bars and in Separation and Undifferentiated bars.

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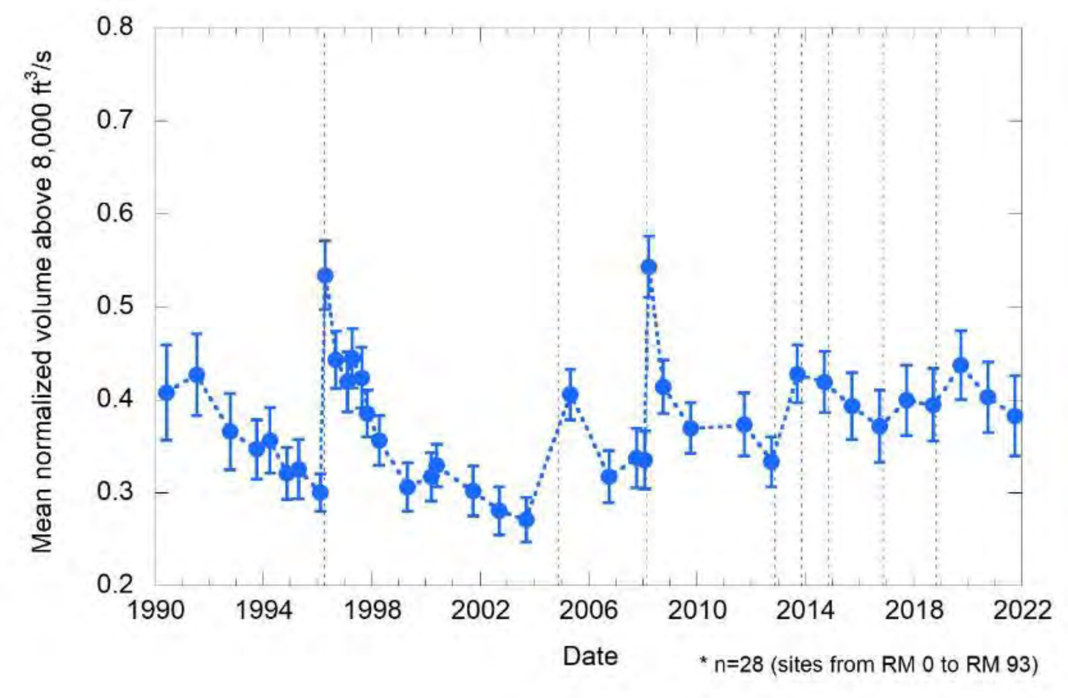
Preliminary results, subject to review, do not cite

USGS

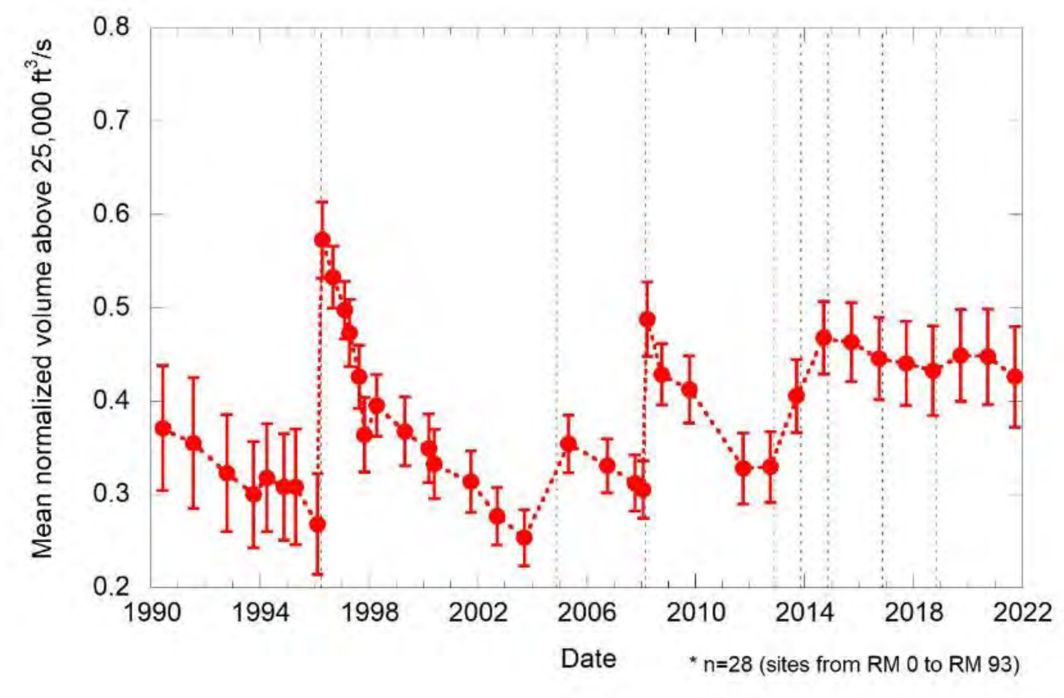
Sandbar monitoring results averaged among all bar types: 1990-2021

All sand above 8,000 ft^3/s stage (includes fluctuating zone intermittently available for camping)



- Deposition from HFEs erodes within 1 to 2 years.
- Upward trend during HFE protocol.
- Downward trend since 2019 (last HFE).

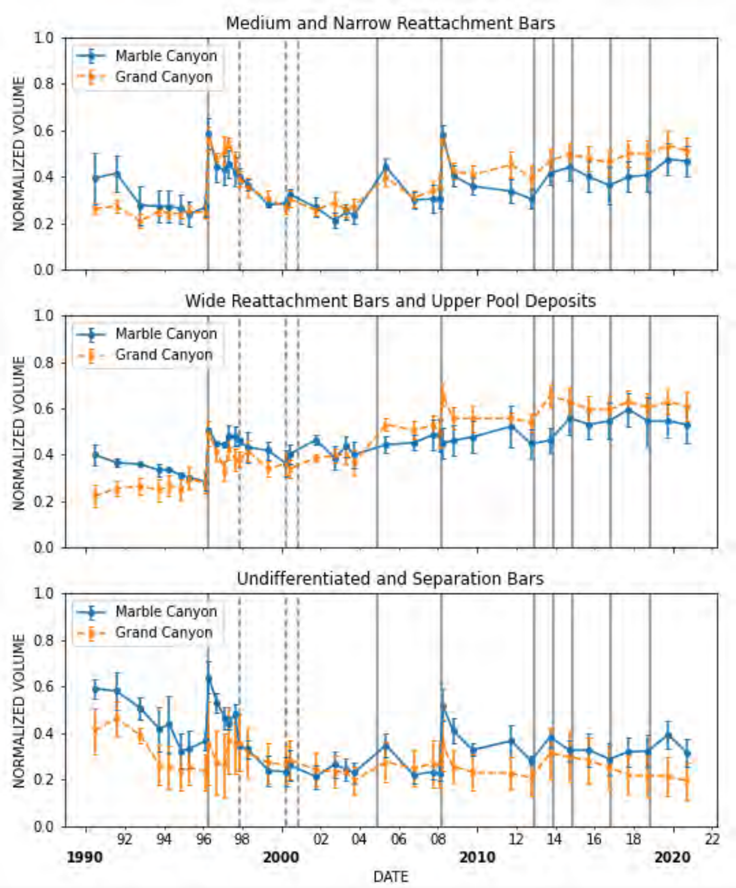
Only sand above 25,000 ft^3/s stage (always usable for camping)



- Deposition from HFEs more persistent.
- Upward trend during HFE protocol.
- Smaller downward trend since 2020.

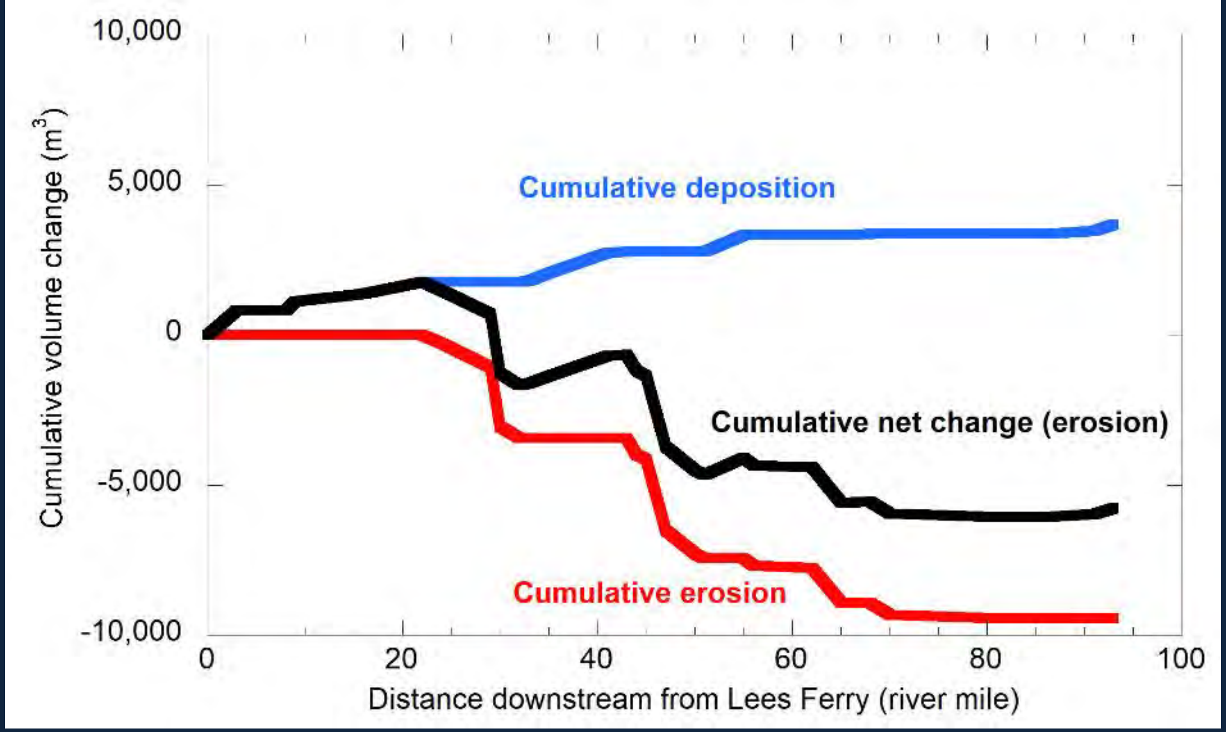
Sandbar changes: Marble Canyon vs. Grand Canyon

1990 to 2020



- Trends in Marble Canyon and Grand Canyon are similar for each bar type
- Differences between bar types greater than differences between Marble Canyon and Grand Canyon

2020 to 2021



- Deposition in Upper Marble Canyon (RM 0 to RM 30)
- Mostly erosion downstream from RM 30

Preliminary results, subject to review, do not cite

USGS

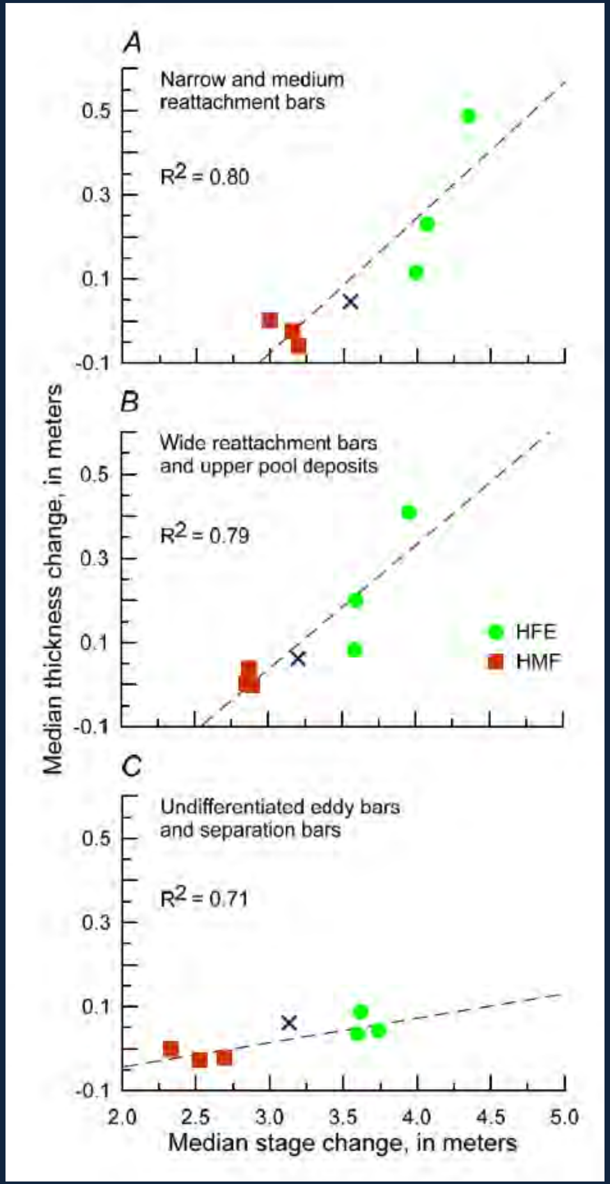
Sandbar response to HFE magnitude

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.

Prediction for 2021 Spring Disturbance Flow: Not much deposition (will cover in afternoon panel discussion)

Thickness of sandbar deposits positively correlated with flow magnitude



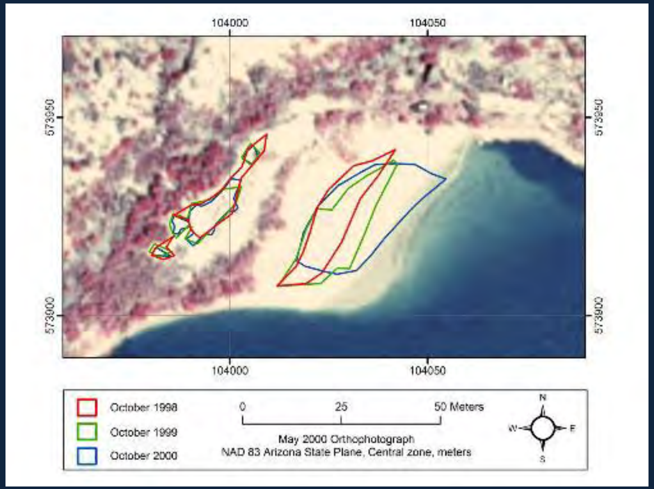
HFE is >40,000 cfs
HMF is ~30,000 cfs

Hazel and others (in press), subject to review, do not cite

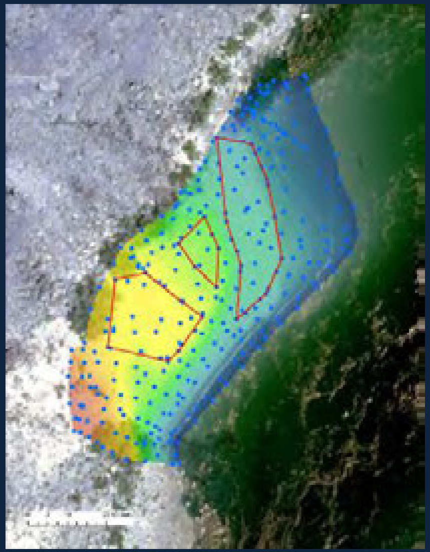
Measurement of campsite area

- Define campsite areas by field survey to create polygons of campsites
- **Campsite Area** = a smooth substrate (sand) with no more than eight degrees of slope with little or no vegetation
- Intersect with topography to compute area for multiple elevation bins

Field survey



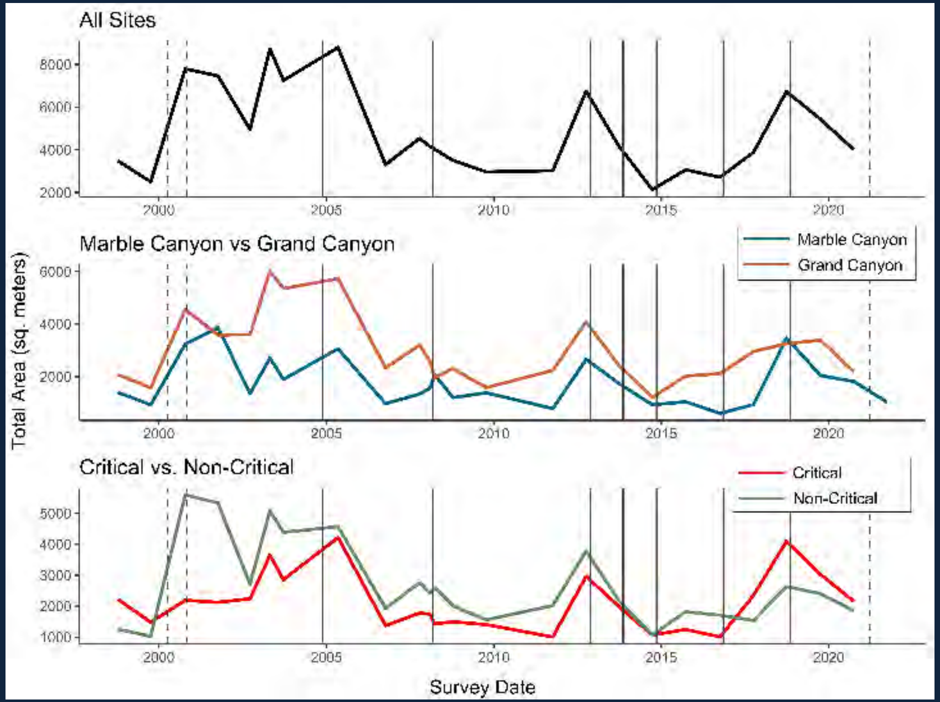
Campsite polygons (multiple years shown)



Campsite polygons intersected with topography

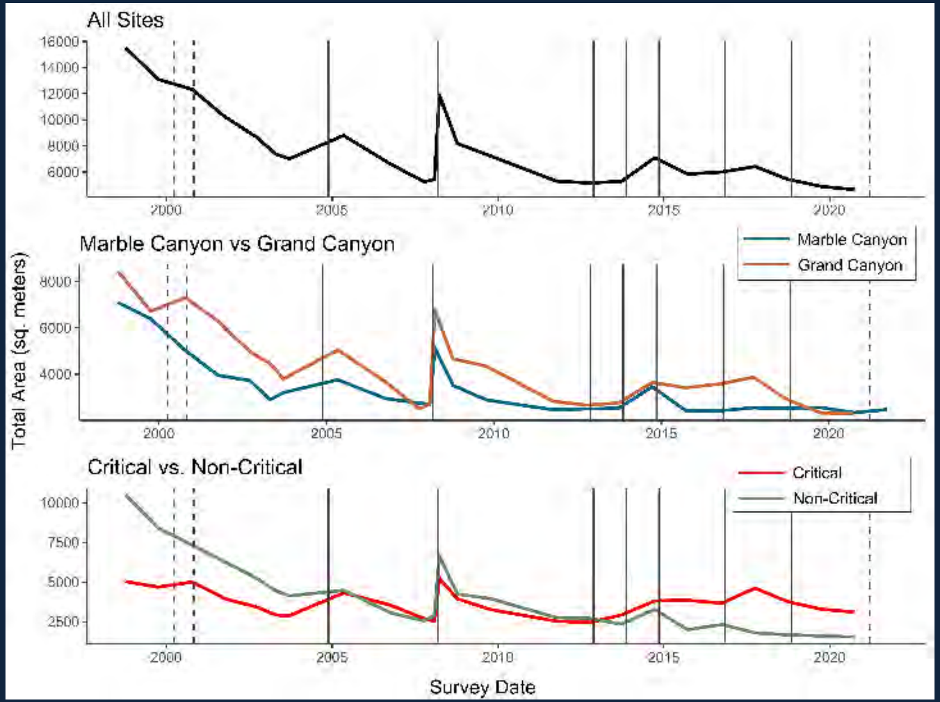
Campsite area in Marble and Grand Canyons

Camp area between 15,000 and 25,000 ft³/s stage



*Only have 2021 data for sites in Marble Canyon

Camp area above 25,000 ft³/s stage



*Only have 2021 data for sites in Marble Canyon

- Low-elevation camp area most responsive to HFEs
- Decreased since last HFE in 2018
- Decrease has continued in Marble Canyon

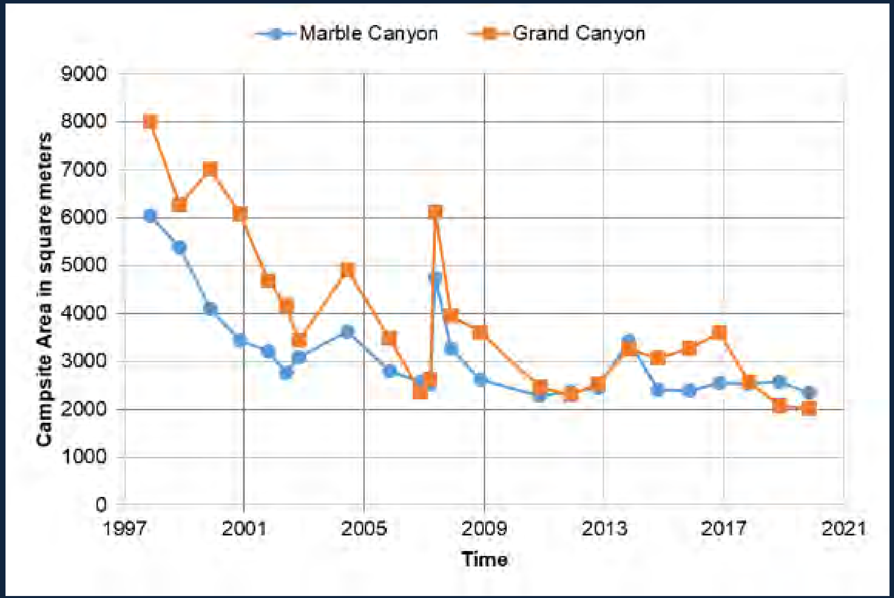
- High-elevation camp area increased following some HFEs
- Surveys are ~11 months following HFEs, so
- vegetation encroachment
- Decrease has continued in Marble Canyon

Preliminary results, subject to review, do not cite

Vegetation expansion impact on campsites

Major vegetation expansion at wide reattachment bars in late 1990's and early 2000's (Hadley and others, 2018)

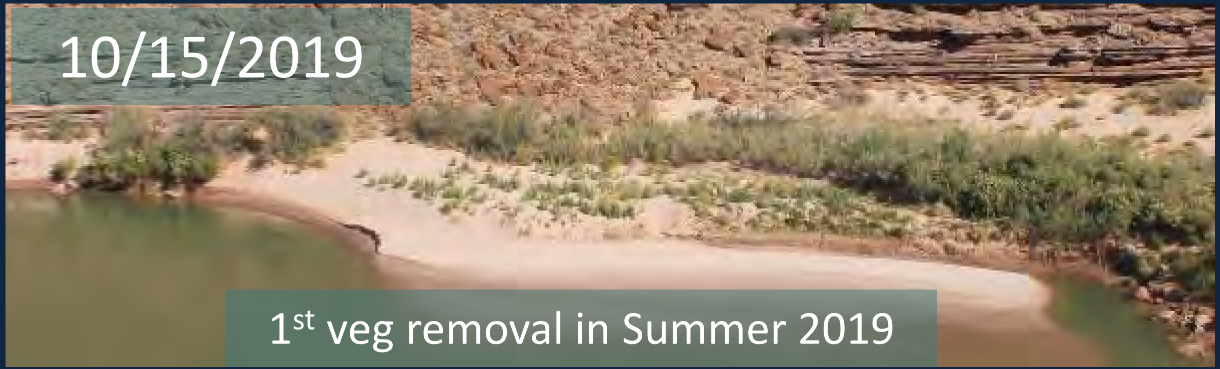
Vegetation expansion continues to occur at many sites

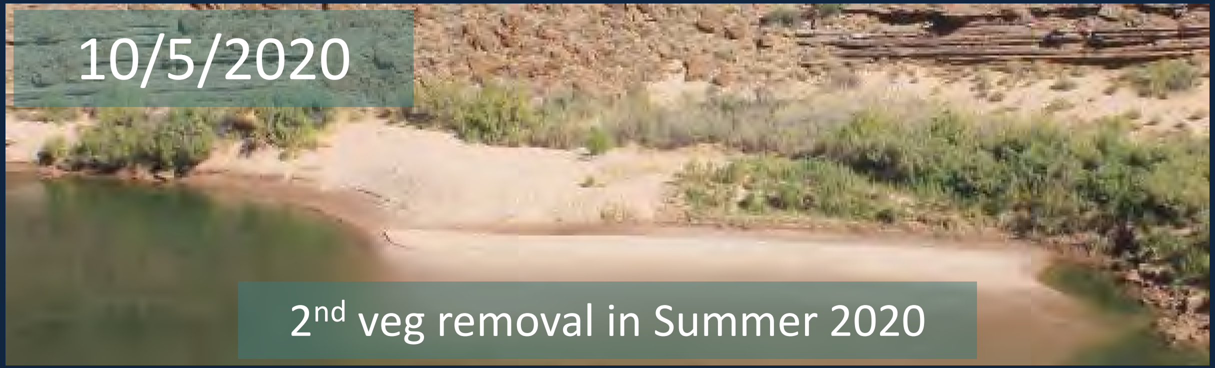


Preliminary results, subject to review, do not cite

USGS

HFE's and vegetation treatment





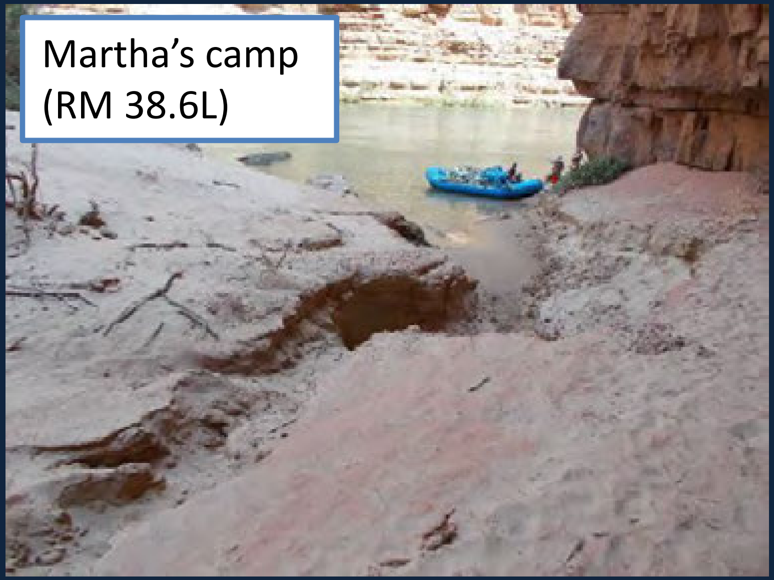
- NPS is conducting vegetation treatment at 3 long-term sandbar monitoring sites
- We'll monitor to see if treatment effects response to future HFEs

Summer 2021 monsoon rains impact on campsites

Tatahatso camp destroyed by hillslope runoff during monsoon rains

Summer 2021 monsoon rains impact on campsites

Tatahatso camp
(RM 37.9L)



Martha's camp
(RM 38.6L)

Upper Blacktail camp
(RM 120R)

Talking Heads camp
(RM 133.6L)

Matcat Hotel camp
(RM 149L)

National Canyon camp
(RM 167L)

Sandbar model

Developed by former postdoc Erich Mueller.

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

Erich R. Mueller[1] and Paul E. Grams[2]

Geophysical Research Letters

Models changes in sandbar volume based on:

Suspended sand flux into eddy:

$q_{s,in} = \lambda V_e C_s$ *Mass/time*

Deposition rate in eddy:

$S_d = w_s C_e$ *Mass/area*

Mass balance in eddy:

$\lambda V_e C_s = \lambda V_e C_o + w_s C_e A_e$

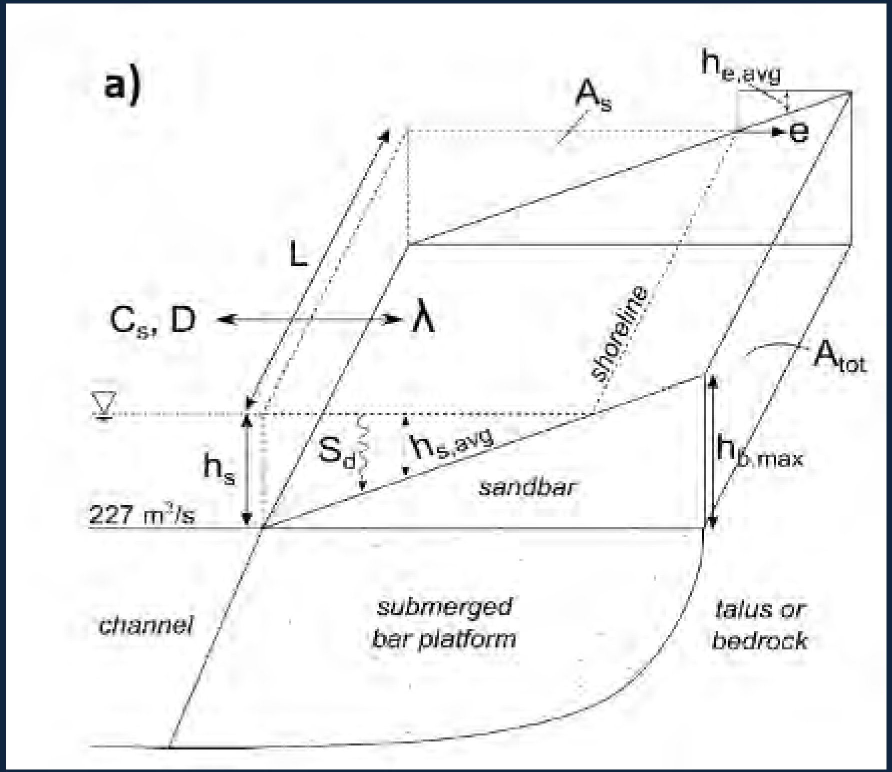
Total flux in = flux out + deposition

Erosion:

$\frac{dV}{dt} = -kV$ *where k is rate parameter (1/s)*

Exponential decay with bar "half-life" of approximately 2 years

λ: Eddy Exchange Coefficient
C_s: Sand Concentration
D: Sand Grain Size
S_d: Sand Deposition Rate (function of settling velocity, w_s)
→**e**: Erosion Rate (exponential decay)
L: Bar Dimensions
A: Submerged (*s*) and total (*tot*) area
h: Thickness of submerged (*s*) and exposed (*e*) bar

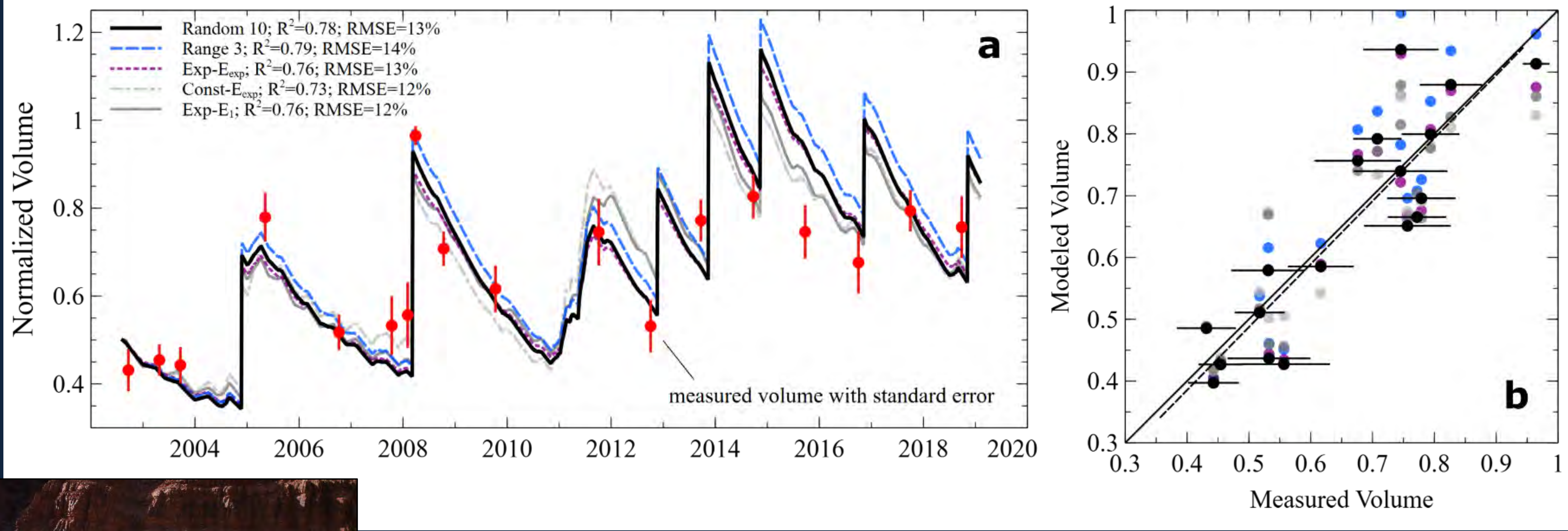


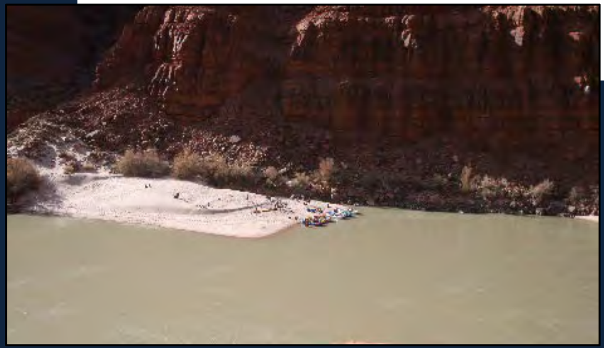
Model Results: 2002-2019

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

Erich R. Mueller[1] and Paul E. Grams[2]

Geophysical Research Letters





The model predicts sandbar response for narrow reattachment bars (the "group 1a" sites of Mueller et al., 2018). It was calibrated using data from 9 narrow reattachment bars located throughout Marble and Grand Canyon. Other sandbar types tend to be less responsive.

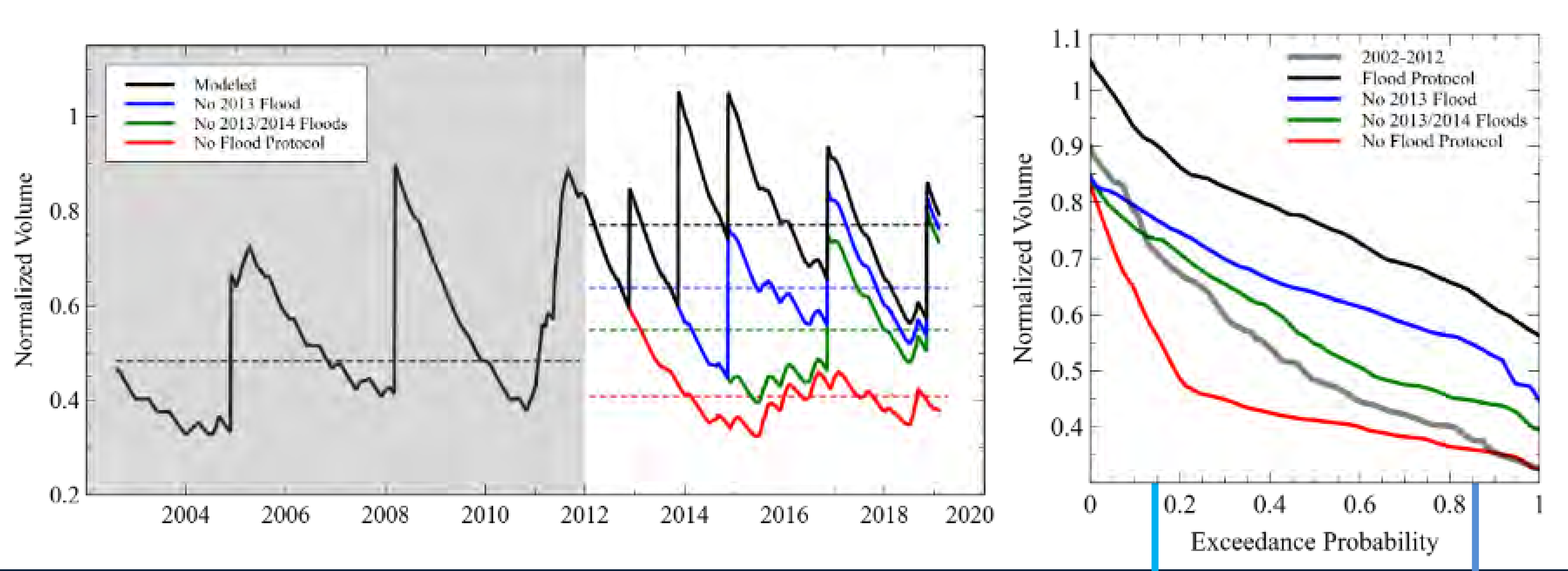
Mueller and Grams, 2021

USGS

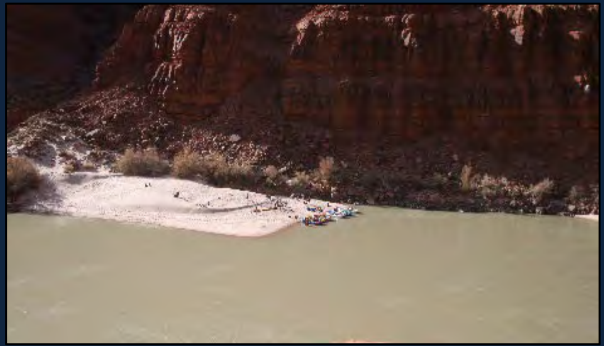
Post-hoc Controlled Flood Scenario Modeling

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.

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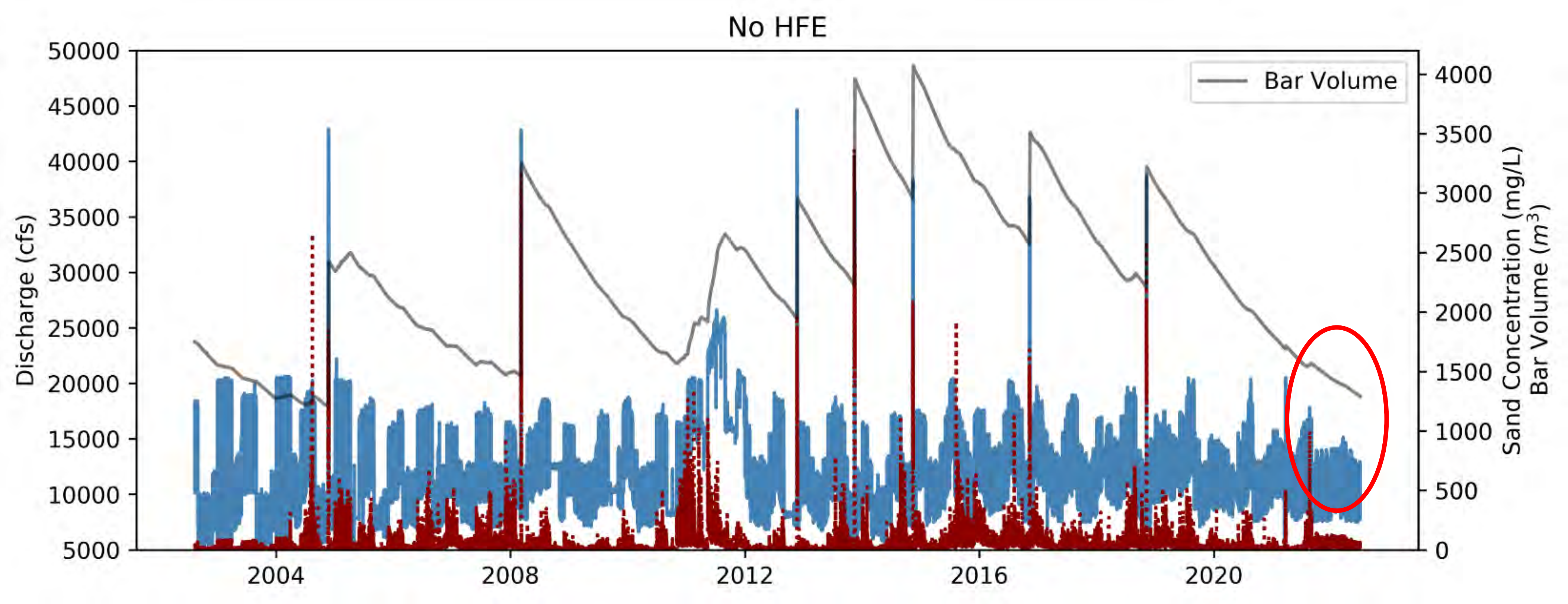
Model predicts that anticipated low release volumes in 2022 lead to continued erosion

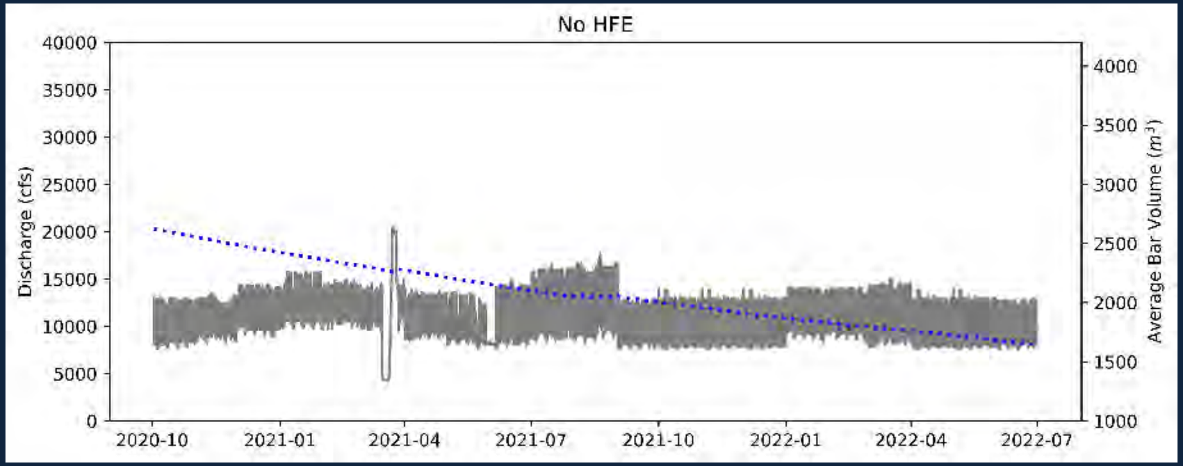


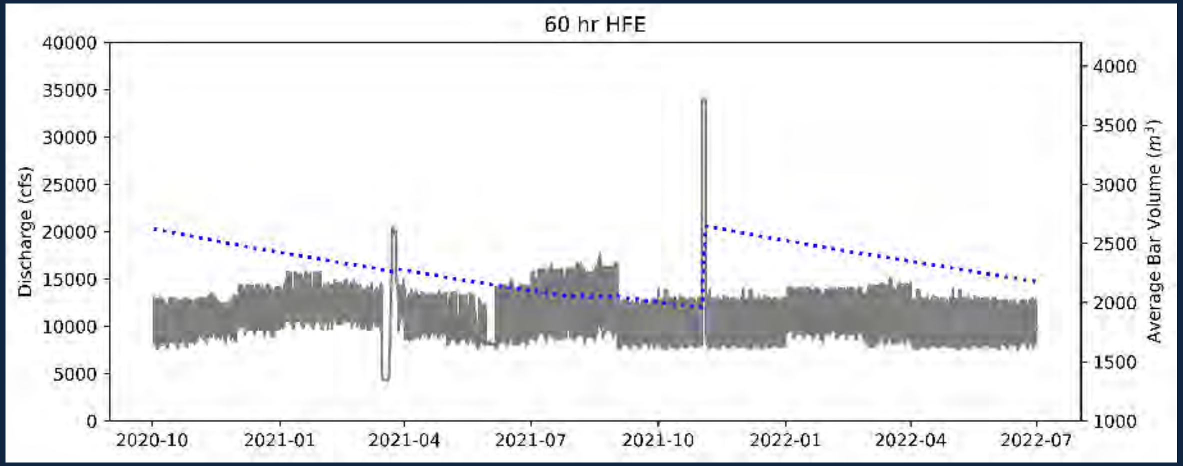
May need to re-parameterize if flows or bar conditions (i.e. vegetation) are considerably different than calibration period

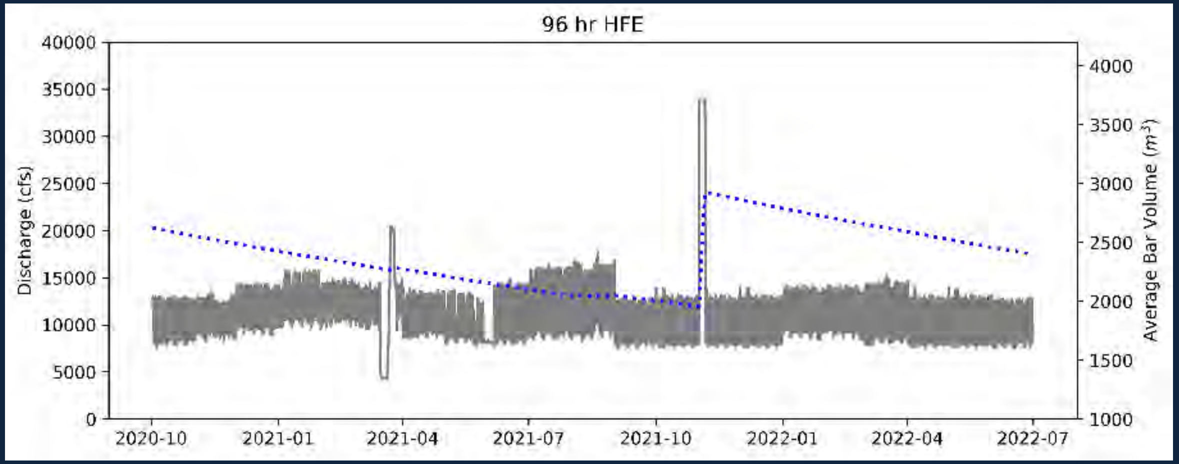
Preliminary results based on Mueller and Grams (2021) model, subject to review, do not cite

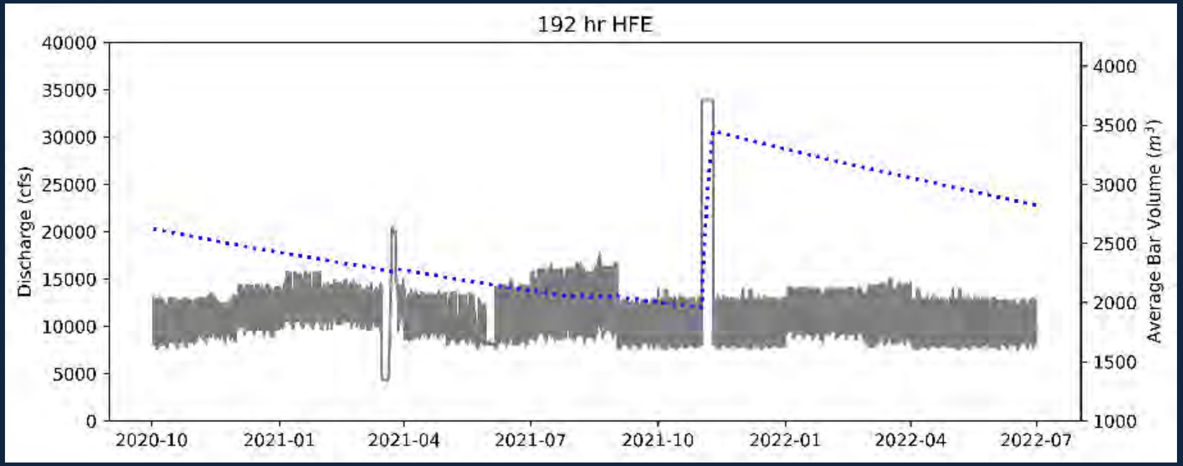
USGS

Sandbar model for HFE scenario testing





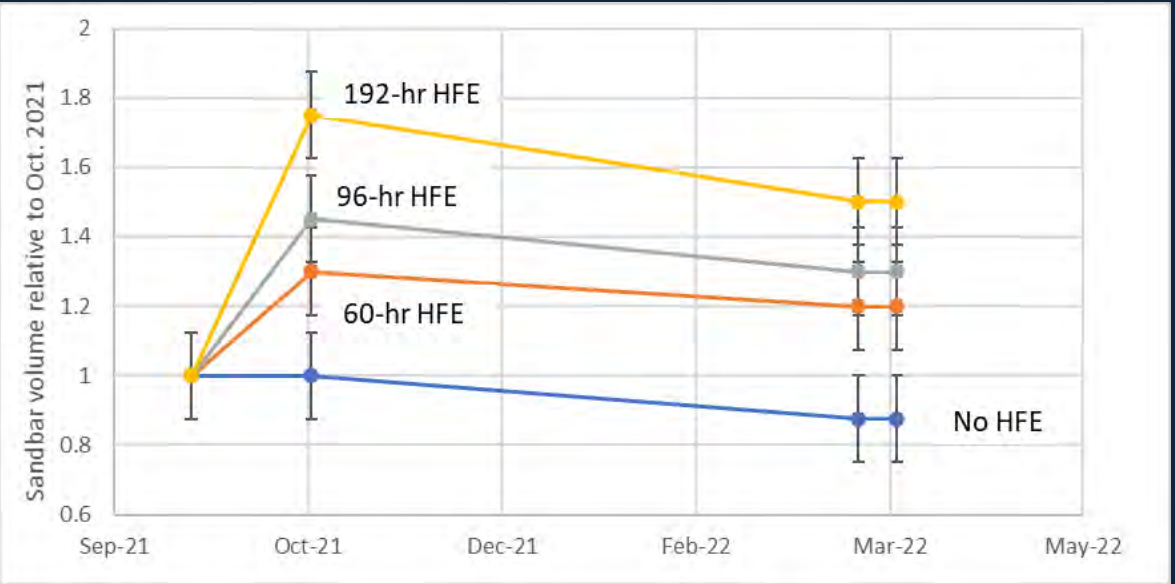




Predict sandbar volume through summer 2022, beginning with observed size in October 2020.

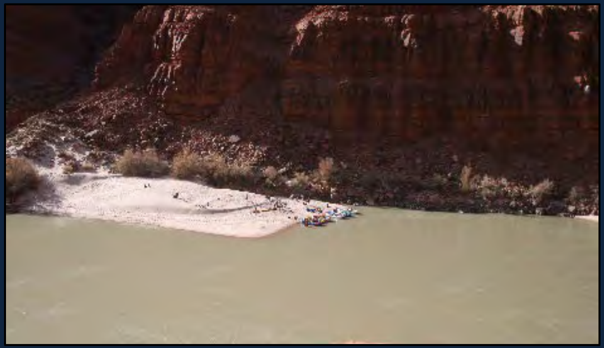
Preliminary results based on Mueller and Grams (2021) model, subject to review, do not cite

Predicted sandbar volume in April 2022 relative to October 2021 for the four HFE scenarios



Event	Expected sandbar size immediately after HFE	Expected sandbar size in April 2022
192-hr HFE	+ 75%	+ 50%
96-hr HFE	+ 45%	+ 30%
60-hr HFE	+ 30%	+ 20%
No HFE	+ 0%	- 10%

- Although 60-hr HFE, is likely to have less benefit than longer duration HFEs, model predicts significant positive response
- The 65-hr HFE in 2018 resulted in bar deposition in all segments of Marble Canyon and Grand Canyon
    - Most bars that increased during longer HFEs also increased during the 2018 HFE



Preliminary results based on Mueller and Grams (2021) model, subject to review, do not cite

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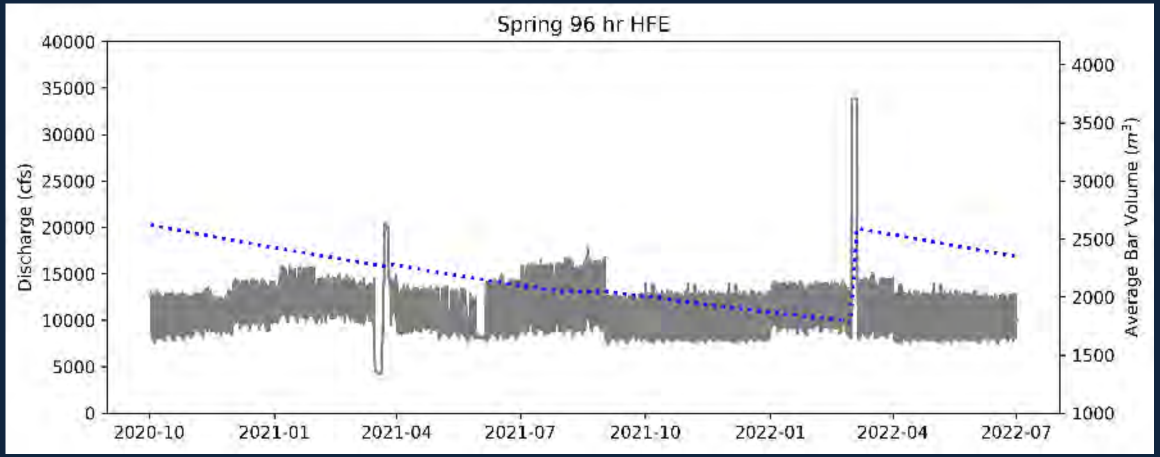
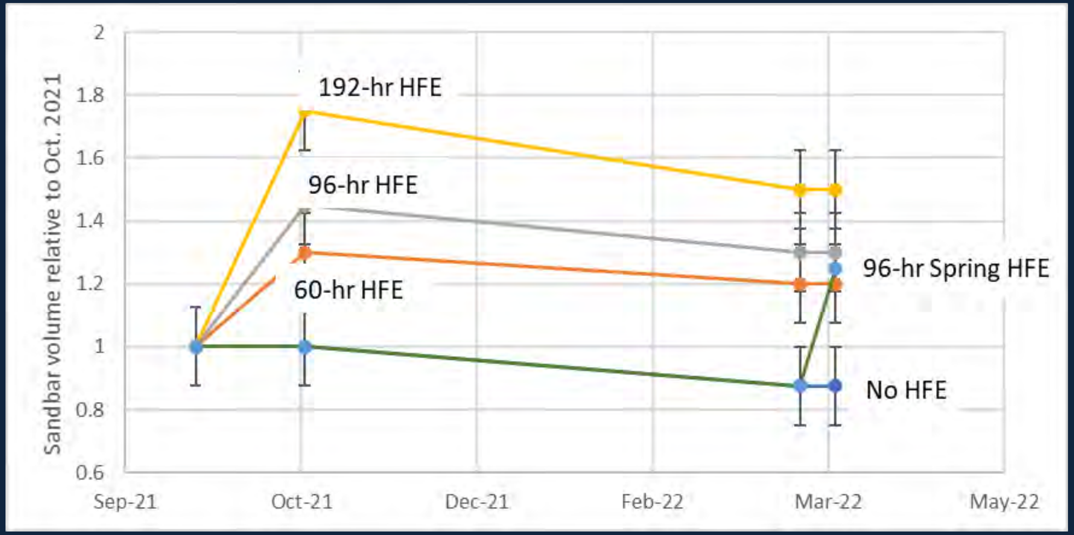
Predicted sandbar volume in April 2022 relative to October 2021 for a spring HFE





Event	Expected sandbar increase from pre- to post-HFE	Expected sandbar size in April 2022 relative to October 2021
192-hr HFE	+ 75%	+ 50%
96-hr HFE	+ 45%	+ 30%
60-hr HFE	+ 30%	+ 20%
No HFE	+ 0%	- 10%
96-hr Spring HFE	+ 38%	+25%

* Modeling based on sediment inputs through mid-September 2021 and anticipated dam releases (model has not been re-run with Oct.-Dec. actual releases)

Preliminary results based on Mueller and Grams (2021) model, subject to review, do not cite

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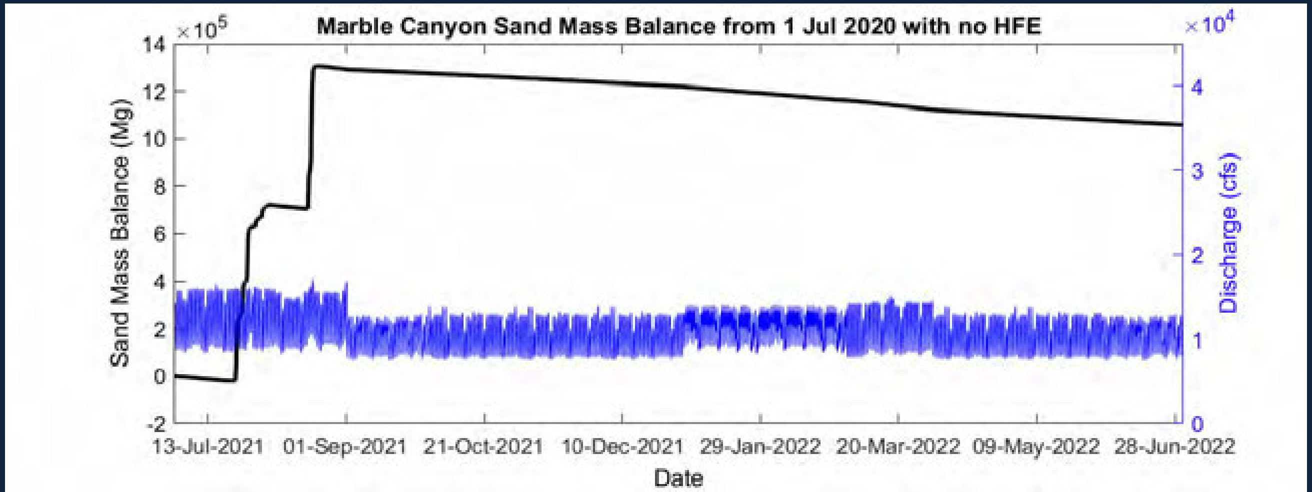
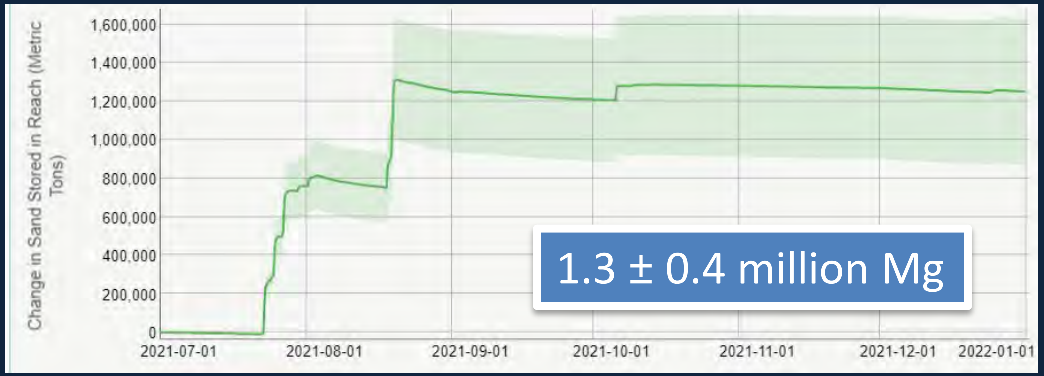
Large 2021 inputs from Paria River combined with relatively low dam releases → Lots of sand remaining in Mable Canyon

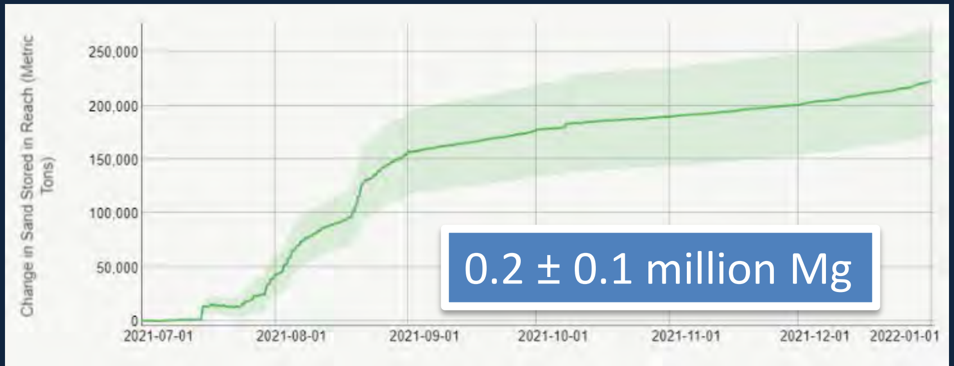


Predicted Mable Canyon (RM 0 to 61) mass balance based on measured inputs through 8/31/2021

- Predicted Marble Canyon mass balance for Jan. 2022 was about 1.2 million Mg
- Observed as of 1/11/2021 is 1.5 ± 0.5 million Mg
- Expect to end sediment year on 6/30/2022 with at least ~1 million Mg positive sand balance in Marble Canyon



Observed Upper Mable Canyon (RM 0 to 30) mass balance



Observed Lower Mable Canyon (RM 30 to 61) mass balance

Preliminary results based on Wright and others (2010) model, subject to review, do not cite

USGS

Summary

- Channel Mapping
  - Expect update in 2022
- Sandbars
  - Increased during HFE protocol
  - Sandbar volume has declined since most recent HFE in 2018
  - Continued vegetation expansion
- Campsites
  - Decreasing in area by vegetation encroachment
- Sandbar model
  - Can be used to interpolate sandbar volume between annual surveys
  - Can be used to predict response to different HFE scenarios
  - Applies to “narrow reattachment bars”
- Sand supply
  - Owing to large sand inputs in 2021 coupled with relatively low reservoir release volumes, the current sand supply in Marble Canyon is large
  - Model predicts substantial sandbar deposition would occur under current sand supply conditions that are predicted to persist through June 2022

RM 122 (narrow reattachment bar)

USGS

References

- Hazel, J. E., Kaplinski, M., Hamill, D., Buscombe, D., Mueller, E.R., Ross, R.P., Kohl, K., and Grams, P.E., ***in press***, Multi-Decadal Sandbar Response to Flow Management Downstream from a Large Dam: the Colorado River in Marble and Grand Canyons, Arizona. U. S. Geol. Surv. Prof. Paper xxxx.
- Mueller, E.R., Grams, P.E., Hazel, J.E., and 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, v. 363, p. 181–199, doi:10.1016/j.sedgeo.2017.11.007.
- 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.
- 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.