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

Project B Update and Riverbed and sandbar response to dam operations and high-flow experiments

Glen Canyon Dam Adaptive Management Program
Annual Reporting Meeting
January 24, 2024

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Southwest Biological Science Center
Grand Canyon Monitoring and Research Center

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Project B personnel:

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Thomas Gushue and Erica Byerley

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Additional collaborators and field assistants:
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photo: Geoff Gourley

photo: Jeff Behan

photo: Geoff Gourley

NORTHERN ARIZONA UNIVERSITY

GRAND CANYON RIVER GUIDES

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Project B: Sandbar and Sediment Storage Monitoring and Research

- Project Elements
  - B.1 Sandbar Monitoring
  - B.2 Bathymetric and topographic mapping for monitoring long-term trends in sediment storage
  - B.3 Control Network and Survey Support
  - B.5* Sediment and Sandbar Modeling
  - FY 2023 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 and model interactions between dam operations, sand transport, and eddy sandbar dynamics.
- Cooperators: Grand Canyon River Guides, Southern Utah University, Northern Arizona University

** Funded with carryover and non-AMP supplemental sources.*

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 monitoring efforts and modeling:
  - 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.
  - Modeling to predict fine sediment transport and sandbar response

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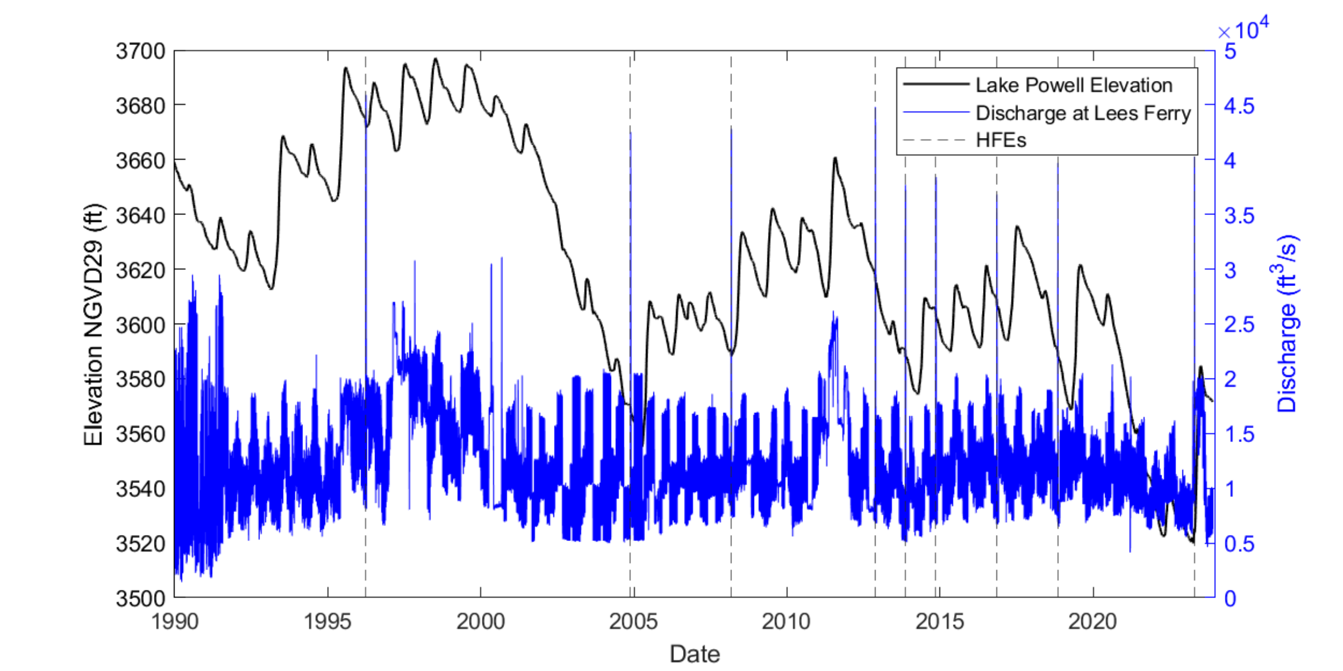
April 2023 HFE

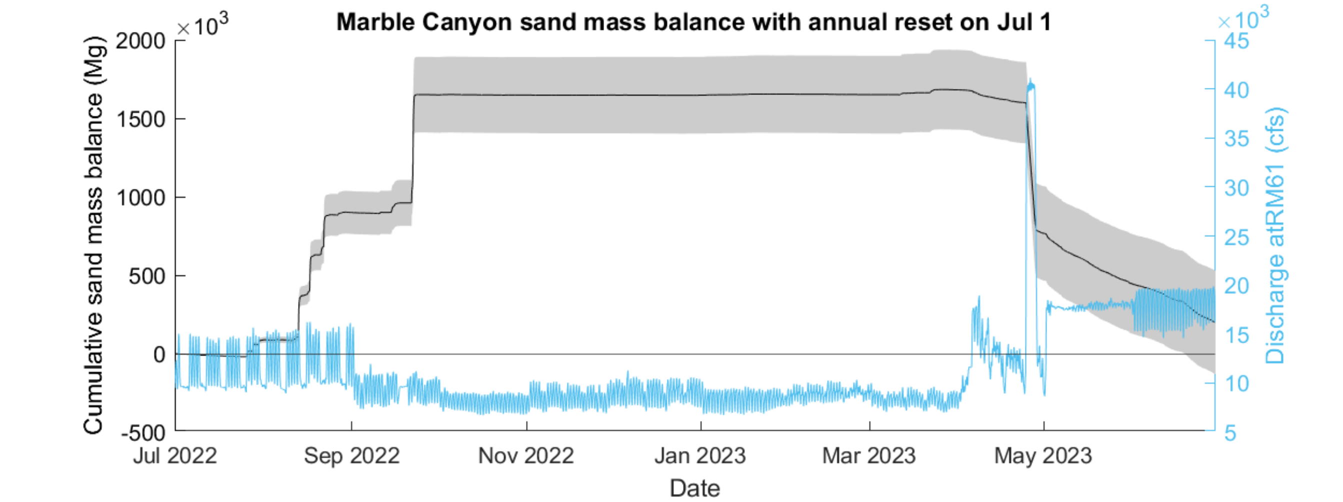
Reservoir conditions

- All previous HFEs implemented when Powell was at ~3550 feet or higher
- April 2023 HFE implemented at ~3525 feet, but ahead of anticipated rise of > 50 feet



Sediment conditions

- More than 1.5 million Mg sand accumulation in Marble Canyon between 7/1/2022 and HFE.
- HFE exported from Marble Canyon ~ 1 million MG of sand.
- Summer 2023 operations exported additional ~700,000 Mg of sand.



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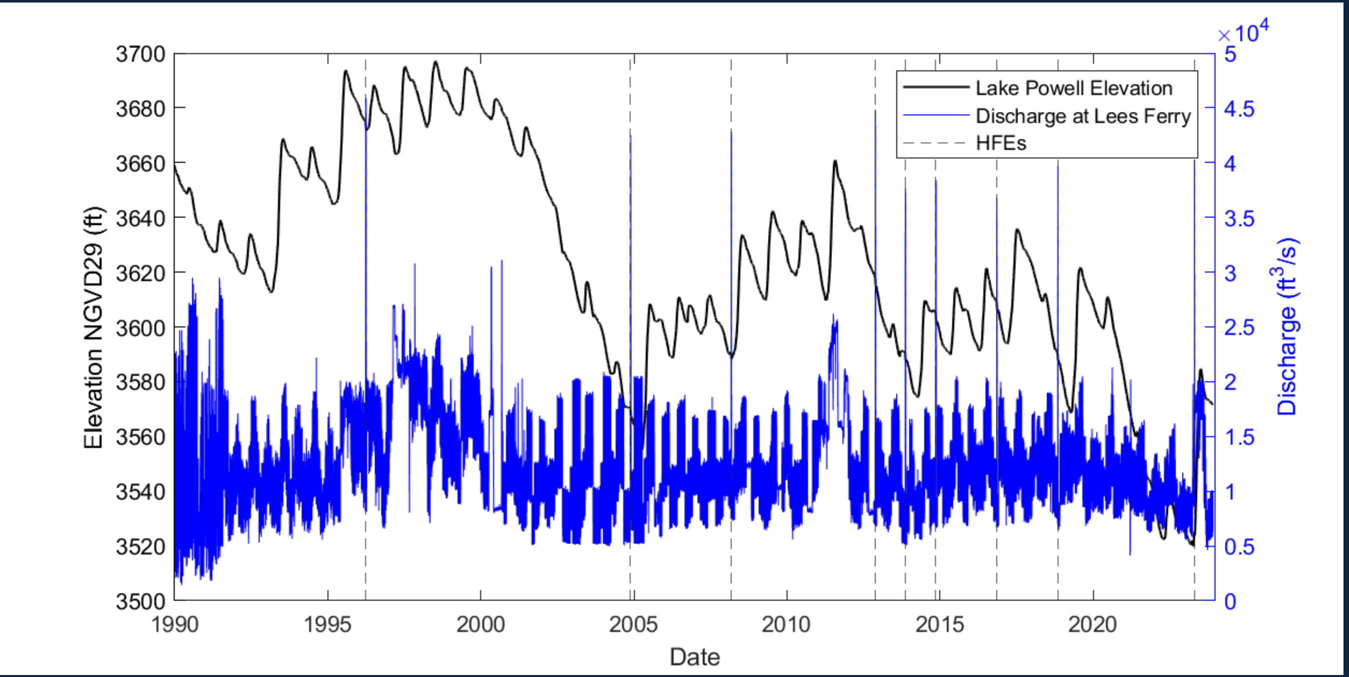
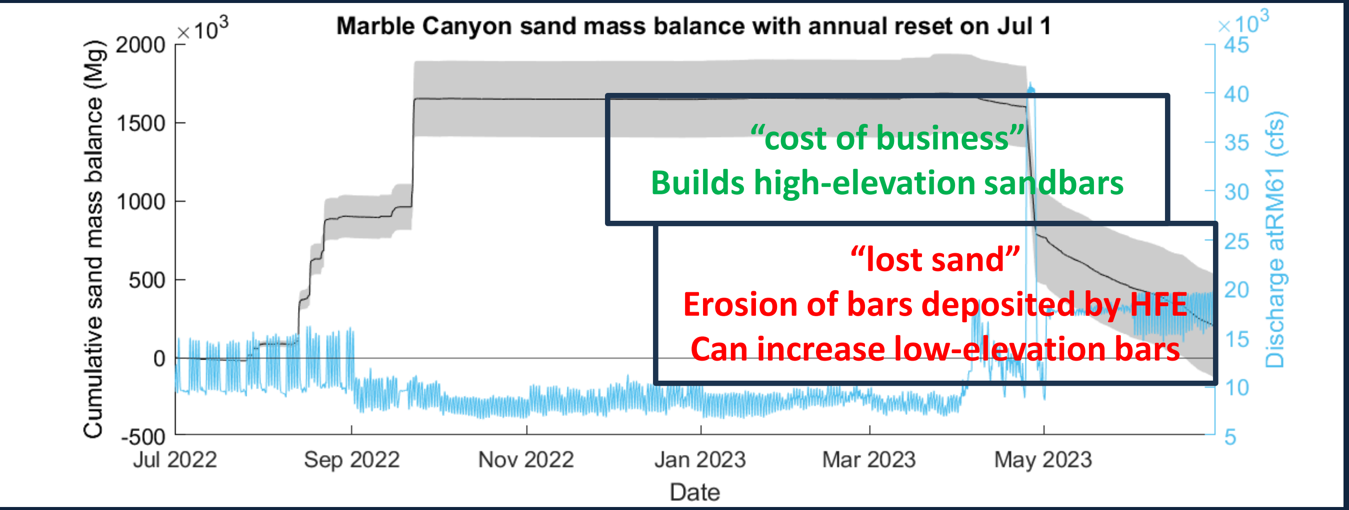
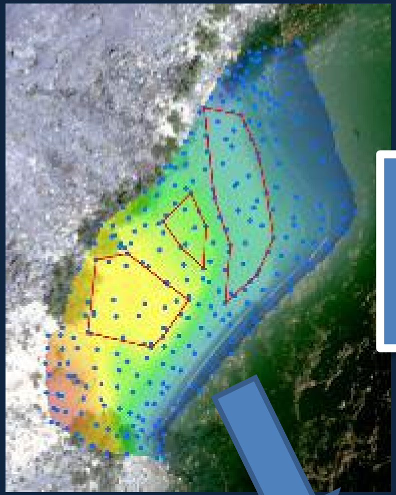


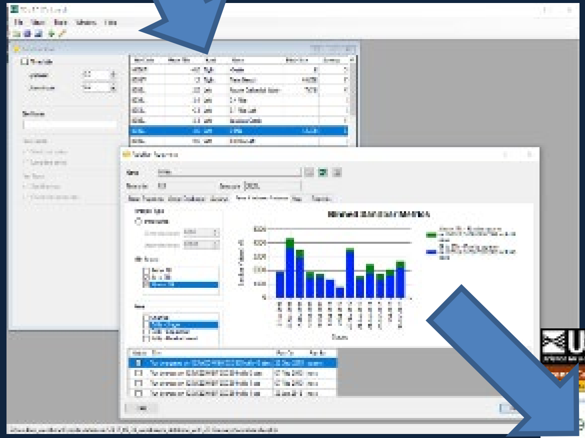


Sandbar monitoring data

data processing and analysis



Topographic surfaces modeled in survey software



Data processed and analyzed in sql database

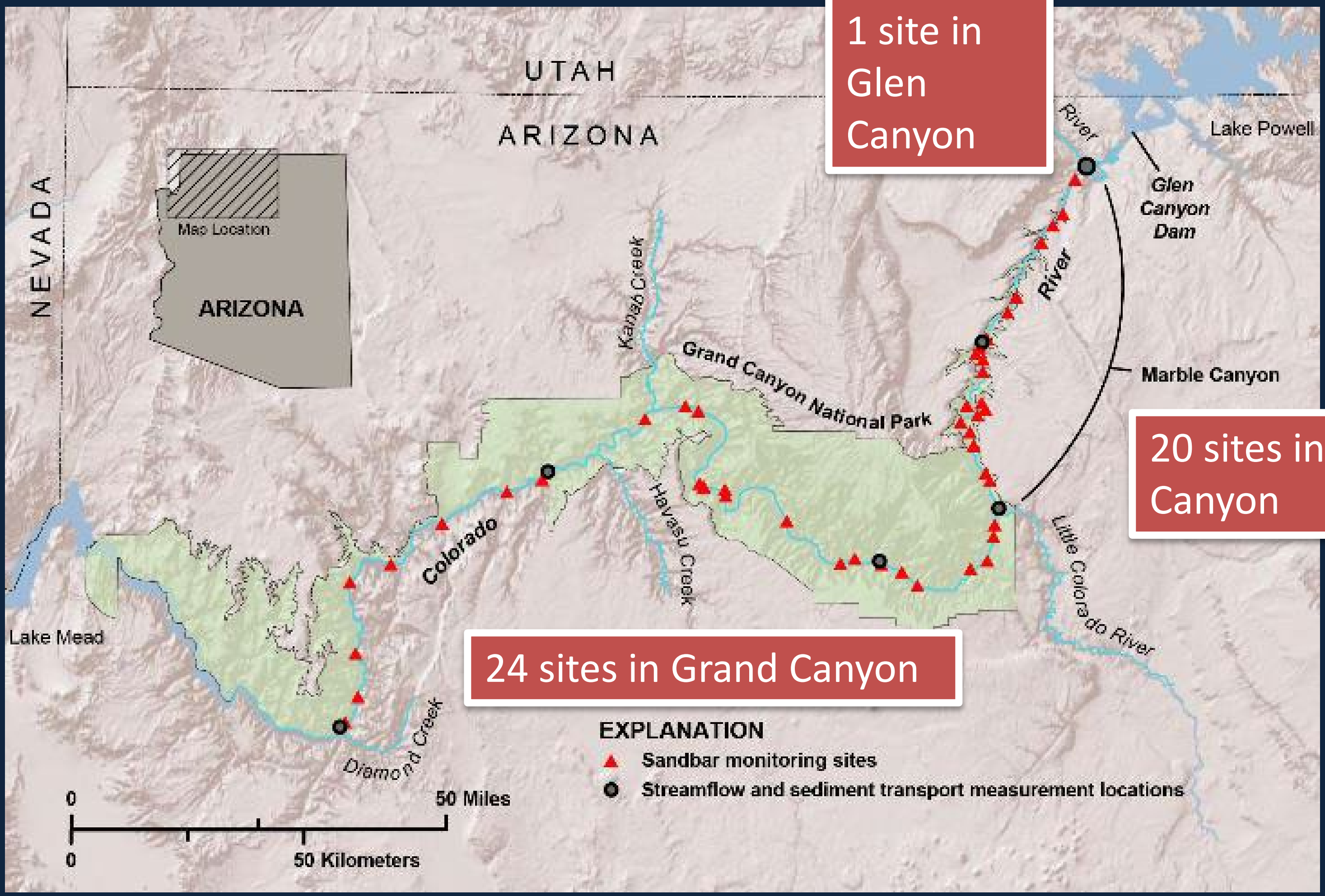
Data served in sandbar web application

Data collection: 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.)

Hazel and others (2022); www.usgs.gov/apps/sandbar

Sandbar monitoring study sites



1 site in Glen Canyon

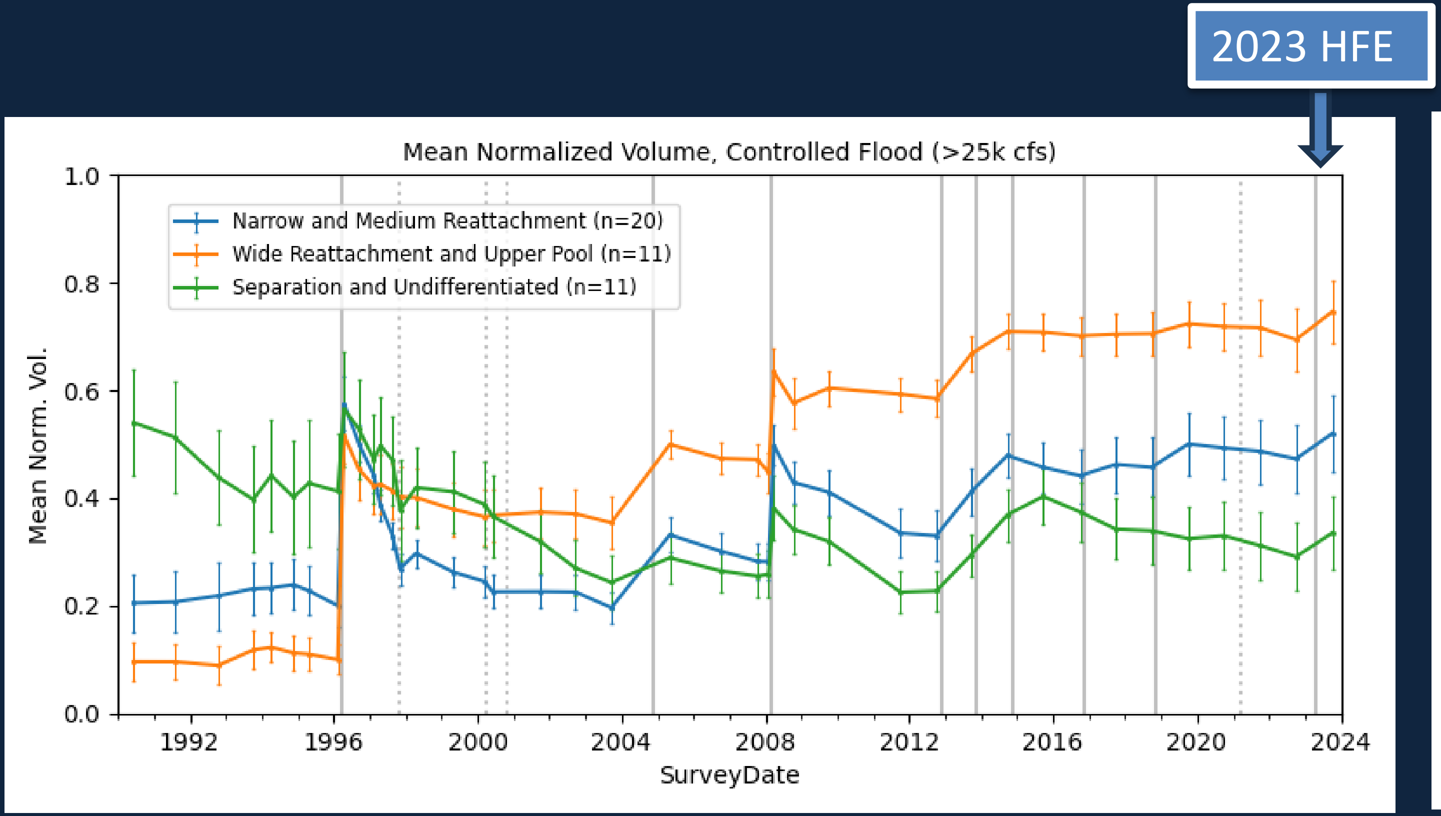
20 sites in Marble Canyon

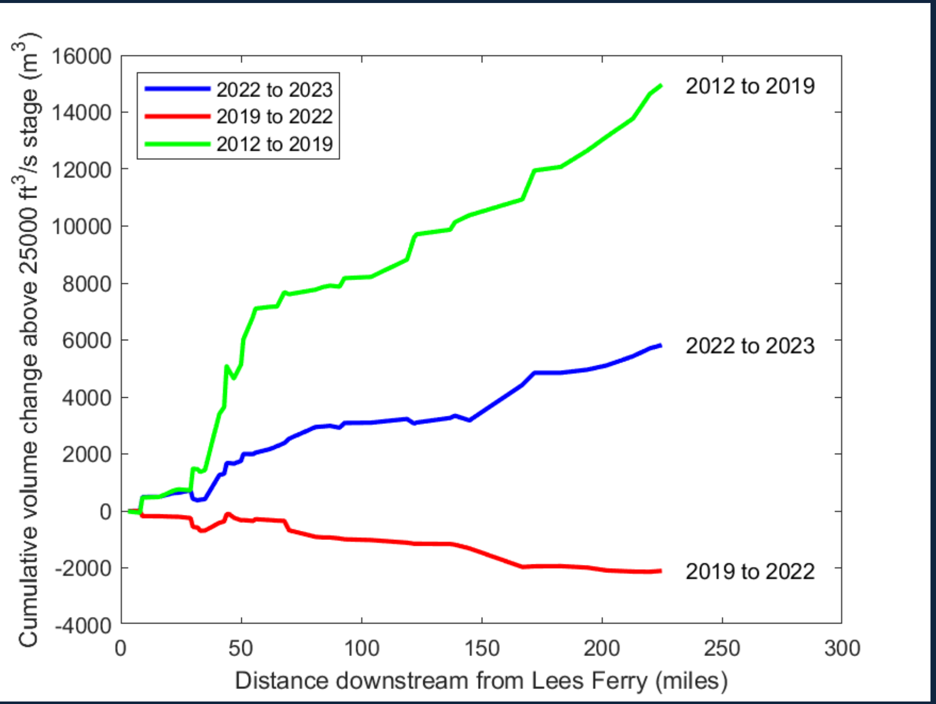
24 sites in Grand Canyon

Monitoring Data

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

Sandbar response to 2023 HFE





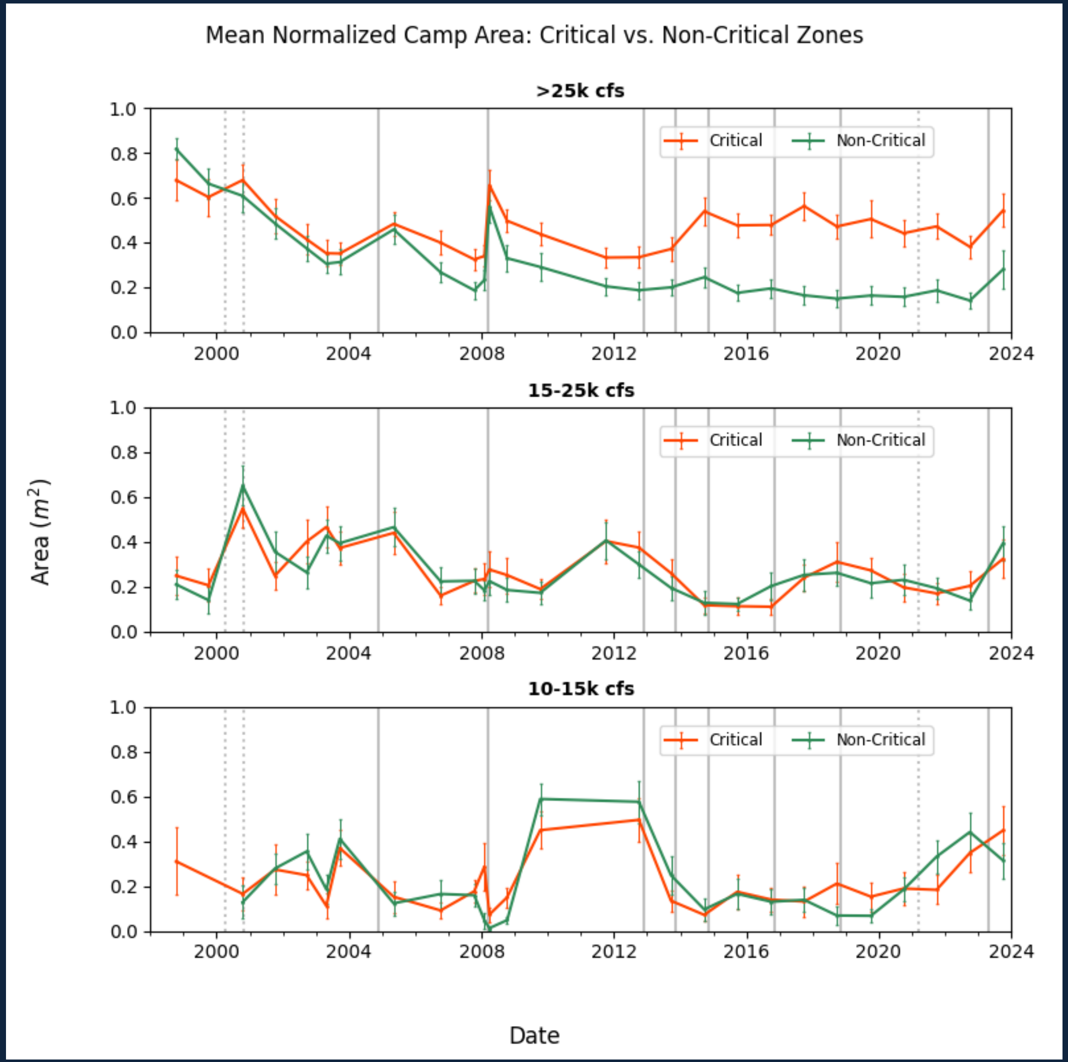
- Reattachment bars and upper pool bars as large or larger compared to 2013-2019
- Separation and undifferentiated bars increased, but not as large as some previous years

- HFE reversed 2019 to 2022 downward trend
- Increases in bar volume at most, but not all, sites

Campsite response to 2023 HFE

- Increases in campsite area in critical and non-critical camping reaches
- Loss in campsite area only in non-critical reach below 15,000 cfs stage

** Critical reaches are those reaches where campsites are fewer than average and finding a campsite can be competitive.*



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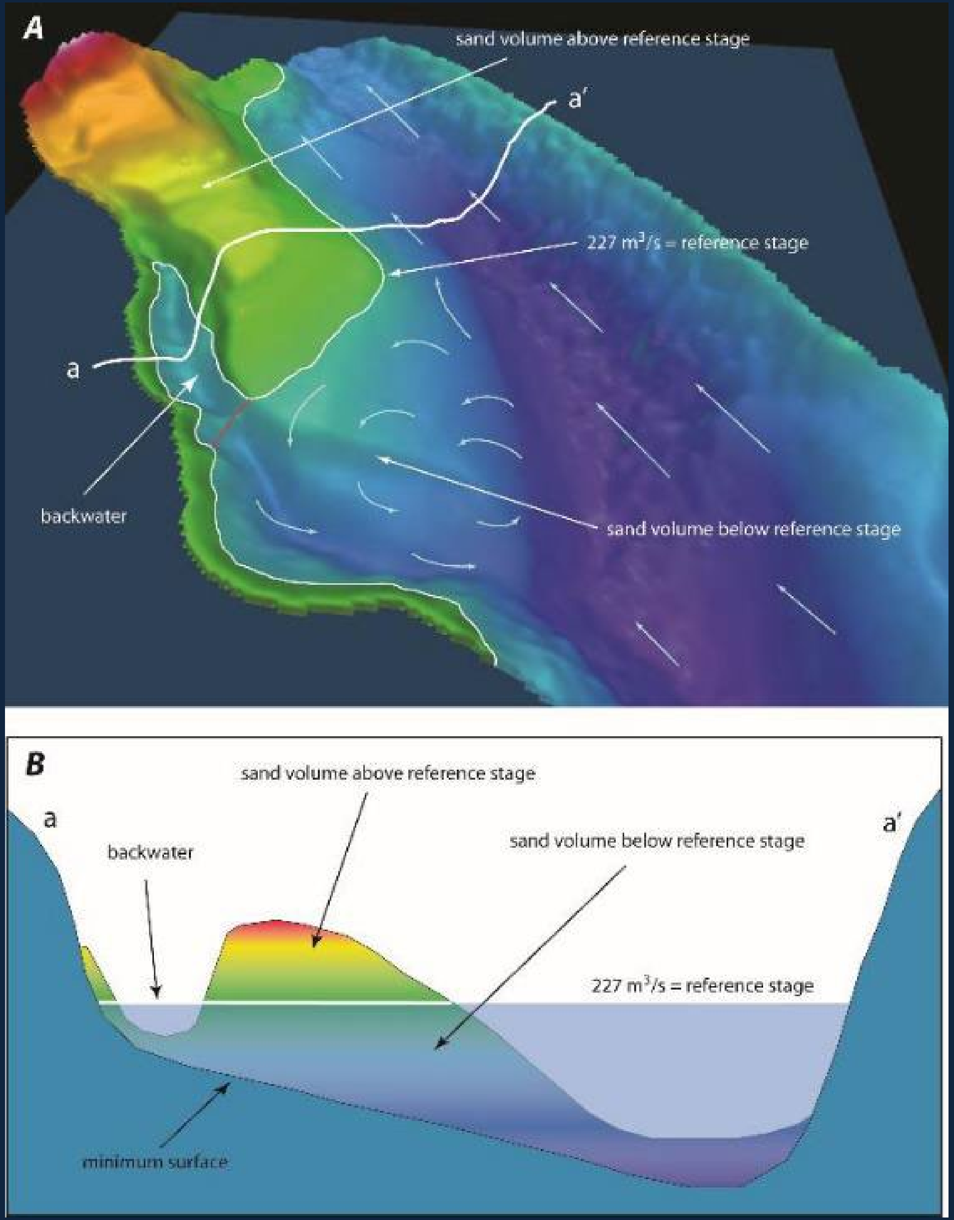
Why measure sand storage by mapping the riverbed?

- Sandbar replenishment controlled by:
  - Flow (need high flows to build large bars)
  - Sand supply (if supply in the channel is low, a net loss from eddy sandbars is risked)
- Sand supply is controlled by:
  - Dam releases (annual volume and release pattern)
  - Inputs from tributaries

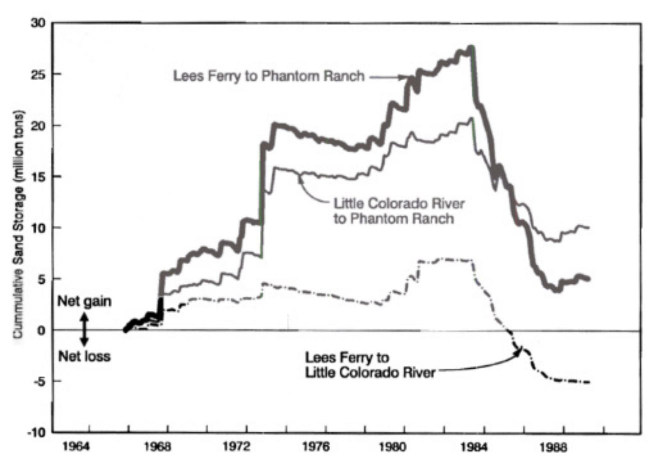
- The sand that builds sandbars is stored on the bed of the river and understanding the sand supply is critical to understanding and predicting sandbar response



Adapted from Hazel and others (2010)

Sand Budgets in Grand Canyon have been incorrect or ambiguous because of inadequate measurements or because of measurement uncertainty

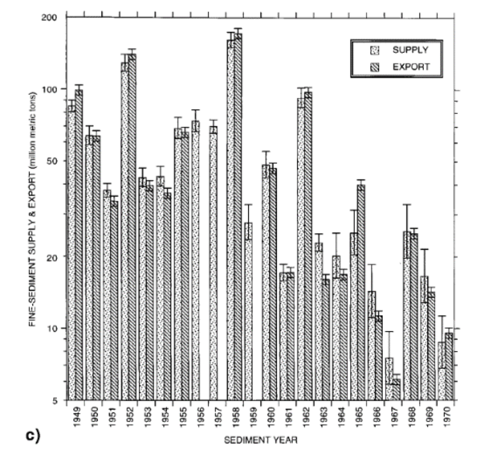
1990's



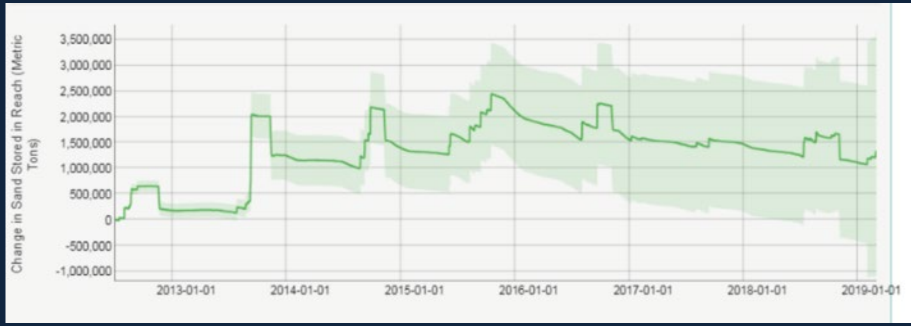
Stable rating curves → **sand accumulation**
(Glen Canyon Dam Environmental Impact Statement, 1994)

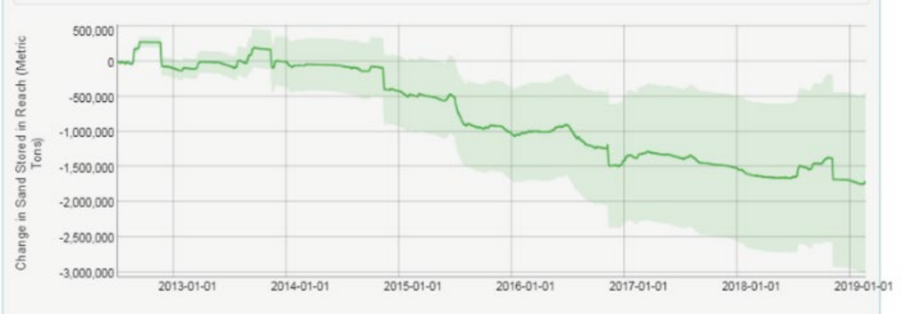
2000's

Analysis of historical data → **no accumulation**
(Topping et al., 2000)



2010's





Continuous measurements of flux →
either accumulation or evacuation may occur, and uncertainty is large

How are channel mapping data used to evaluate the effects of dam operations?

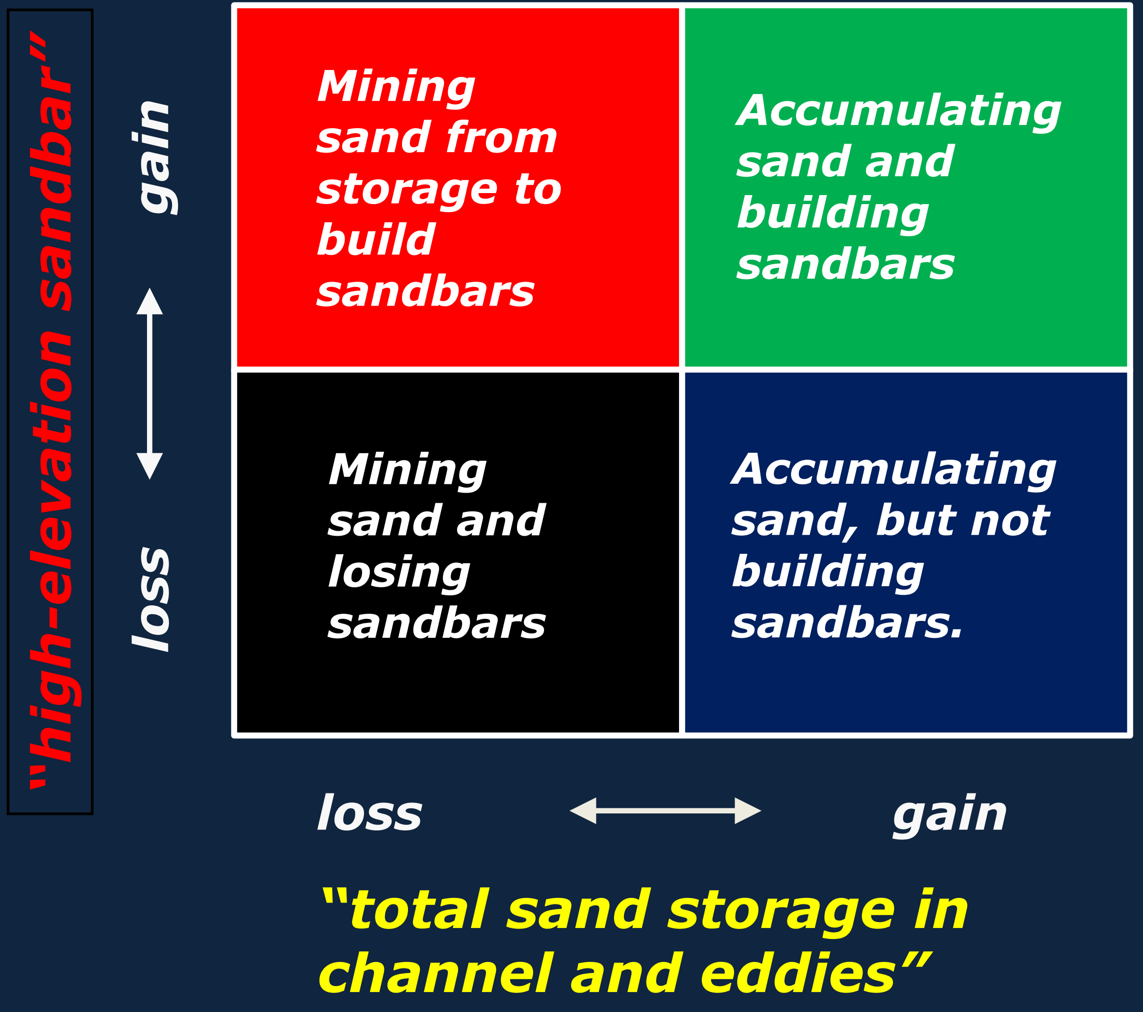
"high-elevation sandbar" (gain ↕ loss)

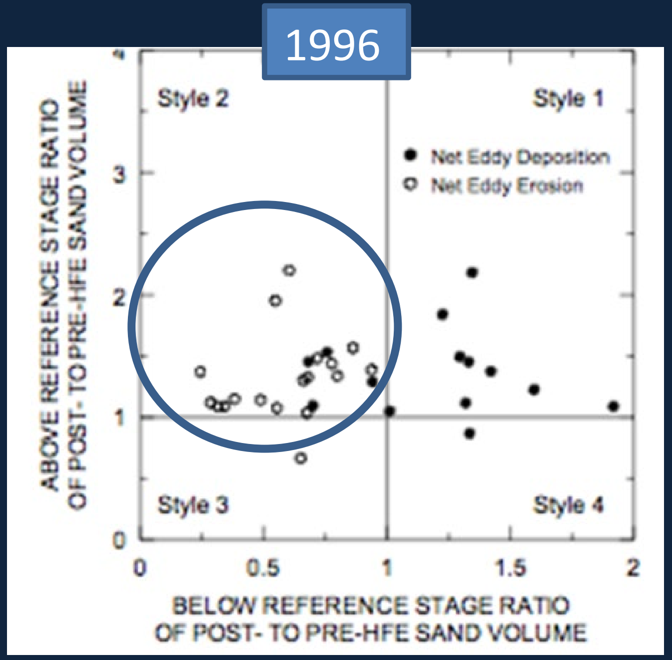
	loss	gain
gain	***Mining sand from storage to build sandbars***	***Accumulating sand and building sandbars***
loss	***Mining sand and losing sandbars***	***Accumulating sand, but not building sandbars.***

loss ⟷ gain

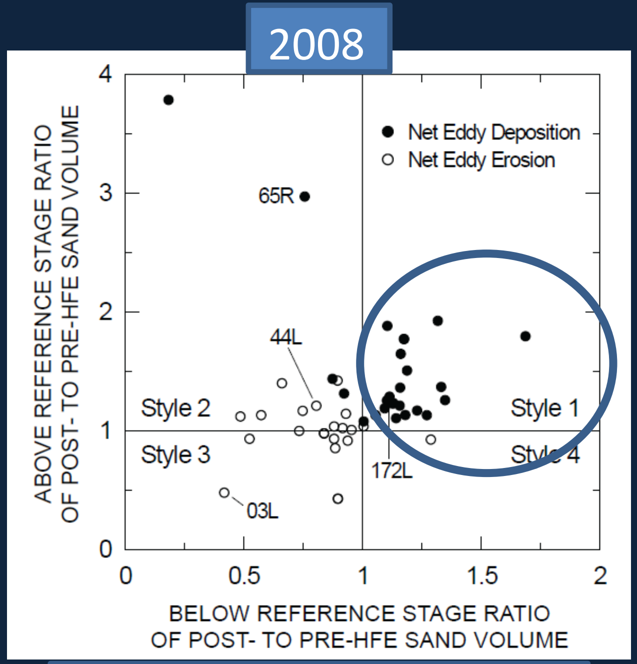
"total sand storage in channel and eddies"

How are channel mapping data used to evaluate the effects of dam operations?





More sites with net eddy erosion

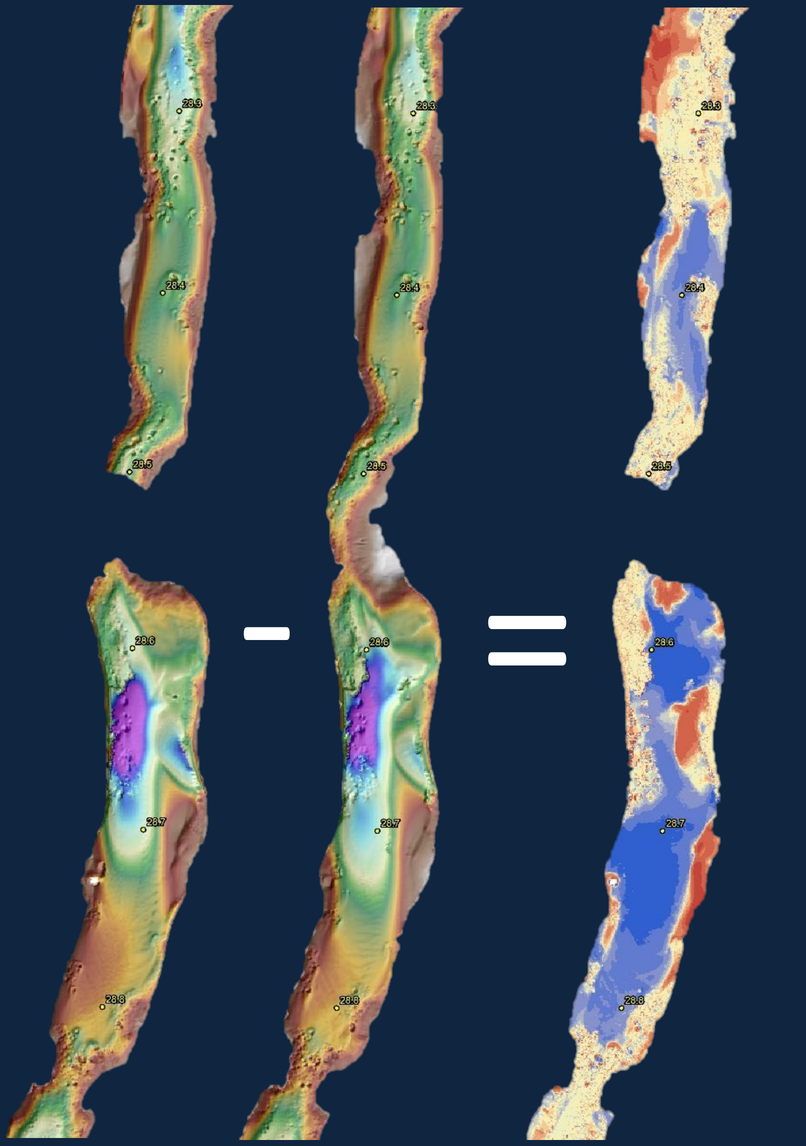


More sites with net eddy deposition

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

How we measure sand storage on the bed

- Repeat topographic and bathymetric measurements
  - Multibeam sonar
  - Singlebeam sonar
  - Total station
- Referenced to geodetic control network
- Use backscatter to classify sand/gravel/rock
- High spatial resolution
- Uncertainty accumulates spatially – not over time



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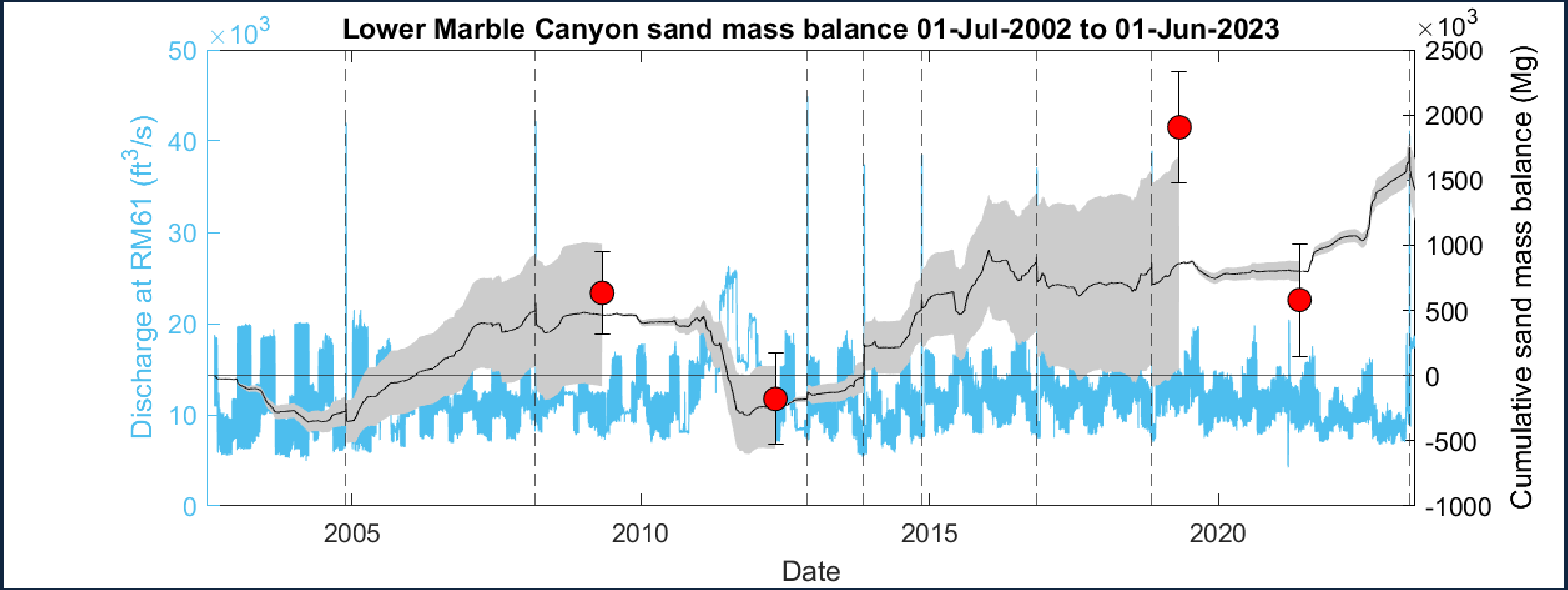
Repeat channel mapping in Lower Marble Canyon

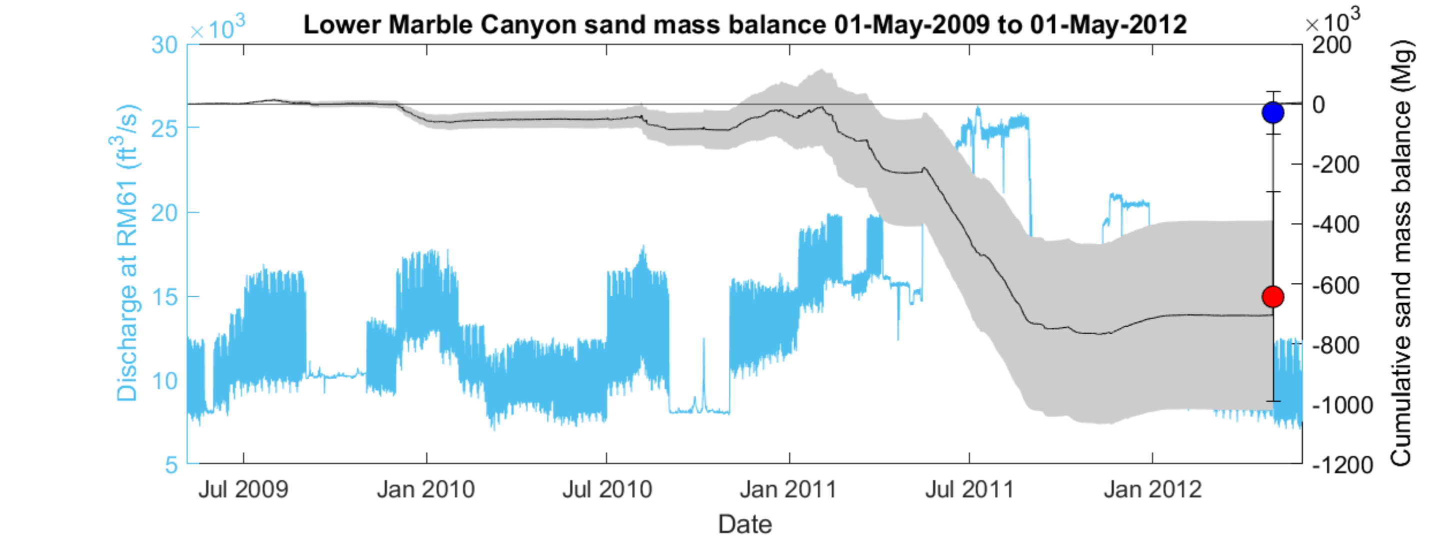


- Repeat measurements of channel bed (red points) verify mass balance sand budget (black line with gray uncertainty band)
- Sand budget has trended upward with the exception of periods of high dam release volumes (equalization and reservoir balancing flows)

Repeat channel mapping in Lower Marble Canyon

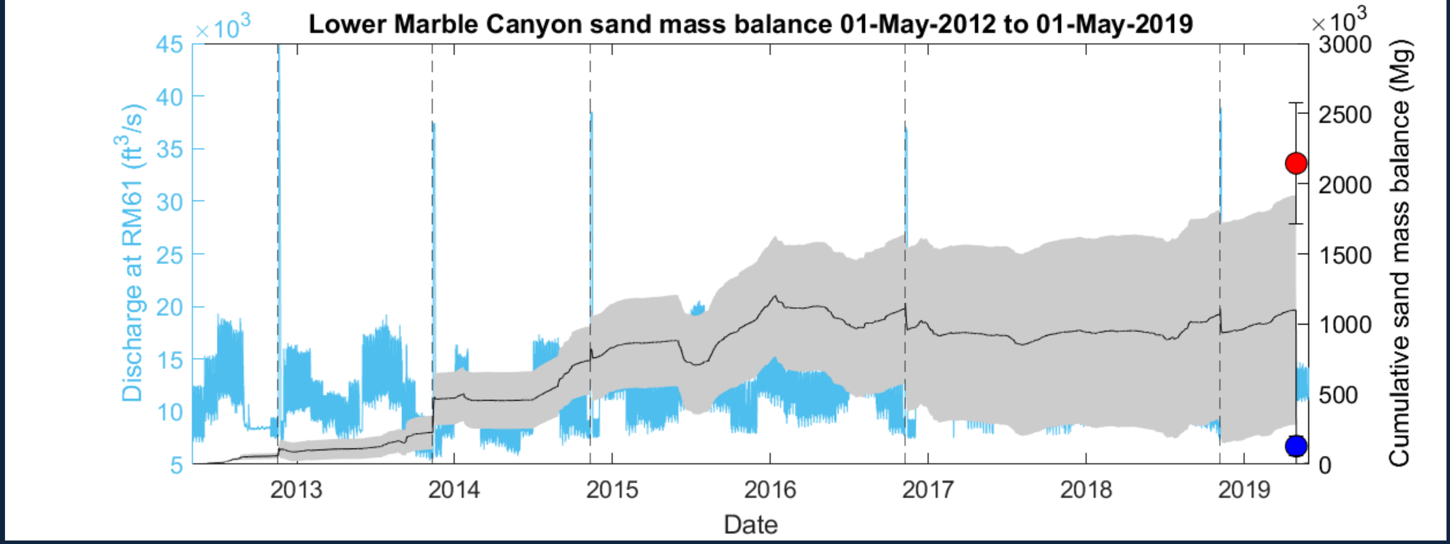
2009 to 2012

- Period of sand erosion during equalization flows
- Sand volume change above 8,000 ft^3/s stage (blue) is ~4% of total erosion (red)

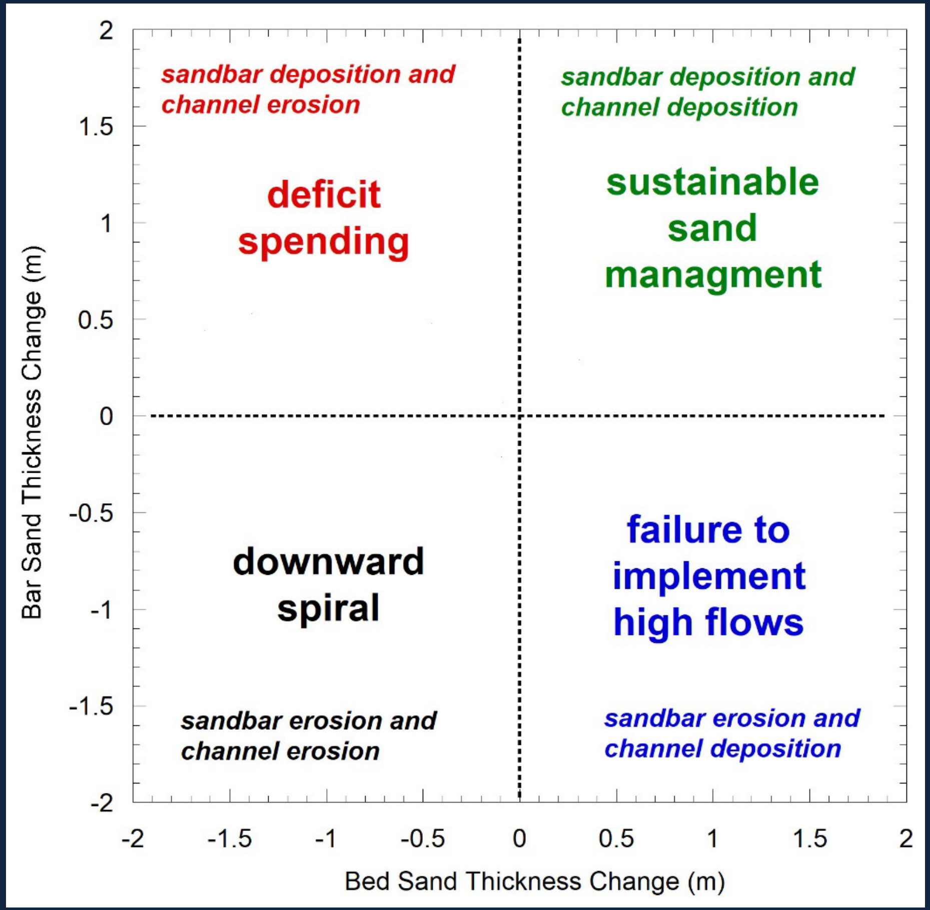


2012 to 2019

- Period of sand accumulation
- Sand volume change above 8,000 ft^3/s stage (blue) is ~6% of total accumulation (red)



Repeat channel mapping: Implications for high flows and dam management



Repeat channel mapping: Implications for high flows and dam management

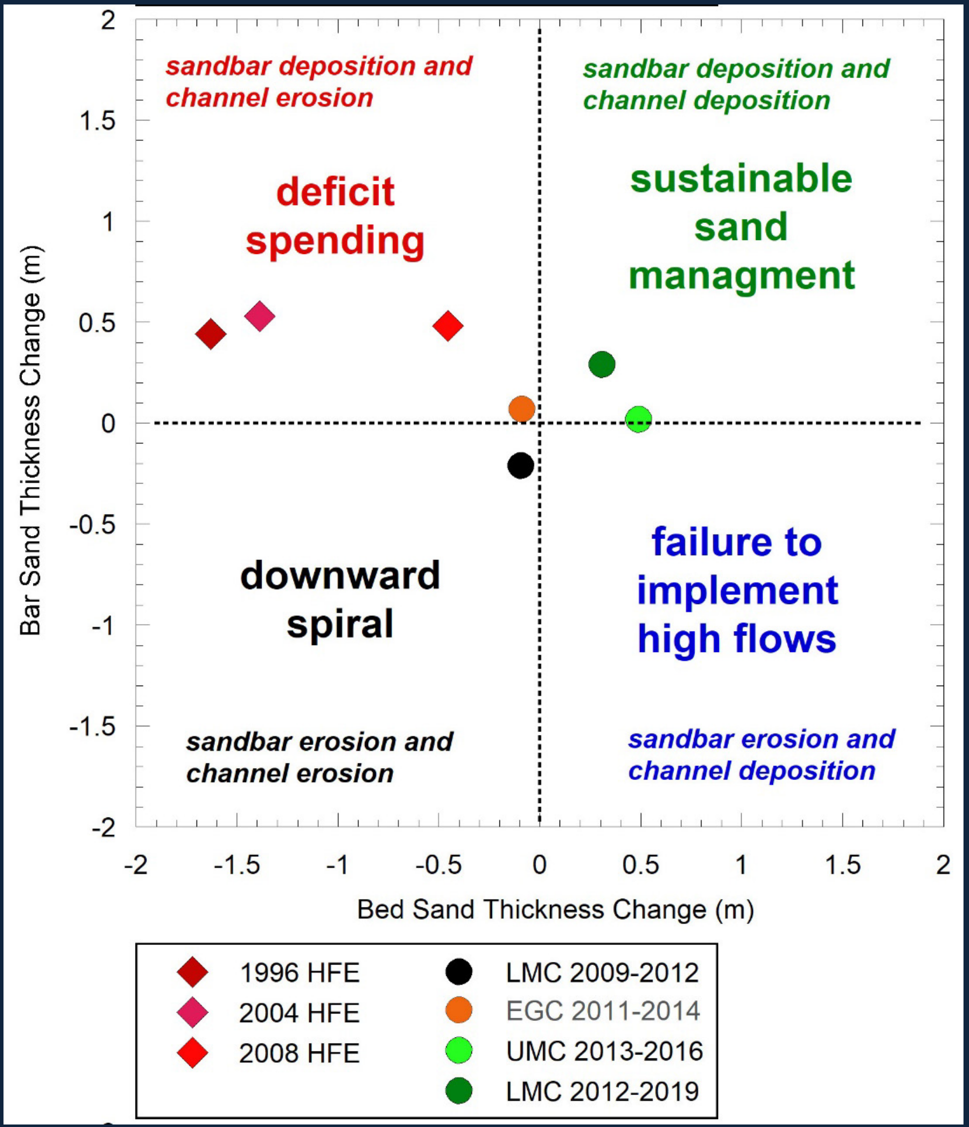
Repeat measurements during HFEs (diamonds)

- HFEs are "deficit spending"
- Need to mobilize all the sand to build sandbars and a large fraction is exported
- But a short-term negative that can be recovered from

Repeat measurements over many years (circles)

- Downward spiral: Equalization flows and no HFEs
- Deficit spending: Equalization flows and HFEs
- Sustainable: No equalization flows and HFEs

The 2004 and 2008 HFEs demonstrated sandbar building under conditions of greater sand enrichment was most effective with less erosion of sand from storage in eddies and channel (Hazel and others, 2010; Schmidt and Grams, 2011).



Conclusions: Sandbars and in-channel sediment storage

Sandbar response to HFEs

- When implemented, HFEs under sand-enriched conditions cause increases in sandbar area and volume.
  - When HFEs are not implemented, sandbars and campsites decline.
- From 2019 through 2022, sandbar volume decreased for most bar types because monsoon failure (2019, 2020) and low reservoir levels (2021, 2022) prevented HFE implementation for 4 consecutive years.
- Sandbar building accomplished by April 2023 HFE comparable to previous November HFEs for most bar types.
- Deposition at sandbars is likely stage-limited (bars not likely to get larger without larger HFEs).

Changes in sand storage

- Lower Marble Canyon has alternately gained and lost sand as function of dam operations and tributary sediment supply.
- Because changes in sandbars above 8,000 ft^3/s stage comprise less than 10% of total changes in sand storage, the evaluation of sediment response to dam operations requires measurements of total sediment storage change.
- Measurements indicate “sustainable” sand management has only occurred during periods that include both HFEs and “normal” reservoir operations (no equalization flows).

Project B: Publications (2021-2023)

- Alvarez, L. V., & 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, 126,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.
- 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.
- 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.
- 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.
- Le Coz, J., Perret, E., Camenen, B., Topping, D.J., Buscombe, D.D., Leary, K.C.P., Dramais, G., and Grams, P.E., 2022, Mapping 2-D bedload rates throughout a sand-bed river reach from high-resolution acoustical surveys of migrating bedforms: Water Resources Research, v. 58, no. 11, e2022WR032434, p. 1-16, https://doi.org/10.1029/2022WR032434.
- 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, p. 1–10, doi: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.
- 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
- 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.

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/

Additional references

- Grams, P. E., Topping, D. J., Schmidt, J. C., Hazel, J. E., & Kaplinski, M. (2013). Linking morphodynamic response with sediment mass balance on the Colorado River in Marble Canyon: Issues of scale, geomorphic setting, and sampling design. Journal of Geophysical Research, 118, 21. https://doi.org/doi:10.1002/jgrf.20050
- Grams, P. E., Buscombe, D., Topping, D. J., Kaplinski, M., & Hazel, J. E. (2018). 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*, *44*(1), 160 178. https://doi.org/10.1002/esp.4489
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- 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.
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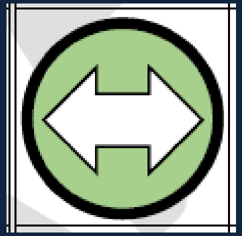
- Wiele, S.M., Andrews, E.D., and Griffin, E.R., 1999, The effect of sand concentration on depositional rate, magnitude, and location in the Colorado River below the Little Colorado River, in Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 110, p. 131 145.
- Wright, S.A., Topping, D.J., Rubin, D.M., and Melis, T.S., 2010, An approach for modeling sediment budgets in supply limited rivers: Water Resources Research, v. 46, p. 1 18, doi:10.1029/2009WR008600.
- U.S. Department of the Interior, 1996, Record of Decision, Operation of Glen Canyon Dam Final Environmental Impact Statement.
- U.S. Department of the Interior, 2016, Record of Decision for the Glen Canyon Dam Long Term Experimental and Management Plan Final Environmental Impact Statement, https://ltempeis.anl.gov/

Supplemental figures

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 sandbars are not defined, each HFE has resulted in deposition demonstrating that the general objective of retaining and/or increasing sand volume above the 8,000 cfs stage can be achieved when sand inputs occur and HFEs are implemented (2012-2018 and 2023).
- 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.
  - From 2019 through 2022, sandbar volume decreased for most bar types because monsoon failure (2019, 2020) and low reservoir levels (2021, 2022) prevented HFE implementation for 4 consecutive years.
  - **The "preemptive" HFE implemented in April 2023 rebuilt eroded sandbars**

OR

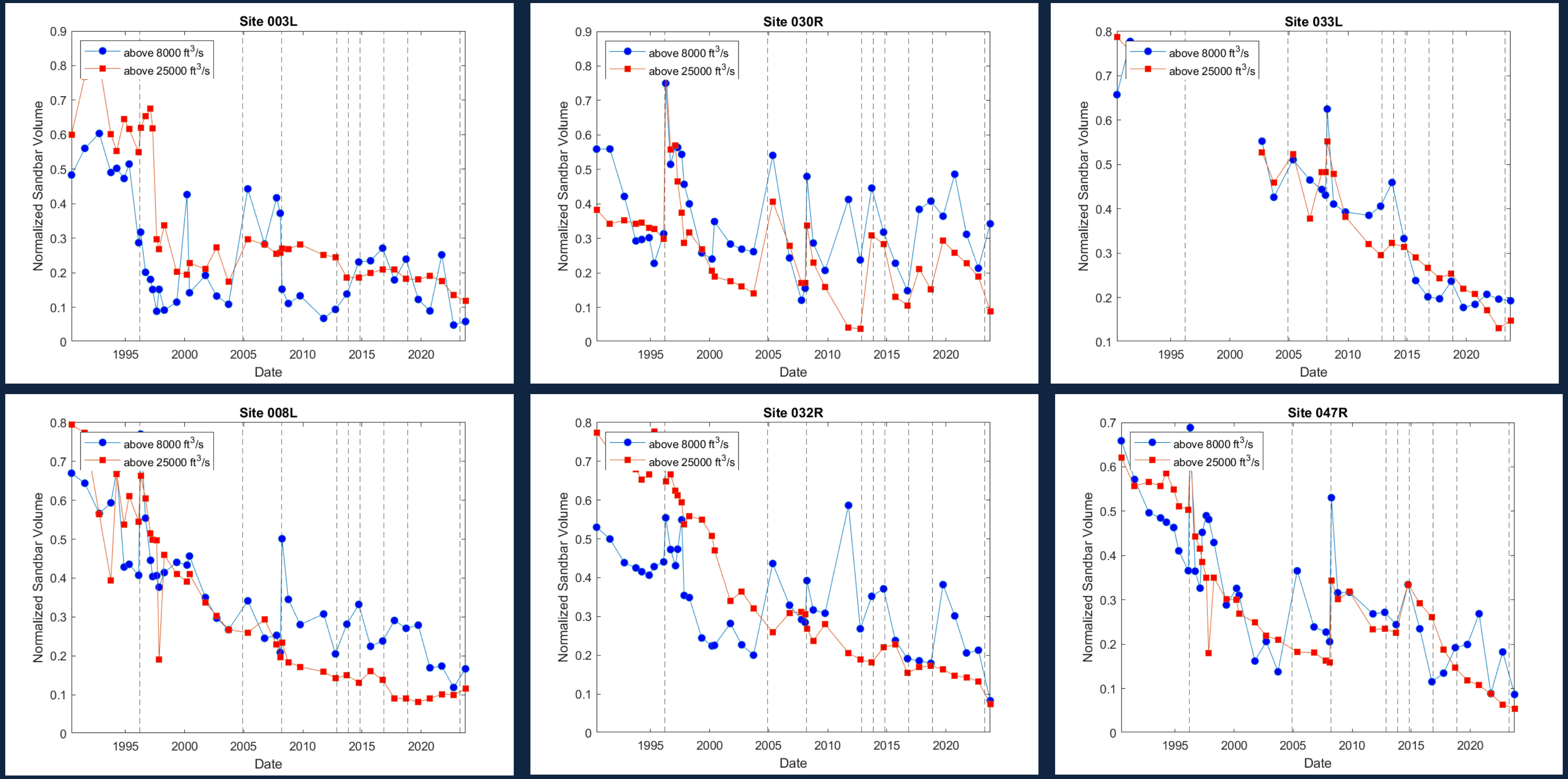


Status: unknown, because targets not defined; or good, because sand volume and area are not currently decreasing

Trend: unchanging because HFEs result in deposition, but bars are not progressively expanding

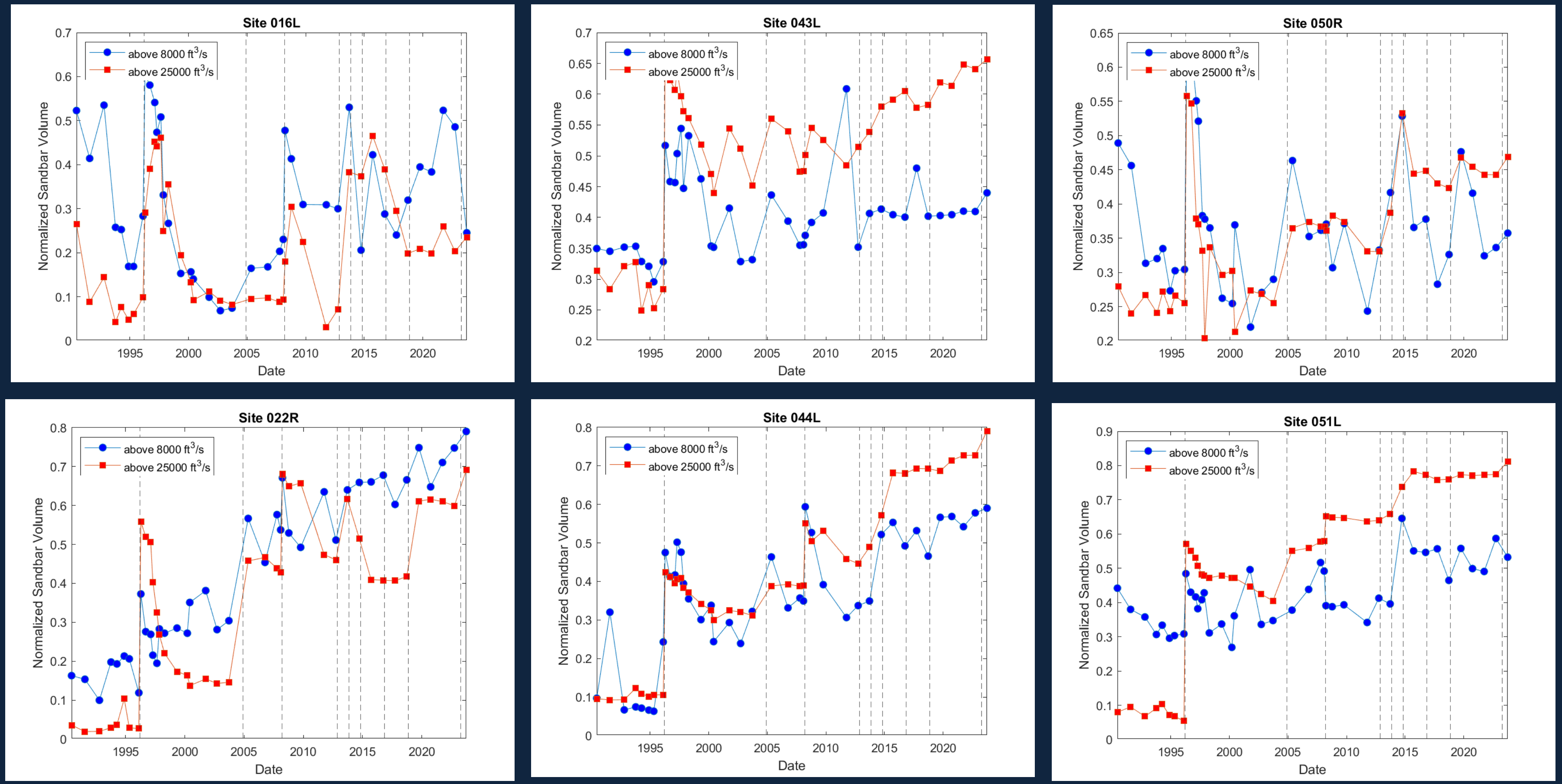
Confidence: high, because the monitoring is robust.

Marble Canyon – Downward trend 1990-2023



Hazel and others (2022); www.usgs.gov/apps/sandbar

Marble Canyon – Upward trend 1990-2023



Hazel and others (2022); www.usgs.gov/apps/sandbar

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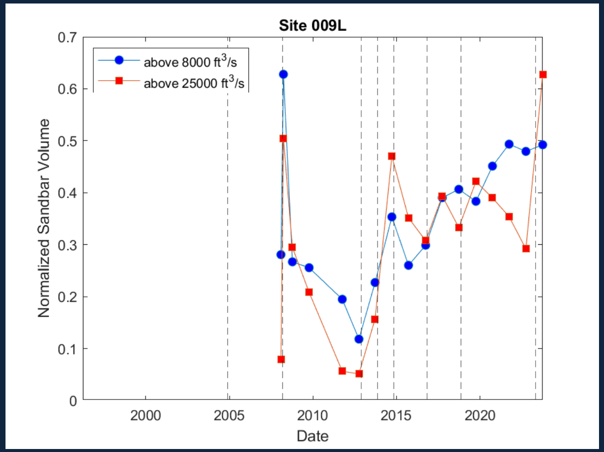
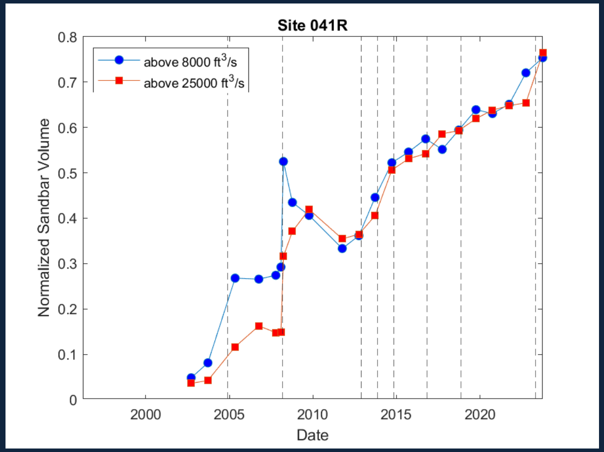
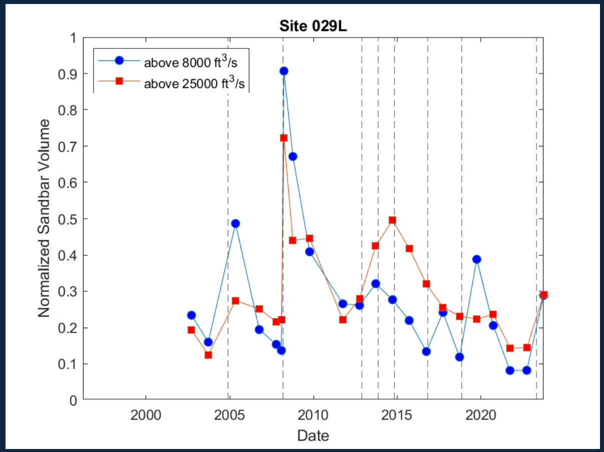
Marble Canyon 2000-2023

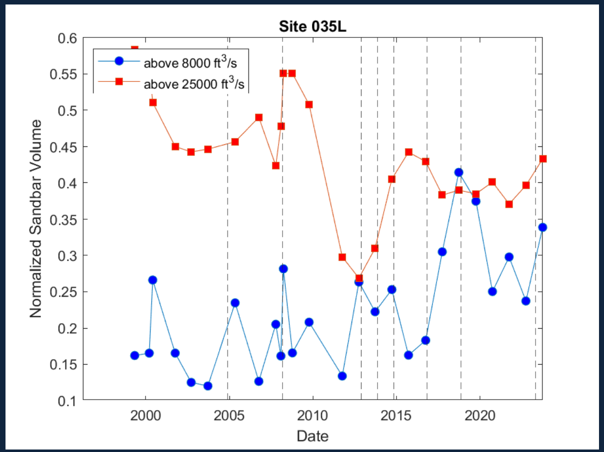
Upward trend

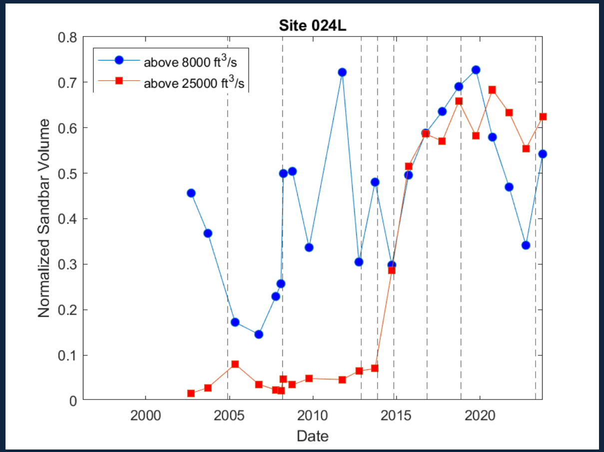
Flat or downward trend

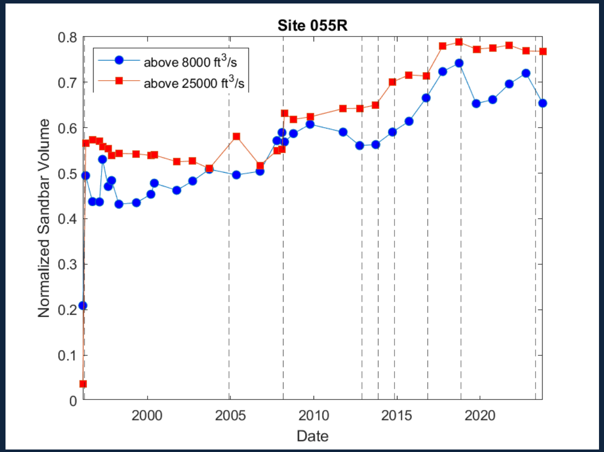


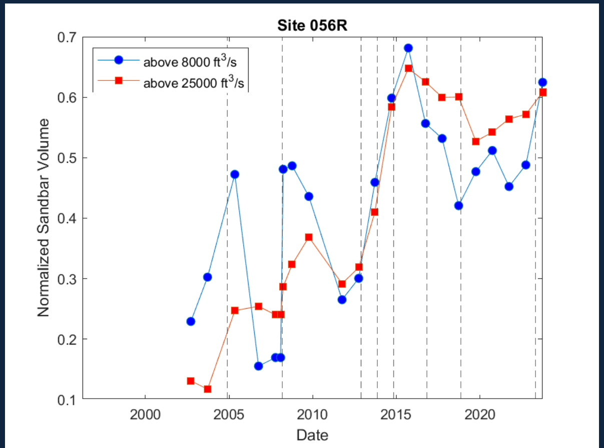


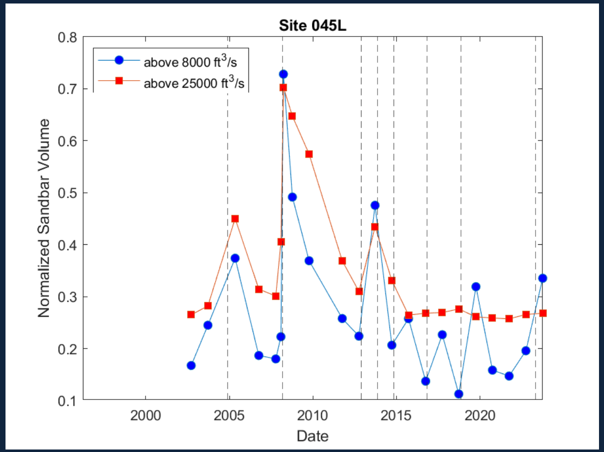








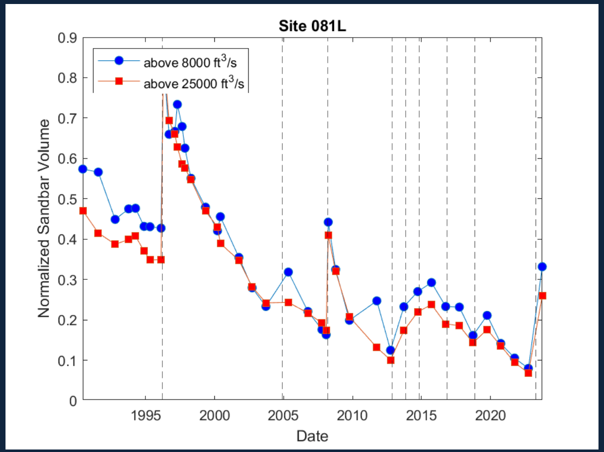


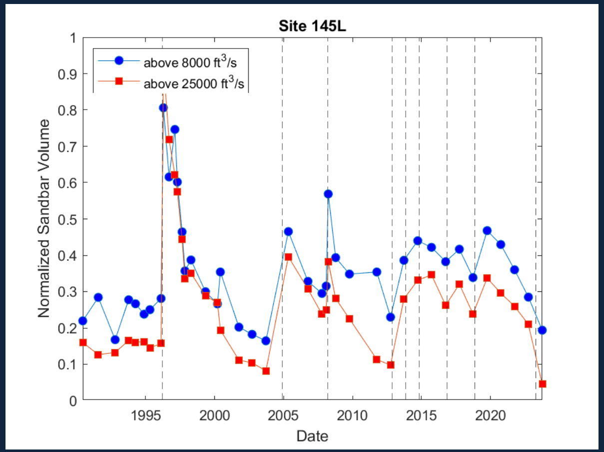


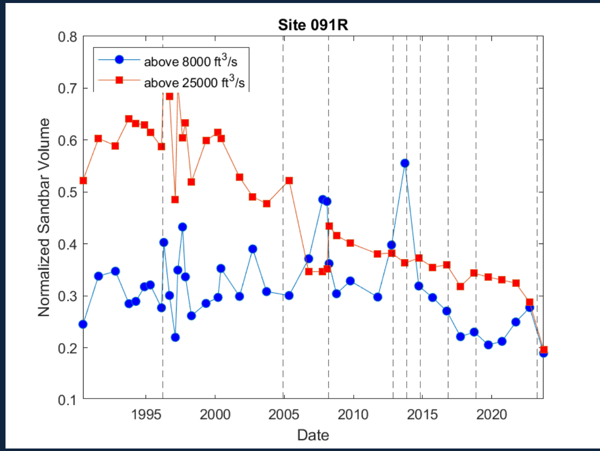
Hazel and others (2022); www.usgs.gov/apps/sandbar

USGS

Grand Canyon – Downward trend or flat 1990-2023



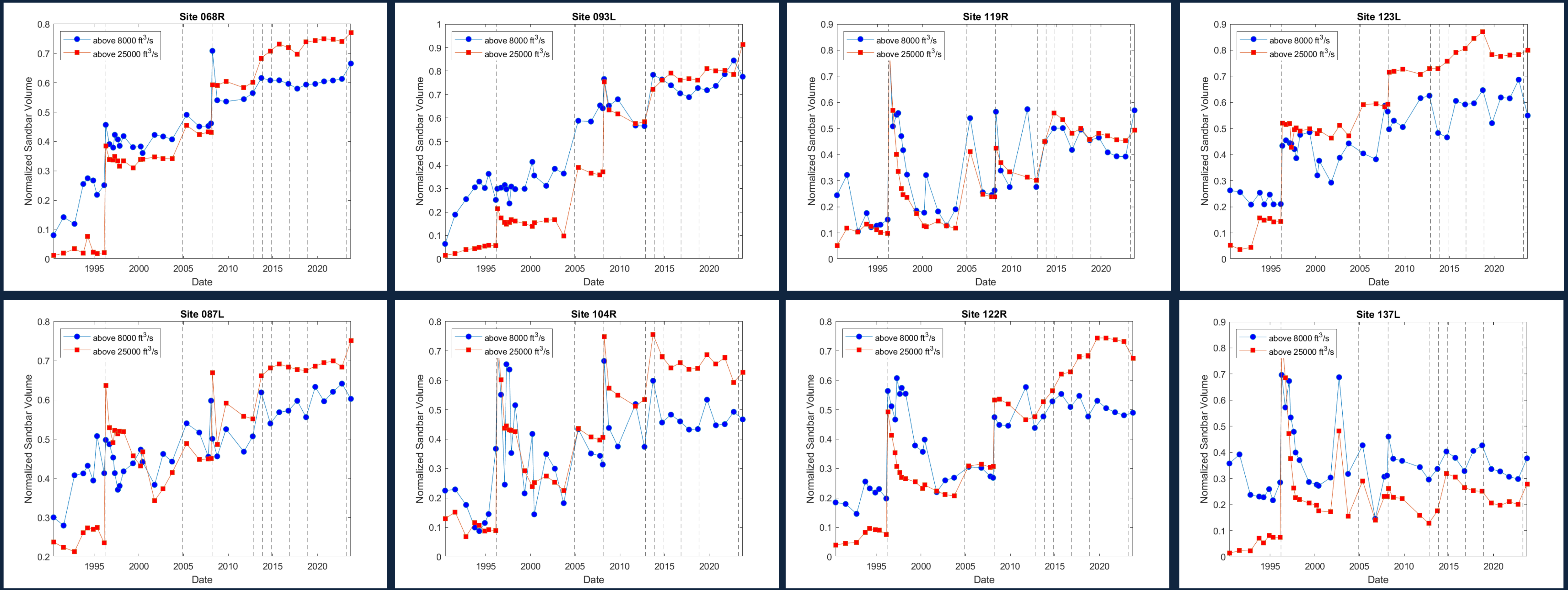




Hazel and others (2022); www.usgs.gov/apps/sandbar

USGS

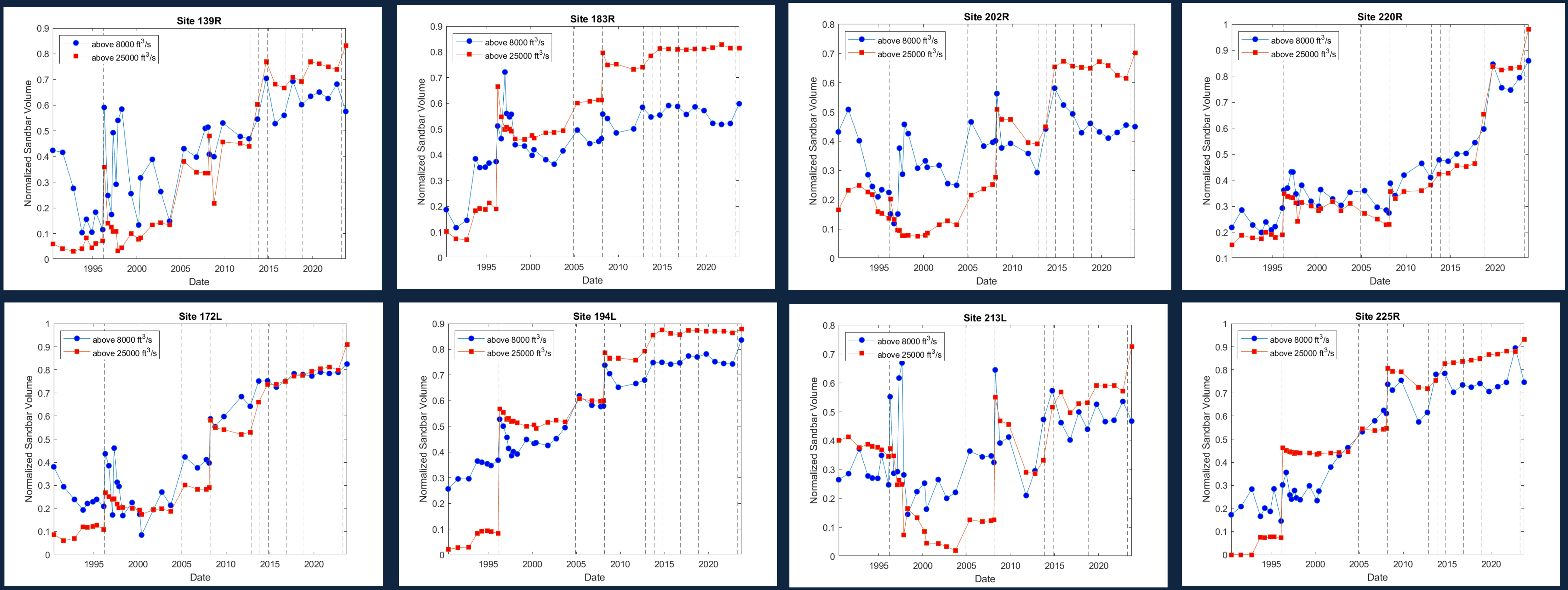
Grand Canyon – Upward trend 1990-2023



Hazel and others (2022); www.usgs.gov/apps/sandbar

USGS

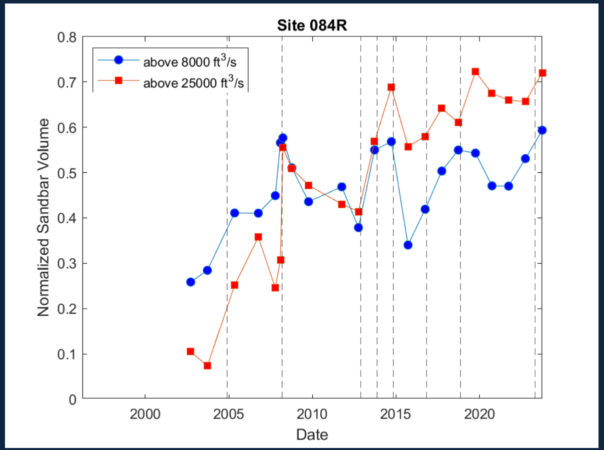
Grand Canyon – Upward trend 1990-2023



Hazel and others (2022); www.usgs.gov/apps/sandbar

Grand Canyon – 2000-2023

Upward trend



Flat or downward trend