

Riverbed and Sandbar Response to Glen Canyon Dam Operations and High-Flow Experiments

Glen Canyon Dam Adaptive Management Program
Annual Reporting Meeting
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U.S. Department of the Interior
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Acknowledgements



Project B personnel:

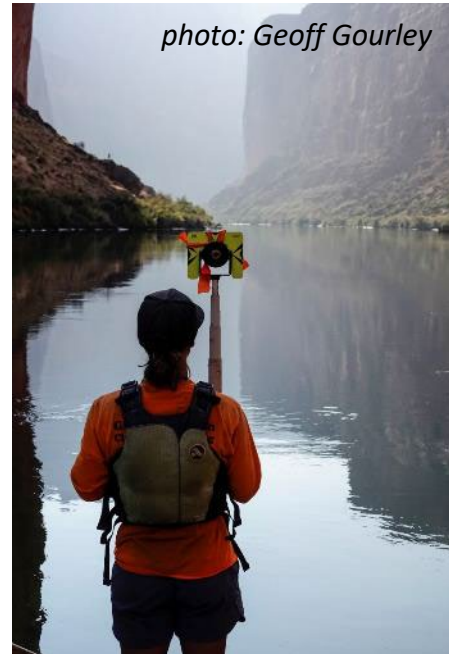
Paul Grams, Katie Chapman, Matt Kaplinski, Gerard Salter, Shannon Sartain, Robert Tusso, and Keith Kohl (now at National Geodetic Survey)

GIS and website support (Project K):

Thomas Gushue and Erica Byerley

Collaborators and cooperators:

David Topping and Project A, Erich Mueller, Scott Wright



Additional collaborators and field assistants:

GCRG, Jeff Behan, Jesse Collier, Robert Ross, Joel Sankey, Karen Koestner, Geoff Gourley, Lydia Manone, John O'Brien, Morgan Bannard, Reyn Hutten, Joe Pollock, Sean Hatch, Tim Garcia, Betsy Black, Madeline Kelly, Nathan Bonham, Sarah Baker, Rayni Lewis, Keegan Donovan, Ryan Lima, Ben Siebers, Lucien Bucci, Ann-Marie, and more!



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Sandbar monitoring and Goal 7 metrics (presented in poster session)



Goal 7 Sediment

“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”

Matt Kaplinski, David Topping, Paul Grams, Katherine Chapman, Robert Tusso, Gerard Salter, and Shannon Sartain

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Introduction

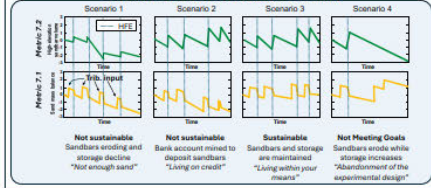
One of the objectives of the Long-Term Experimental and Management Plan (LTEMP) is to achieve the management goal for sediment (sand, silt, and clay) in the Colorado River ecosystem by utilizing dam operations and the available tributary fine-sediment supply (i.e., no sediment augmentation). Achievement of this goal requires that the fine-sediment mass balance be neutral to positive in the Colorado River on a segment-by-segment basis over multi-year to multi-decadal timescales (DOI, 2016). Management of sand is focused on maintaining/increasing the size of sandbars whereas management of silt and clay is focused on maintaining sufficient quantities of silt and clay for ecological processes (DOI, 2016).

The Metrics

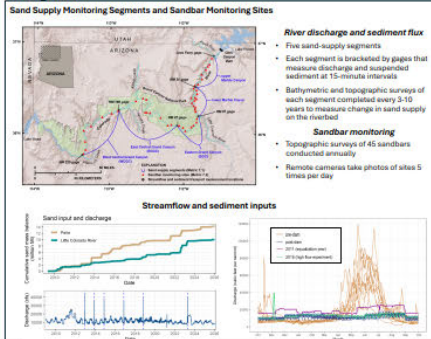
- Metric 7.1 Sand Supply (sand mass balance)**
The sand supply metric is critical because the goal to increase and retain fine sediment cannot be achieved without maintaining the sand supply, which is directly impacted by dam operations.
- Metric 7.2.1 Sandbar Volume**
The sandbar volume metric is a direct measurement of the status of high-elevation sandbars that are the primary focus of the sediment goal.
- Metric 7.2.2 Sandbar Response to High-Flow Experiments**
Response to high-flow experiments (HFEs) is included as a separate metric because the annual measurements for the sandbar volume metric do not capture the immediate response to HFEs. The metric is needed to ensure that HFEs continue to produce the intended sandbar-building response.
- Metric 7.3 Silt and Clay Retention**
The silt and clay metric tracks the retention of silt and clay relative to ecologically critical thresholds.

Management Applications of Metrics

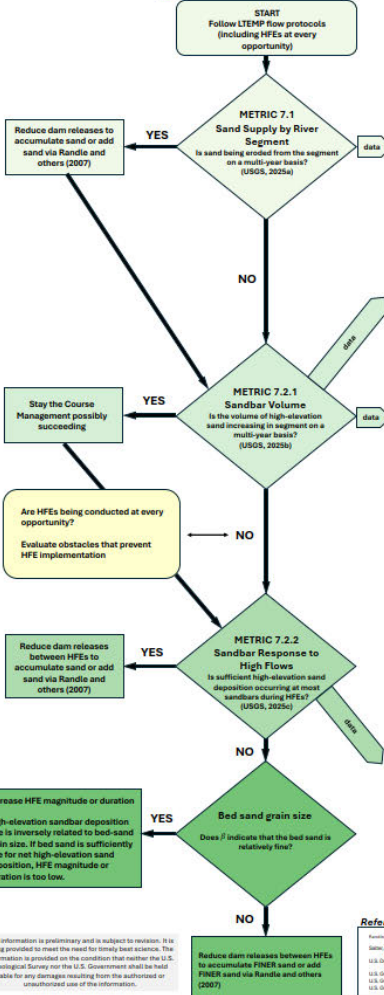
The sediment metrics are used both to conduct experiments during the implementation of LTEMP (see flowcharts) and to evaluate the performance of LTEMP over the 20-year implementation period (below).



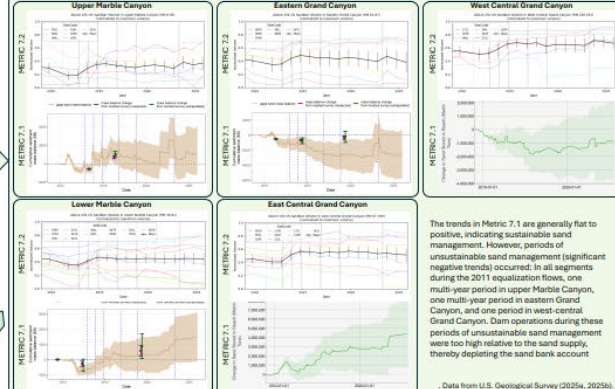
Background



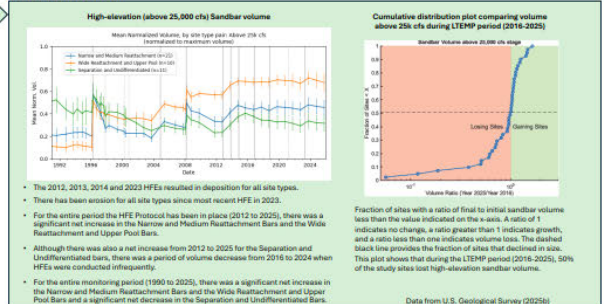
Sand Management Flow Chart



Sand Supply



Sandbar Volume



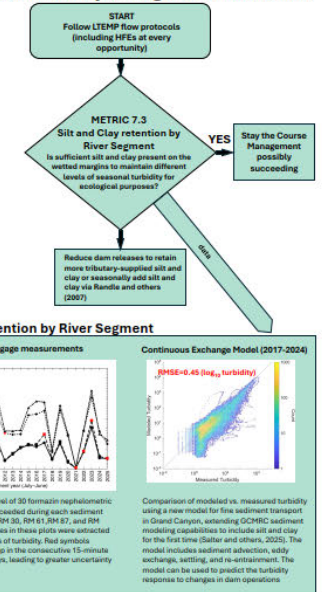
Sandbar Response to High Flows

Post-HFE	Pre-HFE	2012 HFE (n=16)	2013 HFE (n=42)	2014 HFE (n=40)	2015 HFE (n=43)	2016 HFE (n=40)	Average (n=40)
Large deposition	12%	13%	14%	14%	12%	10%	13%
Moderate deposition	33%	33%	42%	42%	34%	33%	43%
Wedge change	39%	30%	13%	33%	22%	28%	31%
Moderate erosion	0%	10%	10%	7%	10%	0%	9%
Large erosion	0%	7%	2%	5%	2%	0%	2%

Conclusions

- Metric 7.1 Sand Supply by River Segment:** Sustainable sand management is possible as long as long-duration high releases (equalization flows) are infrequent, and tributary inputs continue to occur.
- Metric 7.2.1: Sandbar Volume**
Net increases in high-elevation sandbars occur during periods with frequent HFEs. Net decreases occur during extended periods (3 to 4 years) without HFEs. During the LEMP period (2016 to 2025), the trend is flat or negative, with over half of the sandbars losing high-elevation sandbar volume.
- Metric 7.2.2: Sandbar Response to High Flows**
Each HFE that has been implemented since 2012 has resulted in deposition at a majority of monitoring sites and negligible change or slight erosion at some sites.
- Metric 7.3: Silt and Clay Retention by River Segment**
Relatively turbid conditions (> 30 FNUs) occur more than 10% of the time in most years in all segments. A new model has been developed to predict changes in turbidity in response to dam operations.

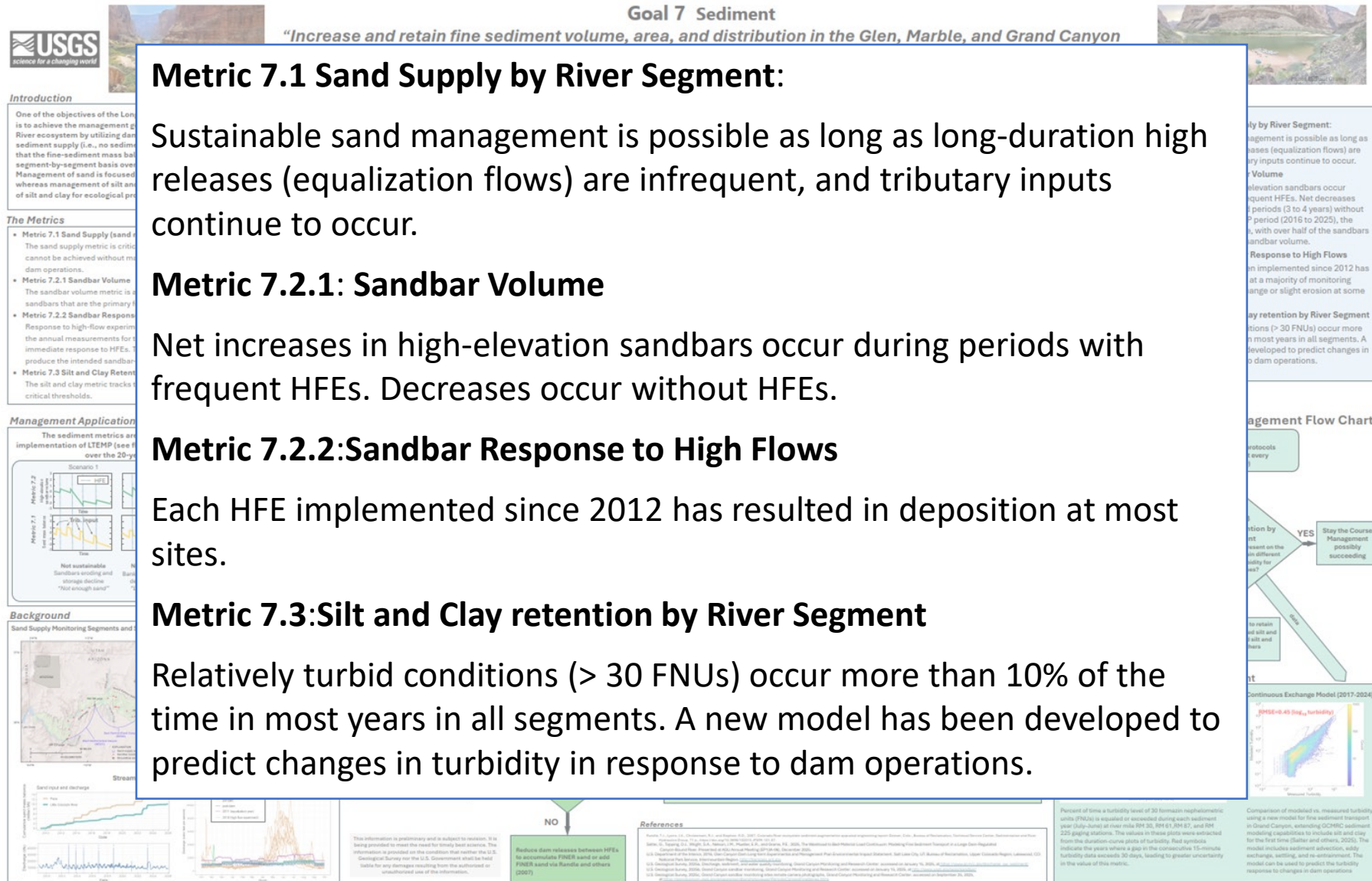
Silt and Clay Management Flow Chart



References

Reynolds, J. L., et al. (2016). ...
 US Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Flagstaff, AZ

Sandbar monitoring and Goal 7 metric for sandbars (presented in poster session)



Channel Response to High Flows in Western Grand Canyon (presented in poster session)

Monitoring and predicting channel change in Western Grand Canyon in response to Glen Canyon Dam flows and High Flow Experiments

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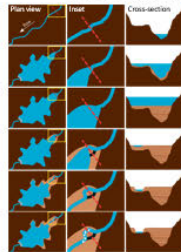


Shannon Sartain¹, Paul Grams¹, Matt Kaplinski¹, Katie Chapman¹, Bob Tusso¹, Erich Mueller²
¹ U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center
² Southern Utah University, Department of Geosciences

Background

- 10s of meters of Colorado River sediment have accumulated at the former delta of Lake Mead, filling in the pre-dam channel.
- Following reservoir decline, the river now flows over reservoir sediments, in some places out of its pre-dam channel
- We used multibeam sonar to measure the present-day river channel 9 times over 4 years.
- Question: How do Glen Canyon Dam operations affect this rapidly changing reach?

Reservoir fill and decline



- 1 Pre-dam river
- 2 Reservoir filling: sedimentation begins
- 3 Reservoir at full pool
- 4 Reservoir decline begins
- 5 Displaced river channel
- 6 Displaced river hits bedrock: knickpoint formation

Lake Mead River/Reservoir Interface Study Area

Map of study area

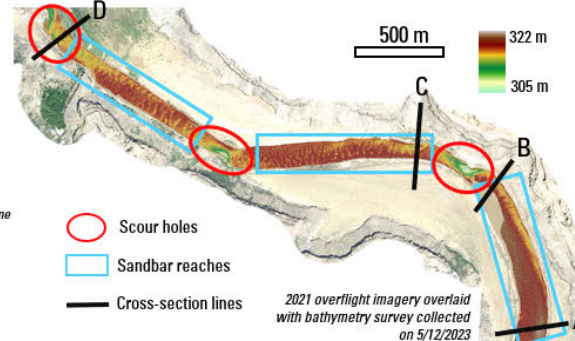


At Lake Mead, Pearce Ferry Rapid separates the study area from the current reservoir fluctuation zone

Pearce Ferry Rapid



Pearce Ferry Rapid has formed where the Colorado River is out of its initial channel and flowing over bedrock, following Lake Mead decline.



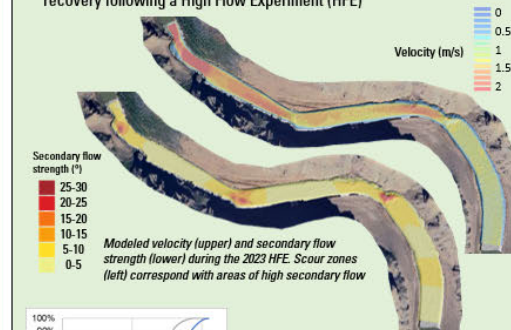
- Scour holes
- Sandbar reaches
- Cross-section lines

2021 overflight imagery overlaid with bathymetry survey collected on 5/12/2023

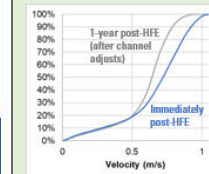
The study area is a section of the Colorado flowing through Lake Mead reservoir sediments (shown by row 5 in schematic drawing). Here, the river is over 60 m above its pre-dam channel. It is ~4.5 river miles upstream of a knickpoint (shown by row 6 in schematic drawing). Where bedrock is exposed, scour holes up to 12 m deep form. Between scour holes are shallow (0.5 to 4m), sandbar reaches with shifting dunes.

Developing a Hydraulic Model

- We have developed a two-dimensional hydraulic model using *FaSTMECH*, allowing us to estimate flow depth, velocity, and bed shear stress and other parameters for a variety of bed topographies and discharges.
- The results of this flow model provide insight into the mechanism for channel recovery following a High Flow Experiment (HFE)



Modeled velocity (upper) and secondary flow strength (lower) during the 2023 HFE. Scour zones (left) correspond with areas of high secondary flow

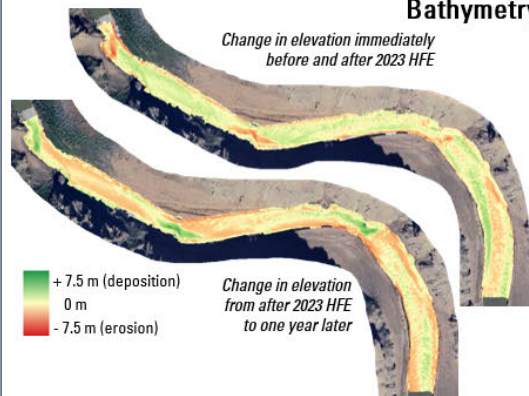


Cumulative distribution plot of model output velocities at two different bed topographies. Velocities are higher immediately post-HFE than one year post-HFE

During an HFE, decreases in scour hole elevation and increases in sandbar reach elevation lead to increased relief over the channel (elevation change plots).

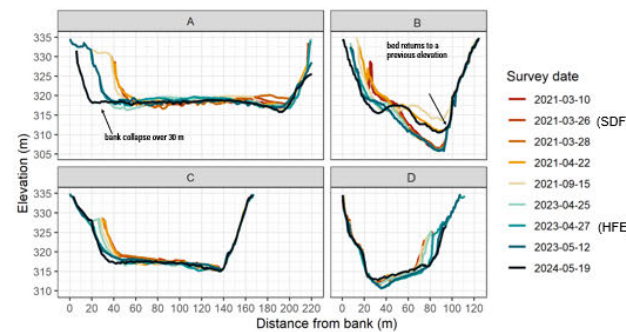
Following an HFE however, shallower elevations in sandbar reaches lead to higher velocities (figure left and above) which then erode and shift sandbars that were built during the HFE.

Bathymetry Survey Results



There is erosion from pools and accumulation in sandbar reaches during High Flow Experiments (HFEs), but these trends are reversed in the following year.

Riverbed and bank cross-sections



Cross sections collected during a period containing a high flow experiment (HFE) and spring disturbance flow (SDF). Cross-sections do not show a trend of sediment accumulation during the study period. Instead, we see channel widening and laterally shifting thalweg. Channel depth fluctuates but may return to a previous elevation.

Conclusions

- During HFEs, sediment is eroded from scour holes, where there is bedrock at river level, and deposited in sandbar reaches, where navigability is a concern
- However, in the period following HFEs, the pattern of erosion and deposition reverses, indicating a return to pre-HFE bed elevations
- Changes in velocity patterns and no evidence of sediment accumulation in the reach indicate that hydraulics, not sediment supply, control the distribution of sediment in the reach.

Channel Response to High Flows in Western Grand Canyon (presented in poster session)

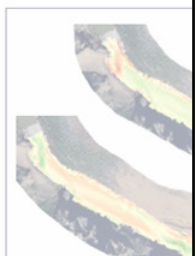
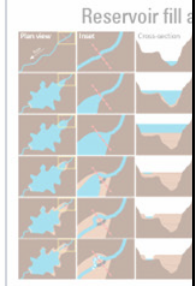
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Background

- 10s of meters of Coloradoan sediment accumulated at the form of sandbars during the pre-dam channel filling in the pre-dam channel
- Following reservoir drawdown, sediment over reservoir sediments has shifted its pre-dam channel
- We used multibeam sonar to map the present-day river channel
- Question: How do Glen Canyon Dam operations affect this reach?



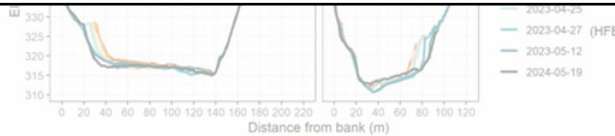
Lake Mead River/Reservoir Interface Study Area

Conclusions

- During HFEs, sediment is **eroded from scour holes**, where there is bedrock at river level, and **deposited in sandbar reaches**, where navigability is a concern
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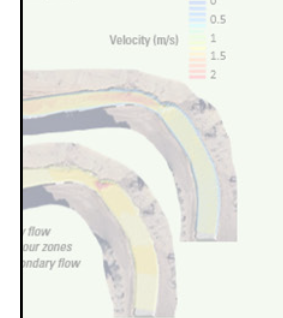
There is erosion from pools and accumulation in sandbar reaches during High Flow Experiments (HFEs), but these trends are reversed in the following year.



Cross sections collected during a period containing a high flow experiment (HFE) and spring disturbance flow (SDF). Cross-sections do not show a trend of sediment accumulation during the study period. Instead, we see channel widening and laterality shifting thalweg. Channel depth fluctuates but may return to a previous elevation.

Developing a Hydraulic Model

Hydraulic model using *FaSTMECH*, velocity, and bed shear stress and other factors to investigate the mechanism for channel change (HFE).



During an HFE, decreases in scour hole depth and increases in sandbar reach lead to increased relief over the reach (elevation change plots). Following an HFE however, shallower scour holes in sandbar reaches lead to increased velocities (figure left and above) which then erode and shift sandbars that built during the HFE.

Conclusions

- Sediment is **eroded from scour holes**, where there is bedrock at river level, and **deposited in sandbar reaches**, where navigability is a concern
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- Changes in velocity patterns and no evidence of sediment accumulation in the reach indicate that **hydraulics, not sediment supply**, control the distribution of sediment in the reach.

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.”*
- Project B addresses goal by two monitoring efforts and modeling:
 - Annual sandbar and campsite monitoring
 - Topographic surveys measure the **effects of HFEs and other dam operations on sandbars**
 - Remote time-lapse cameras to assess **immediate response to HFEs**
 - Periodic channel mapping of long river segments
 - **Evaluation of LTEMP performance** by measurements of sand storage change on the riverbed and large sample of sandbars
 - Studies of **riverbed response to high flows in Western Grand Canyon**
 - Modeling to predict fine sediment transport and sandbar response (*Not funded in FY2025-2027 TWP*)

Role of sediment and sandbars in Grand Canyon



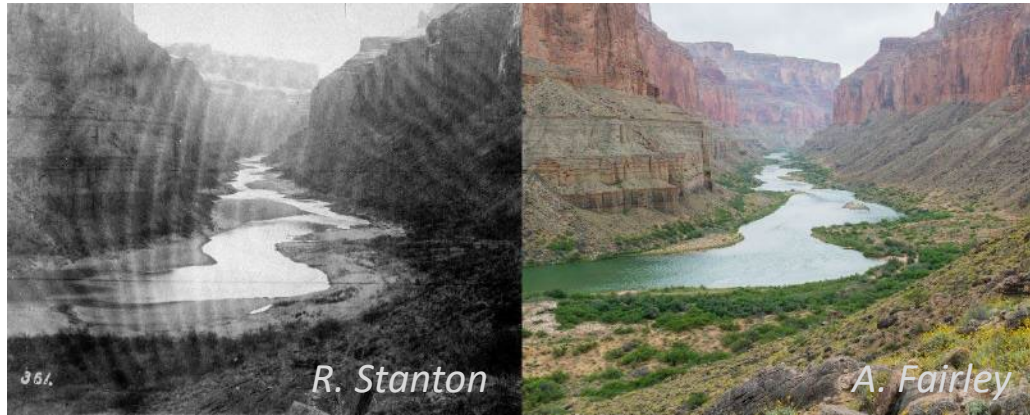
sand dunes
(archeological sites)



shoreline aquatic habitat



beaches, campsites, and
riparian ecosystem



fundamental part of pre-dam landscape



and major part of post-dam river and reservoir systems
(navigation, water quality, turbidity)

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 (RM 66). View is downstream.

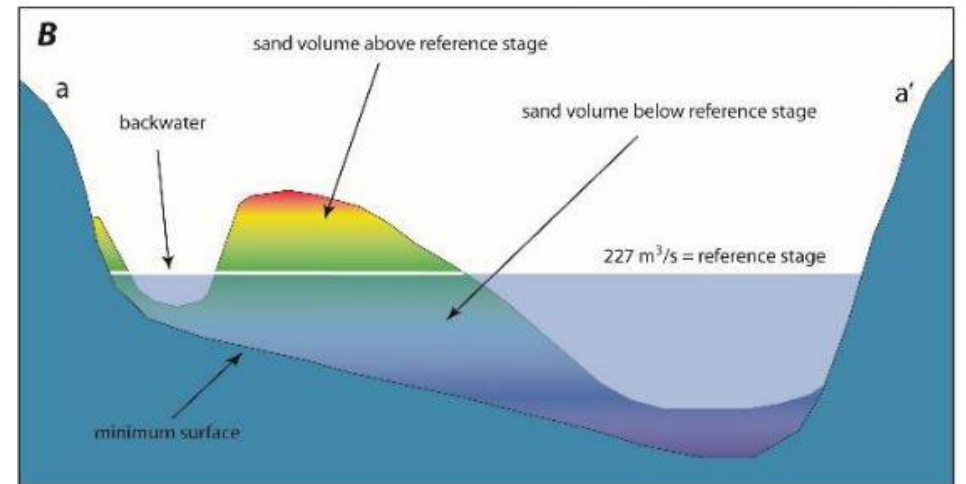
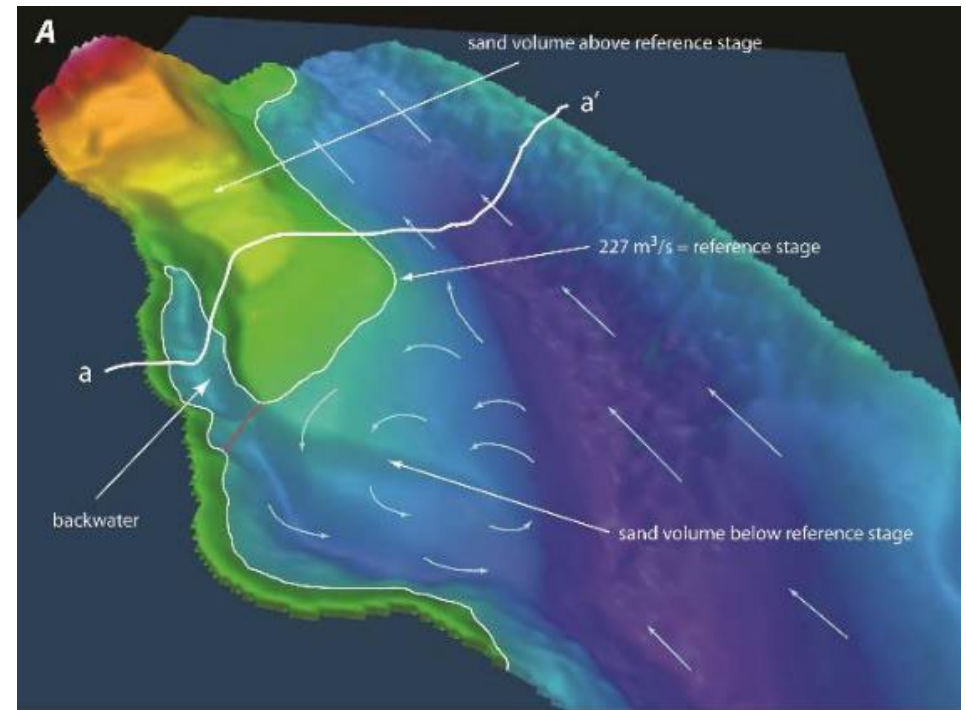


Sandbar erosion near Tapeats Creek (RM 134). View is downstream.

Repeat channel mapping for monitoring sand storage on the riverbed AND sandbars

Why measure sand storage by mapping the riverbed?

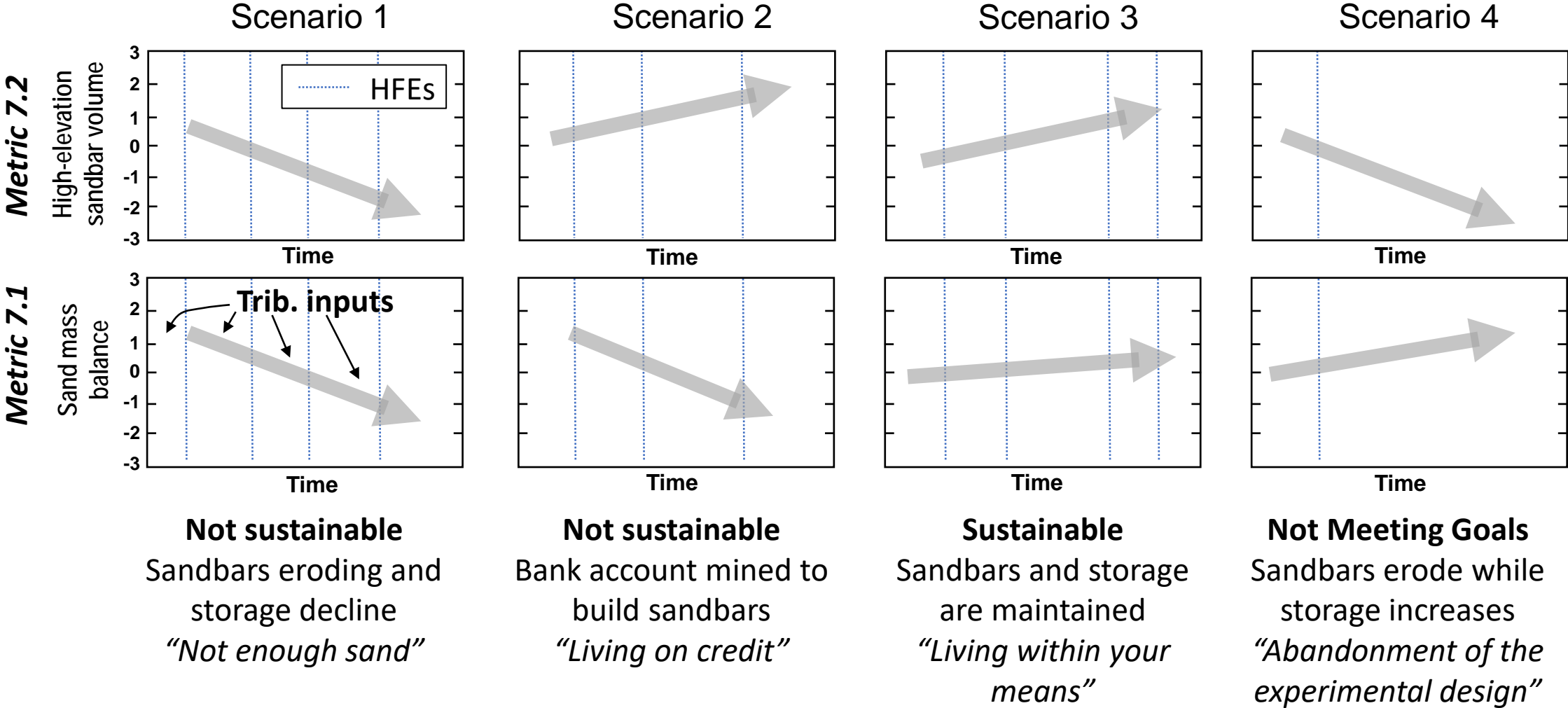
- Sandbar replenishment is controlled by:
 - Flow (need high flows to build large bars)
 - Sand supply (if supply in the channel is low, a net loss from eddy sandbars is risked)
- Sand supply is controlled by:
 - Dam releases (annual volume and release pattern)
 - Inputs from tributaries



Adapted from Hazel and others (2010)

Using sandbar change and sand mass balance to evaluate LTEMP

Four possible sandbar response and sand supply outcomes:



Channel mapping is only data that includes both high-elevation sand (above 8k cfs) and sand in the channel and eddies to reveal which of the four scenarios is occurring.



"high-elevation sandbar"

gain
↑
↓
loss

<p><i>Scenario 2: Mining sand from storage to build sandbars</i></p>	<p><i>Scenario 3: Accumulating sand and building sandbars</i></p>
<p><i>Scenario 1: Mining sand and losing sandbars</i></p>	<p><i>Scenario 4: Accumulating sand but not building sandbars.</i></p>

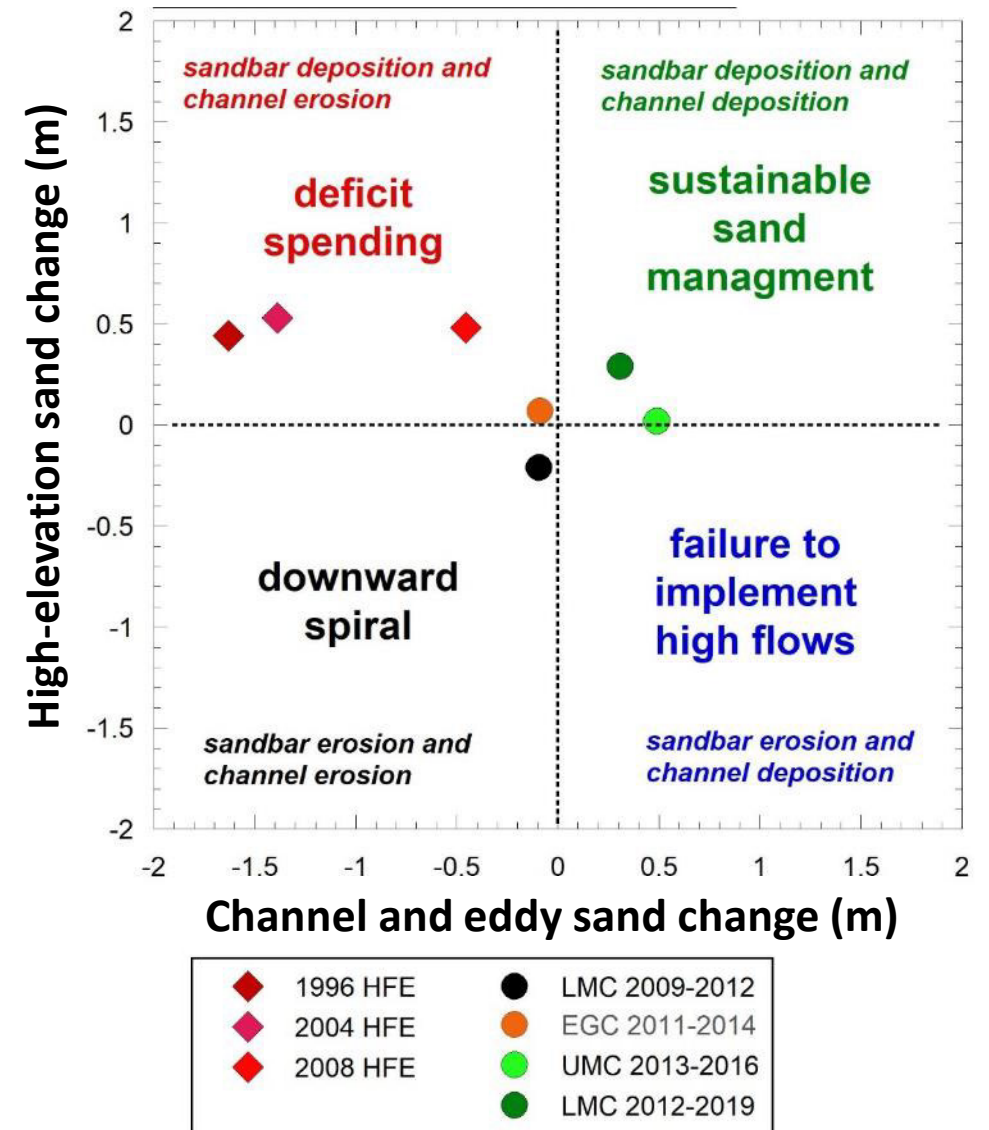
loss ← → gain

"total sand storage in channel and eddies"

Repeat channel mapping: Implications for high flows and dam management

Repeat measurements during HFEs (diamonds)

- HFEs are “deficit spending” (1996, 2004, and 2008 HFEs)
- Need to mobilize all the sand to build sandbars and a large fraction is exported
- The loss is a short-term negative and followed by recovery



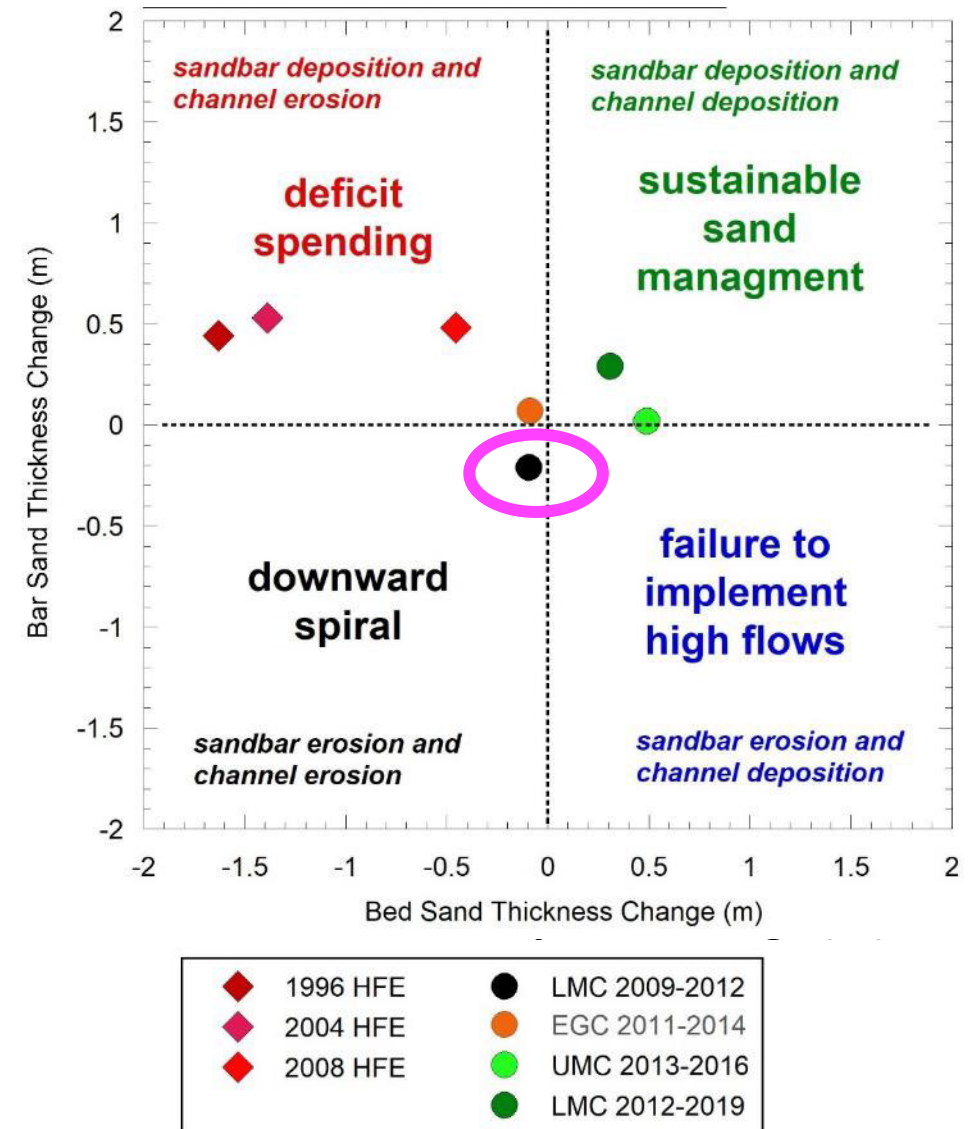
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Repeat measurements over many years (circles)

- **Downward spiral:** Equalization flows and no HFEs (LMC 2009-12)



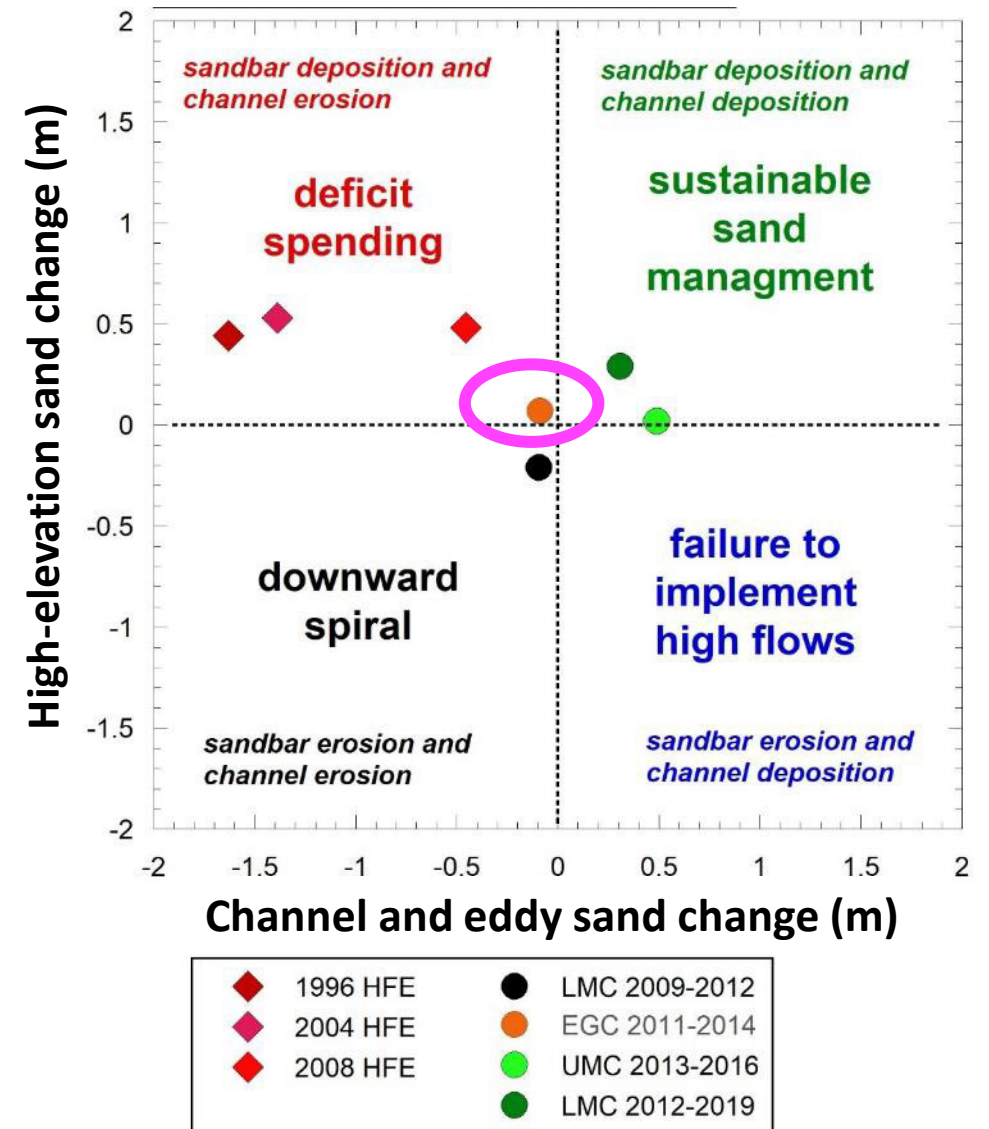
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Repeat measurements over many years (circles)

- Downward spiral: Equalization flows and no HFEs (LMC 2009-12)
- **Deficit spending: Equalization flows and HFEs (EGC 2011-14)**



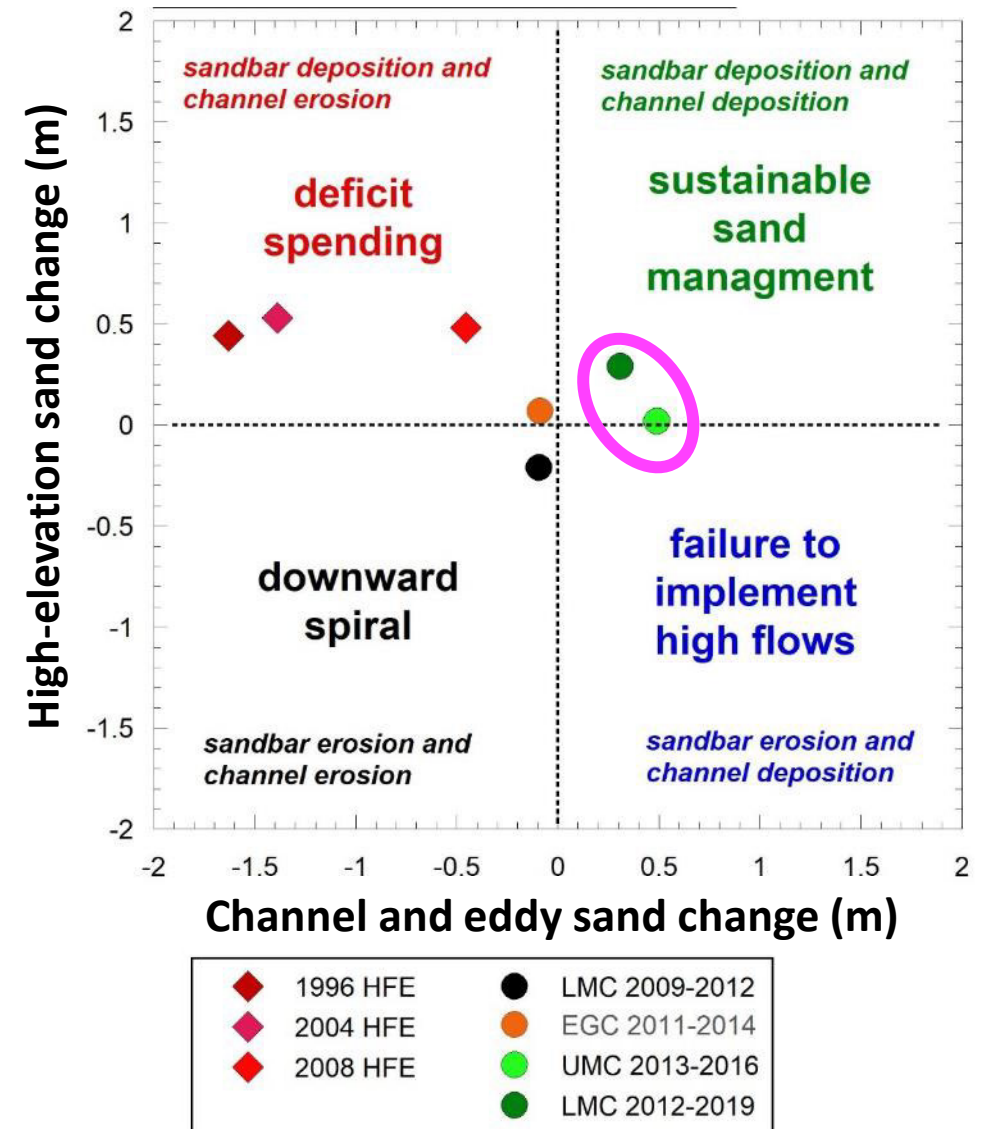
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Repeat measurements over many years (circles)

- Downward spiral: Equalization flows and no HFEs (LMC 2009-12)
- Deficit spending: Equalization flows and HFEs (EGC 2011-14)
- Sustainable: No equalization flows and HFEs (UMC 2013-16)



Repeat channel mapping: Implications for high flows and dam management

Repeat measurements during HFEs (diamonds)

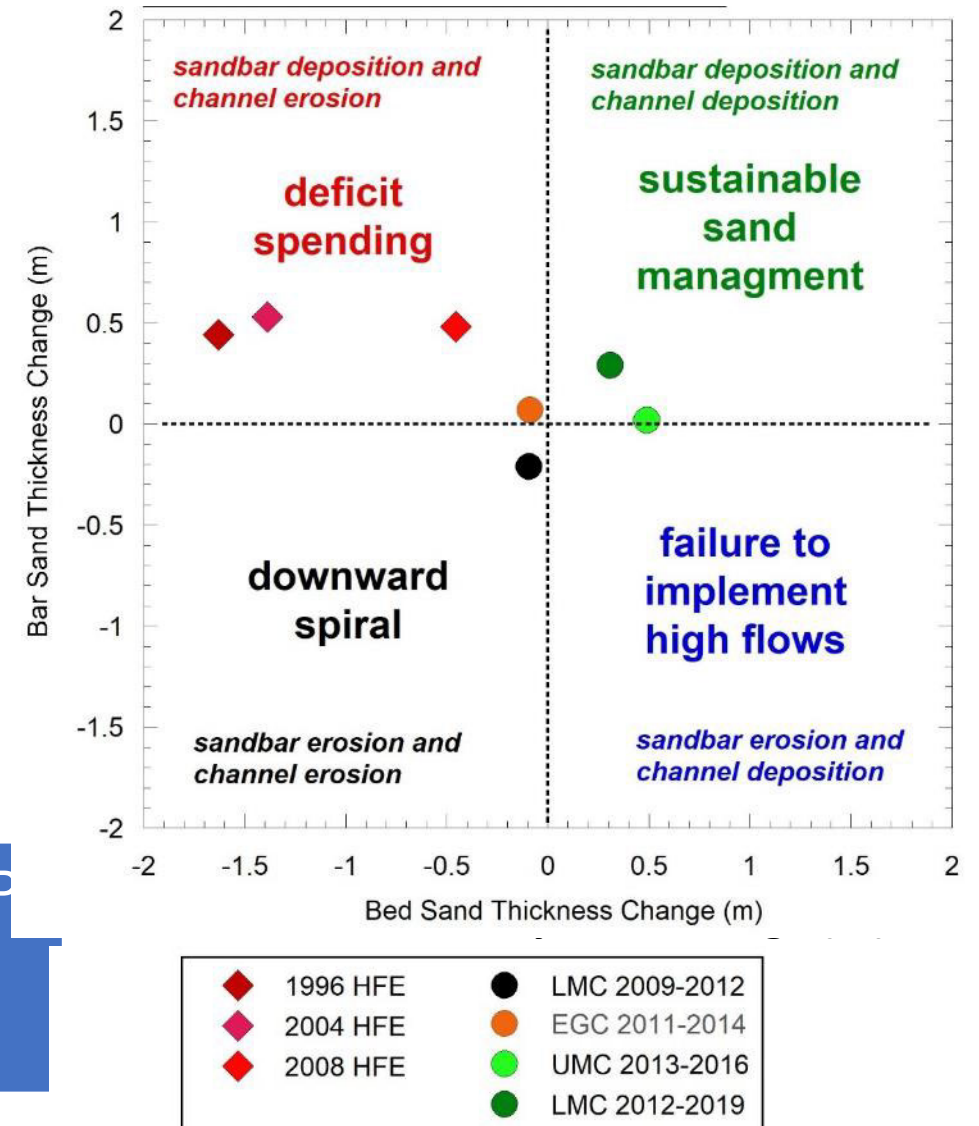
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- Deficit spending: Equalization flows and HFEs (EGC 2011-14)
- Sustainable: No equalization flows and HFEs (UMC 2013-16)

The fundamental sediment-related question for LTEMP
Where will we be on this plot after 20 years of implementation?

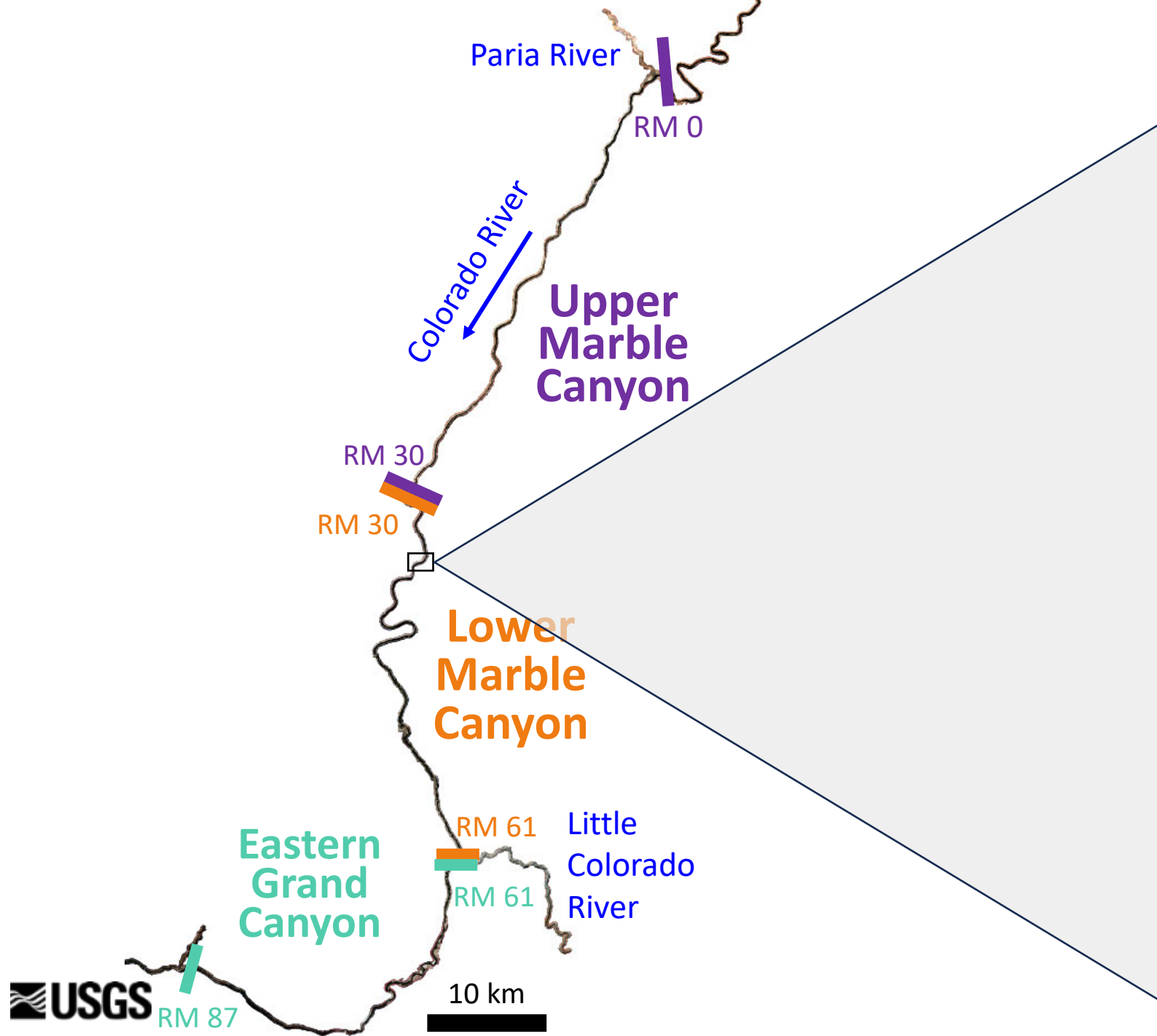
LTEMP??



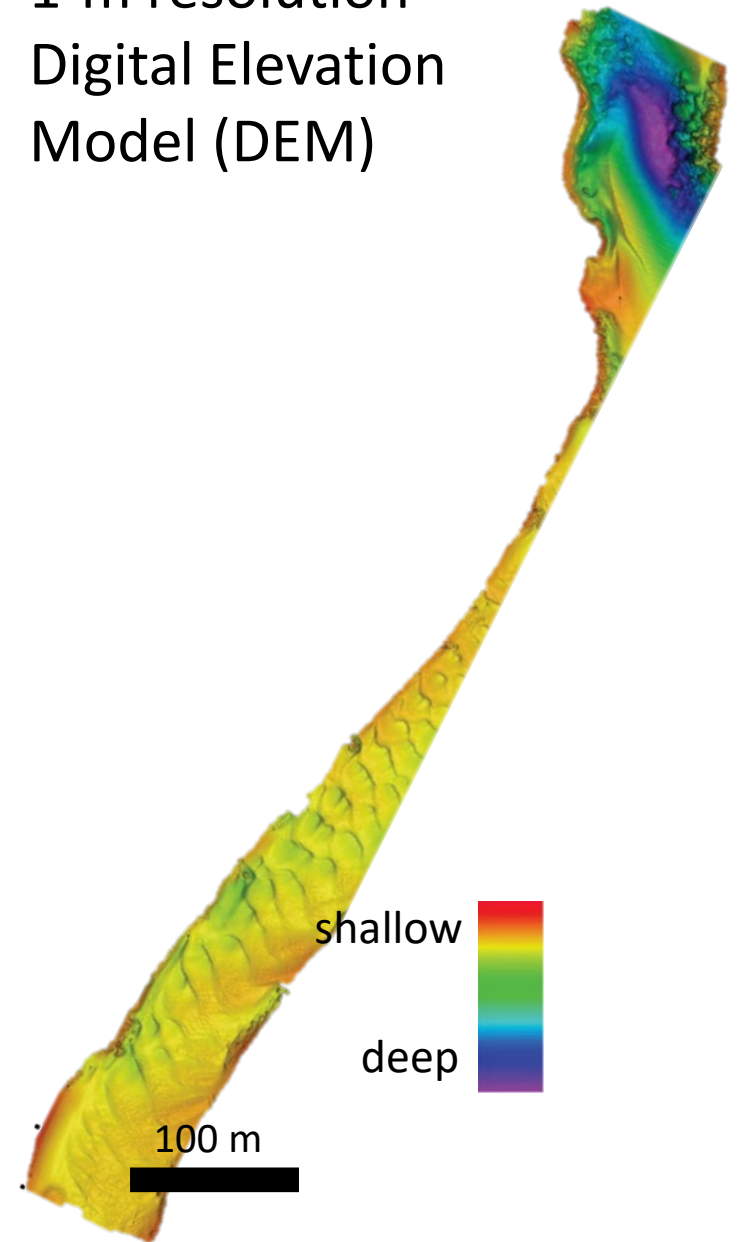
How we measure riverbed sand storage



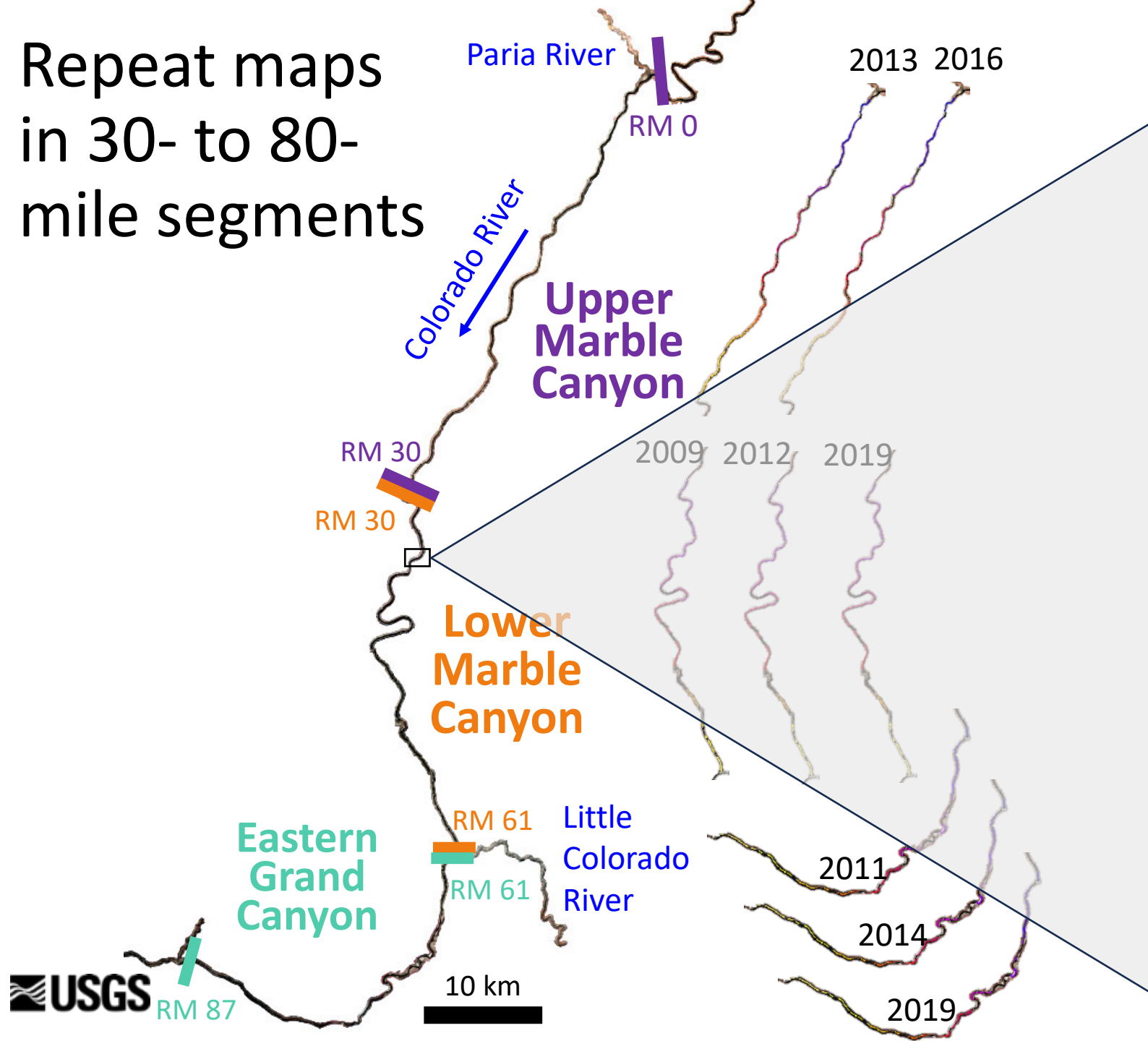
- Multibeam sonar surveys of riverbed in ~30 mi (50 km) or longer segments
- Ground-based surveys of exposed and shallow sandbars
- Map ~70-80% of reach by distance
- Do not map in most rapids or riffles



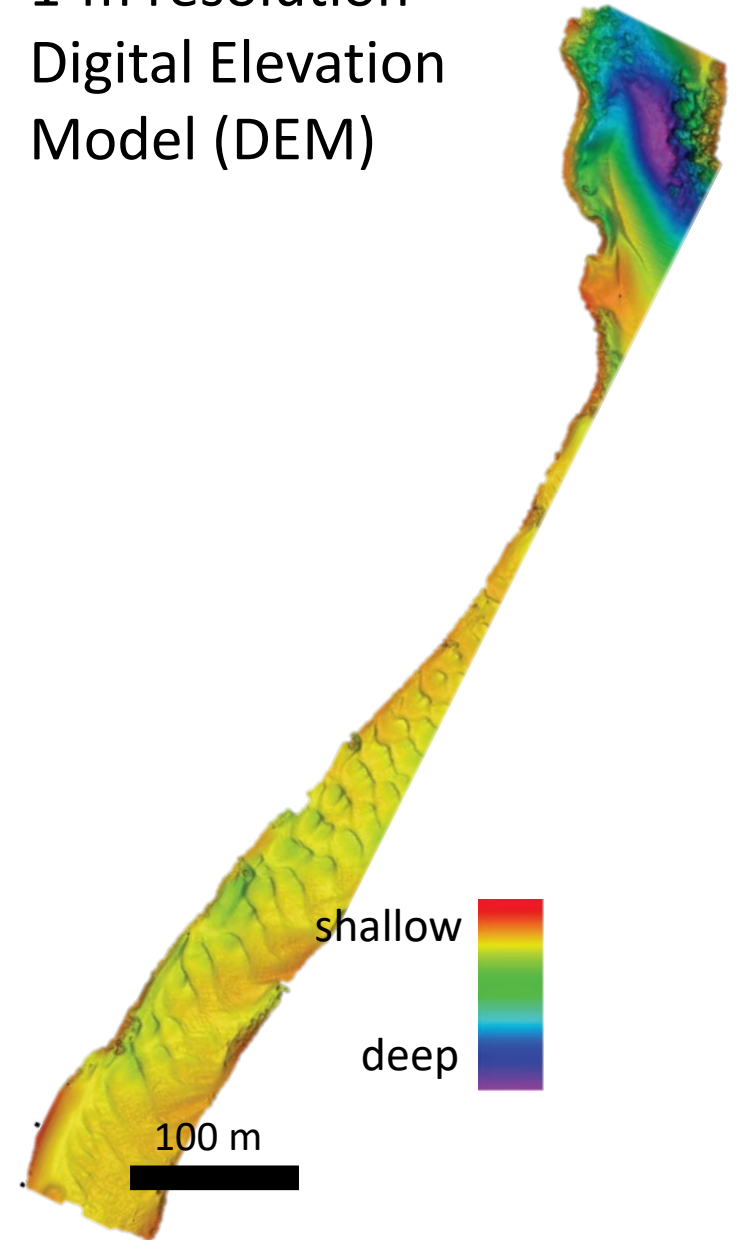
1-m resolution
Digital Elevation
Model (DEM)



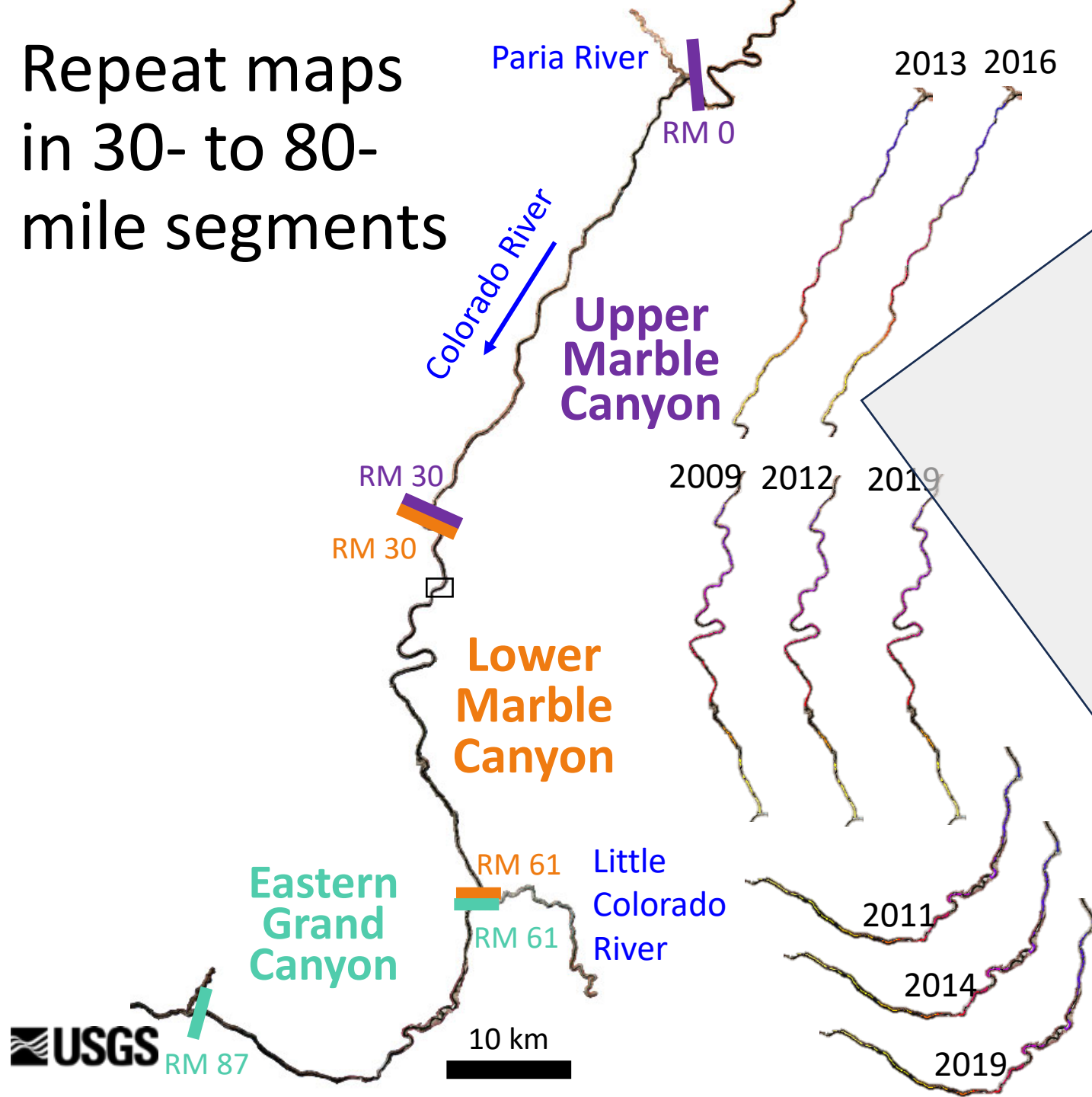
Repeat maps
in 30- to 80-
mile segments



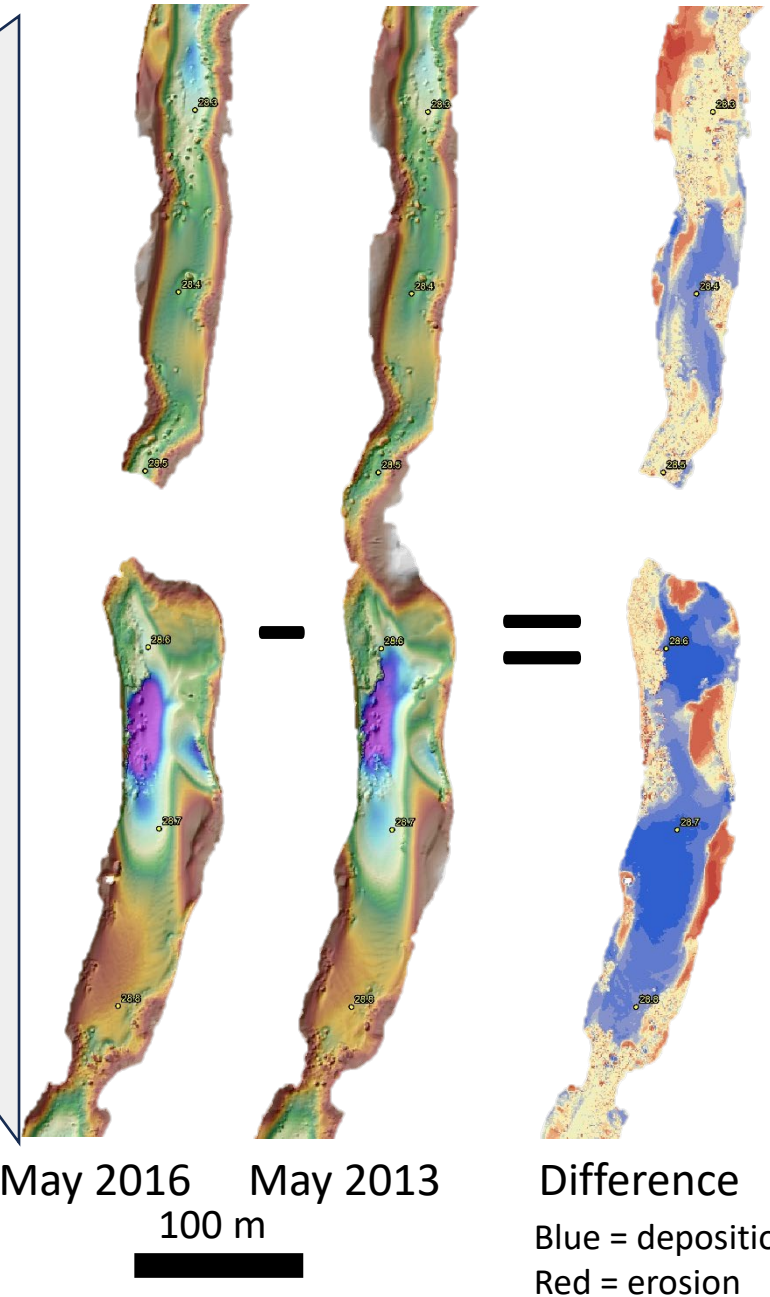
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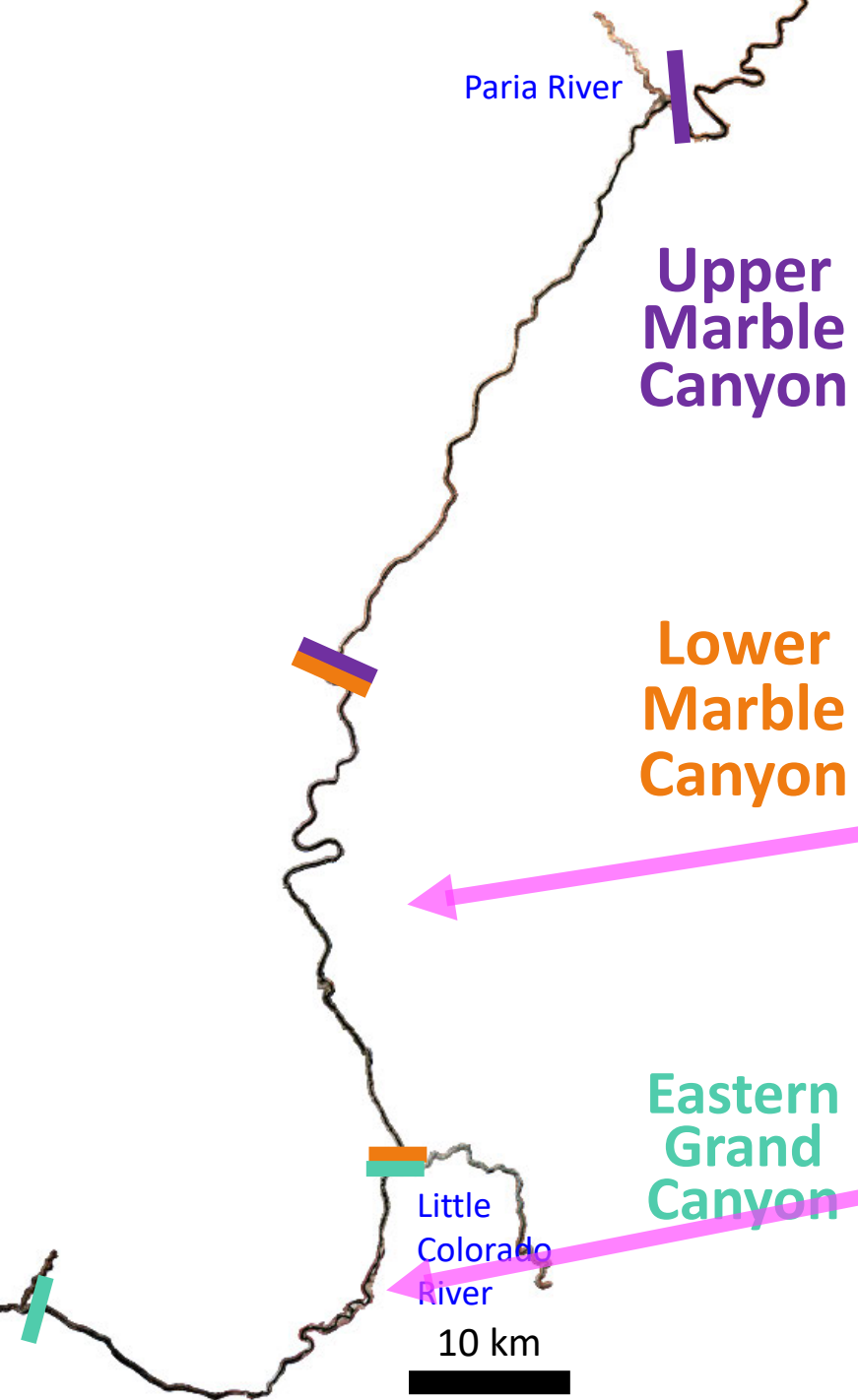


Repeat maps
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Calculate change between surveys

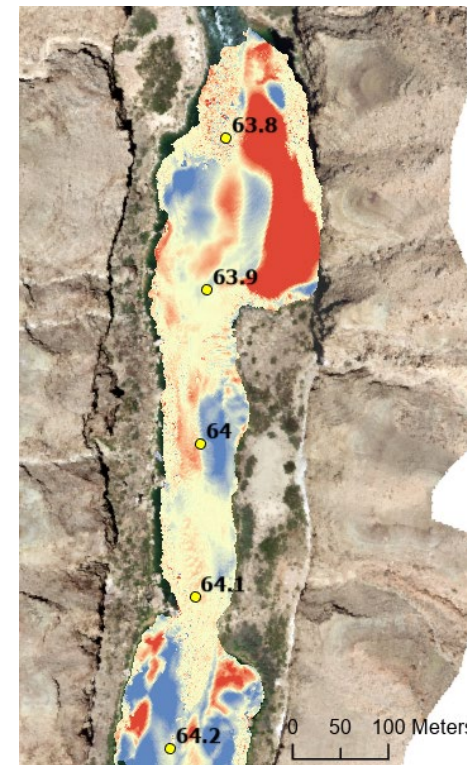
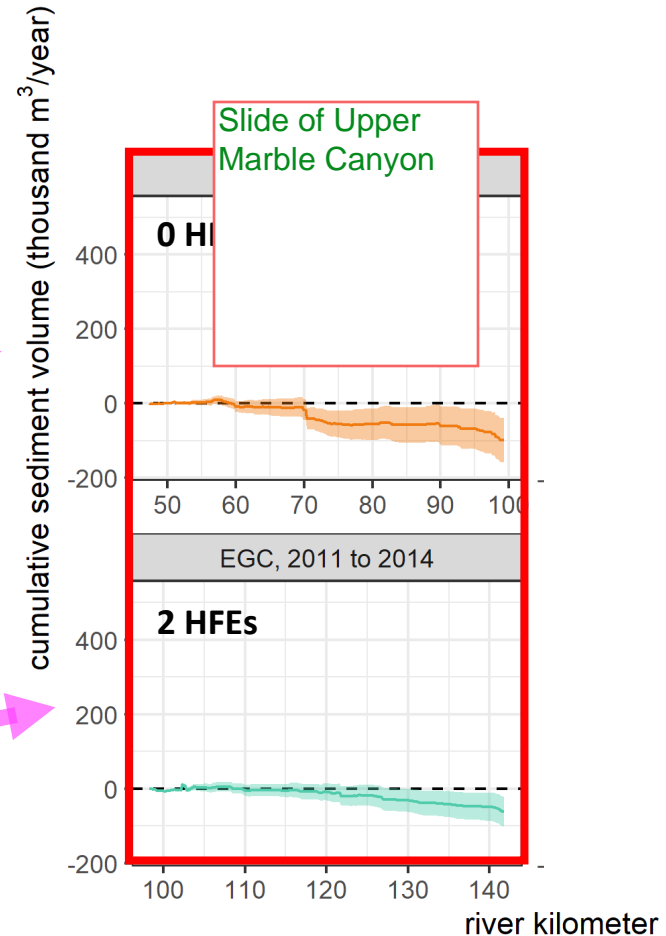




measurement of erosion and deposition volumes throughout reach

Intervals with equalization flows

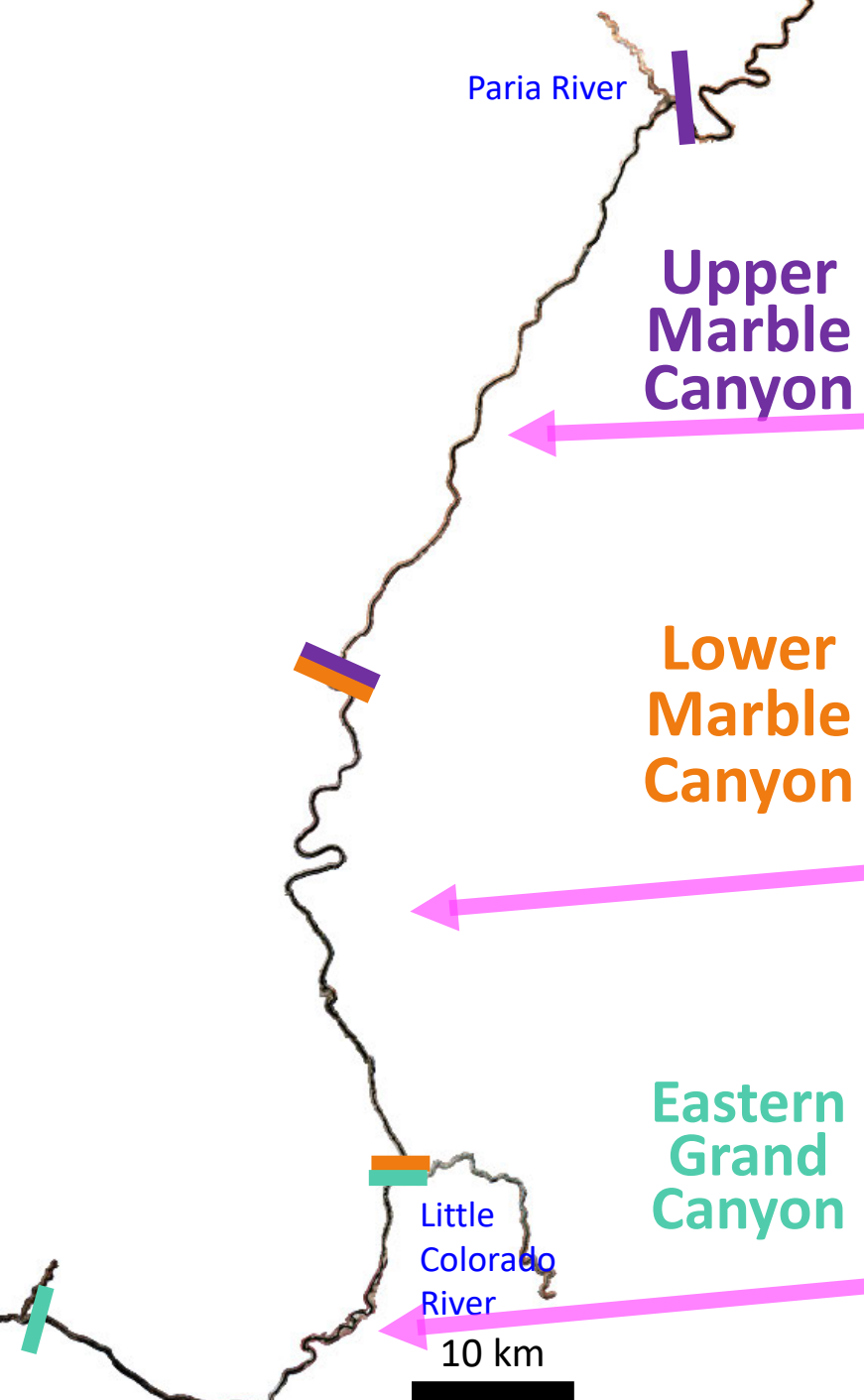
Equalization flows:
Scour throughout length of river segment with or without HFEs.



But not spatially uniform!

Difference
Blue = deposition
Red = erosion

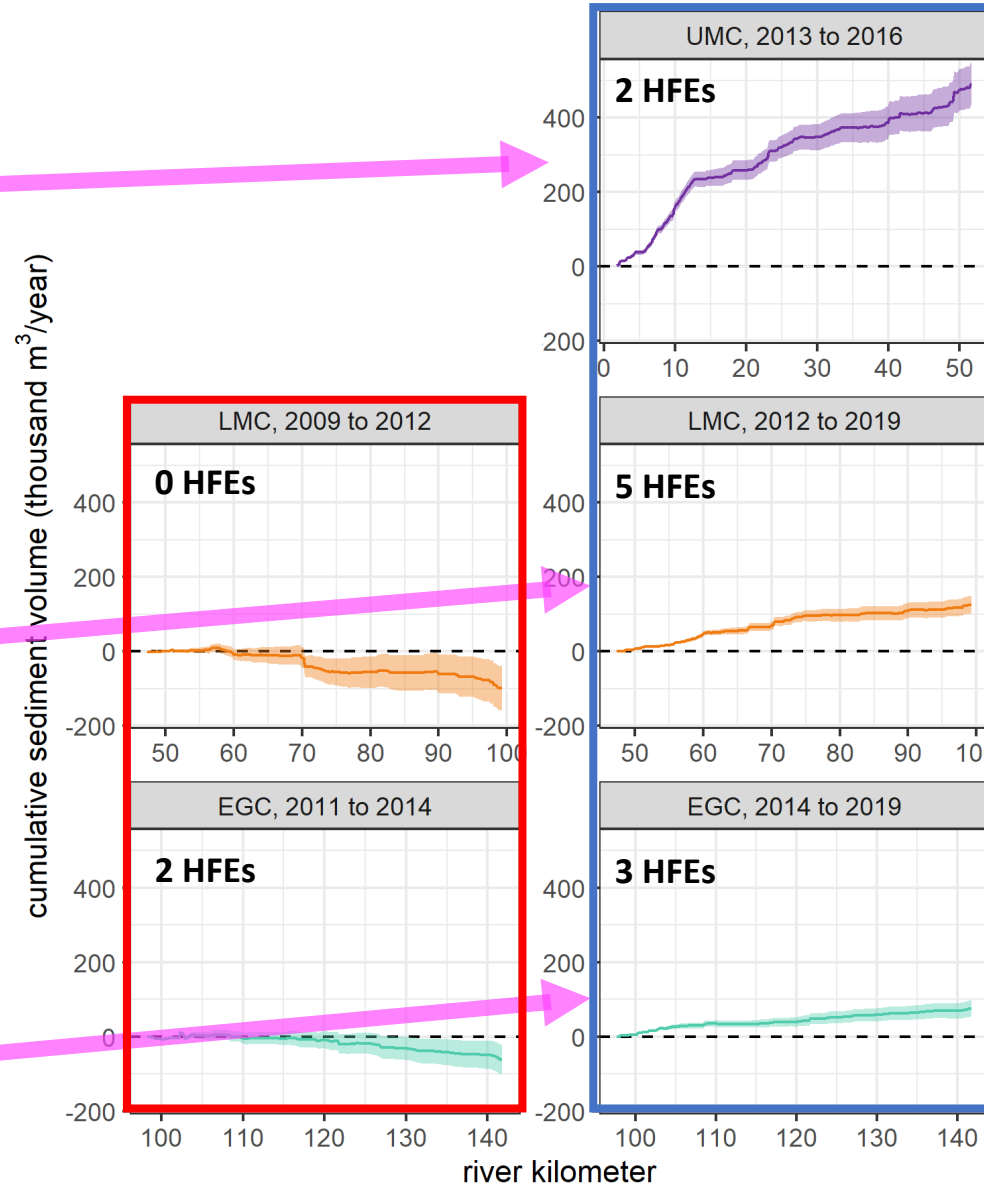
measurement of erosion and deposition volumes throughout reach



Intervals with equalization flows

Intervals without equalization flows

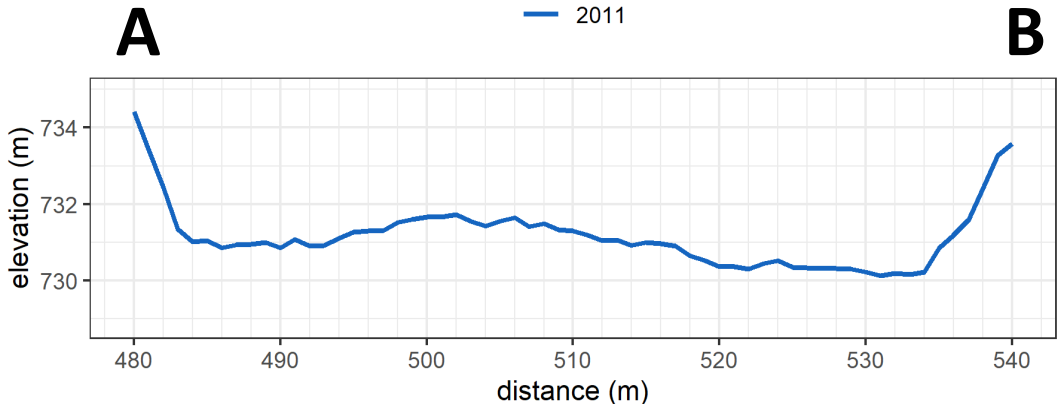
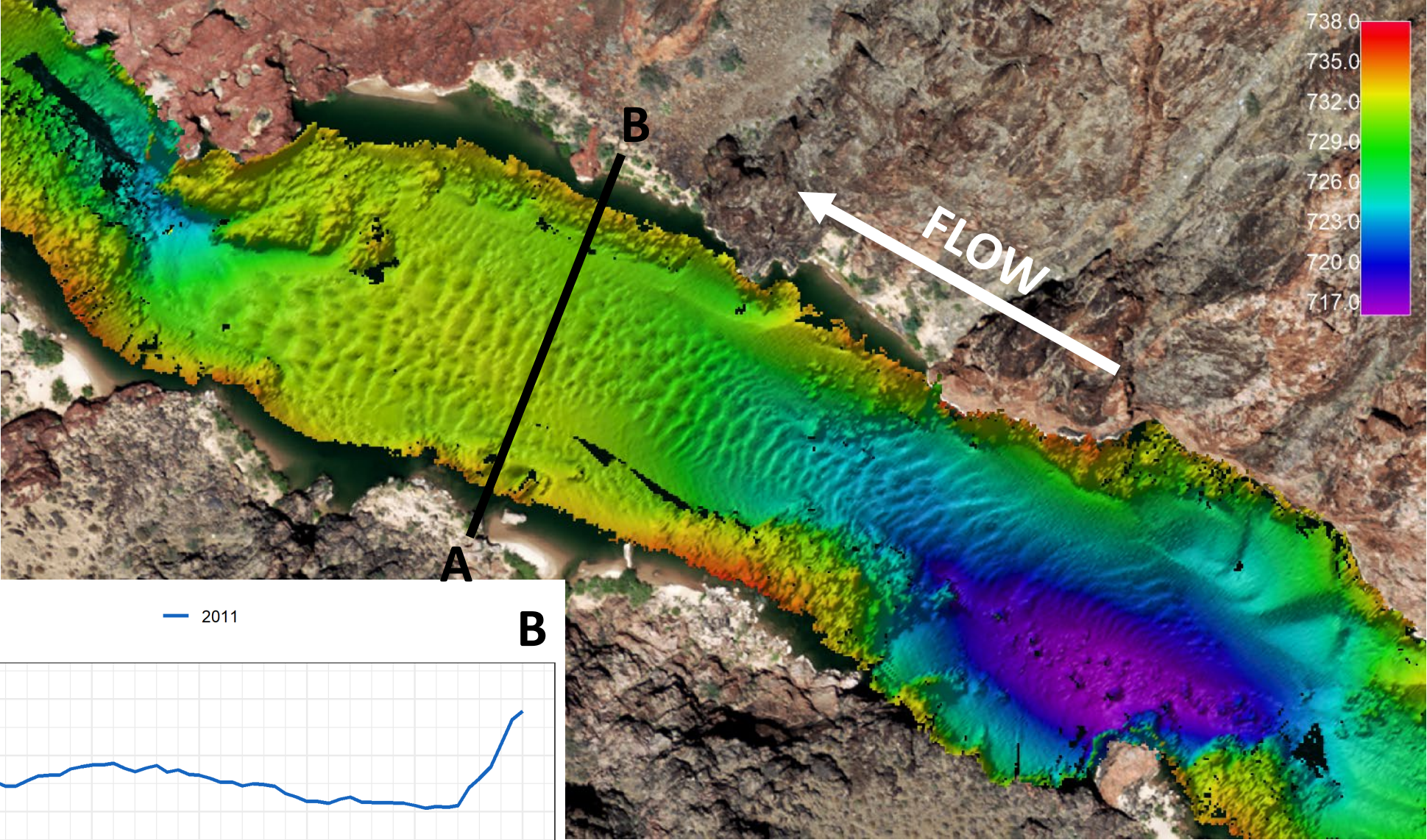
cumulative sediment volume (thousand m³/year)



Equalization flows:
Scour throughout length of river segment with or without HFEs.

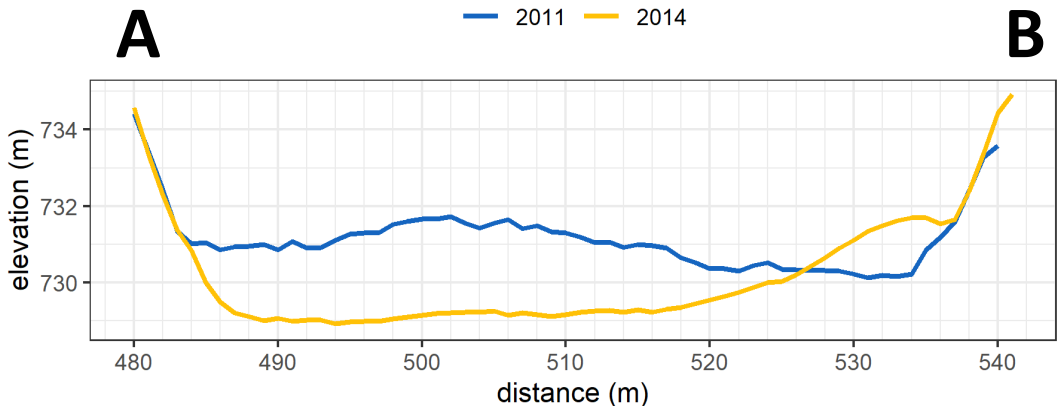
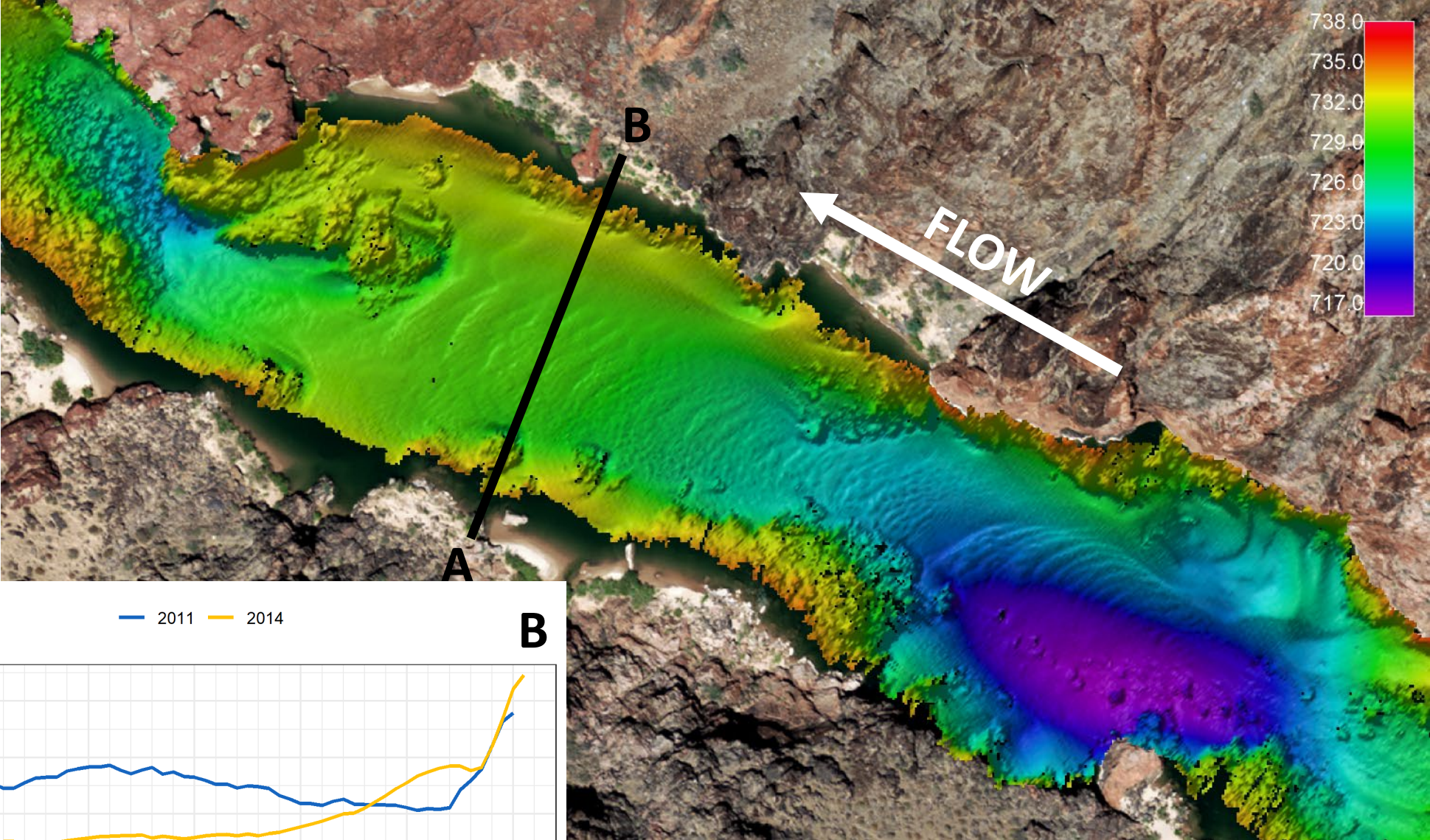
Without equalization flows:
sand accumulates throughout segment and HFEs rebuild sandbars.

April 2011 – Before equalization flows



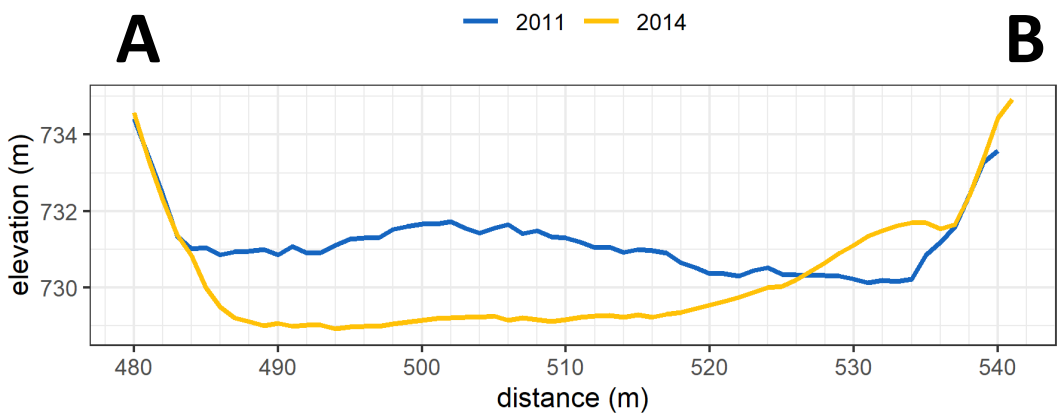
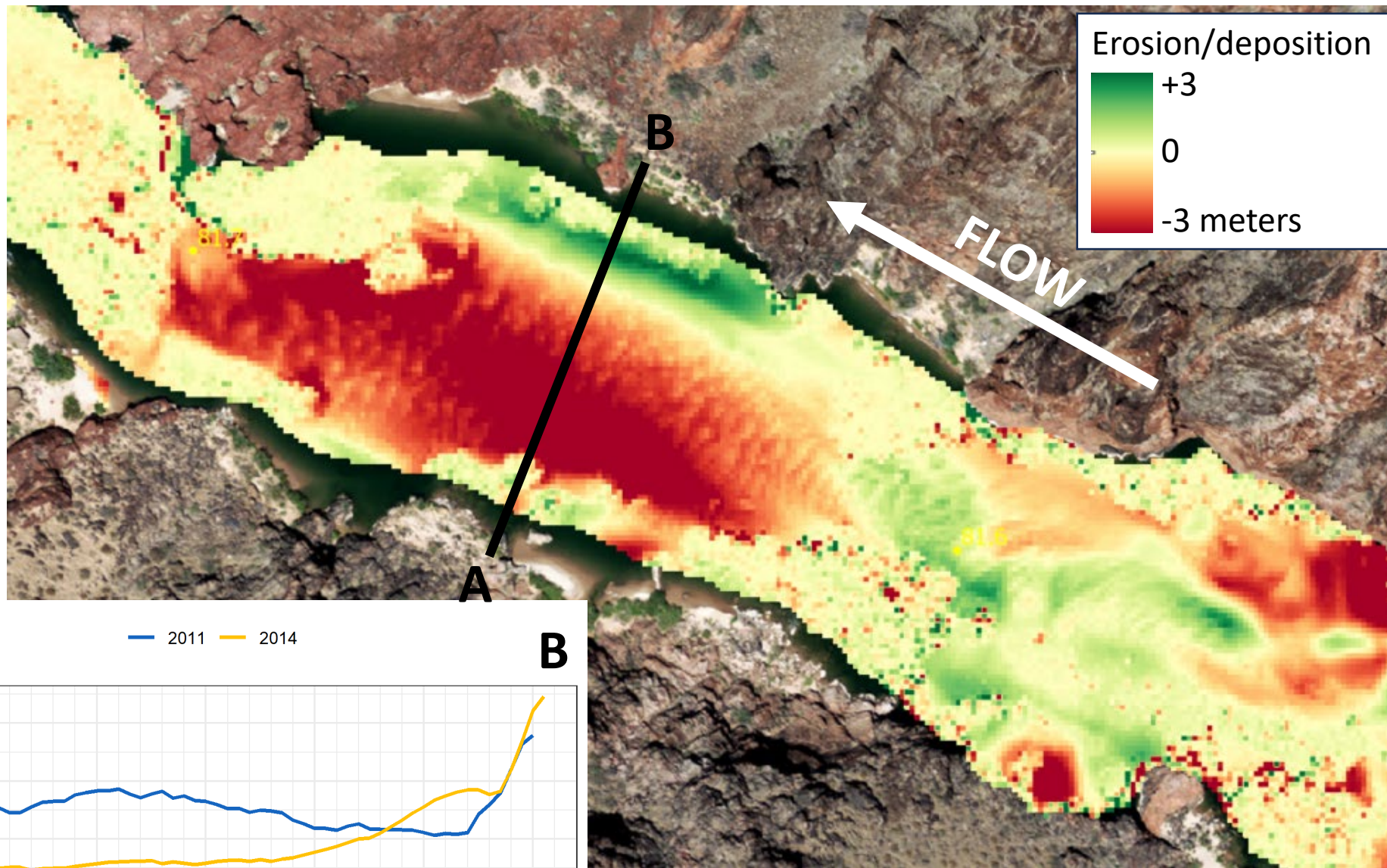
Kaplinski et al. (2025a); and Preliminary results. Do not cite.

April 2014 – After equalization flows and two fall HFEs



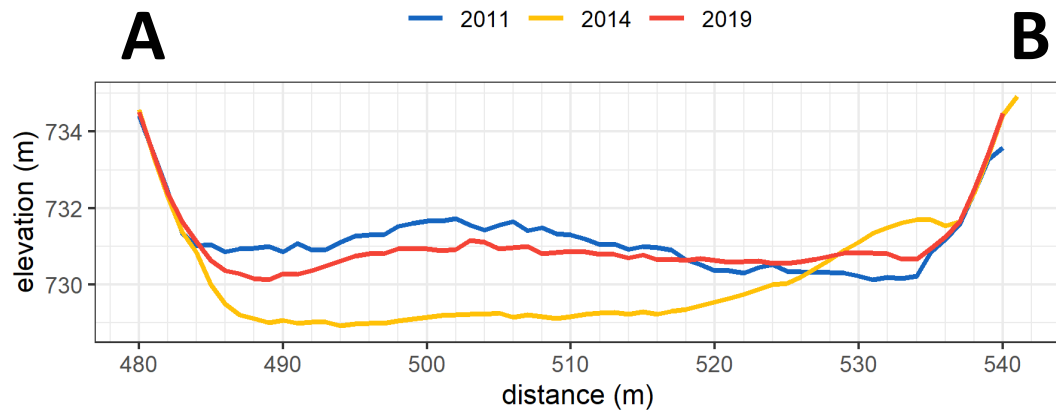
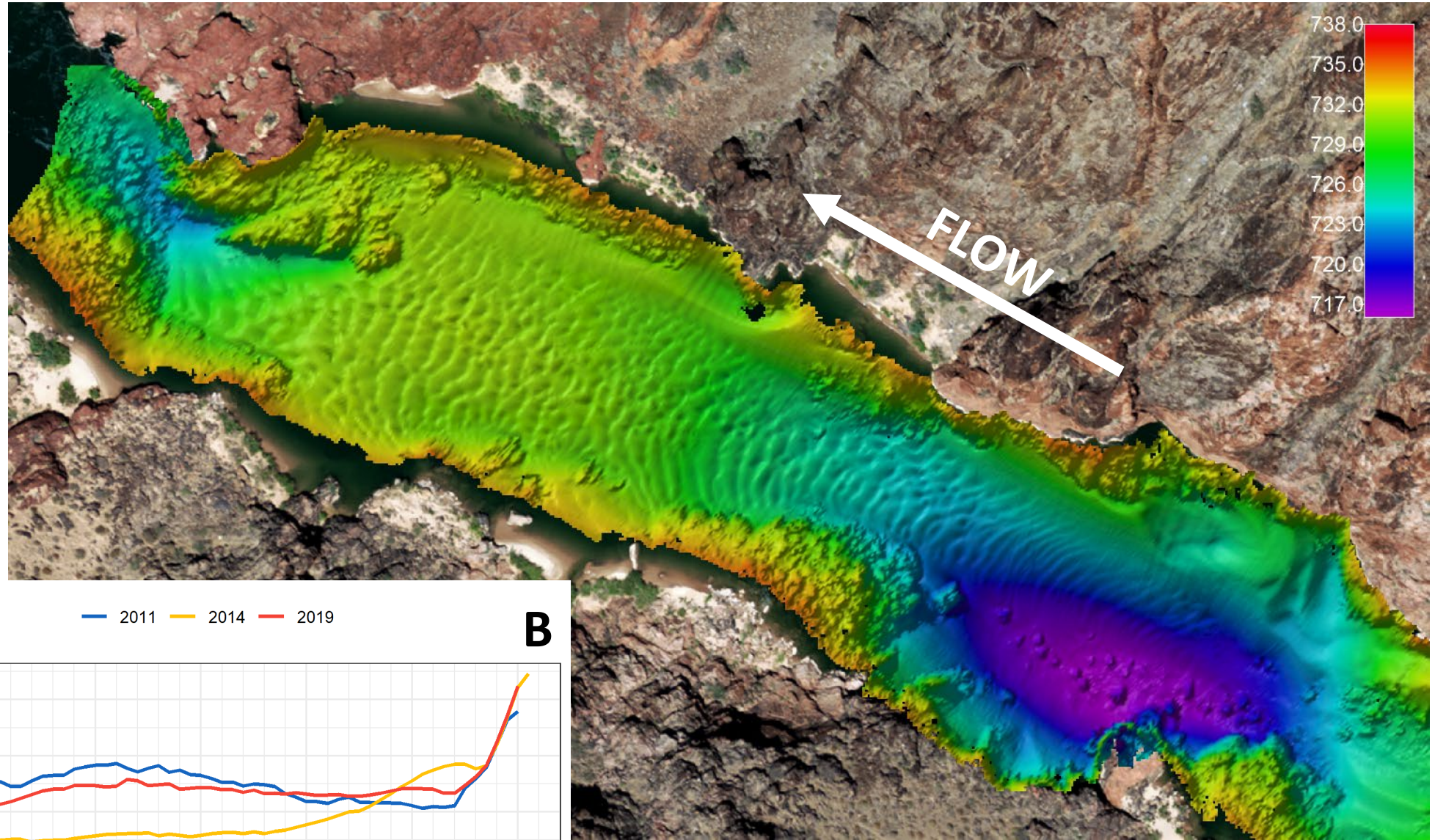
Kaplinski et al. (2025b); and Preliminary results. Do not cite.

2011 to 2014 Erosion – After equalization flows and two fall HFEs

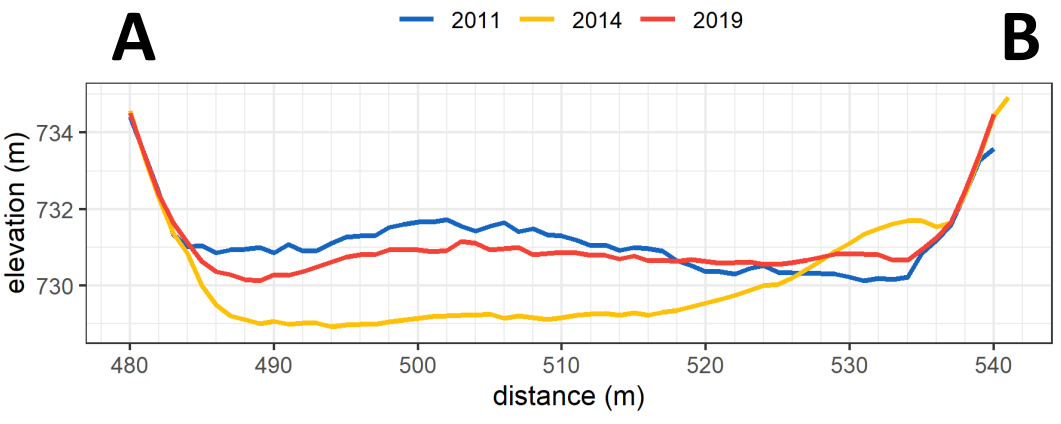
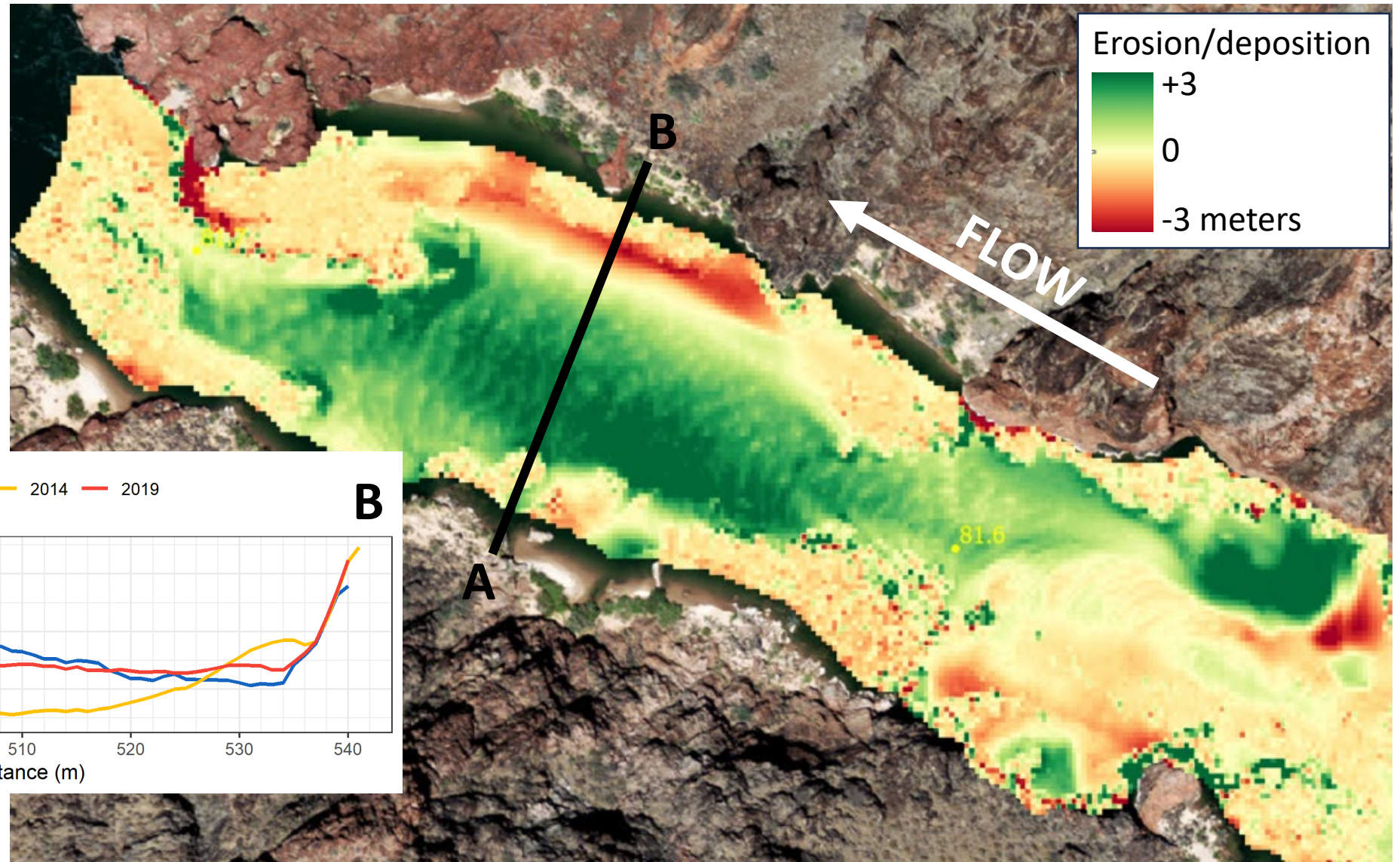


Kaplinski et al. (2025a;b); and Preliminary results. Do not cite.

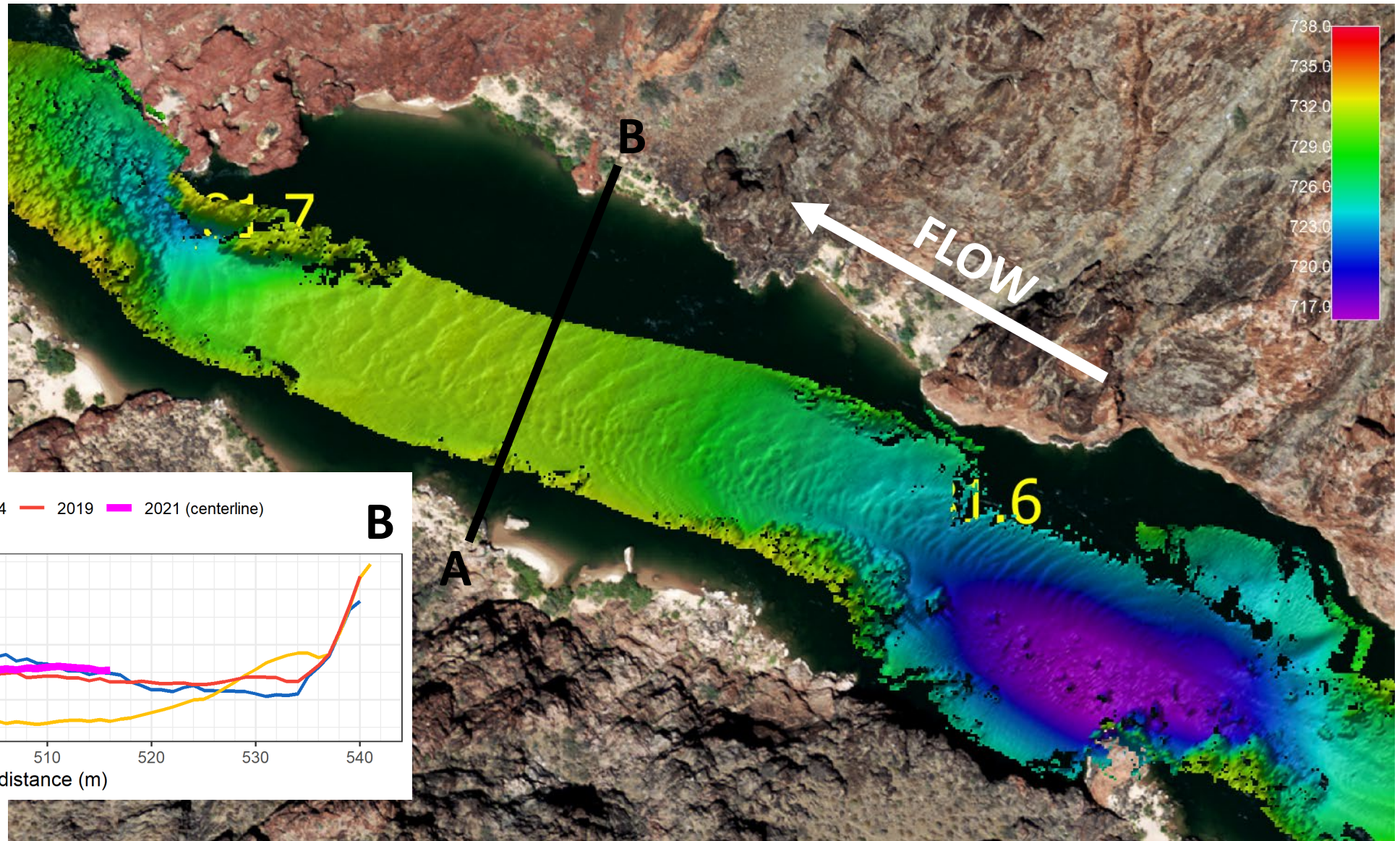
May 2019 – No equalization flows and three fall HFEs



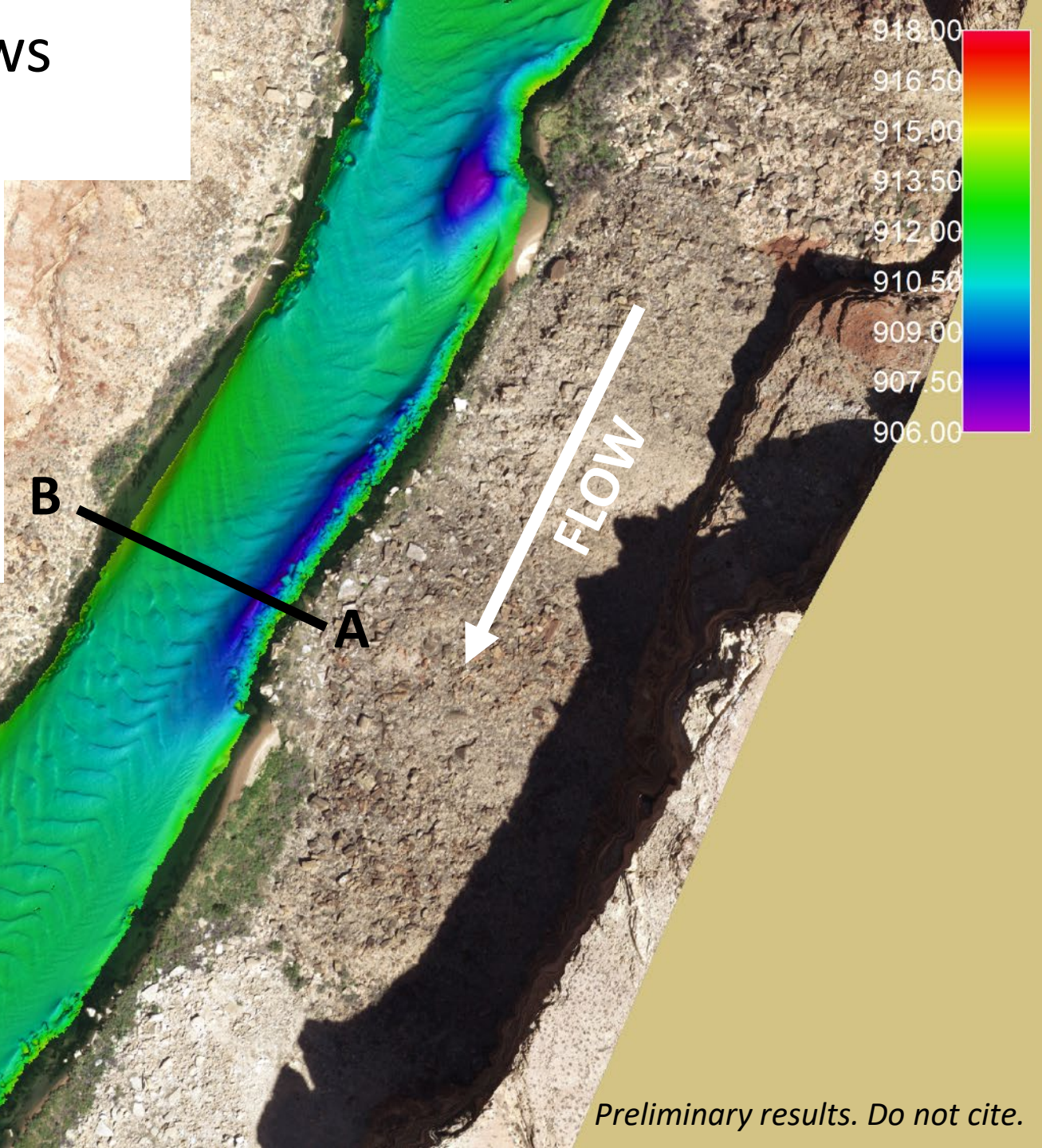
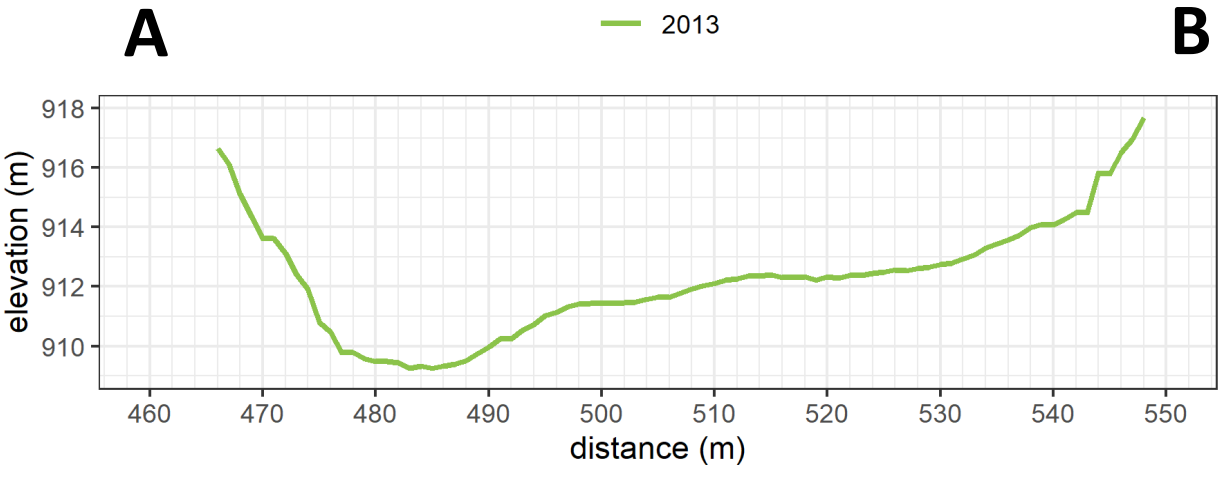
2014 to 2019 Deposition – No equalization flows and three fall HFEs



May 2021 – Centerline survey of water surface and riverbed

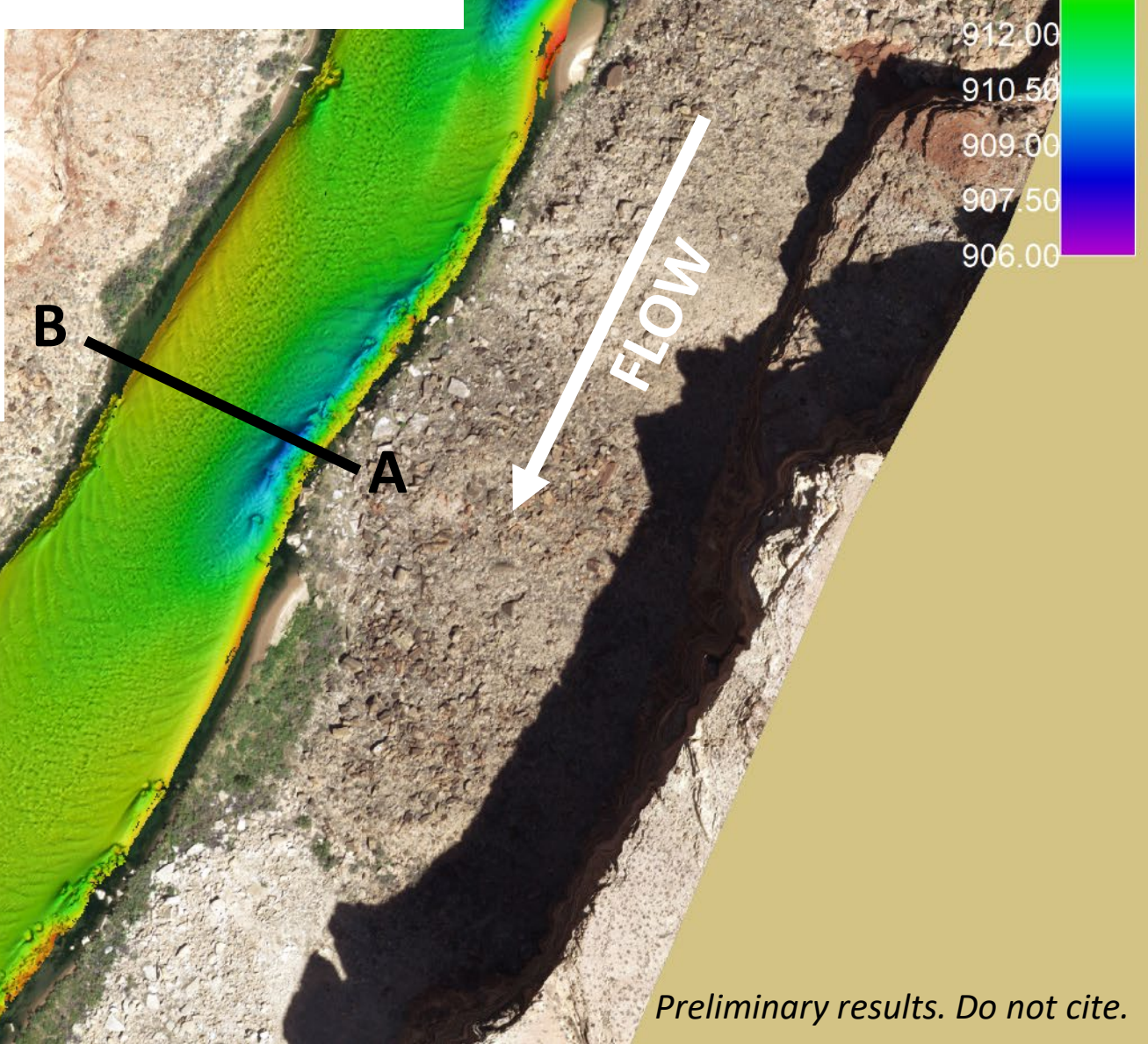
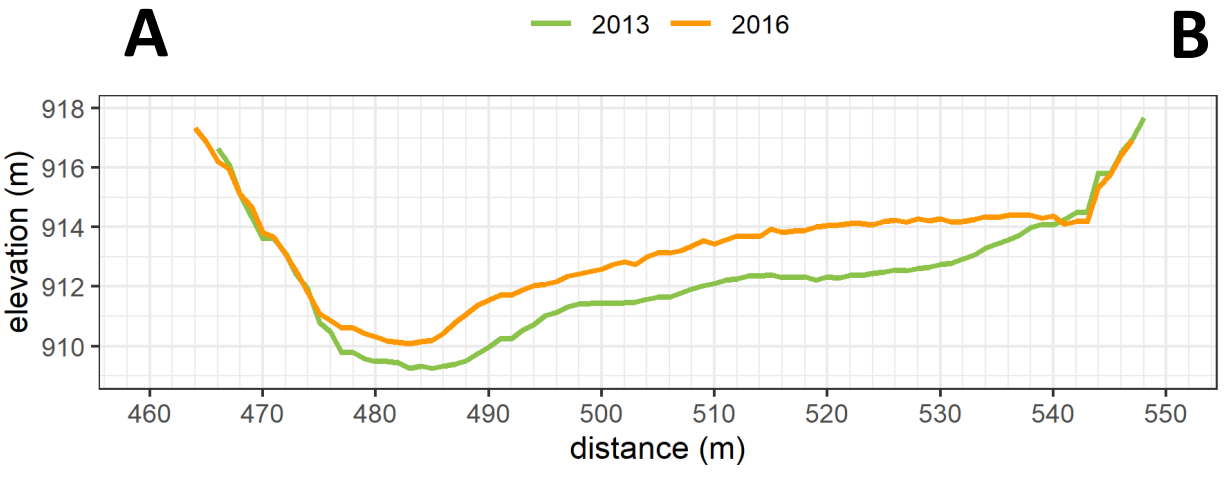


May 2013 – After equalization flows (and fall HFE)



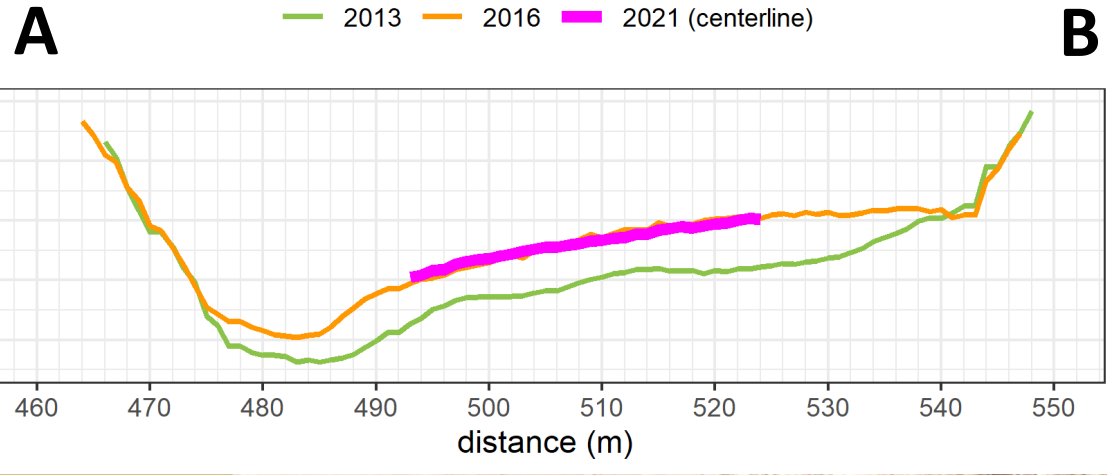
Preliminary results. Do not cite.

May 2016 – After HFEs in 2013 and 2014 (fall HFE triggered in 2015 but not implemented)



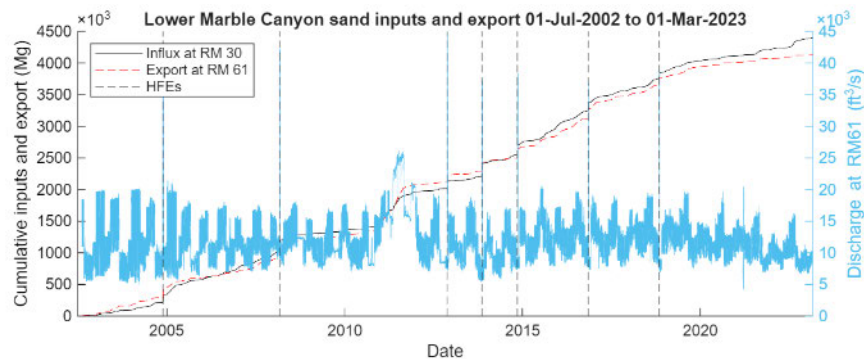
Preliminary results. Do not cite.

May 2021 – After more HFEs in 2016 and 2018



Independent and complementary measures of sediment storage change

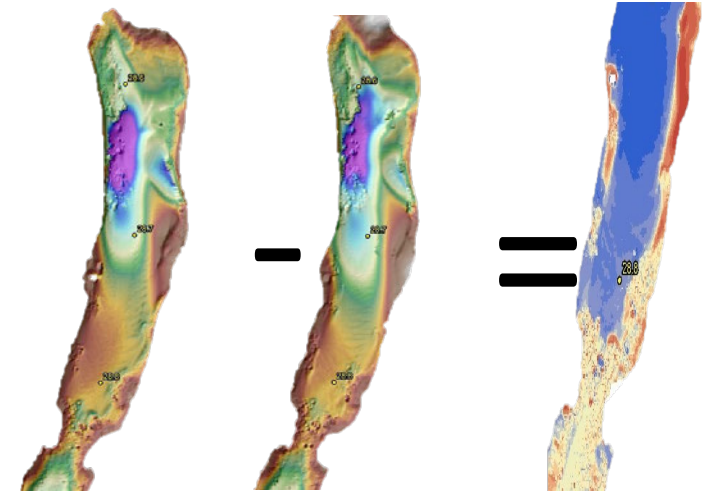
Project A: Suspended sediment flux



Difference of cumulative suspended-sediment loads between stations

- Temporally rich -- may compute budget for any time interval
- Difference between two LARGE numbers
- Potential for undetectable bias in measurements
- **Uncertainty accumulates over time**

Project B: River channel (bed and bank) mapping



May 2016

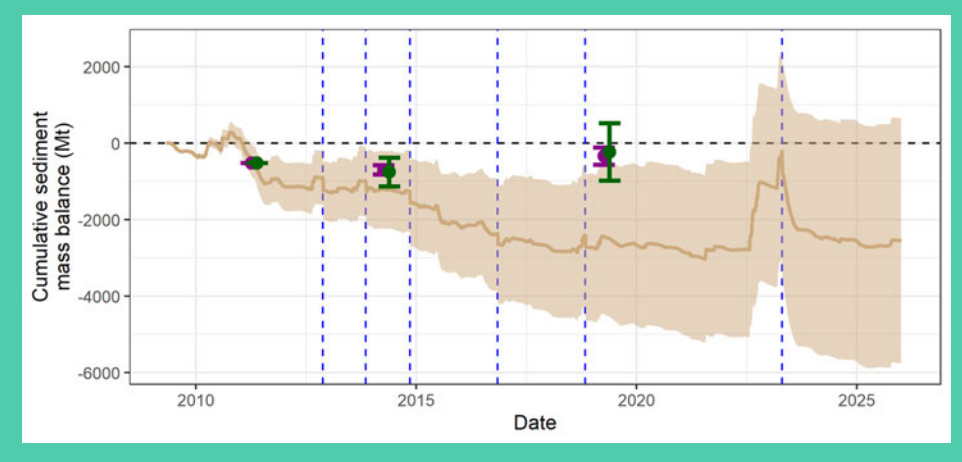
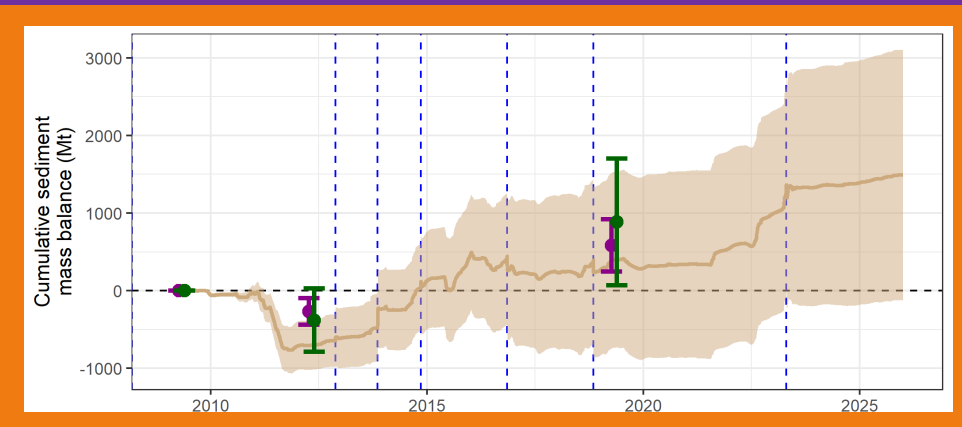
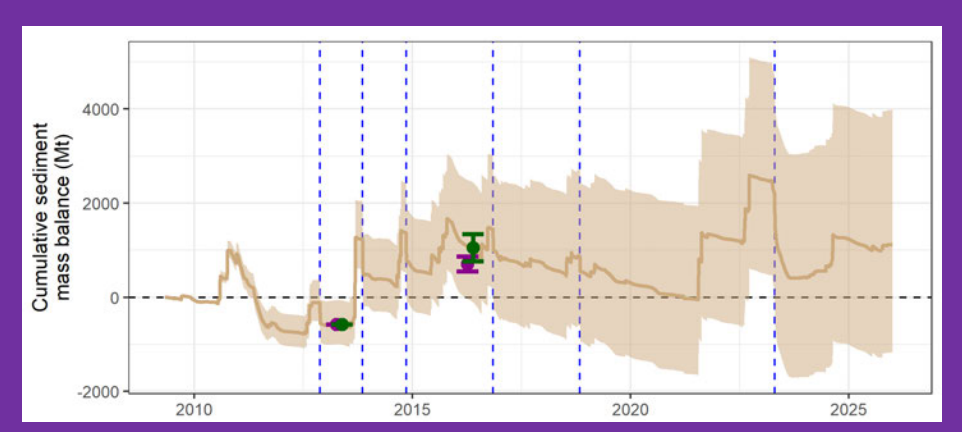
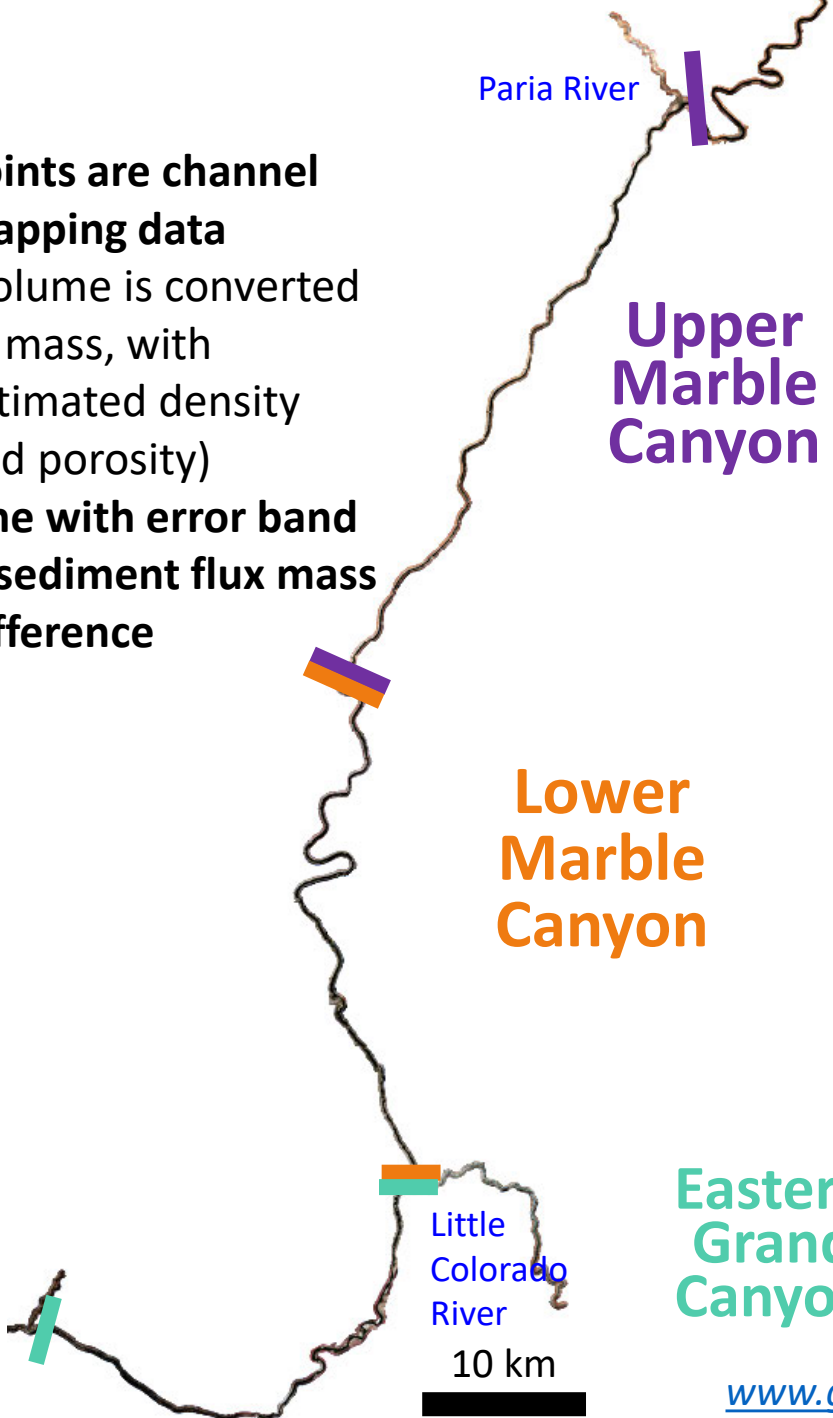
May 2013

Blue = deposition
Red = erosion

Difference between riverbed maps

- Spatially rich – know where change happens and how much
- Uncertainty and bias are well constrained
- Limited to discrete points in time
- **Uncertainty associated with parts of channel and banks not measured (we sample 50 to 75% of a segment)**

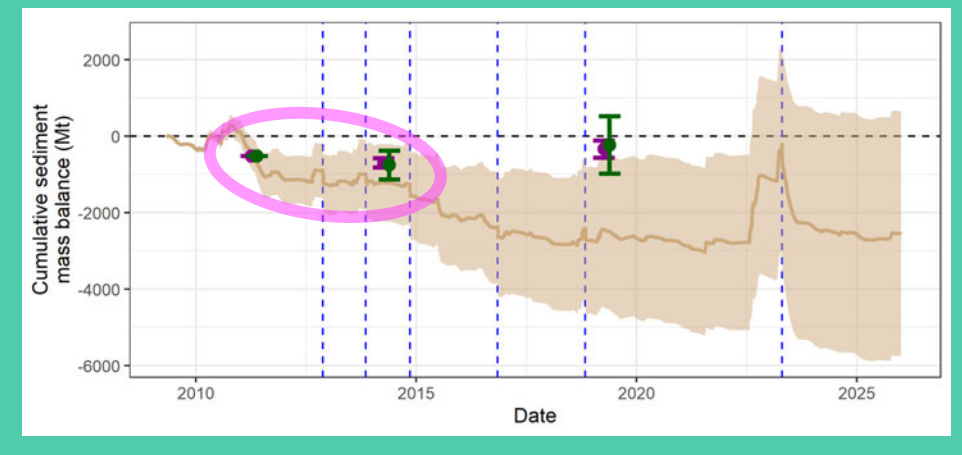
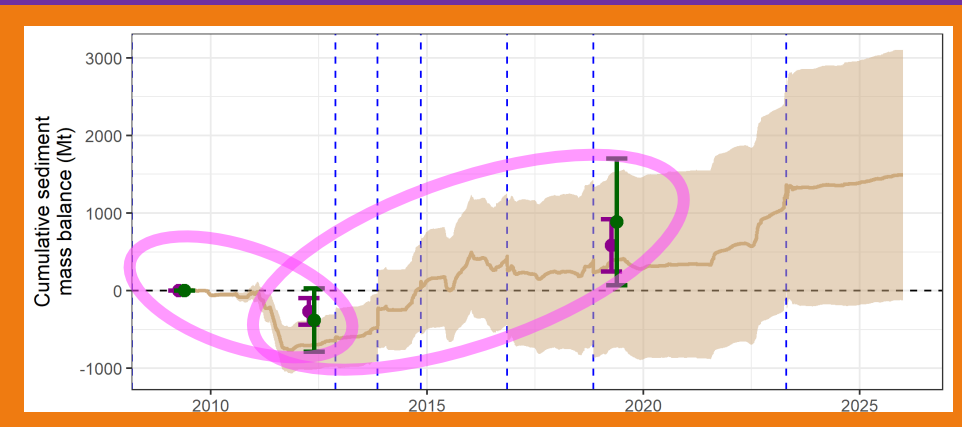
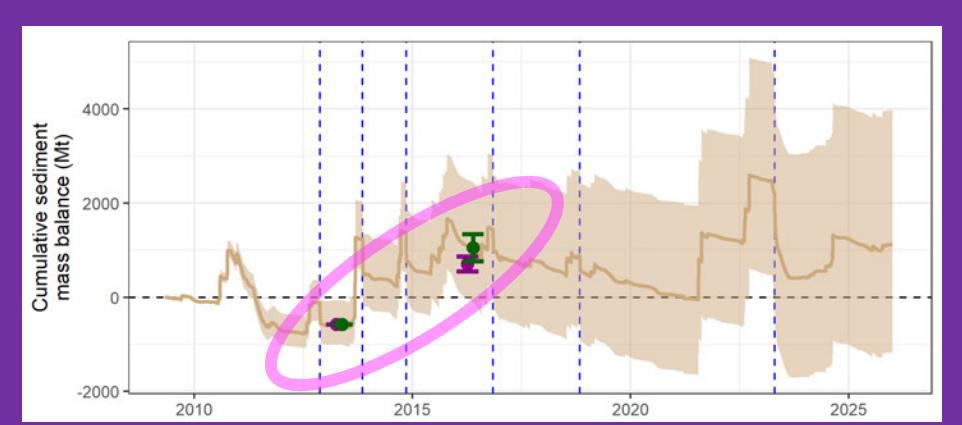
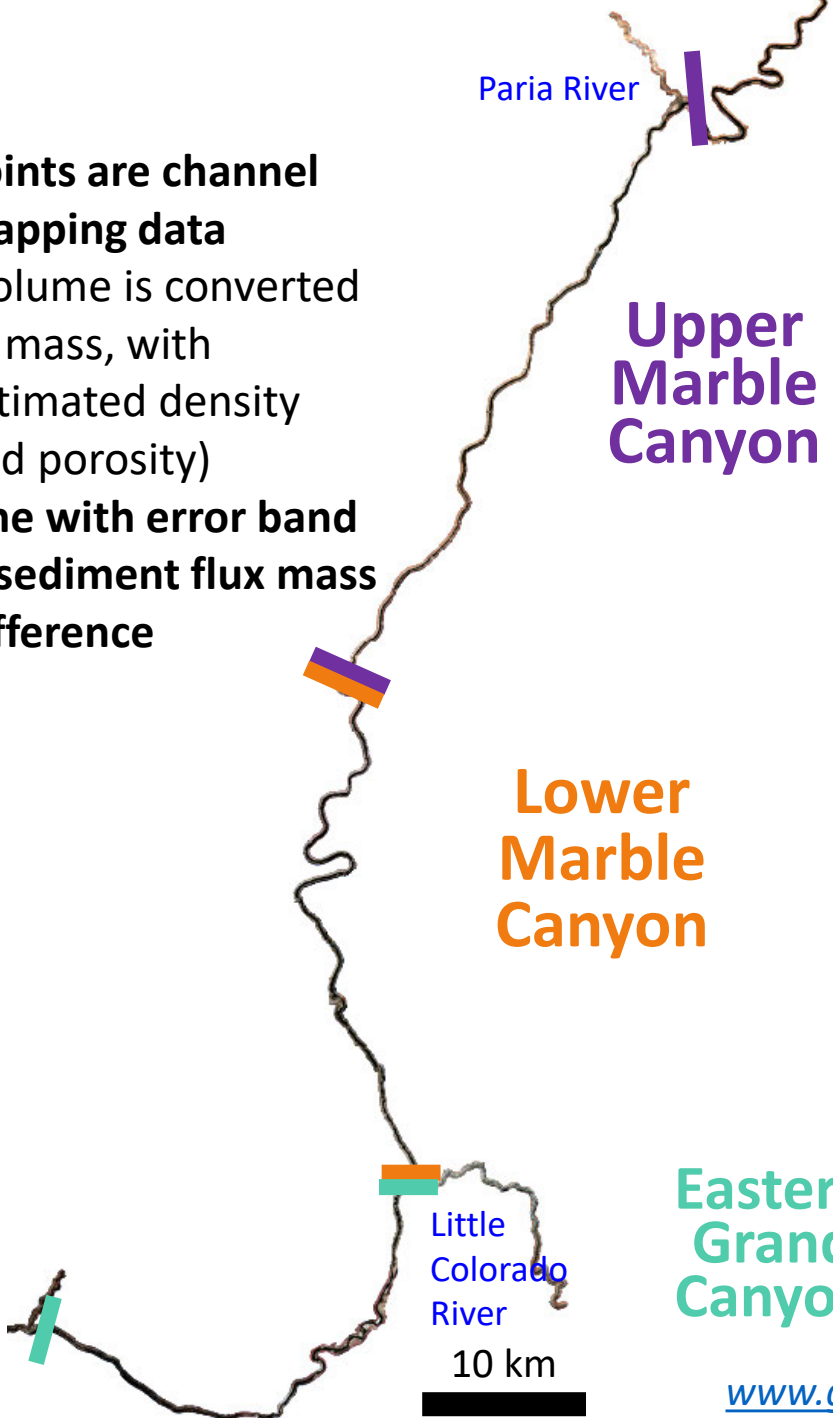
- **Points are channel mapping data** (volume is converted to mass, with estimated density and porosity)
- **Line with error band is sediment flux mass difference**



www.gcmrc.gov/discharge_qw_sediment and Preliminary results. Do not cite.



- **Points are channel mapping data** (volume is converted to mass, with estimated density and porosity)
- **Line with error band is sediment flux mass difference**

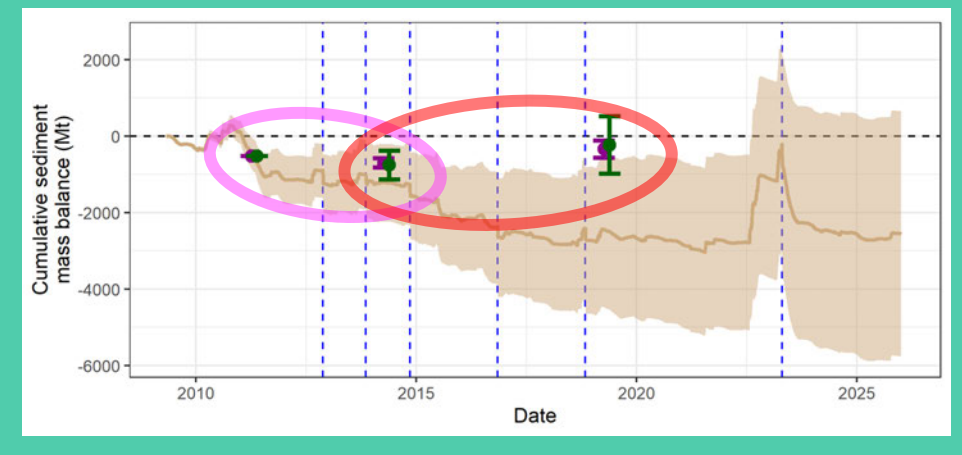
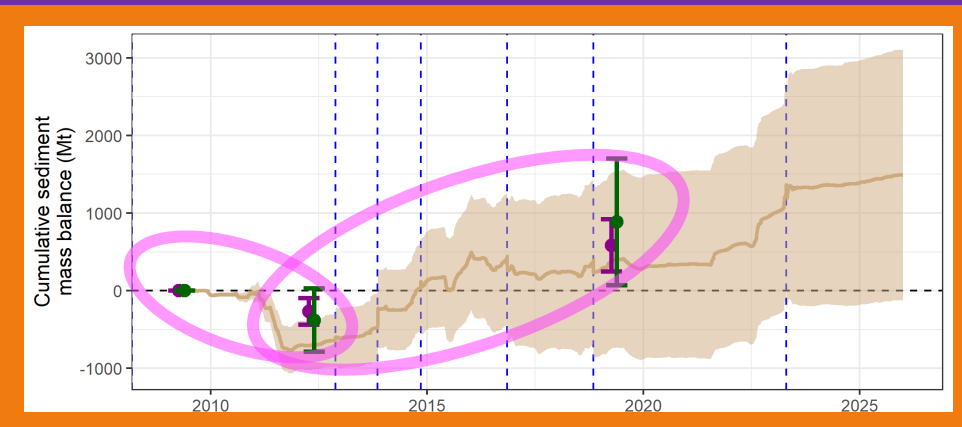
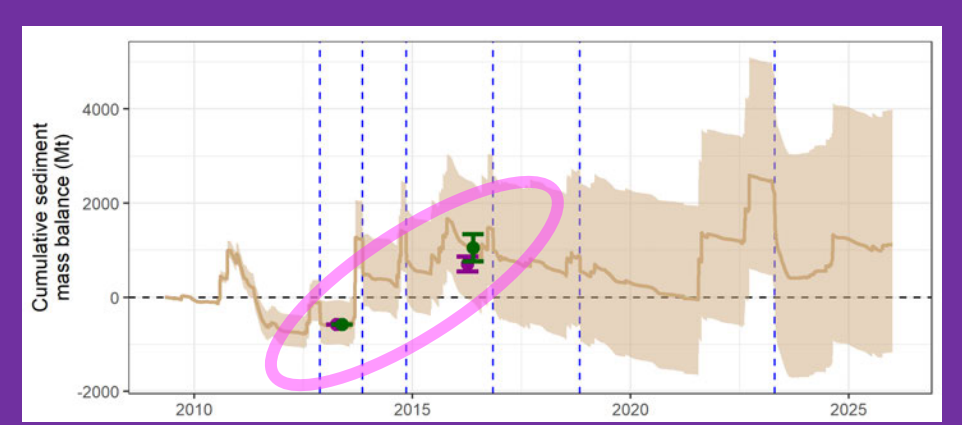
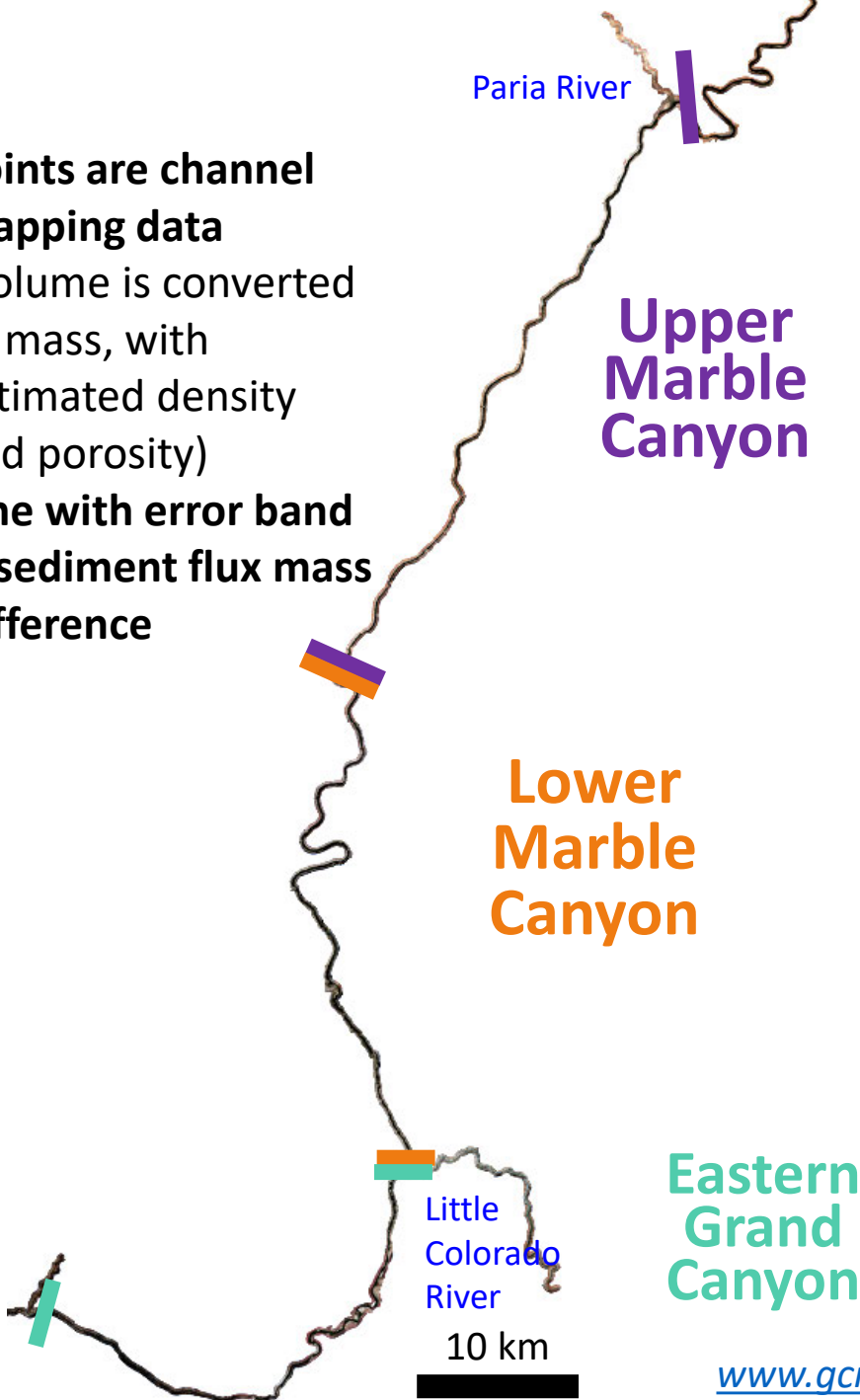


Close agreement

- Report with confidence on magnitude and spatial distribution of change



- **Points are channel mapping data** (volume is converted to mass, with estimated density and porosity)
- **Line with error band is sediment flux mass difference**



Close agreement

- Report with confidence on magnitude and spatial distribution of change

Barely overlapping uncertainty bands

- Alert that we might be missing something
- *Change in unmapped areas?*
- *Unknown bias in sediment flux?*



Repeat channel mapping: Implications for high flows and dam management

Repeat measurements during HFEs (diamonds)

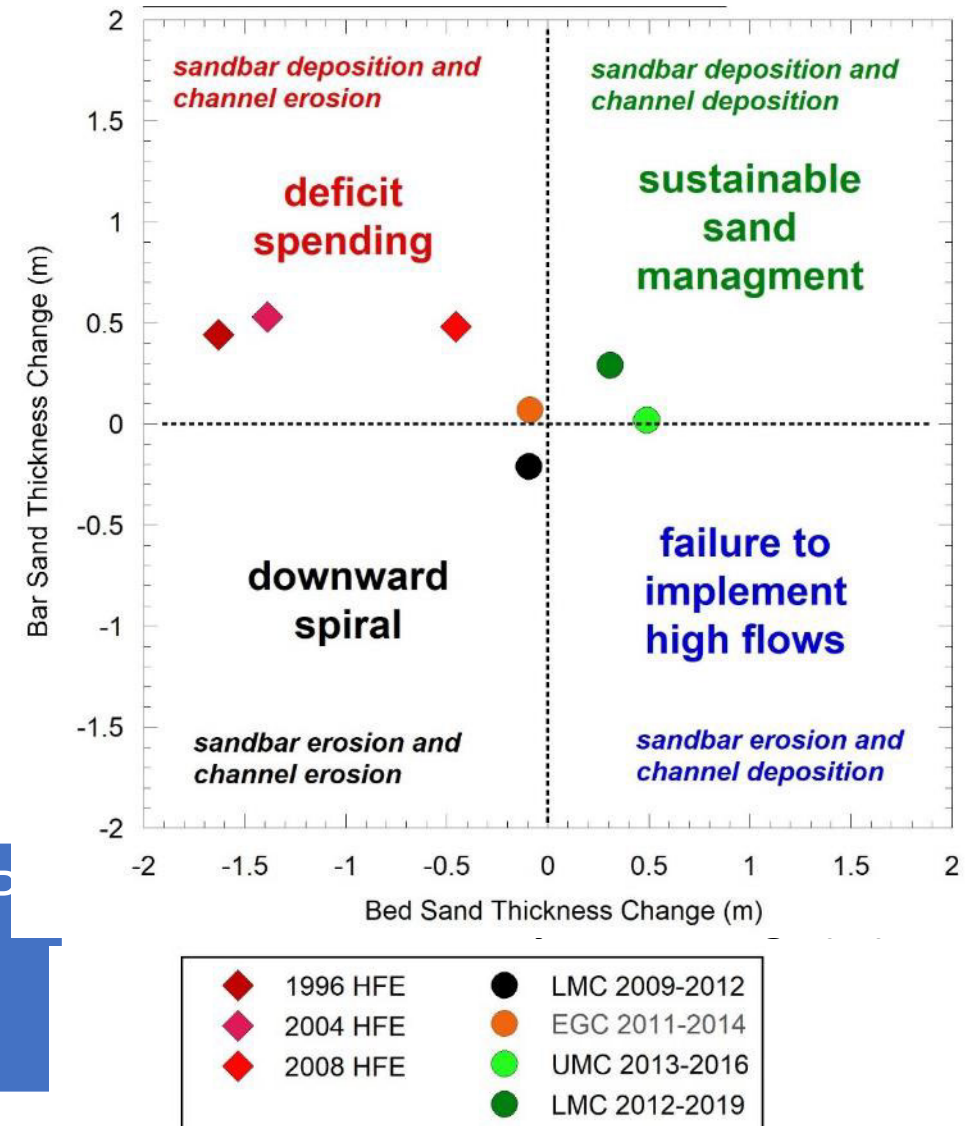
- HFEs are “deficit spending” (1996, 2004, and 2008 HFEs)
- Need to mobilize all the sand to build sandbars and a large fraction is exported
- The loss is a short-term negative and followed by recovery

Repeat measurements over many years (circles)

- Downward spiral: Equalization flows and no HFEs (LMC 2009-12)
- Deficit spending: Equalization flows and HFEs (EGC 2011-14)
- Sustainable: No equalization flows and HFEs (UMC 2013-16)

The fundamental sediment-related question for LTEMP
Where will we be on this plot after 20 years of implementation?

LTEMP??

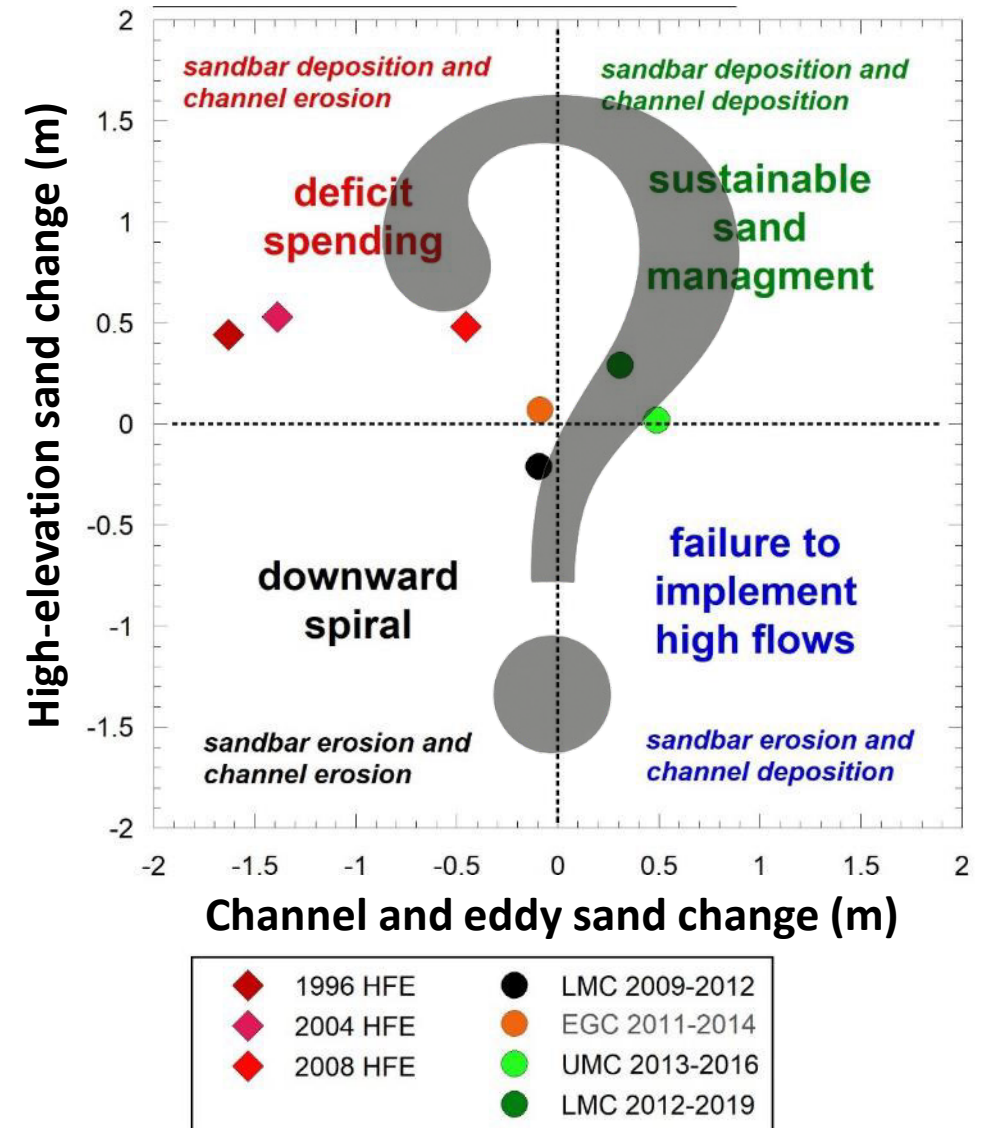


Repeat channel mapping: Implications for high flows and dam management

For upcoming knowledge assessment that leads to 10-year review of LTEMP:

- Robust evaluation of Marble Canyon and Eastern Grand Canyon (RM 0 to 87) based on multiple surveys conducted between 2009 and 2024.
- Currently we only have baseline surveys for downstream segments (RM 87-225)
 - We have mapping trip planned for April 2026 (RM 166-225) to provide the first repeat survey for any downstream segments.

LTEMP??



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
- Sandbars have eroded since 2023 HFE

Changes in sand storage in Marble Canyon and Eastern Grand Canyon

- Joint measurements of riverbed sand storage and sandbar response indicate **“sustainable” sand management has occurred during periods that include multiple HFEs and “normal” reservoir operations.**
- **Sustained high releases** (equalization and other reservoir balancing flows) **cause spatially extensive scour**
- Sand supply change based on measurements of suspended sediment flux closely agree with measurements of riverbed sand change in most cases
 - *Cases of weaker agreement indicate there may be important processes occurring in certain time periods and/or river segments that are not captured in our measurements.*

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