The Effects of High-flow Experiments (HFEs) on Sandbar Dynamics

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USGS

photo : Michael Collier

Project Reporting Slides

- 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
- 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 FY2019 Funding: $1,050,430
- Cooperators: Northern Arizona University, University of Wyoming, Utah State University
- Products

Project B: Sandbar and Sediment Storage Monitoring and Research

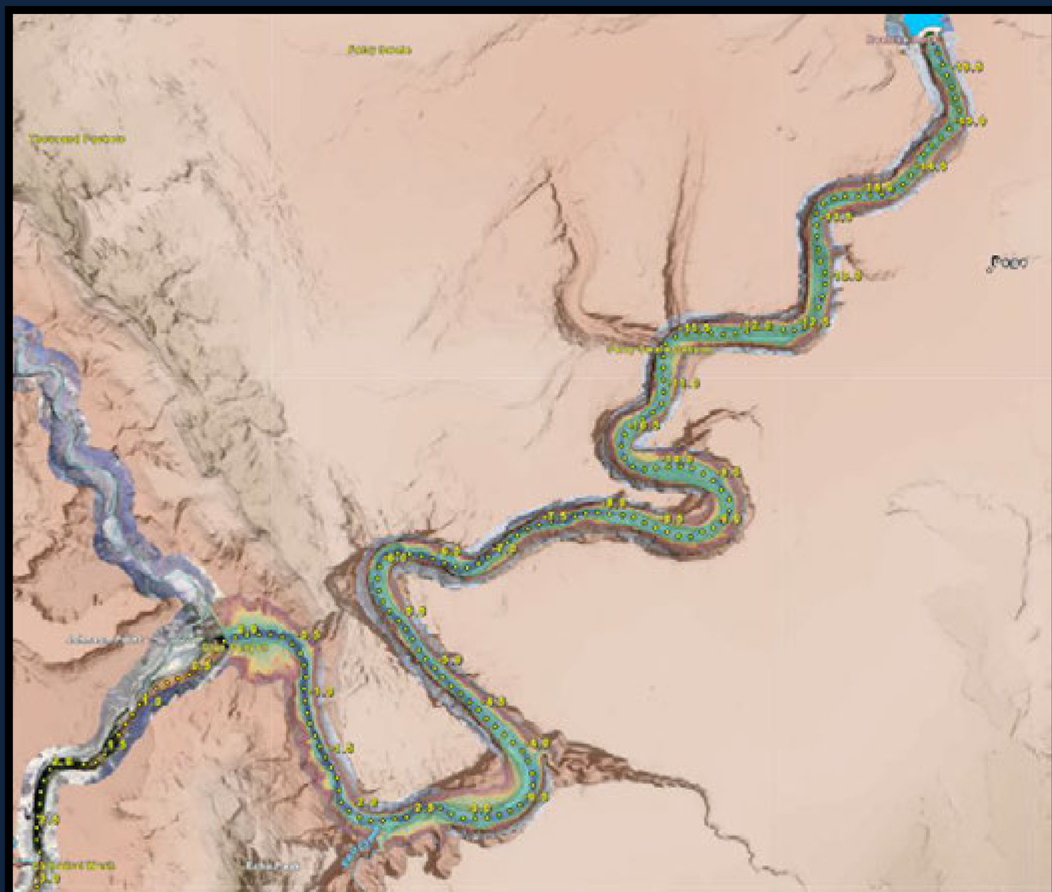
- Data Products
  - Sandbar monitoring photographs
    - www.gcmrc.gov/sandbar OR www.usgs.gov/apps/sandbar
  - Sandbar monitoring data
    - www.gcmrc.gov/sandbar OR www.usgs.gov/apps/sandbar
  - Glen Canyon topographic/bathymetric map
    - grandcanyon.usgs.gov/portal/home
  - Other USGS data releases
    - Campsite report data: doi.org/10.5066/F7FJ2FQQ
    - Sand-area data: doi.org/10.5066/P9SX3MGY
    - Bed classification processing: doi.org/10.5066/F7B56HM0
- Publications

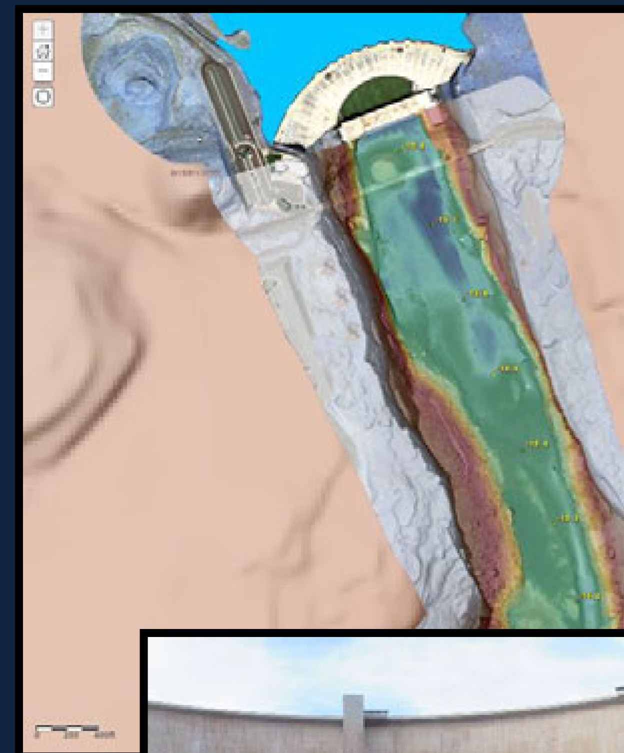
  - Buscombe, D., and Ritchie, A.C., 2018, Landscape classification with deep neural networks: Geosciences, v. 8, no. 7, article 244, https://doi.org/10.3390/geosciences8070244
  - Buscombe, D., and Grams, P.E., 2018, Probabilistic substrate classification with multispectral acoustic backscatter--A comparison of discriminative and generative models: Geosciences, v. 8, no. 11, article 395, https://doi.org/10.3390/geosciences8110395
  - Buscombe, D., Grams, P.E., & Kaplinski, M., 2018, Probabilistic models of seafloor composition using multispectral acoustic backscatter: GeoHab 2018 International Symposium, R2Sonic Multispectral Backscatter competition entry. Download using online form at: https://www.r2sonic.com/geohab2018/
  - Grams, P.E., Tusso, R.B., and Buscombe, D., 2018, Automated remote cameras for monitoring alluvial sandbars on the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 2018-1019, 50 p., https://doi.org/10.3133/ofr20181019.
  - Grams, P.E., Buscombe, D., Topping, D.J., Kaplinski, M.A., and Hazel, J.E., Jr., 2019, How many measurements are required to construct an accurate sand budget in a large river? Insights from analyses of signal and noise: Earth Surface Processes and Landforms, online, https://doi.org/10.1002/esp.4489
  - Hamill, D., Buscombe, D., and Wheaton, J.M., 2018, Alluvial substrate mapping by automated texture segmentation of recreational-grade side scan sonar imagery: PLOS One, v. 13, no. 3 (e0194373), p. 1-28, https://doi.org/10.1371/journal.pone.0194373.

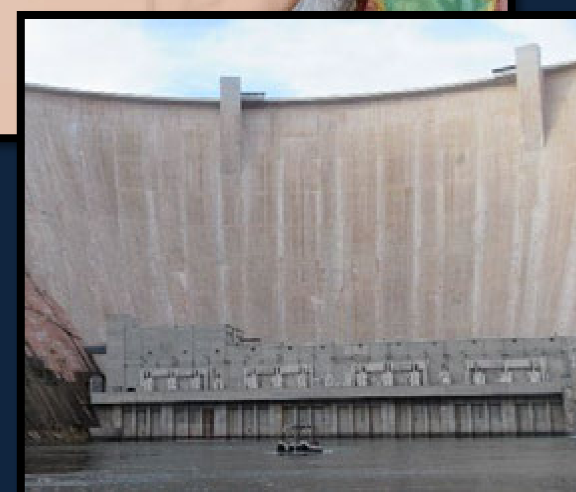
Publications (continued)

- Hadley, D.R., Grams, P.E., and Kaplinski, M.A., 2018, Quantifying geomorphic and vegetation change at sandbar campsites in response to flow regulation and controlled floods, Grand Canyon National Park, Arizona: River Research and Applications, online, https://doi.org/10.1002/rra.3349
- Hadley, D. R., Grams, P. E., Kaplinski, M. A., Hazel, J.E., J., & Parnell, R. A., 2018, Geomorphology and vegetation change at Colorado River campsites, Marble and Grand Canyons, Arizona: U.S. Geological Survey Scientific Investigations Report 2017–5096, 64 p., https://doi.org/10.3133/sir20175096
- Kasprak, A., Sankey, J.B., Buscombe, D., Caster, J., East, A.E., and Grams, P.E., 2018, Quantifying and forecasting changes in the areal extent of river valley sediment in response to altered hydrology and land cover: Progress in Physical Geography: Earth and Environment, online, https://doi.org/10.1177/0309133318795846.
- Mueller, E.R., Grams, P.E., Hazel, J.E., Jr., 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, https://doi.org/10.1016/j.sedgeo.2017.11.007.

Map of bed and banks between Glen Canyon Dam and Lees Ferry





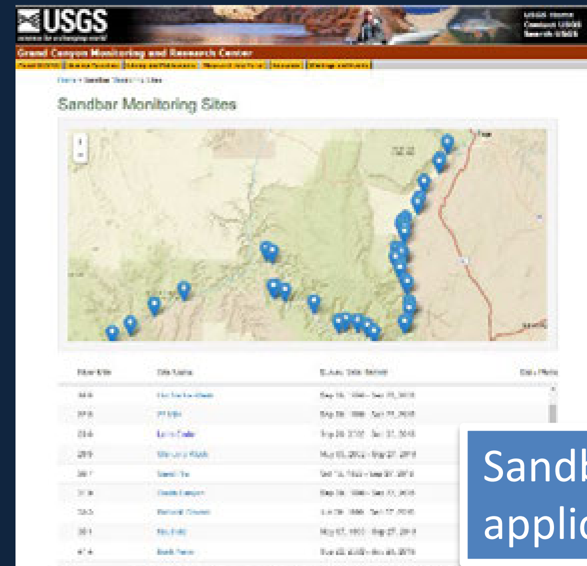


grandcanyon.usgs.gov/portal

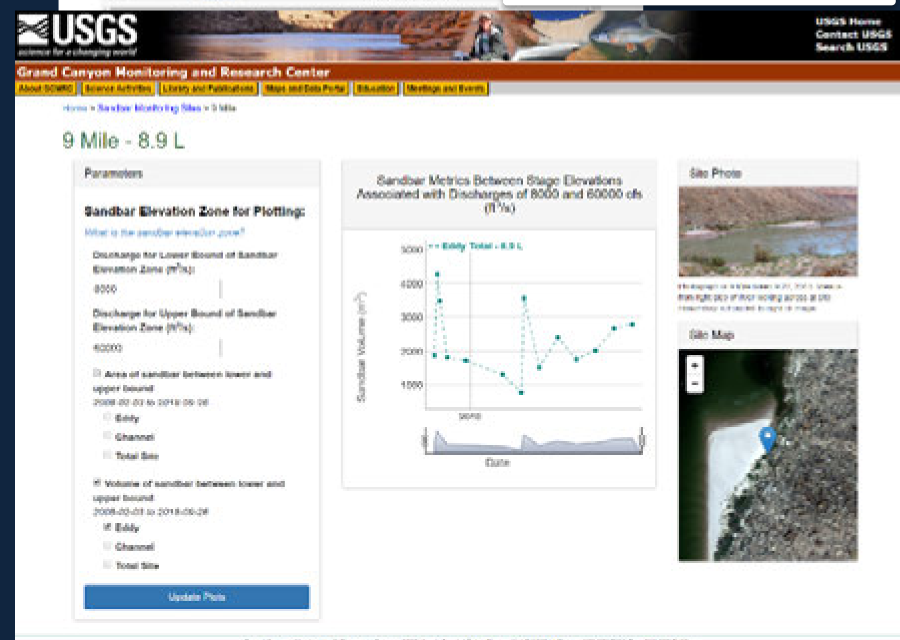
In review for Sciencebase

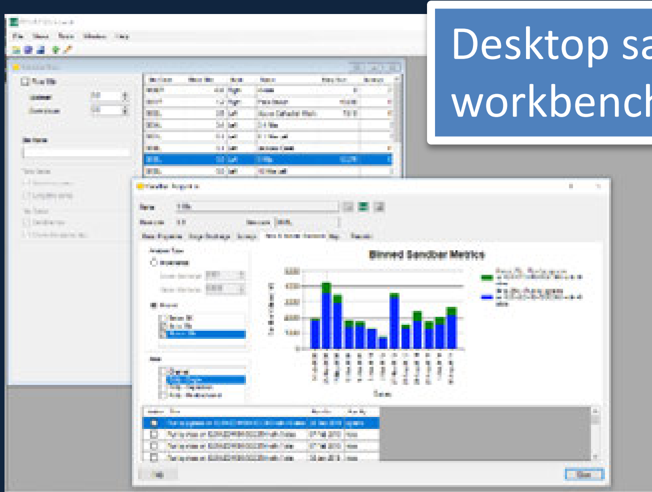
Sandbar database and web application

- In development since 2014
  - Started as a javascript app supported by oracle database
  - Now mainly in python and supported by a sql database (free and open source)
- Includes a desktop “workbench” for loading, processing and viewing data
- Web application for public access to data
- Series of python scripts for generating summary plots
  - Next step is to incorporate those in workbench and web application



Sandbar web application





Desktop sandbar workbench

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

Fifty-six years of dam operations and twenty-three years of high-flow experimentation: High Flows and Sandbar Response

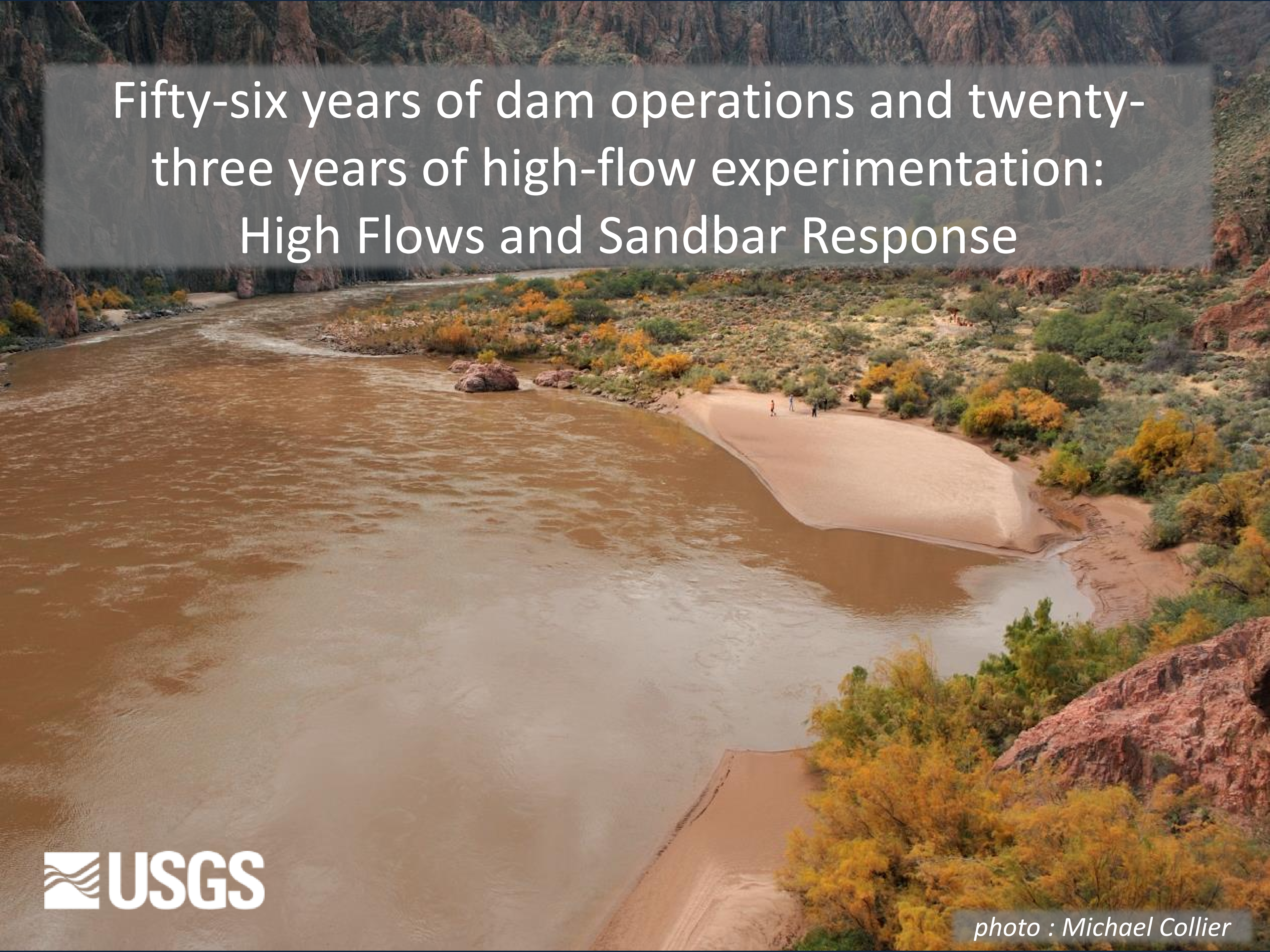


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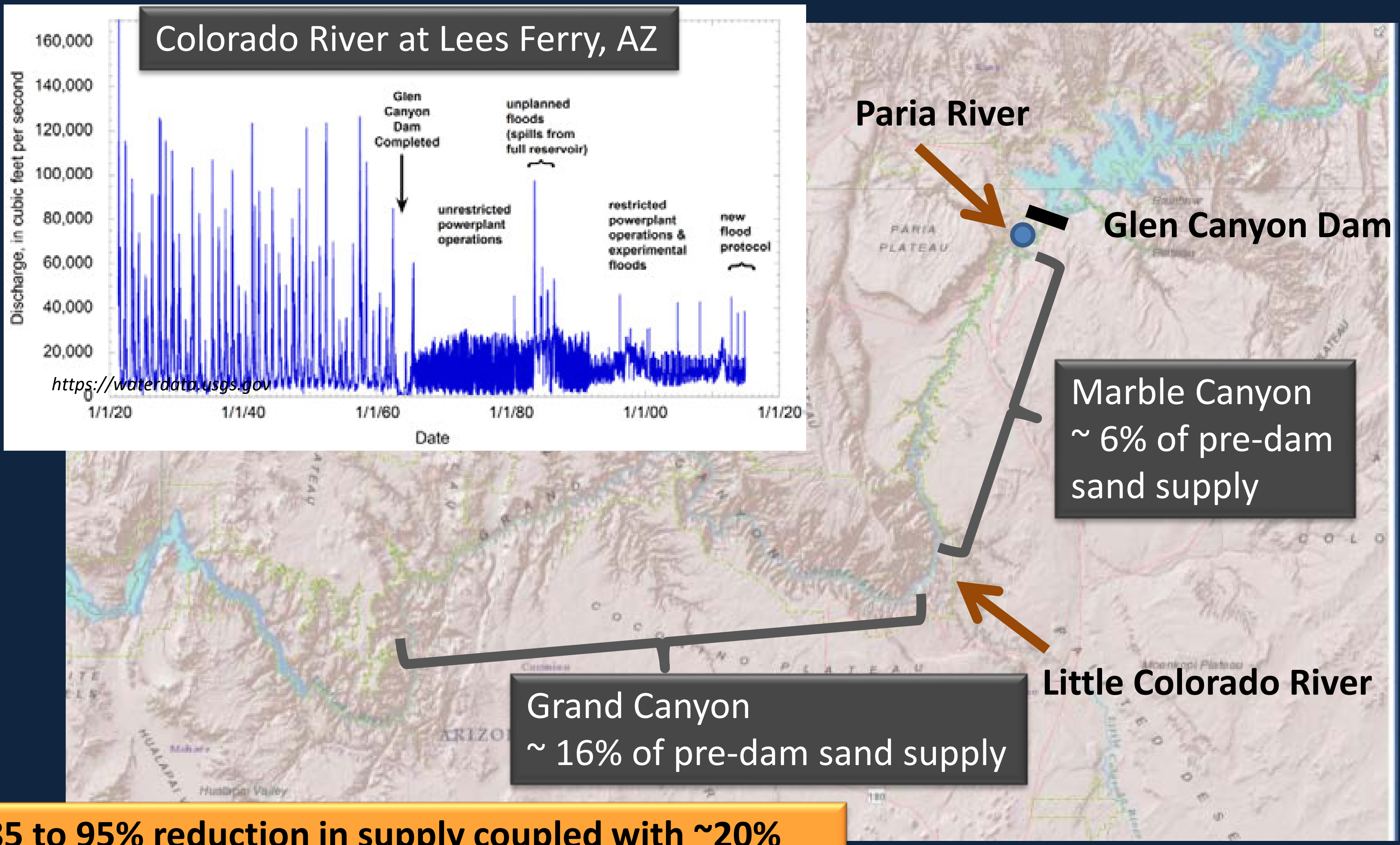
photo : Michael Collier

Overview

- Background on pre-floods, post-dam floods, and high-flow experiments
- Observations of sandbar response to HFEs from 2012-2018
- Cumulative sandbar response for the 2012-2018 period
- Sandbar model results, comparing HFE protocol to period without high flows
- Sand budgets from 2012-2018
- Will HFEs continue to be effective tools?
- What are the HFEs not doing?
- Summary and next steps

USGS

Change in flow regime and disruption of sand supply have caused changes to river morphology and sandbars



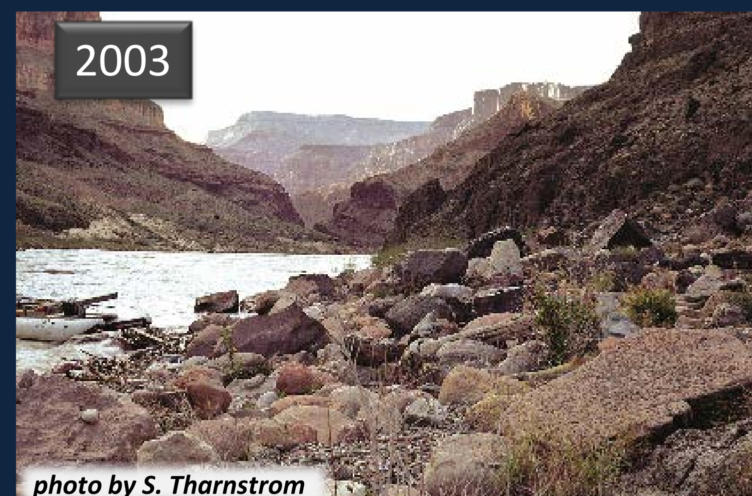
85 to 95% reduction in supply coupled with ~20% reduction in mean annual flow → sediment deficit

Topping et al. (2000)

USGS

Change in flow regime and disruption of sand supply have caused changes to river morphology and decrease in the size of sandbars and campsites

Sandbar erosion and vegetation expansion near Palisades

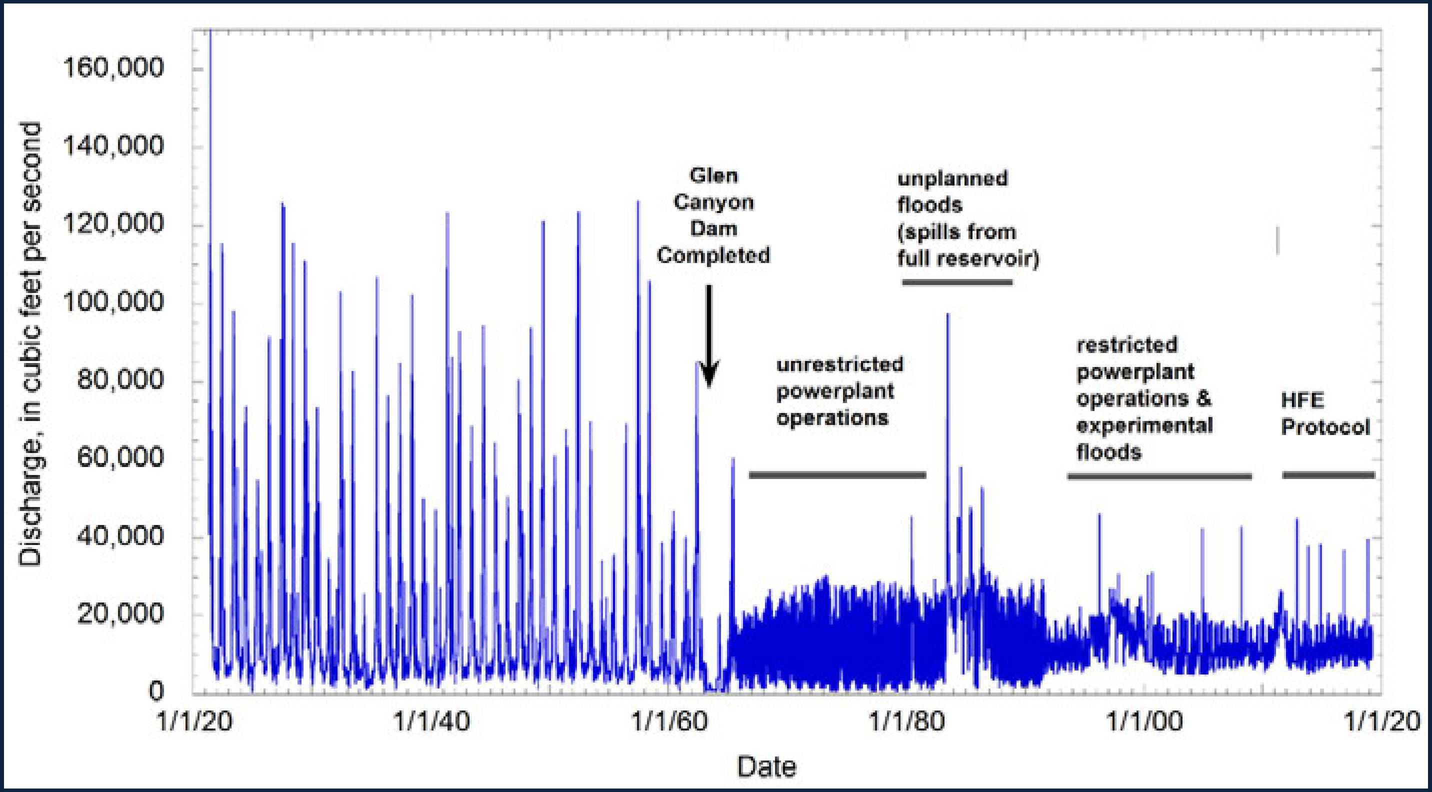


Sandbar erosion near Tapeats Creek

Schmidt and Graf (1990), Kearsley and others (1994)

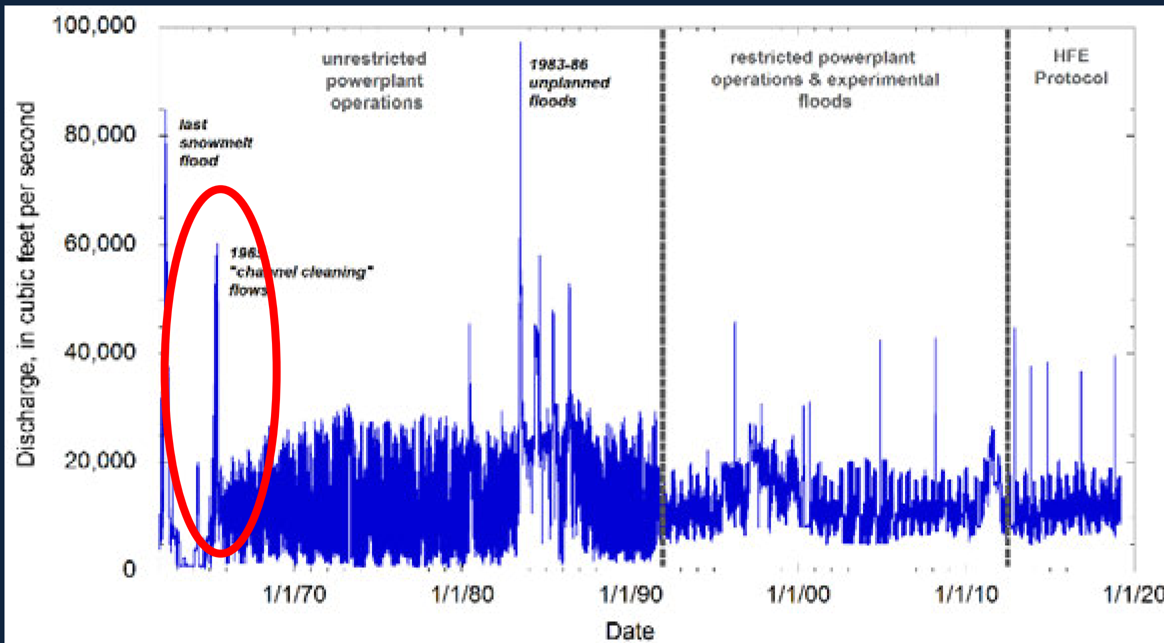
USGS

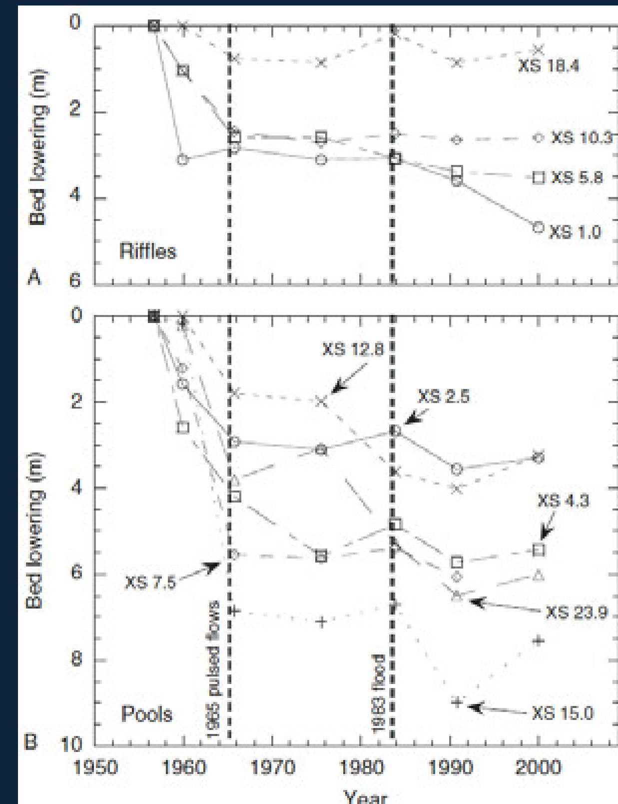
Pre-dam floods and high-flow experiments



- HFEs are small and infrequent compared to pre-dam snowmelt floods.
- Dam releases between HFEs do not resemble pre-dam winter flows.

Post-dam Floods and High-flows: Floods scour the bed





1965 "Channel-cleaning" flows

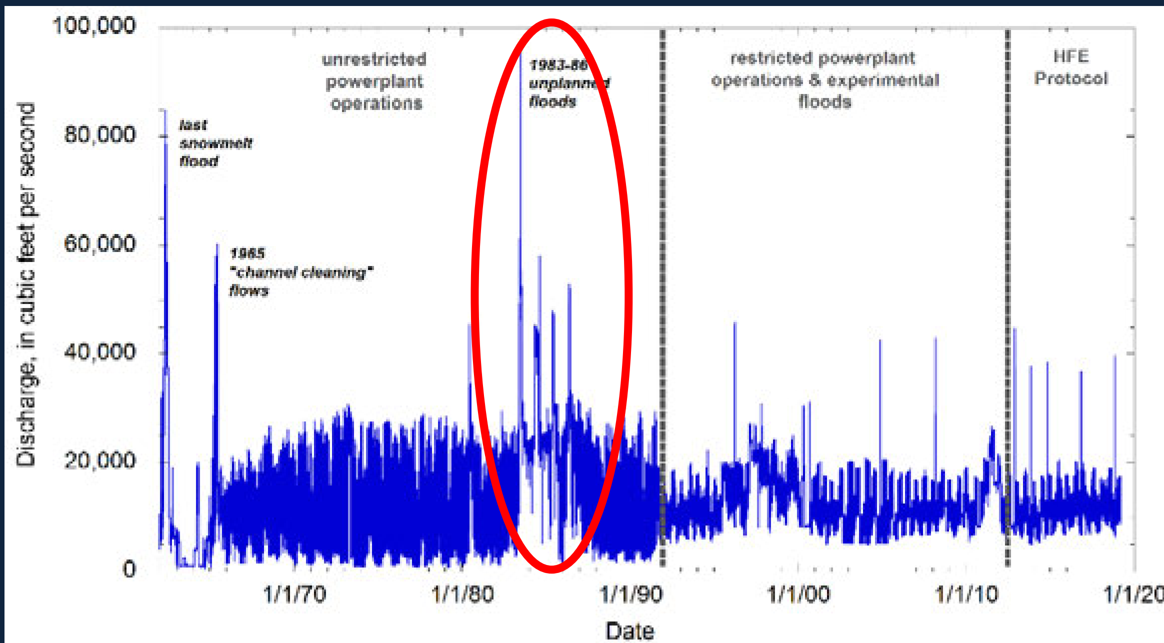
- Scoured an average of 2.6 m from bed in Glen Canyon, eliminating most sand from riverbed in this reach.
- Likely caused in sandbar deposition in Marble and Grand Canyons, but that was undocumented.

Floods in a system with no sand resupply cause irreversible bed scour

Grams and others (2007)

USGS

Post-dam Floods and High-flows: Floods build sandbars



1983-86 “high water” spills

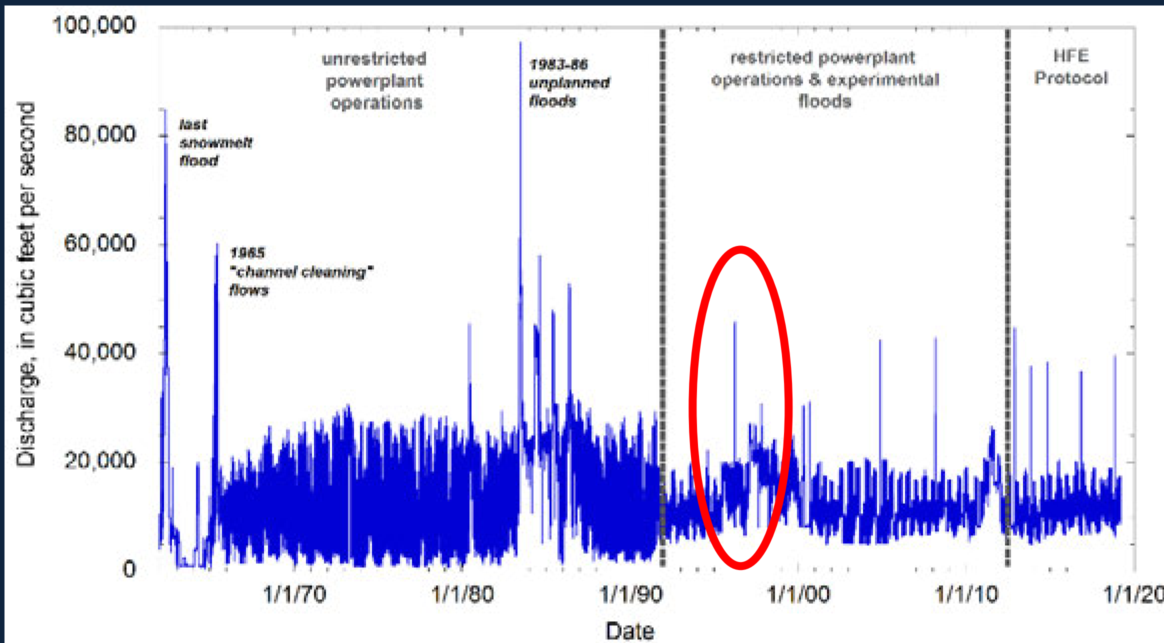
- Caused sandbar deposition, followed by erosion
- Scoured vegetation that had colonized since 1963
- Effects observed, but not well documented (Glen Canyon Environmental Studies Phase I was just initiated)

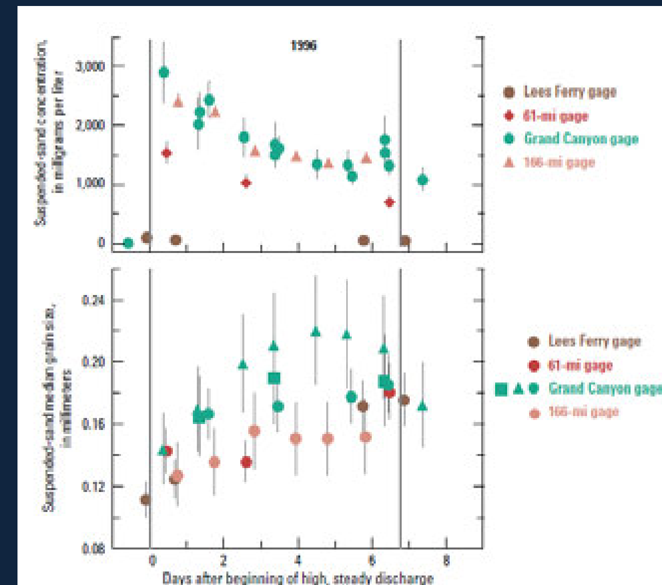
FIGURE 18.—Reattachment deposit at Eminence Break Camp, October 12, 1985, discharge 3,000 ft^3/s.

1980’s floods provided demonstration of sandbar building; amount of bed scour unknown

Schmidt and Graf (1990)

Post-dam Floods and High-flows: Sand supply is limited





Declining sand concentration and increasing sand grain size during 1996 flood revealed limited sand supply

1996 experimental flood

- Planned with hypothesis that sand accumulated on bed since floods of 1980s
- Caused bar building, but net loss of sand from eddies.

Schmidt (1999); Topping and others (2000)

Post-dam Floods and High-flows: higher flows build larger sandbars

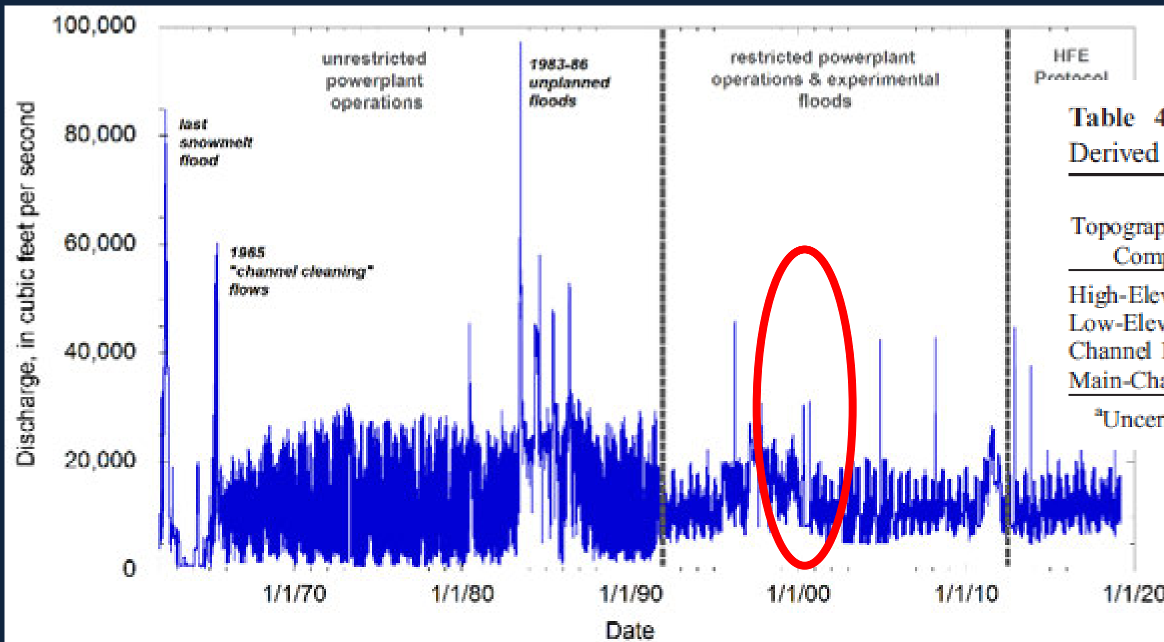


Table 4. Summary of Average Sediment-Thickness Changes Derived from Topographic Data

Topographic Storage Components	1996 Controlled Flood,[a] m	September 2000 Powerplant Capacity Flow,[a] m
High-Elevation Eddy	0.18 ± 0.05	0.03 ± 0.02
Low-Elevation Eddy	−0.36 ± 0.18	0.15 ± 0.08
Channel Margin	0.30 ± 0.10	0.15 ± 0.07
Main-Channel Bed	−0.49 ± 0.13	−0.08 ± 0.07

[a]Uncertainties are 1 standard error.

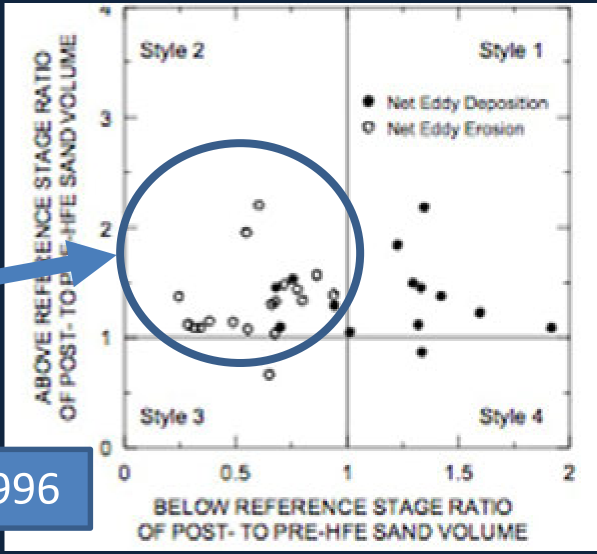
2000 powerplant capacity high flows

Powerplant capacity flows do build sandbars, but lower flood stage = lower flood deposit thickness

Hazel and others (2006)

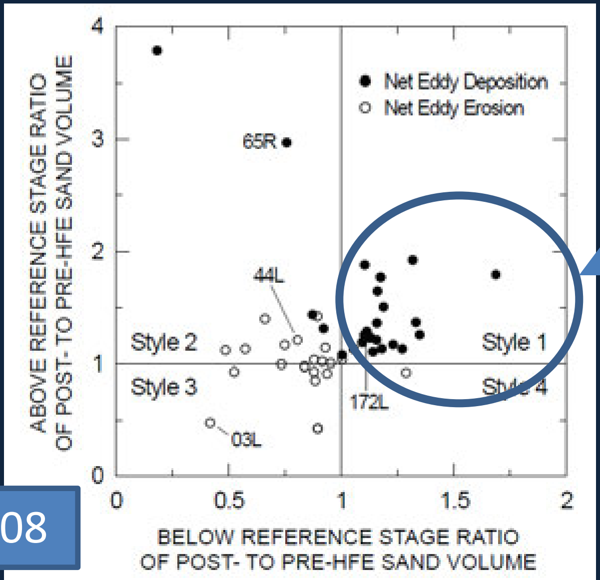
Post-dam Floods and High-flows: Response linked to sand supply

Greater proportion of sites with net eddy erosion in 1996



1996

The 2004 and 2008 HFEs demonstrated sandbar building under conditions of greater sand enrichment → less erosion of sand from storage in eddies and channel



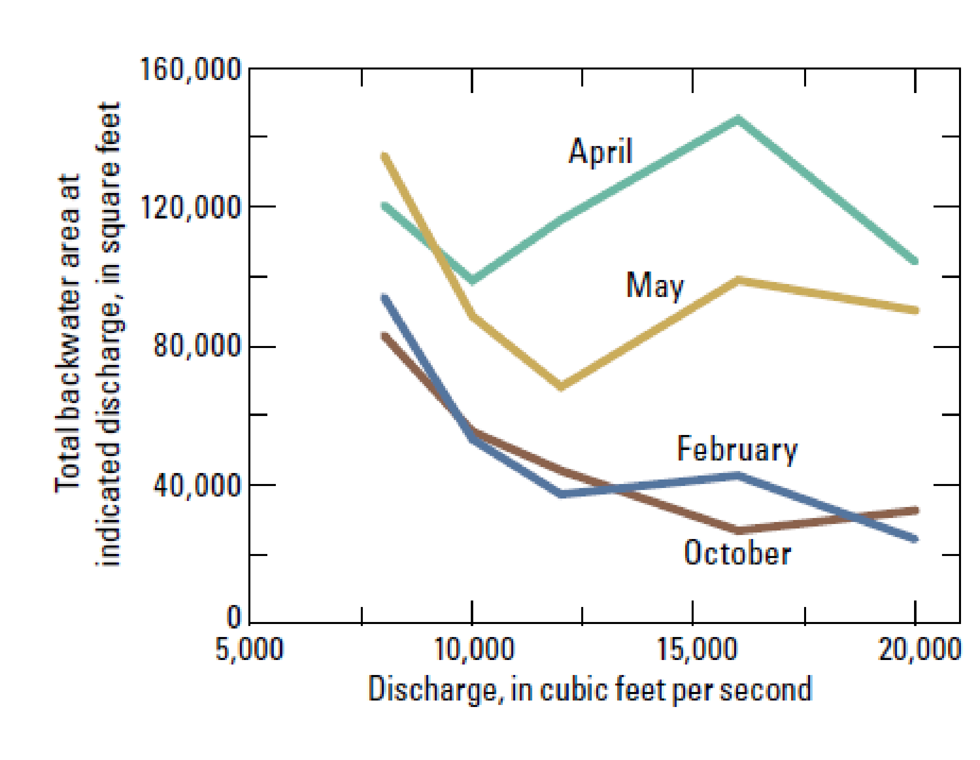
2008

Greater proportion of sites with net eddy deposition in 2008

Hazel and others (2010); Schmidt and Grams (2011)

USGS

Post-dam Floods and High-flows: Floods create backwaters



1 to 6 weeks post-HFE

Pre-HFE and 6 months post-HFE

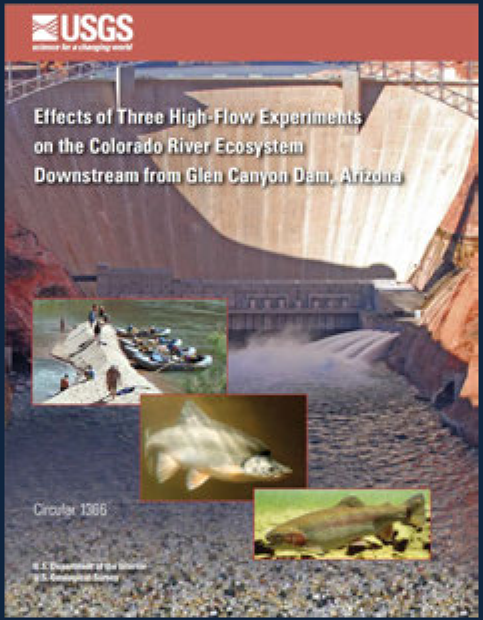
Building of sandbars during high flows greatly increases the area of backwater habitat across a range of flows for a short time, but greatest habitat at low flows (below ~ 12,000 cfs)

Grams and others (2010)

USGS

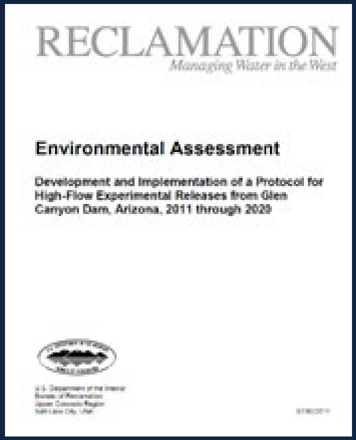
Post-dam Floods and High-flows:
Summary of findings up to start of 2012 HFE Protocol

- Sediment depleted floods scour the bed.
- Sediment-depleted floods can build high-elevation sandbars at expense of erosion from the channel and low-elevation parts of eddies.
- Floods during sediment-enriched conditions build bars without “mining” background sand storage.
- High flows should be timed to best take advantage of recent tributary sand inputs.



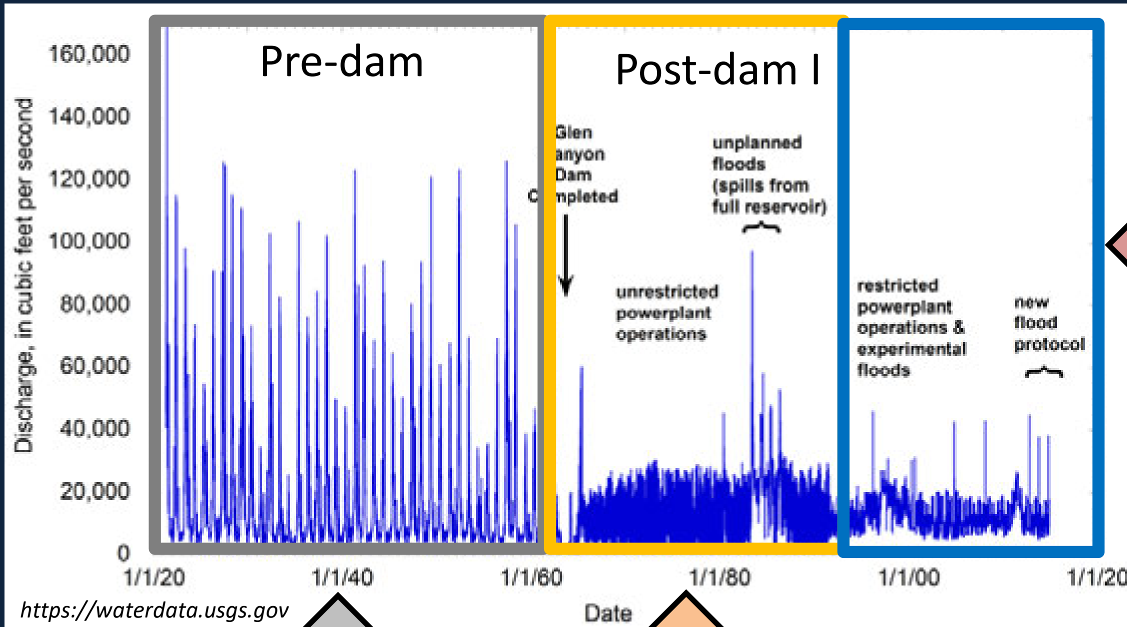
→ These findings are basis of the key components of HFE Protocol:

- Tracking sand inputs from Paria River over the summer-fall storm season.
- Scheduling HFEs to follow the series of inputs when sand storage in Upper Marble Canyon is greatest.
- Scaling the size (magnitude and duration) of HFE to “match” the amount of sand accumulation.



Schmidt and Grams (2011); Wright and Kennedy (2011)

USGS



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

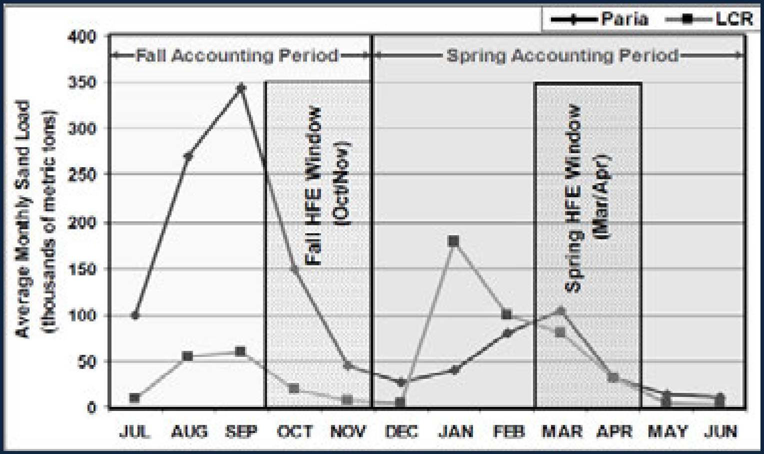
Pre-dam:
- Annual floods
- Abundant sand supply
- Large sandbars

Post-dam I:
- Daily small floods
- Limited sand supply
- Eroding sandbars
- Unplanned floods (spills)

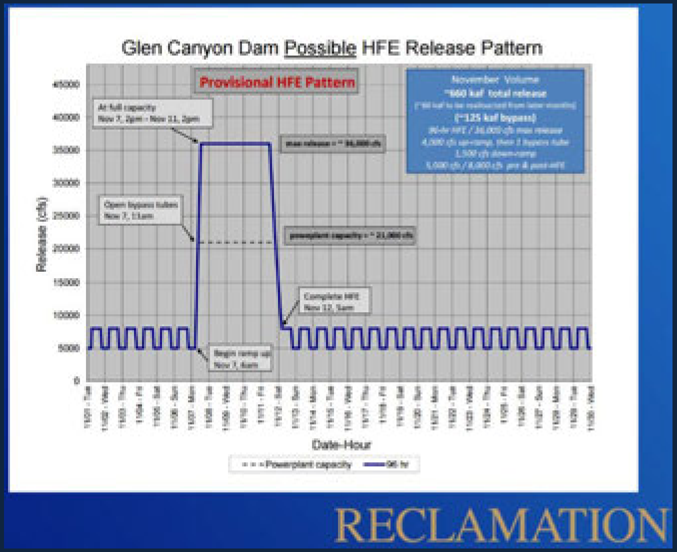
HFE-related Science and Management Questions:
- With frequent HFEs, will sandbars increase in size and abundance?
- Will frequent HFEs cause sand supply in channel to decrease and exacerbate sediment deficit?

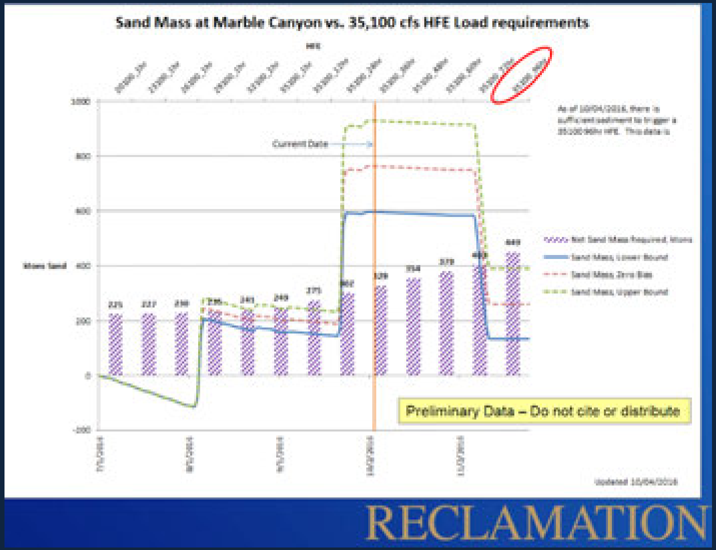
The HFE Protocol:

- Track sand inputs from Paria River and model sand budget during designated accounting periods
  - July 1 – Dec. 1
  - Dec. 1 – Jun. 30
- Find the magnitude and duration of HFE that "fits" the amount of sand available
- Schedule HFE



Wright and Kennedy (2011)





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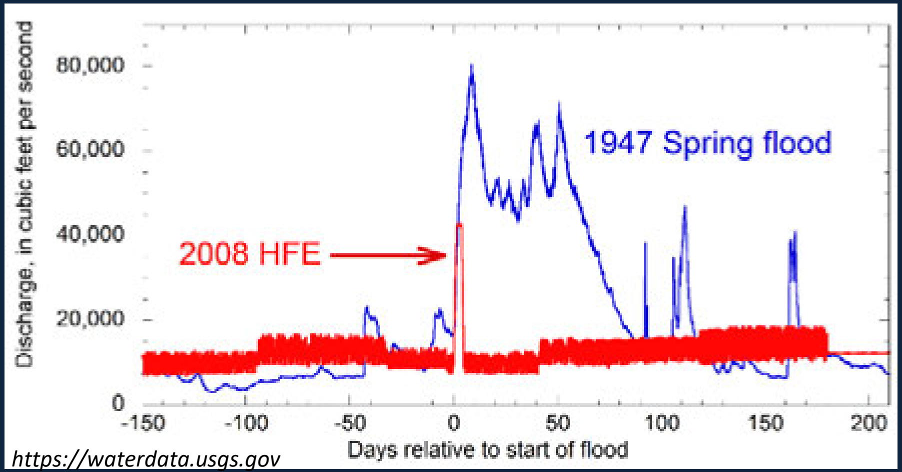
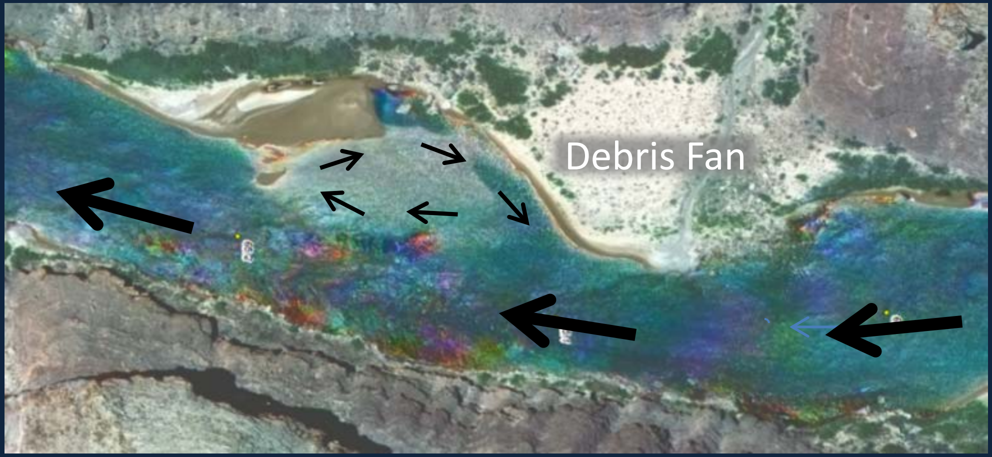
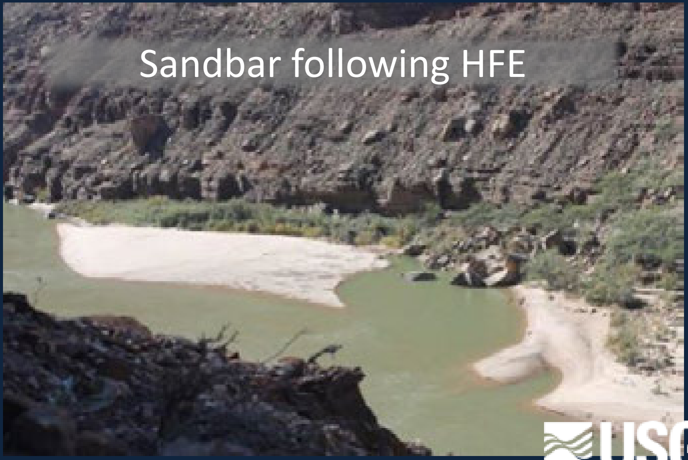
What are the high-flow experiments (HFEs) doing?





HFEs transfer sand from channel and low-elevation parts of eddies to sandbars along channel margins



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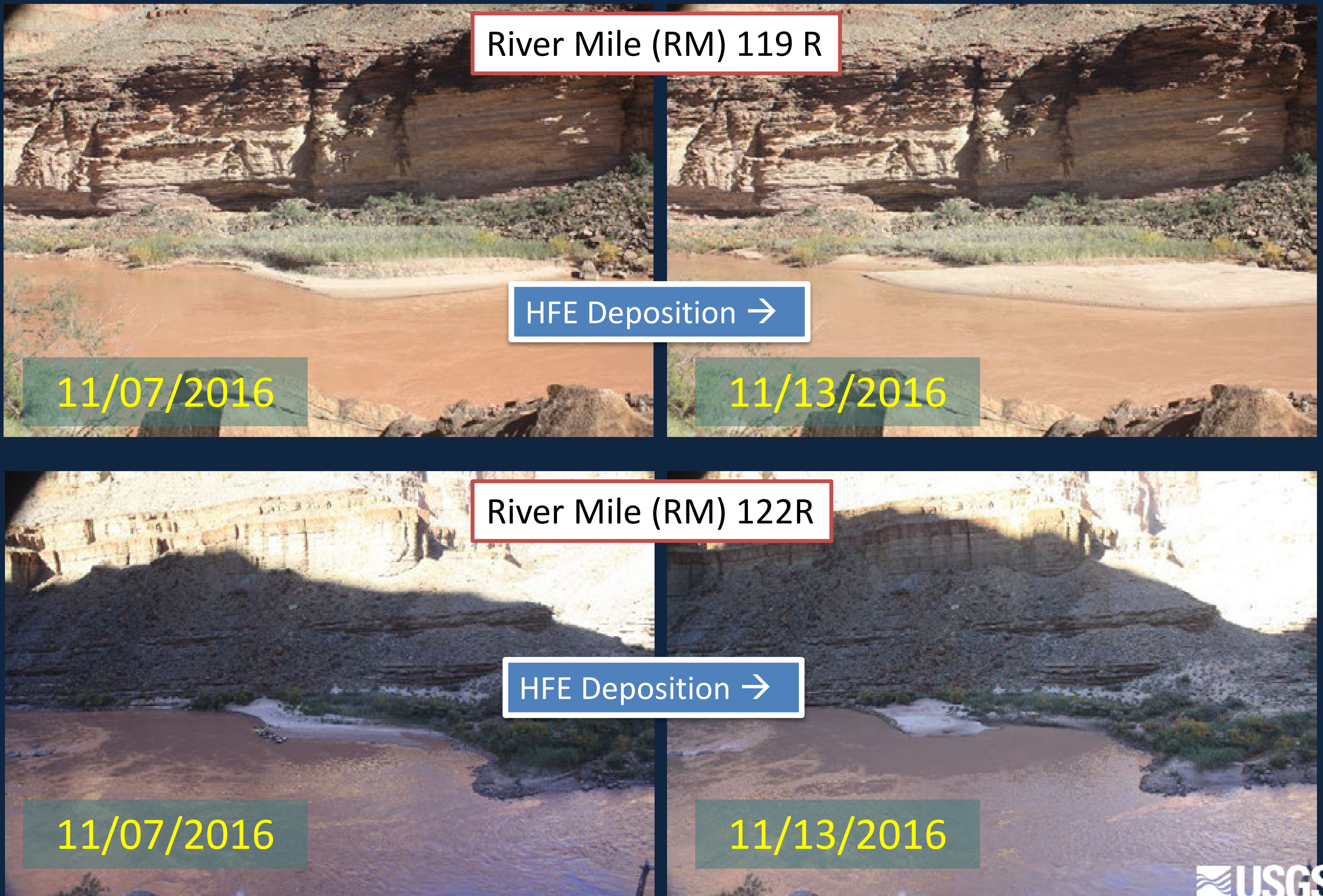
November 2016 High-flow Experiment Sandbar Deposition-1



November 2016 High-flow Experiment Sandbar Deposition-2

River Mile (RM) 23L

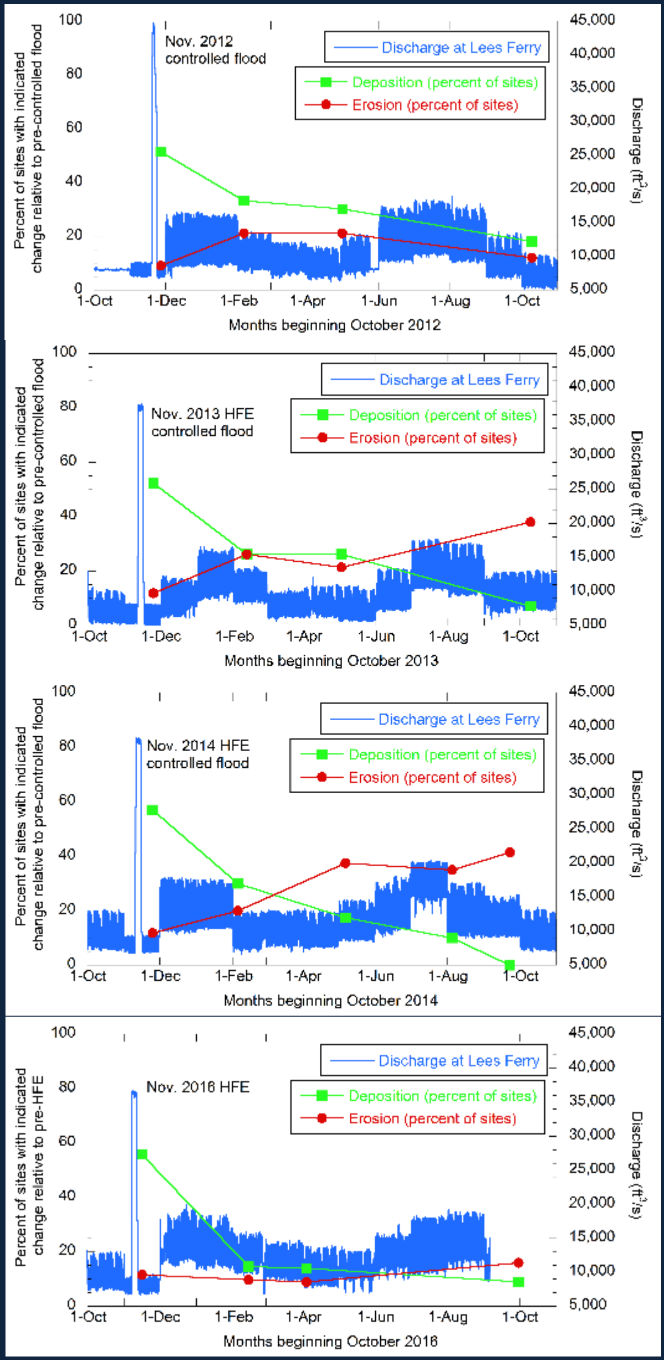
USGS

November 2016 High-flow Experiment Sandbar Deposition-3

River Mile (RM) 23L

What are the HFEs doing?

Most sandbars erode to near pre-HFE size within 6 to 12 months.



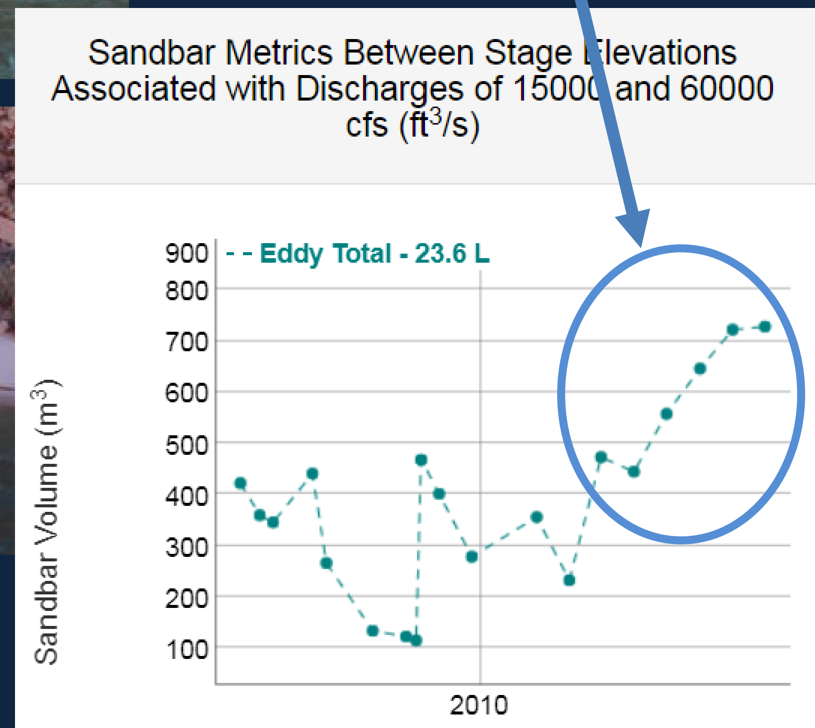
Grams et al. (2018)T

USGS

November 2016 High-flow Experiment Sandbar Deposition

River Mile (RM) 23L

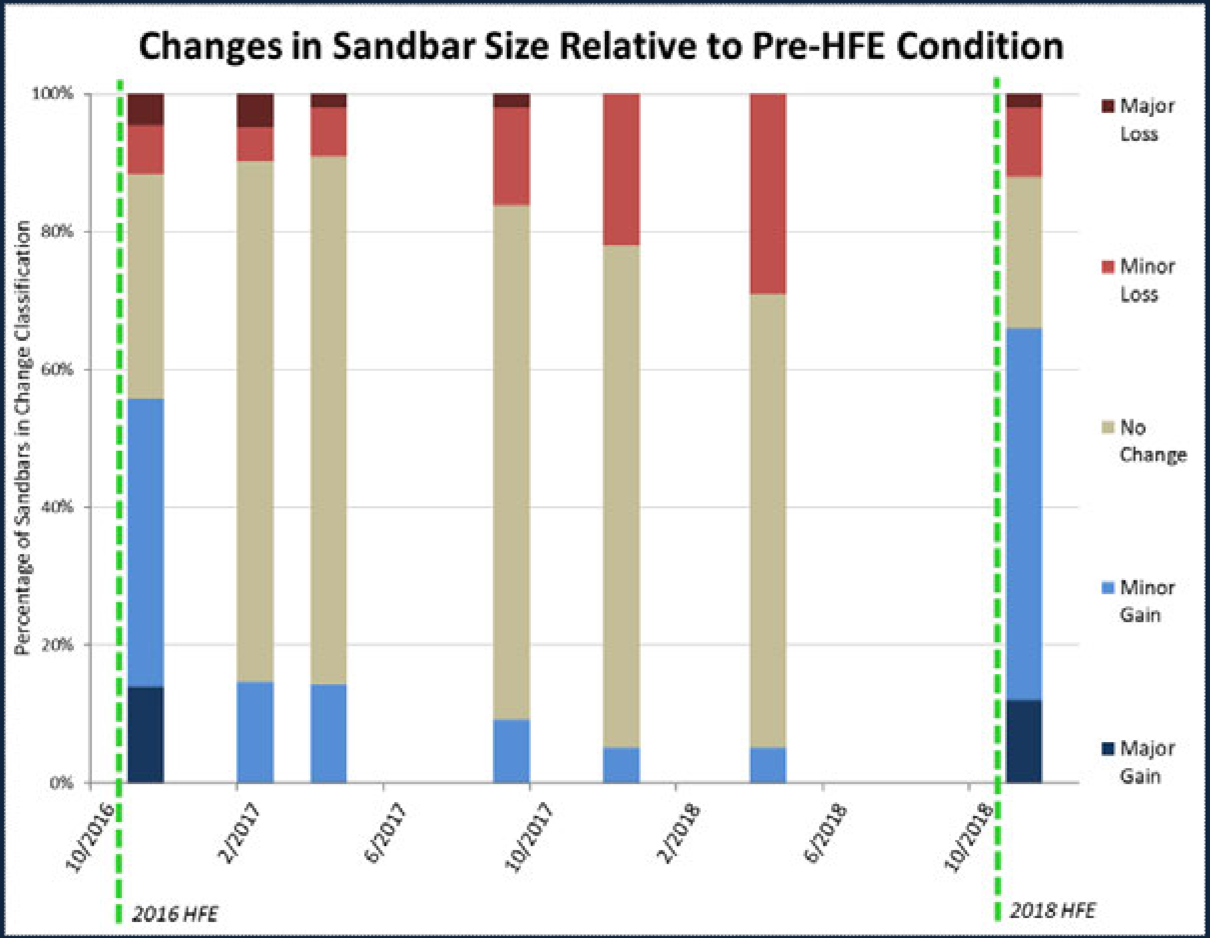
HFE Protocol period



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

USGS

Fall 2018 HFE



Results of 2018 HFE on par with previous HFEs

www.gcmrc.gov/sandbar

Preliminary results, subject to review, do not cite

USGS

Rebuilding of sandbars and campsites affected by tributary floods

- Flash flood and debris flow at 220-mile in 2018 eroded and wiped out middle camp (a long-term monitoring site)
- Also eroded gully through upper camp
- Both partially rebuilt by 2018 HFE

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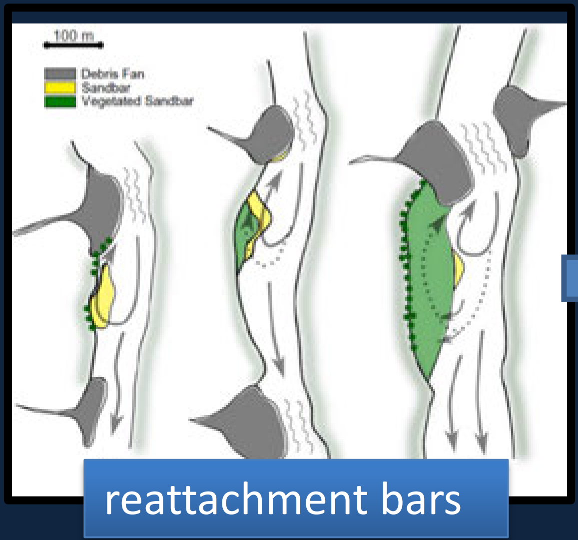
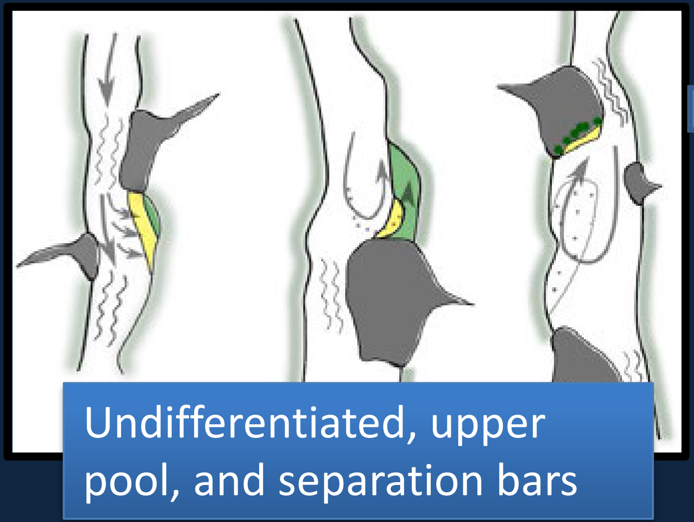
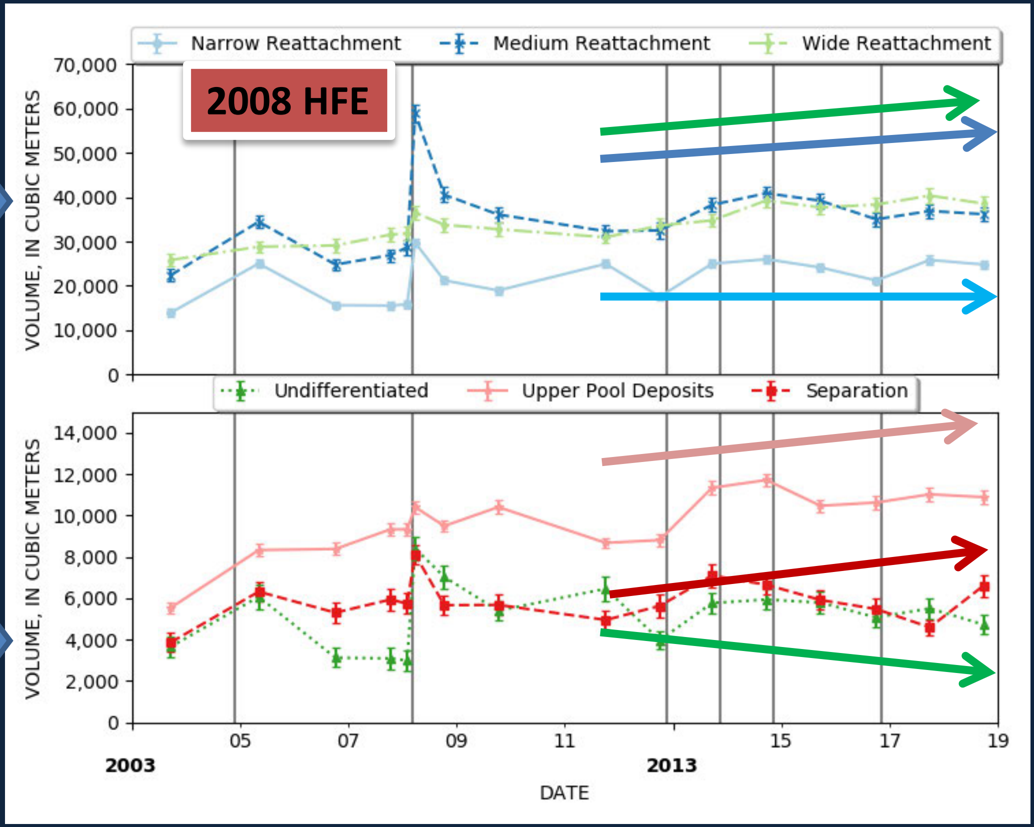
Sandbar size measured in annual fall surveys-1





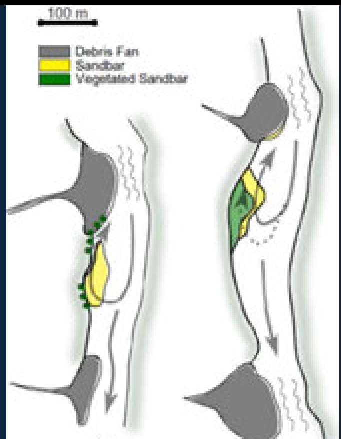
Total sandbar volume for each bar type



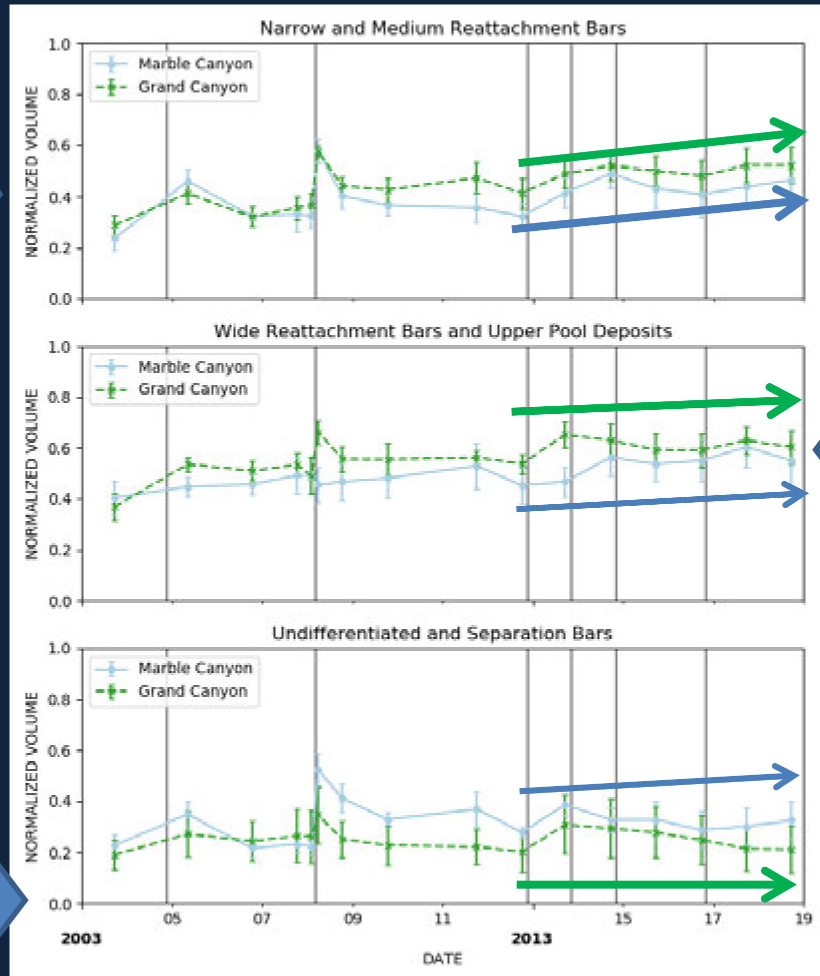
- Very slight upward trends in most bar types and in both Marble and Grand Canyon
- Trend is significant (greater than measurement uncertainty)

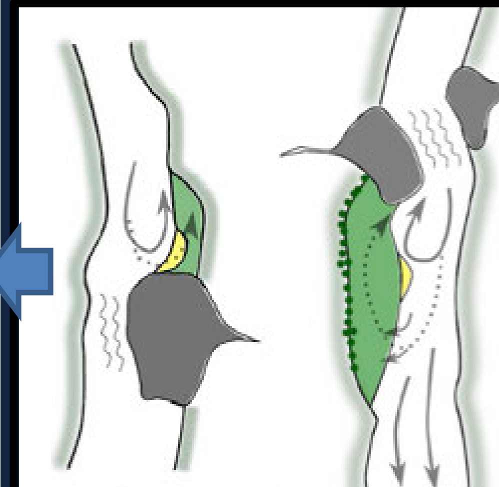
Preliminary results, subject to review, do not cite

Sandbar size measured in annual fall surveys-2

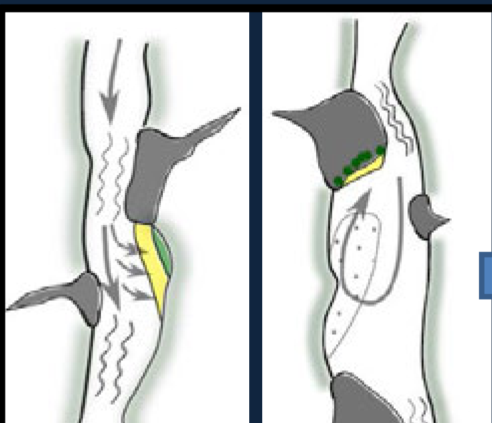


Narrow to medium reattachment bars





Wide, vegetated bars



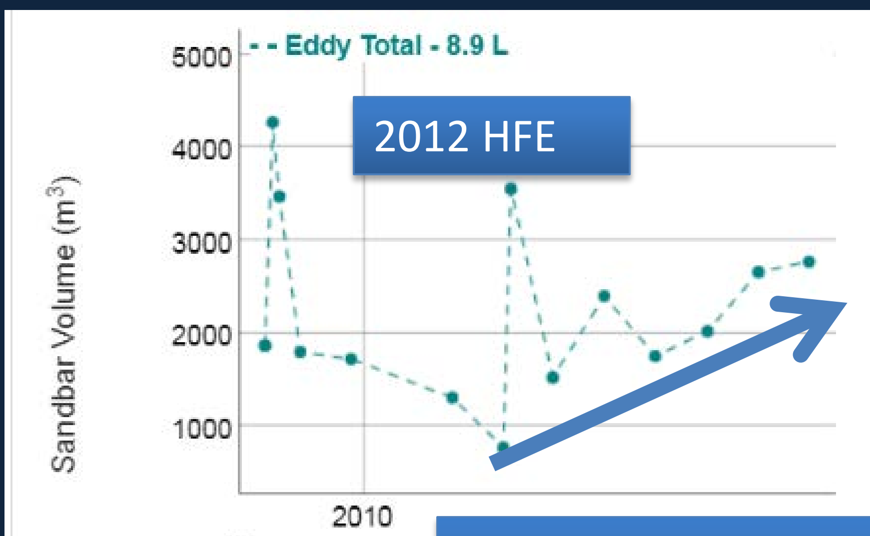
Undifferentiated and separation bars

- Very slight upward trends in most bar types and in both Marble and Grand Canyon
- Large site-to-site variability (large standard error)

USGS

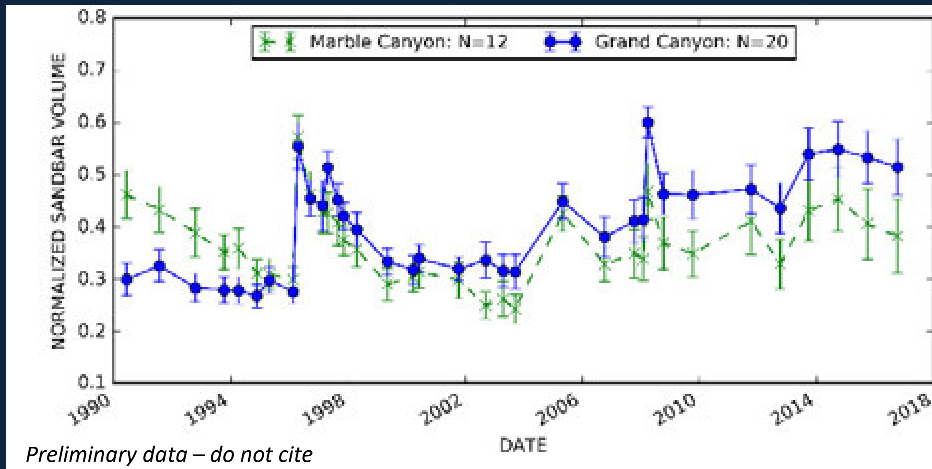
Preliminary results, subject to review, do not cite

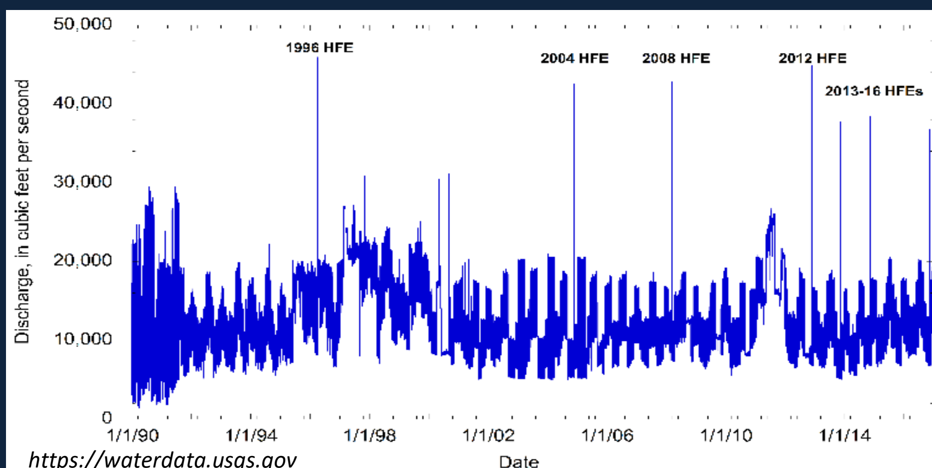
Cumulative increases in sand volume at some sites

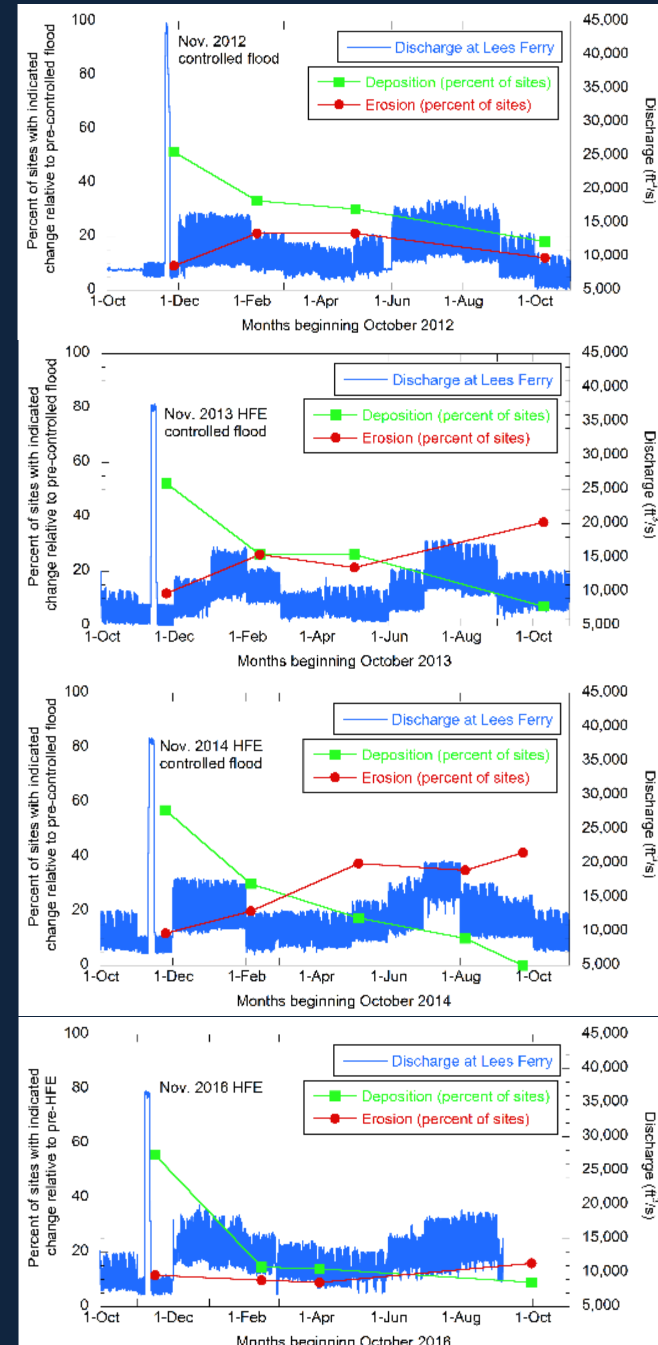


Fall 2012 to Fall 2018 increase

Summary of sandbar response to HFEs







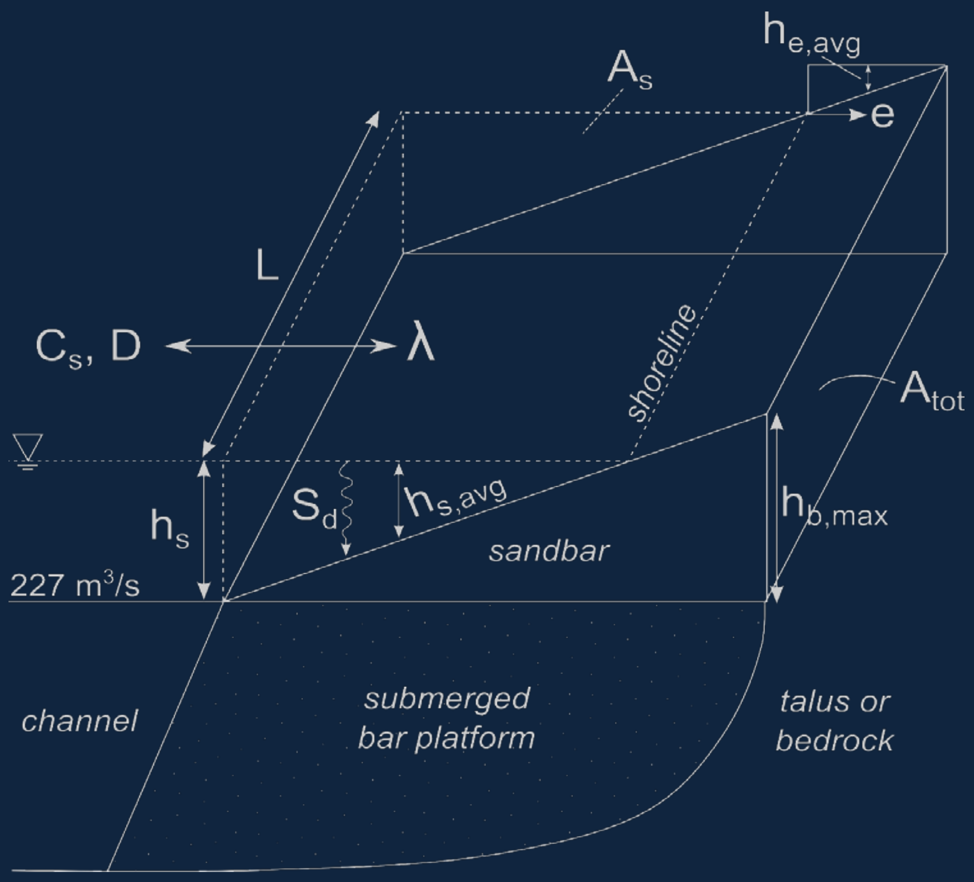
Grams et al. (2018)

- Consistently rebuilding sandbars
- Sandbars consistently erode following HFEs
- But, sandbars are consistently larger than in periods without the HFEs
- Erosion continues in years without HFEs

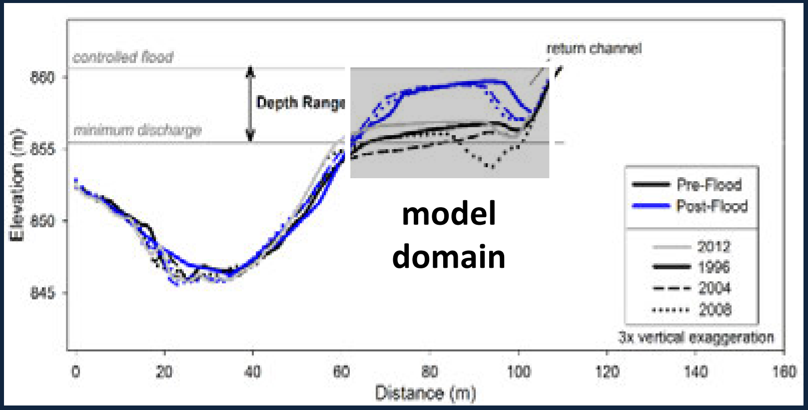
USGS

Preliminary results, subject to review, do not cite

Sandbar morphodynamic model: based on physical processes, calibrated to long-term sandbar monitoring data-1



Model applied above the 8000 cfs stage



30-mile bar

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
(has the form of exponential decay)

L: Bar Dimensions

A: Submerged (*s*) and total (*tot*) area

h: Thickness of submerged (*s*) and exposed (*e*) bar

Preliminary data and results, subject to review, do not cite

Sandbar morphodynamic model: based on physical processes, calibrated to long-term sandbar monitoring data-2

Key model equations
(after Andrews and Vincent, 2007)

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

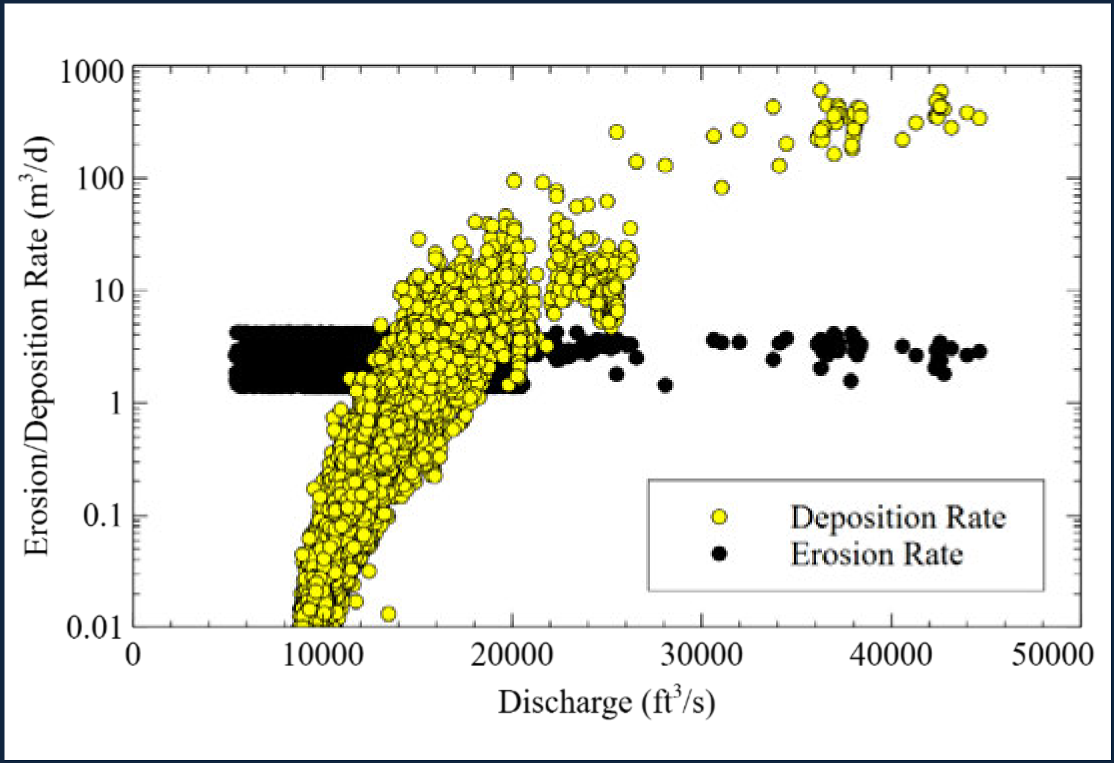
Using a linear approximation for the concentration of sand in the eddy →

Rearrange:

$$S_d = w_s C_e = \frac{\lambda h_e w_s C_s}{\lambda h_e + \frac{w_s}{2}}$$

$V_d = S_d A_e$ *Volume/time*

Uses variables routinely measured at gaging stations (discharge, stage, sand concentration, and grain size)



Erosion estimated as a simple exponential decay with bar volume:

$$\frac{dV}{dt} = -kV$$

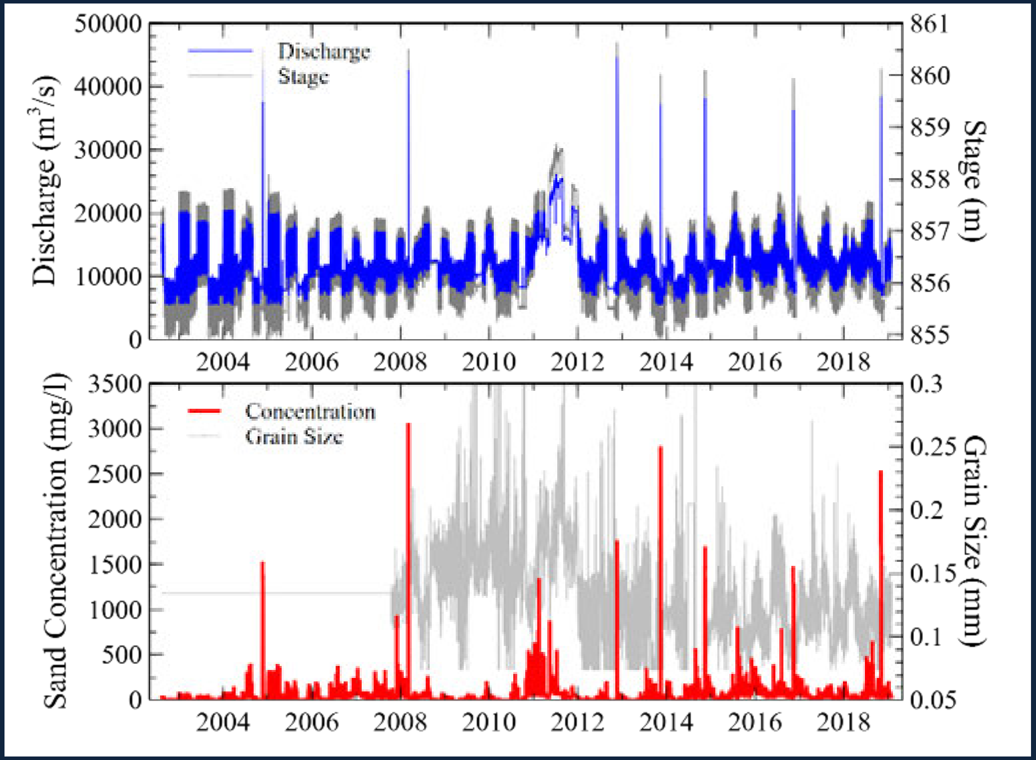
where k is rate parameter (1/s)

Bar "half-life" approximately 2 years

Preliminary data and results, subject to review, do not cite

Sandbar morphodynamic model: based on physical processes, calibrated to long-term sandbar monitoring data-3

Key model inputs are discharge, sand concentration, and sand grain size



Time-series plots of discharge, stage, sand concentration and grain size for the period modeled at the 30-mile gage

In this permutation, the modeled bars represent the scaled average of **nine** dynamic bars (*Mueller et al*., 2018).

Deposition depends on the rate (λ) at which suspended sand enters the eddy using a physically-based approach based on particle settling velocity (*Andrews and Vincent*, 2007).

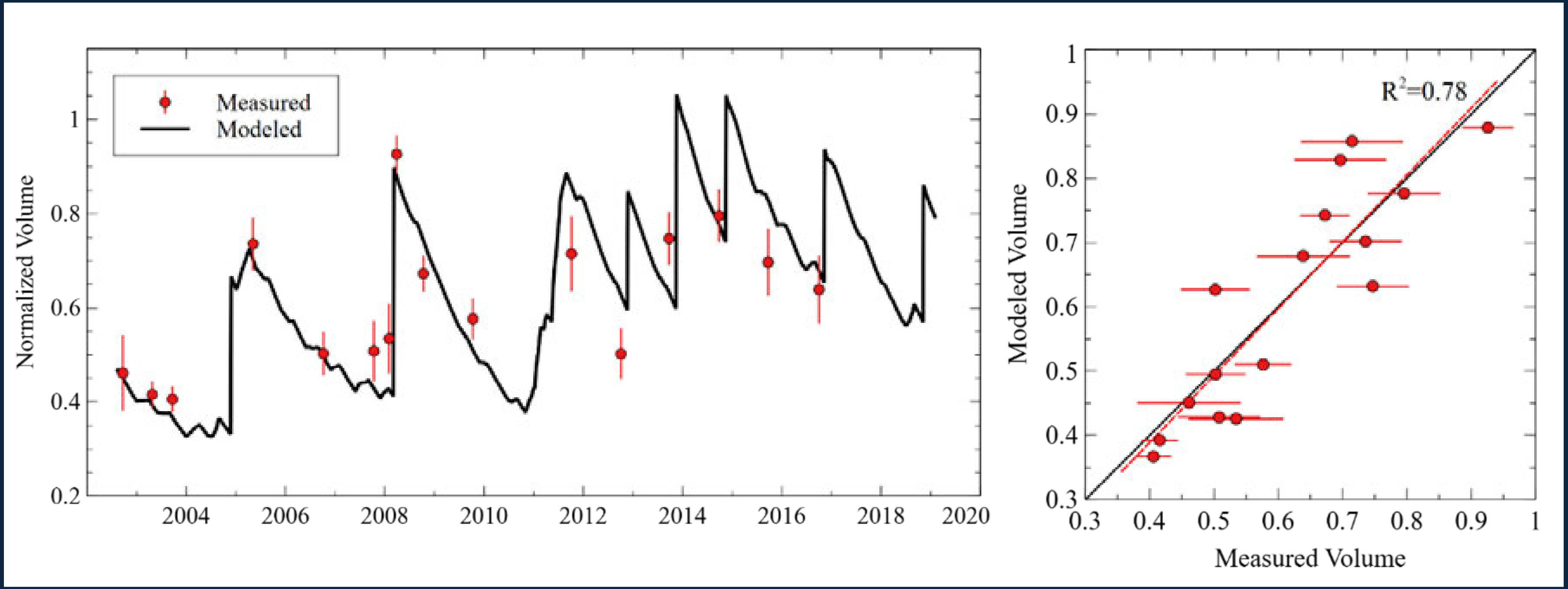
Deposition does not explicitly depend on discharge, but rather the average submerged depth of the bar.

The eddy exchange coefficient (λ) and erosion rate (e) are optimized to fit the measured bar volume. An empirical relation relates bar volume and area.

www.gcmrc.gov/discharge_qw_sediment

Best-fit model for nine dynamic bars:
normalized by their maximum measured volume

Modeled vs. Measured



The model reproduces peak volumes during floods and minima between floods.
Sustained intermediate flows such as the 2011 equalization are more difficult to predict.

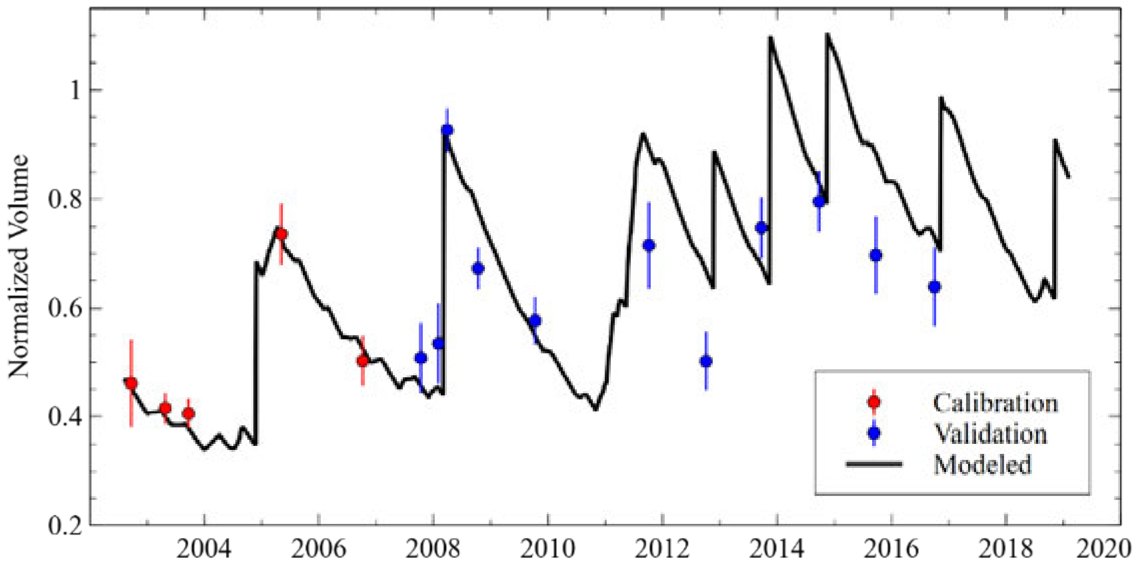
Error bars are the standard error in the normalized measured volume. 2011 was not included in the optimization.

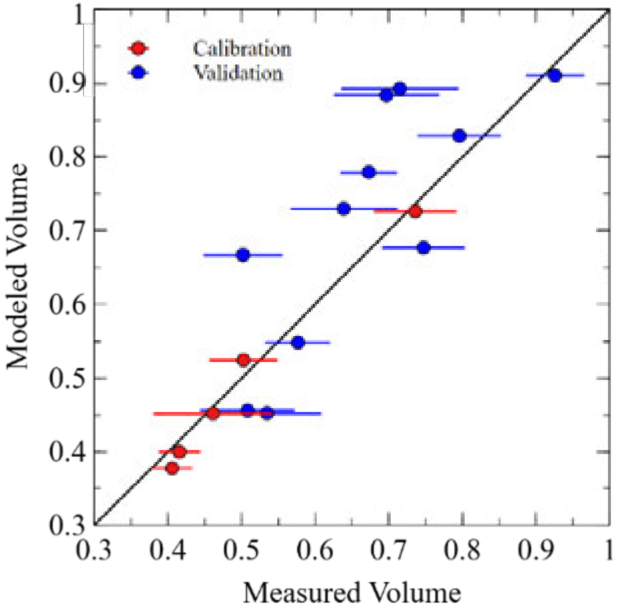
Preliminary data and results, subject to review, do not cite

Calibrated using only 5 measurements:

Validated with more than a decade of measurements

Modeled vs. Measured





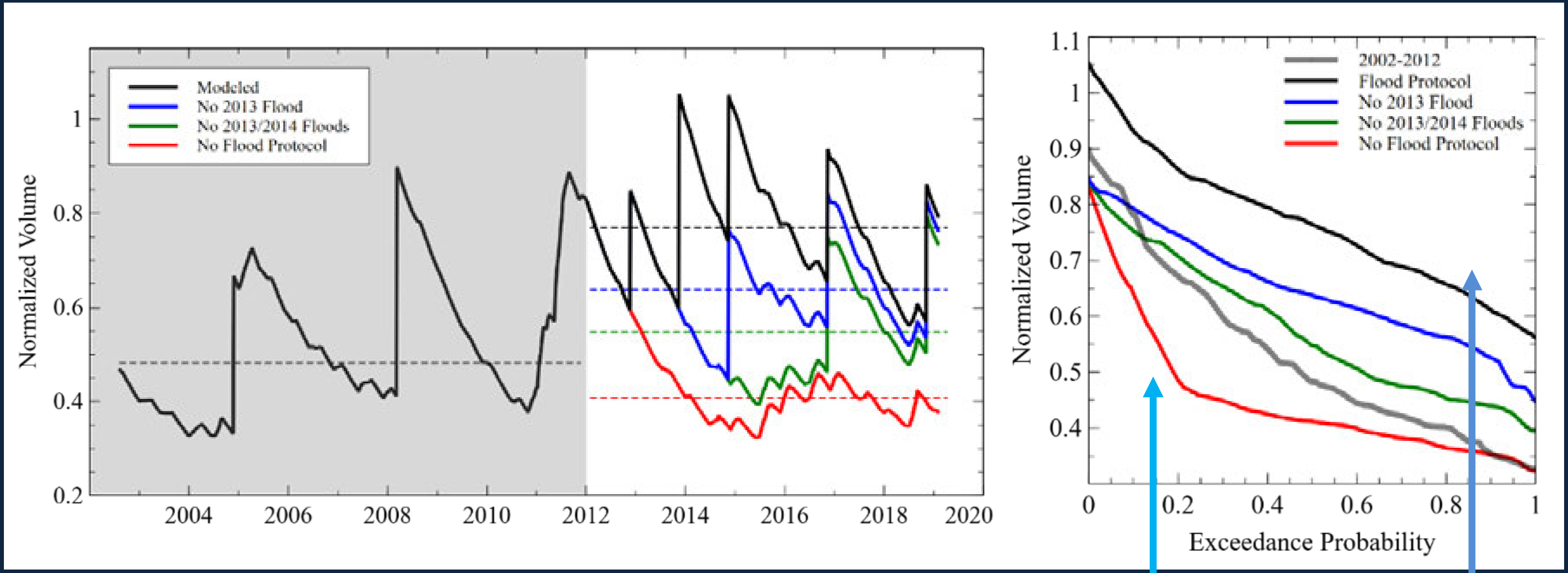
The model is relatively insensitive to the calibration data if they occur over a representative range of conditions. This suggests that physical processes are reasonably well-represented in the model equations.

Preliminary data and results, subject to review, do not cite

Post-hoc Controlled Flood Scenario Modeling

Model simulations reducing the number of HFEs

Proportion of time sandbars are larger during HFE protocol.



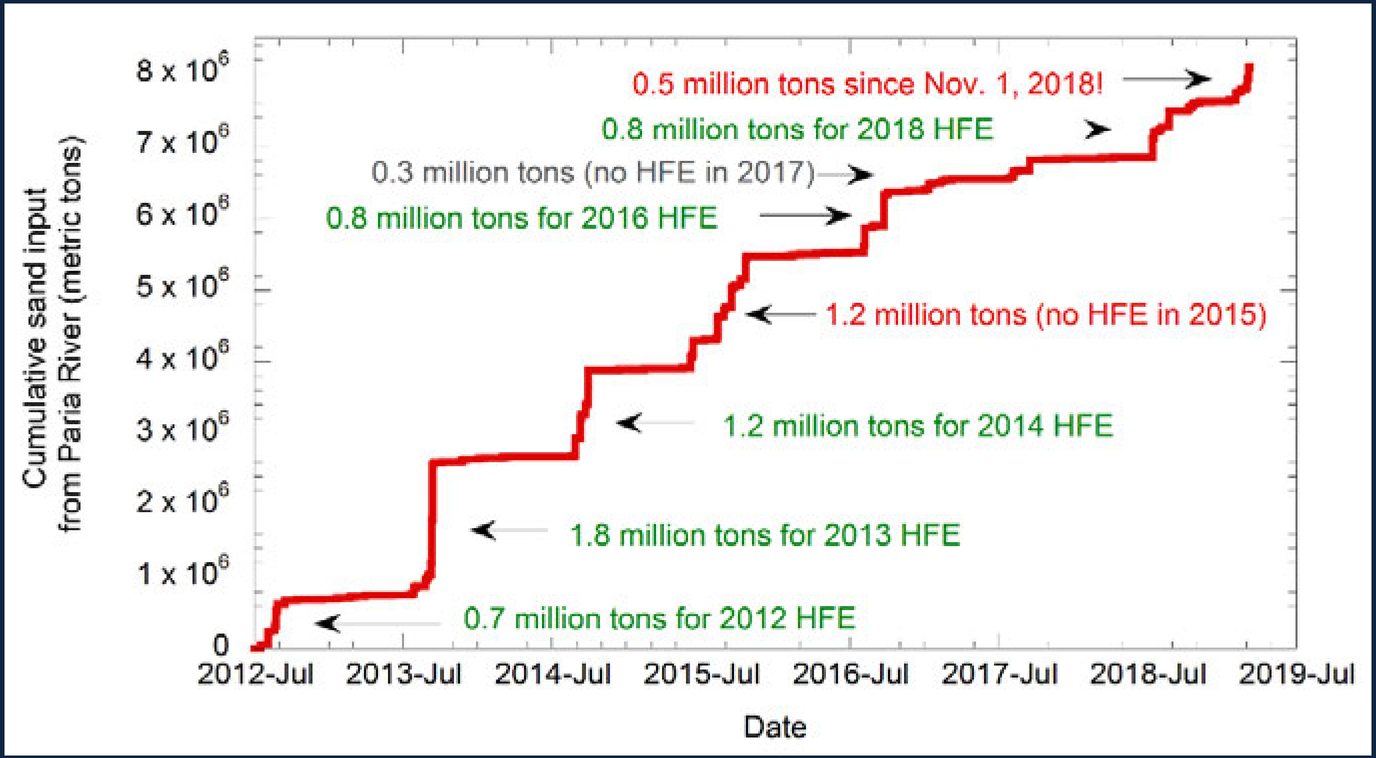
Fewer HFEs = reduced sandbar size

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.

Preliminary data and results, subject to review, do not cite

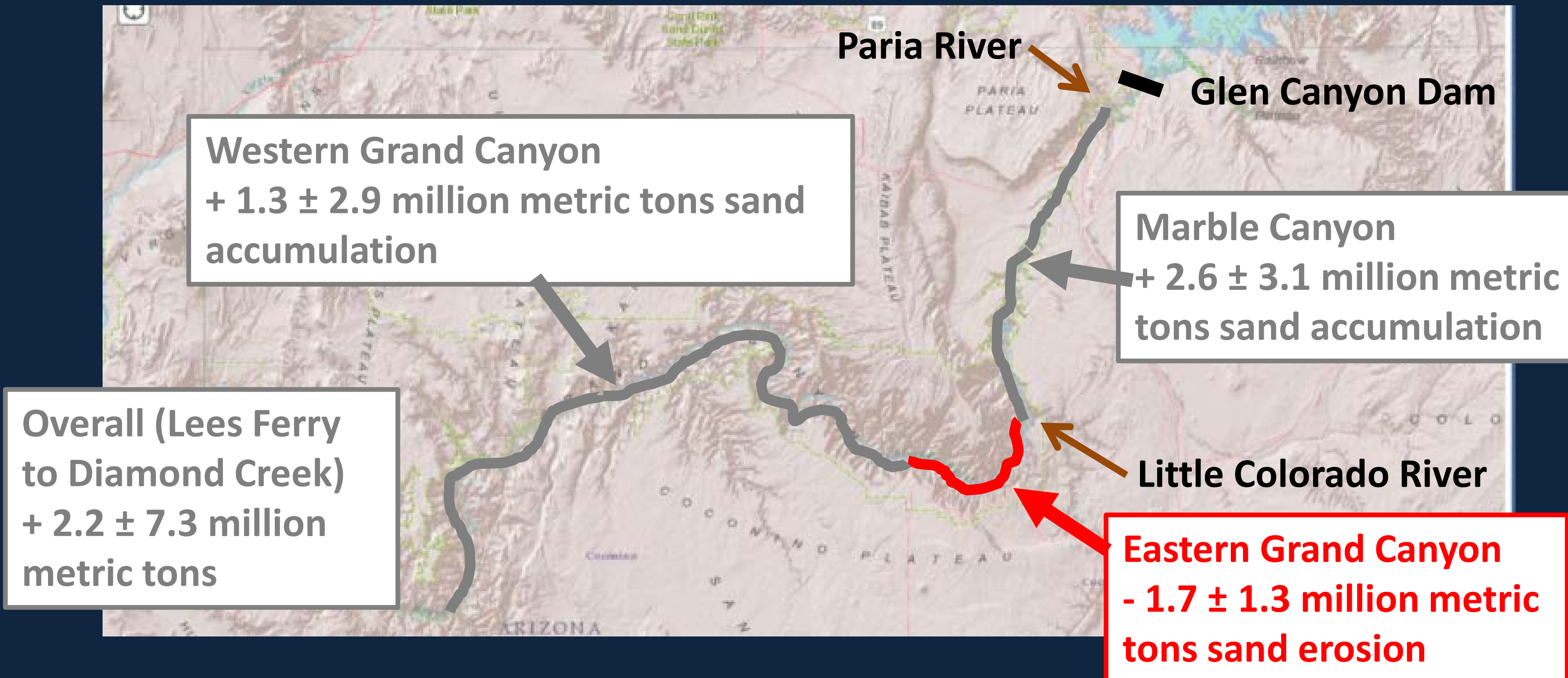
Will HFEs continue to be effective-1?



- Since 2012, the average July-Nov sand inputs have been about 970,000 metric tons, which is about the same as historical average values
- Paria River continues to be a reliable, but unpredictable, source of sand
- Future success depends on continued sand inputs from Paria and Little Colorado rivers

Will HFEs continue to be effective-2?

Sand Budget in Grand Canyon: 2012-2018



- Alternating segments of significant sand accumulation and erosion
- Overall accumulation (but not significant)

→ No evidence for overall net evacuation or accumulation

www.gcmrc.gov/discharge_qw_sediment

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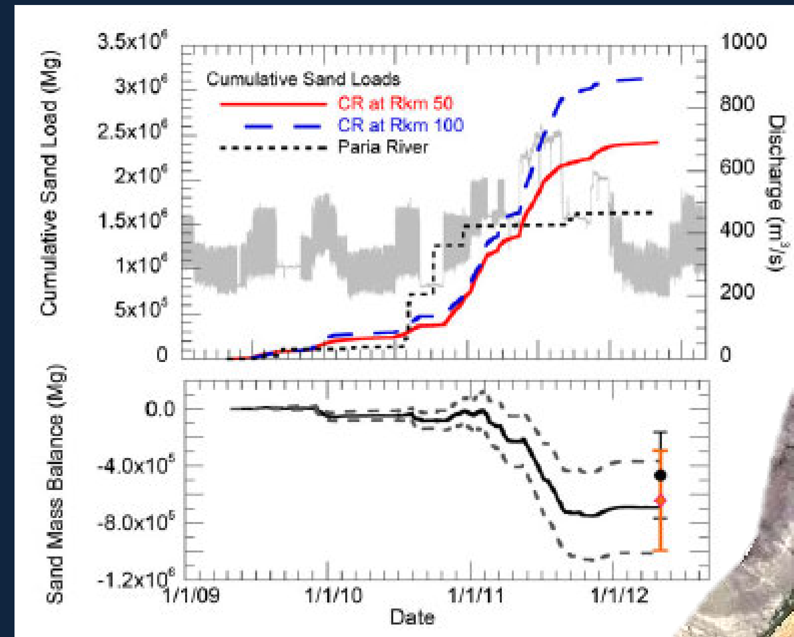
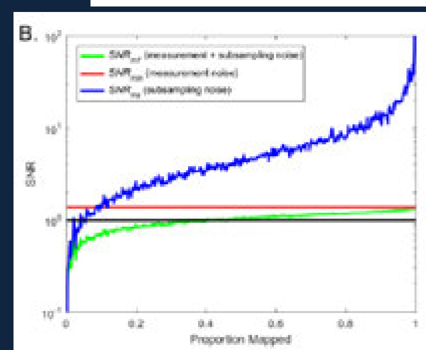
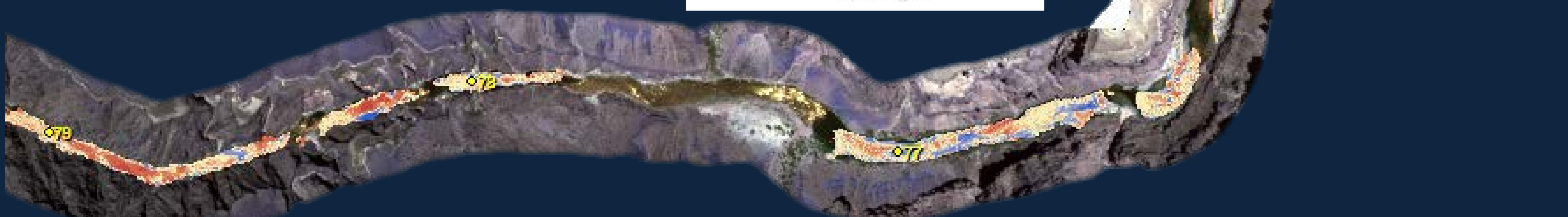
Will HFEs continue to be effective-3?

- Periods of sustained high dam releases (e.g. 2011 equalization flows) result in net sand evacuation.
- Frequency of equalization years will affect long-term sand budget and likelihood of continued success of high flows.
- Repeat maps of river channel show changes in sand storage with well-constrained uncertainty that does not increase over time.
  - Requires measurements comprising ~60% of a study reach or more to see past variability







Grams and others (2019)

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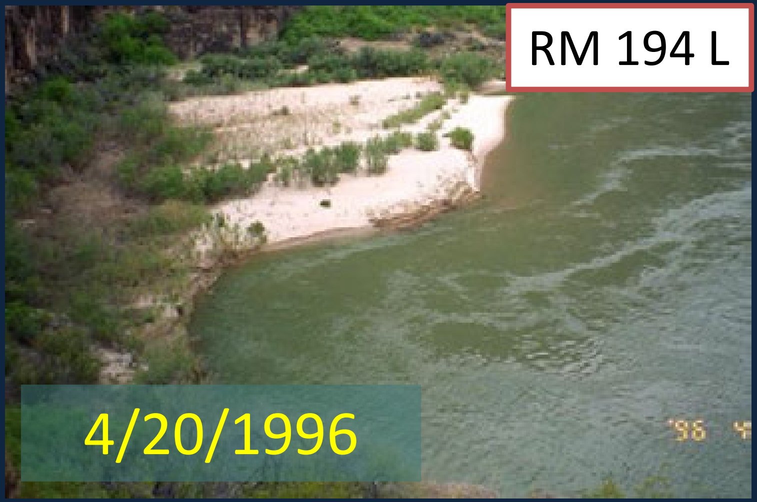
What are the HFEs not doing?

- Not depositing sandbars substantially larger than observed in past HFEs?
- Not depositing sandbars at substantially more locations than observed in past HFEs.
- Response likely constrained by HFEs that are all within narrow range of magnitude and duration.
- Response may also be constrained by hydrograph shape.
- Not removing vegetation or causing channel width to increase



Summary

- Each HFE since 2012 has resulted in sandbar deposition
- Increases in sandbar size occur at 50% or more of monitoring sites.
- Although bars erode, they are larger than they would be without HFEs
  - Some bar types are at least 70% of maximum size 80% of the time, compared to achieving that size only 20% of the time before HFE protocol
- HFEs do not scour or remove vegetation.
- There is evidence for cumulative increases in bar size at some sites.
- Sand budget is indeterminate (no definitive evidence for increase or decrease)
  - Indicates that it is possible to build sandbars with HFEs while maintaining sand supply during periods of ~average inputs and ~average release volumes (no equalization)

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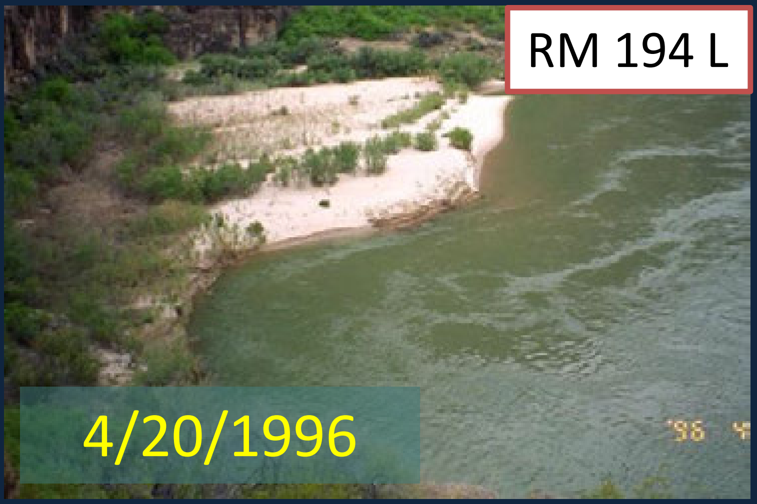
Next steps

- LTEMP calls for evaluation of HFE program after 10 years of implementation (Oct. 2027)
  - In addition to sandbar monitoring results, we will have full evaluation of impact on sand storage in the channel and low-elevation parts of eddies.
- Results indicate future HFEs implemented following the protocol should continue to be equally successful
- Expect some progressive increases in some sandbars
  - Likely will reach upper limit constrained by magnitude of HFE releases.
- May experiment with hydrograph shape to affect sandbar shape (e.g. slope of bar front).
- Address vegetation…

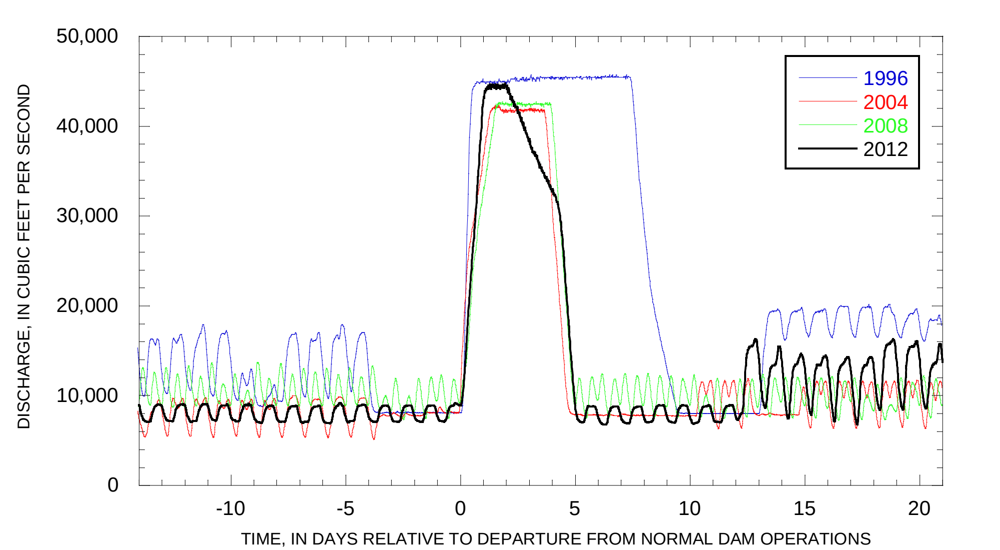


HFE Design Experiments-1

- Extended duration HFEs
  - Up to 8-10 days (compared to 4 days as currently implemented)
  - Only if there is “enough” sand
  - If enough sand, could build larger and more numerous bars
  - LTEMP simulations estimated conditions might occur 5 times in 20 years, LTEMP ROD allows 4 implementations

1996 HFE was 8 days, but was not designed to match recent sand inputs

Makes sense to test when conditions occur.

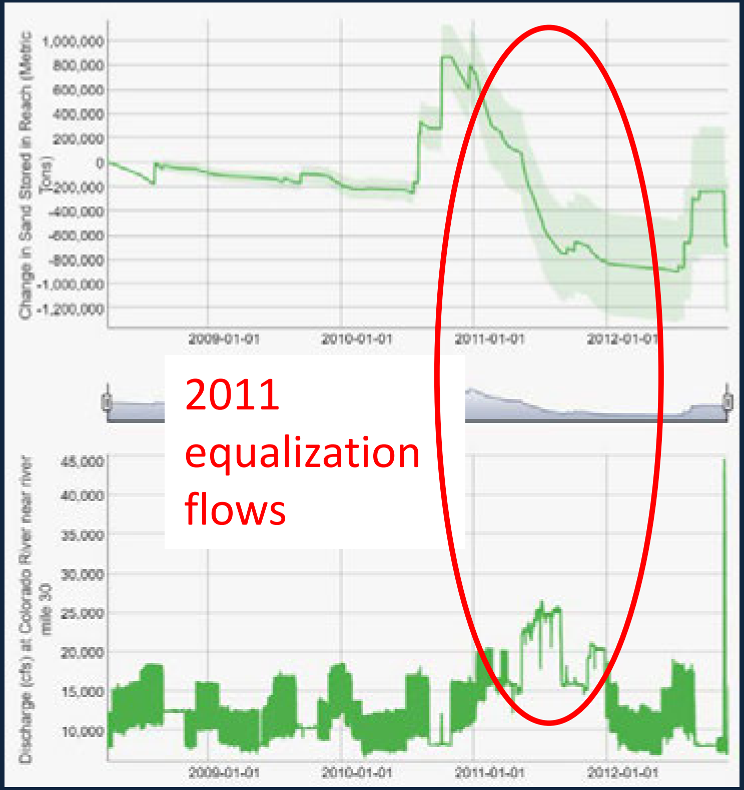


- Monitoring needed for comparison with other HFEs
  - Monitoring sand concentration
  - Sandbar monitoring at all sites with complete surveys
  - Daily surveys at selected sites to measure changes in deposition rates during HFE

Data from: https://www.gcmrc.gov/discharge_qw_sediment

HFE Design Experiments-2

- Proactive HFEs
  - Spring HFE released regardless of sand trigger in advance of summer equalization flows
  - Goal is to create some high-elevation sand deposits in advance of erosion that will occur during sustained high releases.
  - LTEMP simulations estimated conditions might occur twice in 20 years



Makes sense to test when conditions occur.

Conditions in 2011 "inspired" idea for proactive Spring HFE – large sand inputs during previous fall followed by equalization flows

- Monitoring needed for comparison with other HFEs
  - Monitoring sand concentration
  - Sandbar monitoring at all sites with complete surveys
    - Compare deposition with other HFEs
    - Measure summer erosion (what is the size of bars following equalization compared to before the proactive HFE?)

Data from: https://www.gcmrc.gov/discharge_qw_sediment

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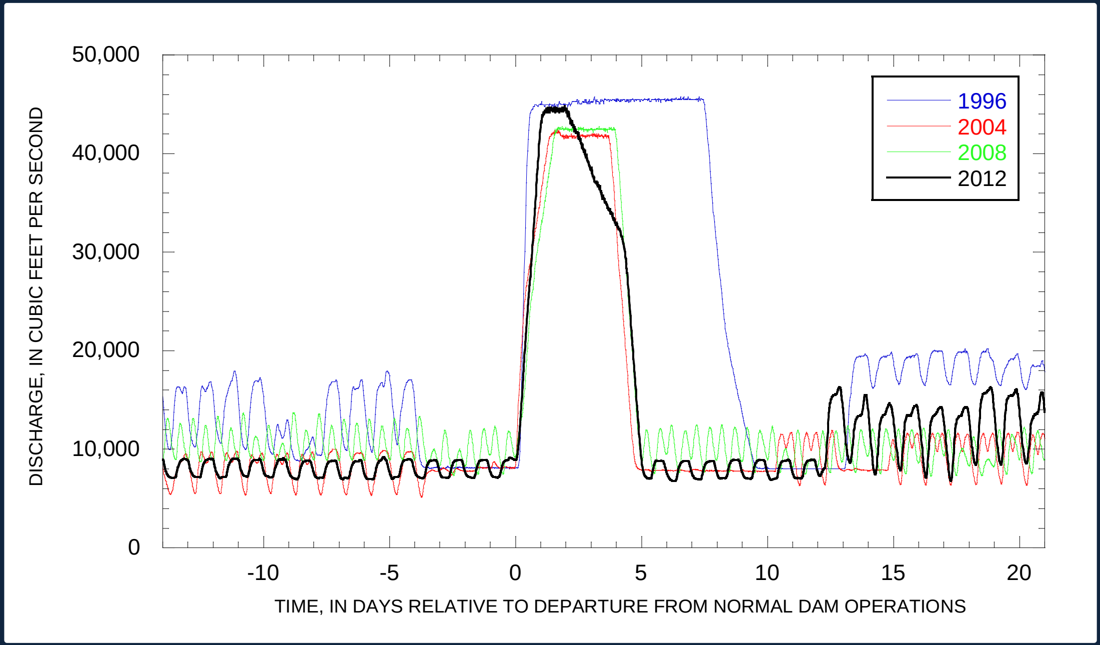
HFE Design Experiments-3

- Changes to hydrograph shape (lower downramp rate)
  - Deposition at range of elevations, instead of focused at elevation of peak stage
  - Expected to produce sandbars that have lower slope on bar face
  - Tested in 2012
    - Limited monitoring indicated some bars did have lower slopes
    - Bars still eroded, but lack enough measurements to compare erosion rates.

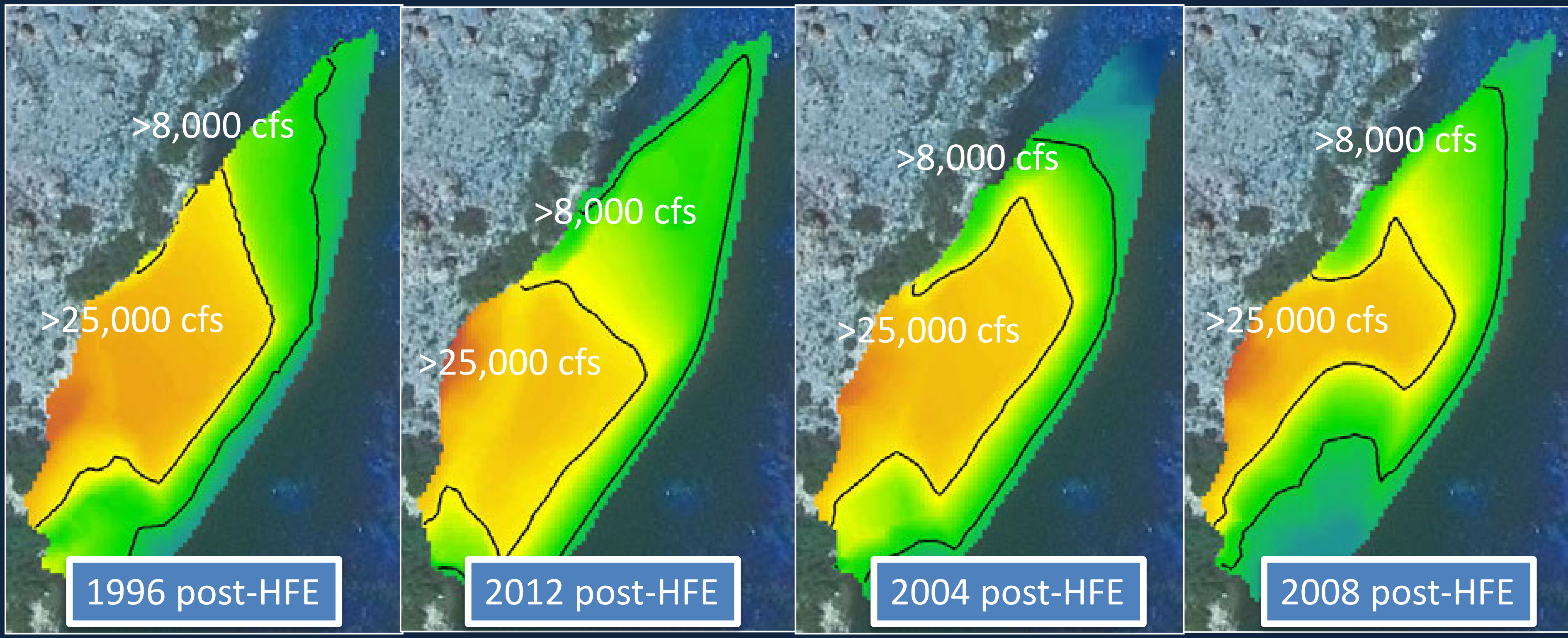


Data from: https://www.gcmrc.gov/discharge_qw_sediment

Since all releases above powerplant capacity count towards the HFE duration, lower downramp comes at expense duration of peak sand concentrations. Best experiment might be to follow a "regular" 96-hour HFE with slow downramp as part of extended duration HFE test.

- Monitoring needed for comparison with other HFEs
  - Sandbar monitoring at all sites with complete surveys
    - Compare deposition with other HFEs

HFE Design Experiments-4



Surveys before and after 2012 HFE at 3 large reattachment bars

- *Bar volume largest in 1996 (highest discharge and longest duration), area above 8,000 cfs stage largest in 2012 (gradual downramp)*
- Slope from bar crest to 8,000 cfs level less steep than other floods

HFE Design Experiments-5

- Low-magnitude HFE (HFE at or near powerplant capacity of 31,500 cfs)
  - Not identified as “experiment” in LTEMP.
  - Allowed by HFE protocol
  - But they have not yet occurred

Is there interest in comparison with larger HFEs if a low-magnitude HFE does occur?

- Monitoring needed for comparison with other HFEs
  - Sandbar monitoring at all sites with complete surveys
    - Compare deposition with other HFEs

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