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

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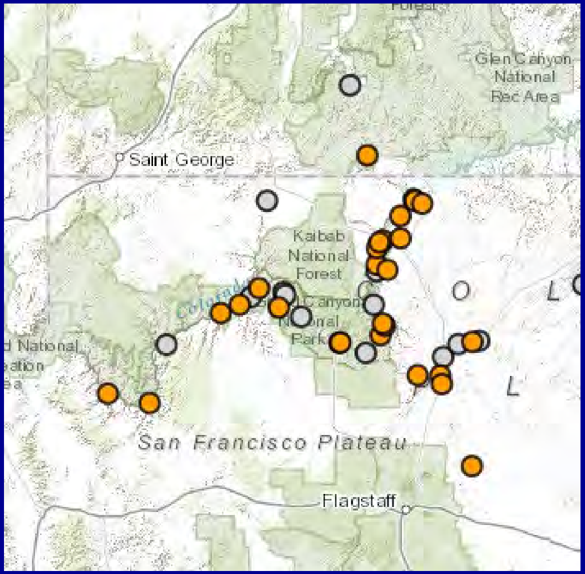
We collect, post, and analyze the following data at stations located through the Colorado River Ecosystem, including key tributaries…



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

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

Funding: GCDAMP provided $1.2 million during FY 2021

Work completed in FY 2021 addressed the following two hypotheses paraphrased from the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Environmental Impact Statement (EIS) and earlier GCDAMP documents

- Glen Canyon Dam can be operated such that the sand resources in the Colorado River ecosystem (CRe) are sustainable.
- Glen Canyon Dam can be operated such that the other CRe resources affected by dam operations can be sustainably managed. In this usage, "dam operations" refers to the amount and quality of the water released from the dam, where "amount" refers to stage and streamflow, and "quality" refers to temperature, salinity, turbidity, and dissolved oxygen.

FY 2021 products

- All required monitoring data collected but only LARGELY processed and posted to Project A's website (https://www.gcmrc.gov/discharge_qw_sediment/) and to NWIS
- 1 peer-reviewed article in the Journal of Geophysical Research (JGR), 2 USGS reports, and 2 USGS data releases published (see list in Annual Report)

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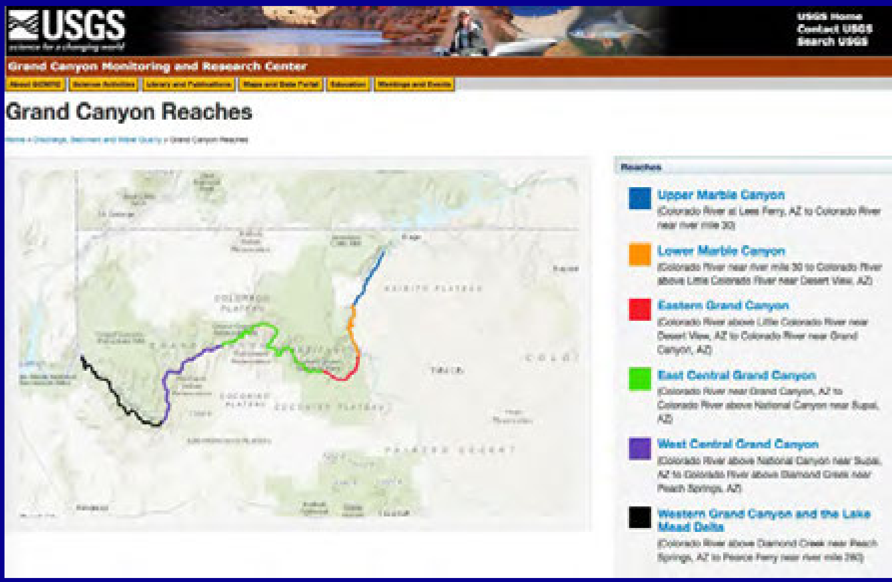
Change in sand mass during July 1, 2021 – December 31, 2021



	million metric tons
Upper Marble Canyon	+1.3±0.3
Lower Marble Canyon	+0.22±0.05
Eastern Grand Canyon	+0.26±0.14

- Paria River supplied **~1.4 million metric tons of sand (2nd largest amount after summer–fall 2013 during years when HFEs were allowed)**
- Little Colorado River supplied **~420,000 metric tons of sand**
- **Indeterminate change** of only **-7,800±92,000** metric tons of sand in East-Central Grand Canyon between 7-1-2021 and 8-30-2021
- **Erosion** of only **63,000±49,000** metric tons of sand from West-Central Grand Canyon between 7-1-2021 and 8-30-2021

Data from U.S. Geological Survey (2022)

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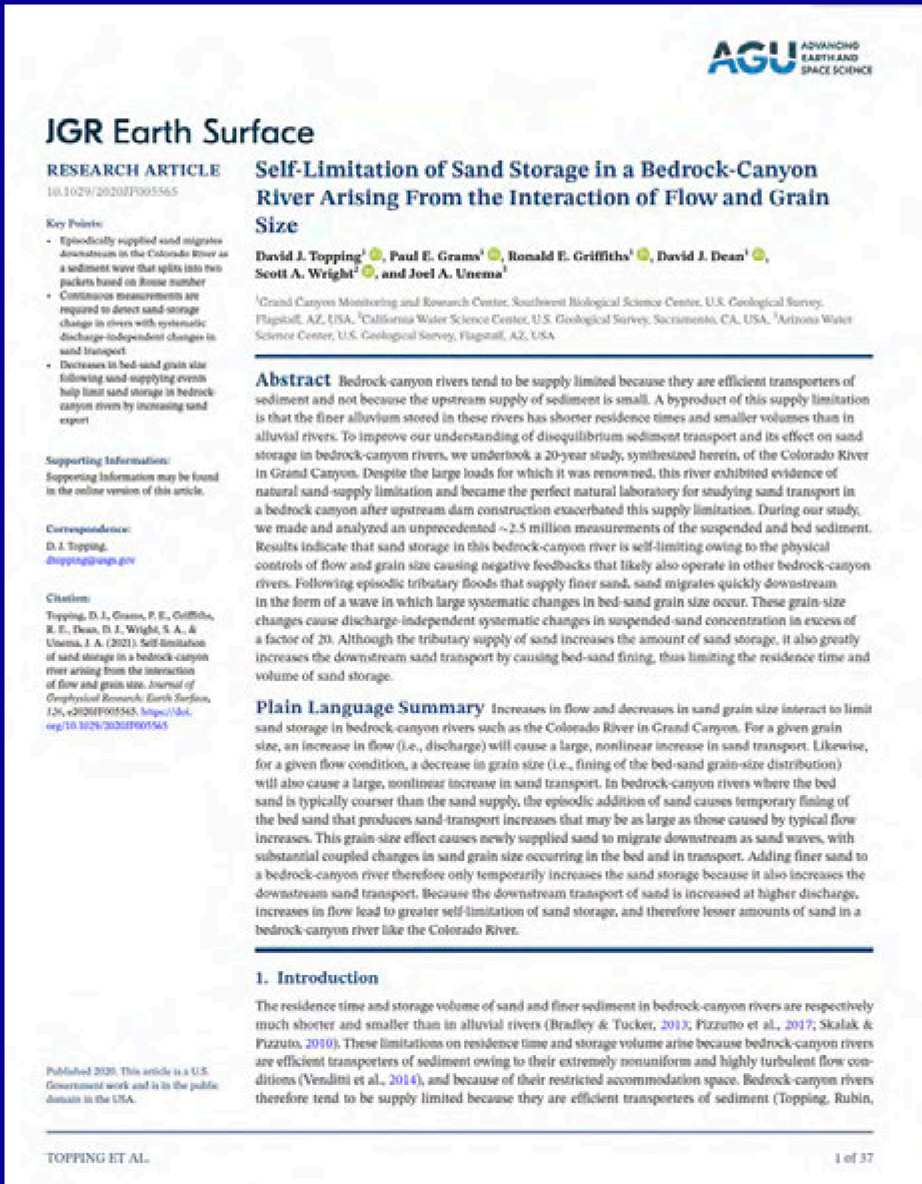
2021 Journal of Geophysical Research article synthesizing 1998–2017 sediment results from Project A


AGU ADVANCING EARTH AND SPACE SCIENCE

JGR Earth Surface

RESEARCH ARTICLE
10.1029/2020JF005565

Key Points:
- Episodically supplied sand migrates downstream in the Colorado River as a sediment wave that splits into two packets based on Rouse number
- Continuous measurements are required to detect sand-storage change in rivers with systematic discharge-independent changes in sand transport
- Decreases in bed-sand grain size following sand-supplying events help limit sand storage in bedrock-canyon rivers by increasing sand export

Supporting Information:
Supporting Information may be found in the online version of this article.

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Self-Limitation of Sand Storage in a Bedrock-Canyon River Arising From the Interaction of Flow and Grain Size

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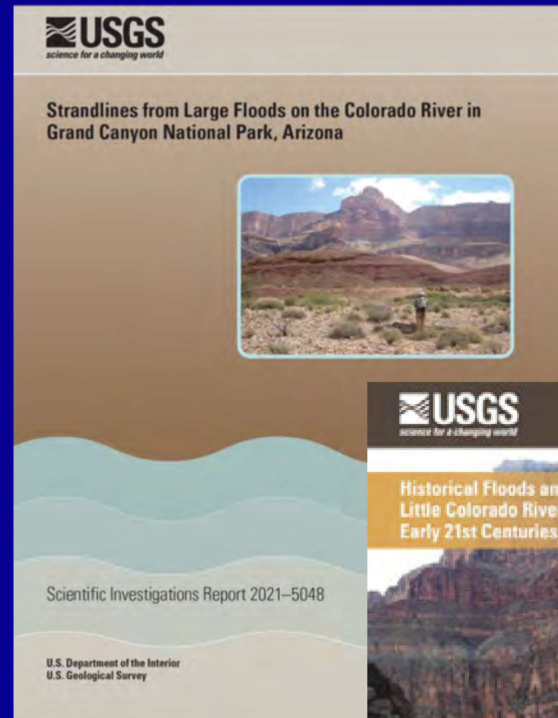
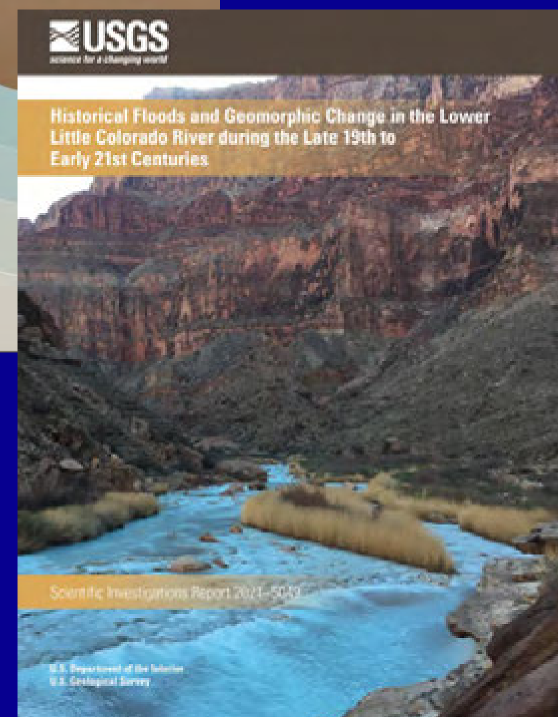
Abstract Bedrock-canyon rivers tend to be supply limited because they are efficient transporters of sediment and not because the upstream supply of sediment is small. A byproduct of this supply limitation is that the finer alluvium stored in these rivers has shorter residence times and smaller volumes than in alluvial rivers. To improve our understanding of disequilibrium sediment transport and its effect on sand storage in bedrock-canyon rivers, we undertook a 20-year study, synthesized herein, of the Colorado River in Grand Canyon. Despite the large loads for which it was renowned, this river exhibited evidence of natural sand-supply limitation and became the perfect natural laboratory for studying sand transport in a bedrock canyon after upstream dam construction exacerbated this supply limitation. During our study, we made and analyzed an unprecedented ~2.5 million measurements of the suspended and bed sediment. Results indicate that sand storage in this bedrock-canyon river is self-limiting owing to the physical controls of flow and grain size causing negative feedbacks that likely also operate in other bedrock-canyon rivers. Following episodic tributary floods that supply finer sand, sand migrates quickly downstream in the form of a wave in which large systematic changes in bed-sand grain size occur. These grain-size changes cause discharge-independent systematic changes in suspended-sand concentration in excess of a factor of 20. Although the tributary supply of sand increases the amount of sand storage, it also greatly increases the downstream sand transport by causing bed-sand fining, thus limiting the residence time and volume of sand storage.

Plain Language Summary Increases in flow and decreases in sand grain size interact to limit sand storage in bedrock-canyon rivers such as the Colorado River in Grand Canyon. For a given grain size, an increase in flow (i.e., discharge) will cause a large, nonlinear increase in sand transport. Likewise, for a given flow condition, a decrease in grain size (i.e., fining of the bed-sand grain-size distribution) will also cause a large, nonlinear increase in sand transport. In bedrock-canyon rivers where the bed sand is typically coarser than the sand supply, the episodic addition of sand causes temporary fining of the bed sand that produces sand-transport increases that may be as large as those caused by typical flow increases. This grain-size effect causes newly supplied sand to migrate downstream as sand waves, with substantial coupled changes in sand grain size occurring in the bed and in transport. Adding finer sand to a bedrock-canyon river therefore only temporarily increases the sand storage because it also increases the downstream sand transport. Because the downstream transport of sand is increased at higher discharge, increases in flow lead to greater self-limitation of sand storage, and therefore lesser amounts of sand in a bedrock-canyon river like the Colorado River.

1. Introduction

The residence time and storage volume of sand and finer sediment in bedrock-canyon rivers are respectively much shorter and smaller than in alluvial rivers (Bradley & Tucker, 2013; Pizzuto et al., 2017; Skalak & Pizzuto, 2010). These limitations on residence time and storage volume arise because bedrock-canyon rivers are efficient transporters of sediment owing to their extremely nonuniform and highly turbulent flow conditions (Venditti et al., 2014), and because of their restricted accommodation space. Bedrock-canyon rivers therefore tend to be supply limited because they are efficient transporters of sediment (Topping, Rubin,





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Major results from 2021 JGR article

- Under ≥8.23 million-acre-foot releases, only those High-Flow Experiments (HFEs) released within several months of a large Paria River flood will have access to the finest sand size classes that lead to the largest sandbar-deposition rates in Marble Canyon.

- Multi-year sand accumulation is only possible during years when the tributary sand supply exceeds ~130% of average and dam-released discharges are below the 1964–2017 average.

- Sand erodes during years of below-average to average tributary sand supply and higher discharge.

- Maintaining a sufficient sand supply (bank account) to rebuild sandbars may require timing periods of higher and lower dam-released discharge based on tributary sand-supply conditions.

- Whether the sand resources of the Colorado River in Grand Canyon National Park can be sustainably managed in perpetuity therefore remains an open question.

Topping and others (*JGR*, 2021)

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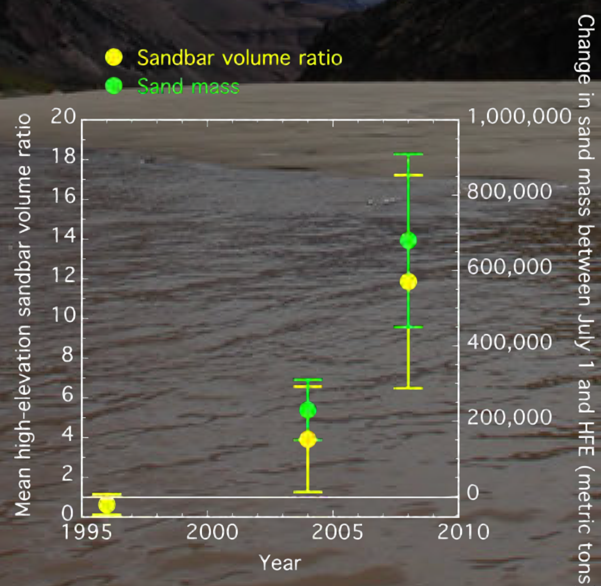
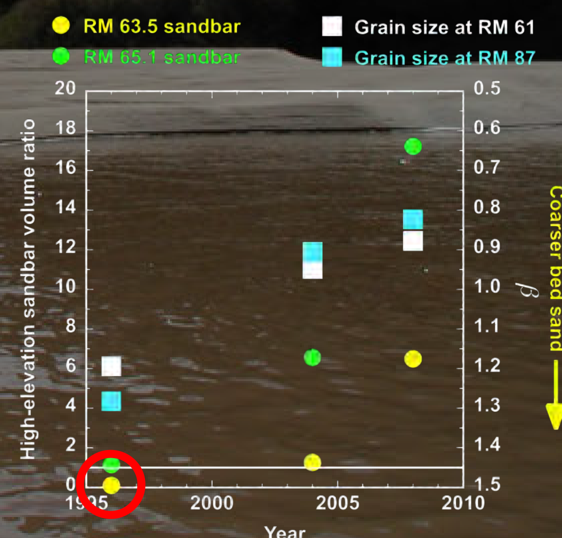
Two conditions must be met to enlarge high-elevation sandbars

1) High stage
2) Large amount of relatively fine sand on the bed



Sandbar *n* = 2
(RM 63.5, 65.1)



Post-HFE volume only 10% of pre-HFE volume when bed-sand was coarse during 1996 HFE!

Figures from Topping and others (2019)

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Some of the sand involved in sandbar deposition during HFEs is part of a "bank account" that cannot be replaced

- **Although the Paria River is by far the dominant modern supplier of sand (Topping and others, *JGR*, 2021), a large percentage (~30–50%) of the sand stored in sandbars is relict "pre-dam" sand (Chapman and others, *GSA Bulletin*, 2020)**

- **Stratigraphic and ground-penetrating-radar data suggest strongly that pre-dam sand exists at depth in at least some sandbars (Barnhardt and others, *USGS-OFR*, 2001)**

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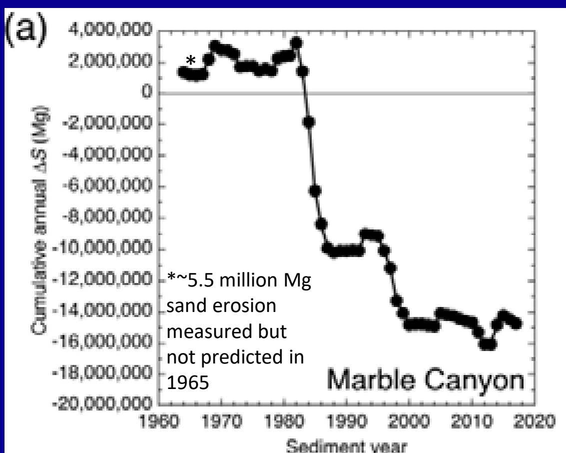
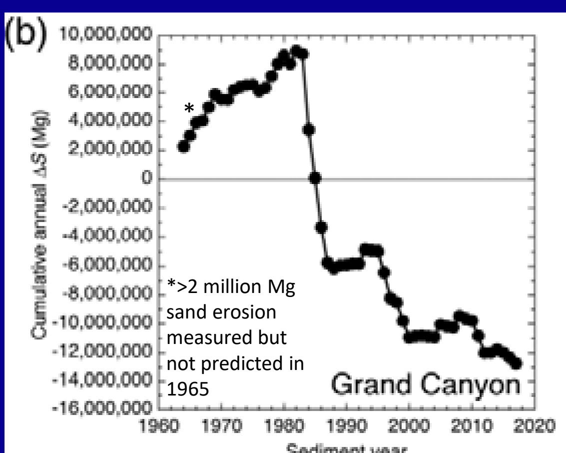
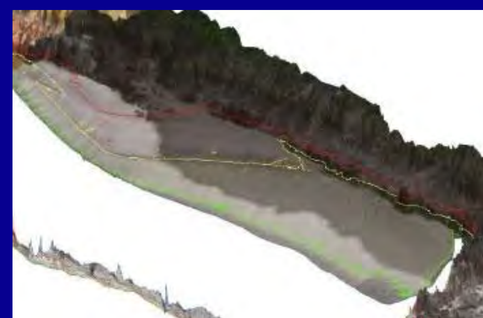
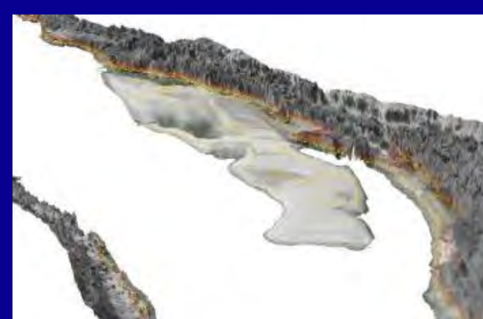
Downward spiral has likely occurred in long-term sand mass balance… and reflected in the high-elevation volume of an unknown percentage of the sandbars

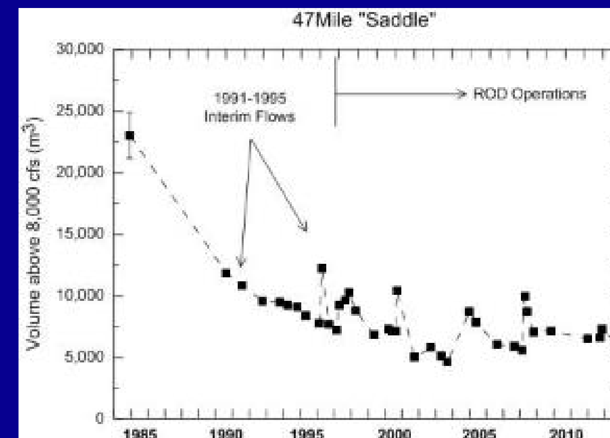
>28 million metric tons of sand eroded since 1963, mostly during 3–4 periods of sustained high dam releases (Topping and others, *JGR*, 2021)

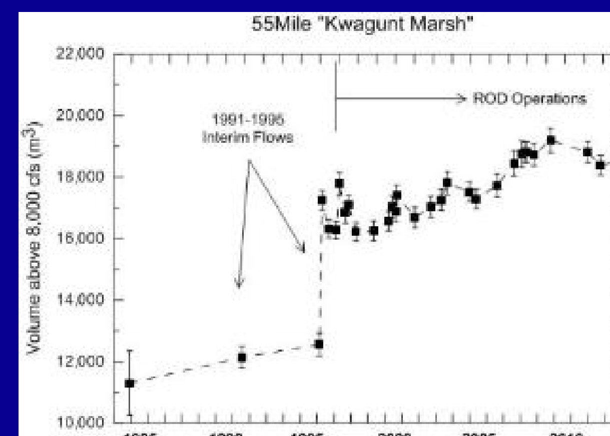












Figures from Topping and others (*JGR*, 2021)

Preliminary figures from Grams, Gushue, Hazel (do not cite)

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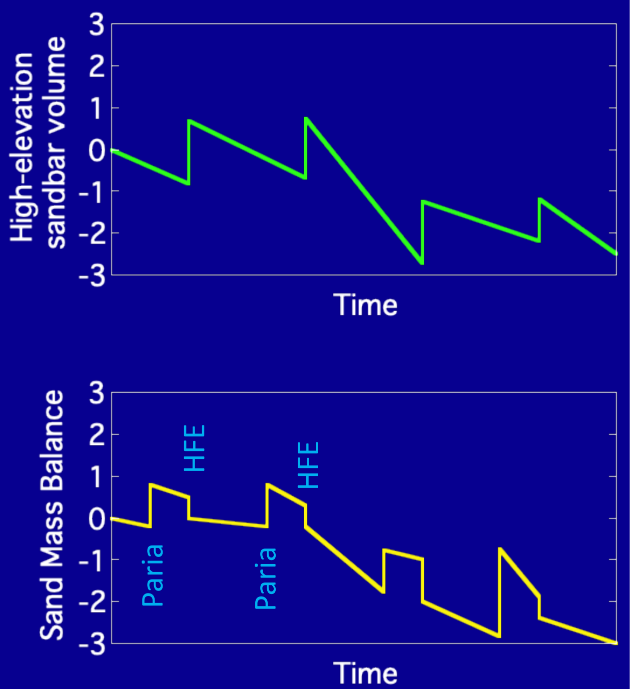
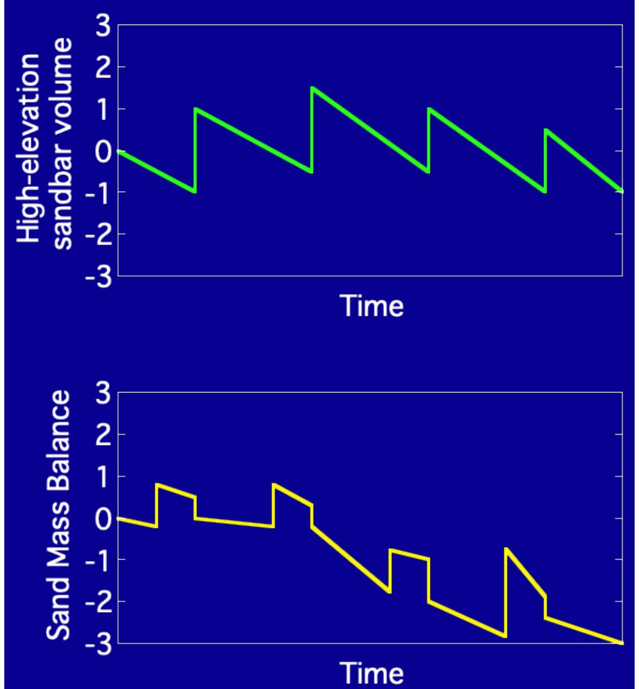
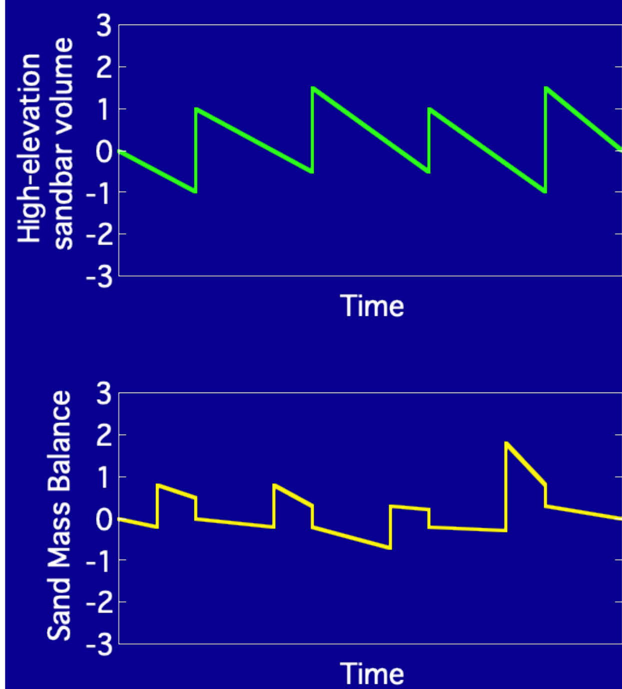
Sustainable management of sand under the LTEMP sediment goal thus requires neutral to positive trends in both the sand mass balance (i.e., the bank account) and the high-elevation sandbar volume (i.e., your expenditures) over decades



Not sustainable

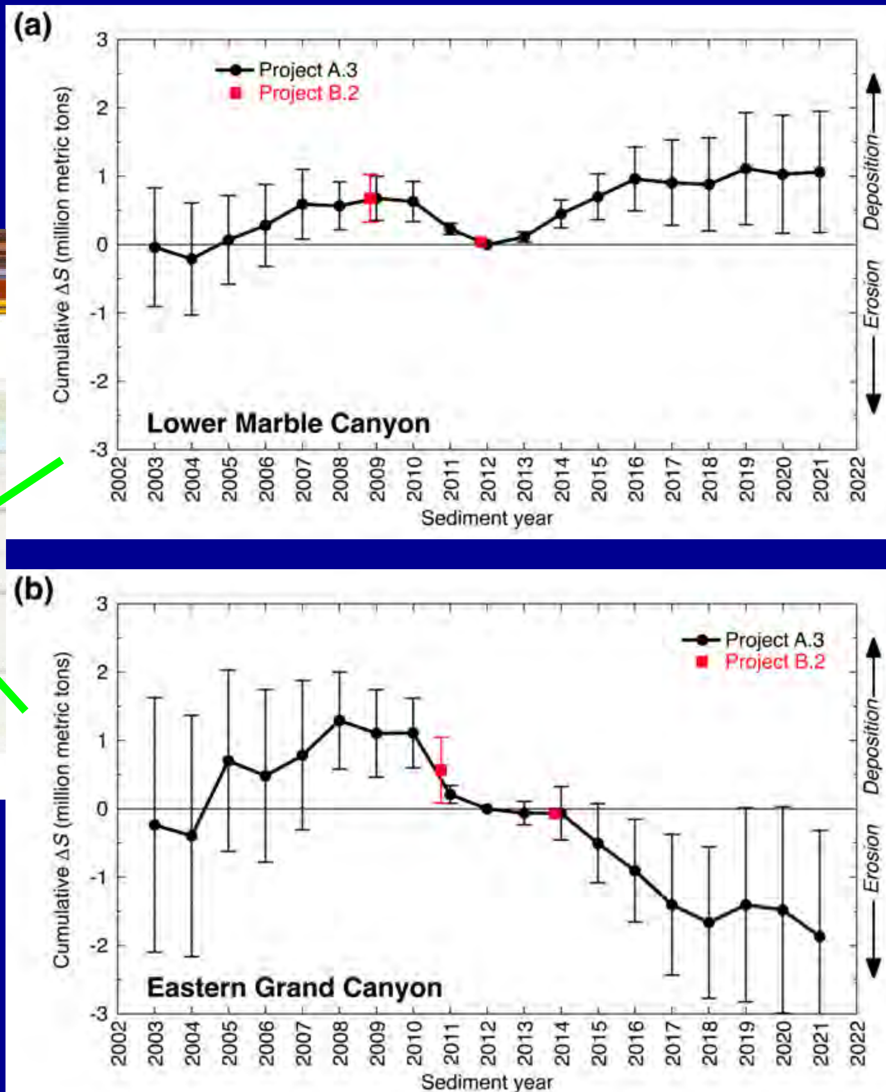


Not ultimately sustainable because sandbar response lags mass balance
"Living on credit"



Sustainable
"Living within your means"

Metrics Example: The Bank Account



POSSIBLE SUCCESS! Sustainable in Lower Marble Canyon if high-elevation sandbar volume is positive during this period.

POSSIBLE FAILURE Not sustainable in Eastern Grand Canyon regardless of whether high-elevation sandbar volume is positive during this period.

Sand bank account is being depleted. Will this situation turn around should larger Little Colorado River floods occur?

Data from Topping and others, *JGR*, 2021; USGS (2022)

Thank you

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