Century-Scale Changes in Fine Sediment Storage, Marble and upper Grand Canyon

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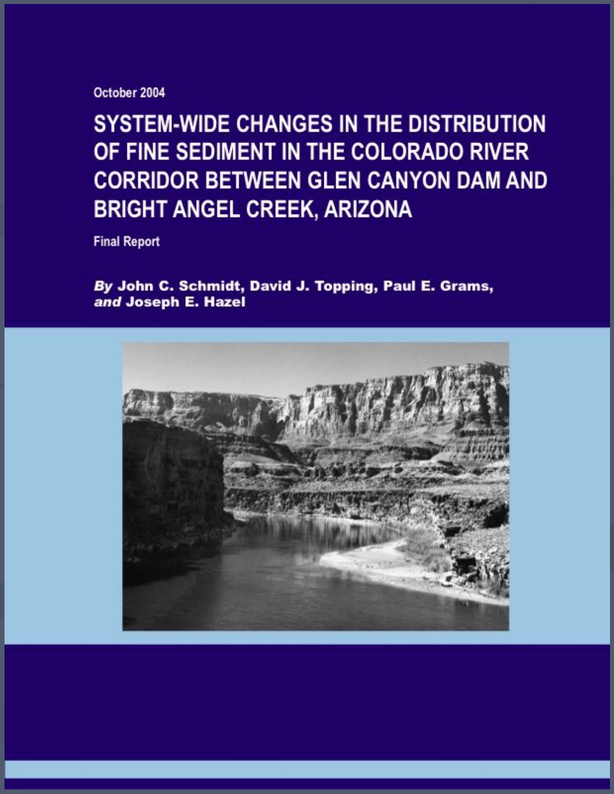
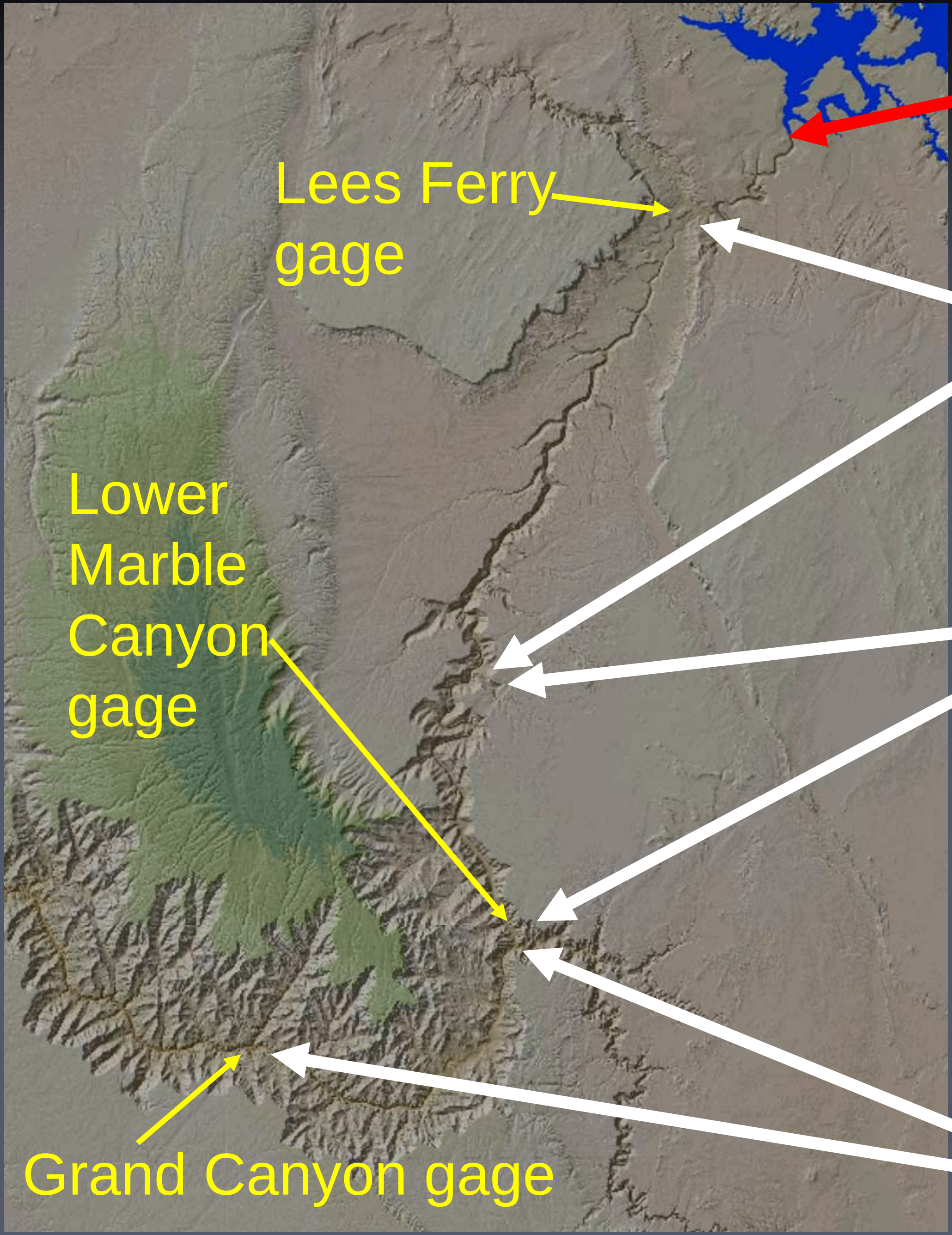

October 2004

SYSTEM-WIDE CHANGES IN THE DISTRIBUTION OF FINE SEDIMENT IN THE COLORADO RIVER CORRIDOR BETWEEN GLEN CANYON DAM AND BRIGHT ANGEL CREEK, ARIZONA

Final Report

By John C. Schmidt, David J. Topping, Paul E. Grams, *and* Joseph E. Hazel

Funded by Grand Canyon Monitoring and Research Center



Glen Canyon Dam

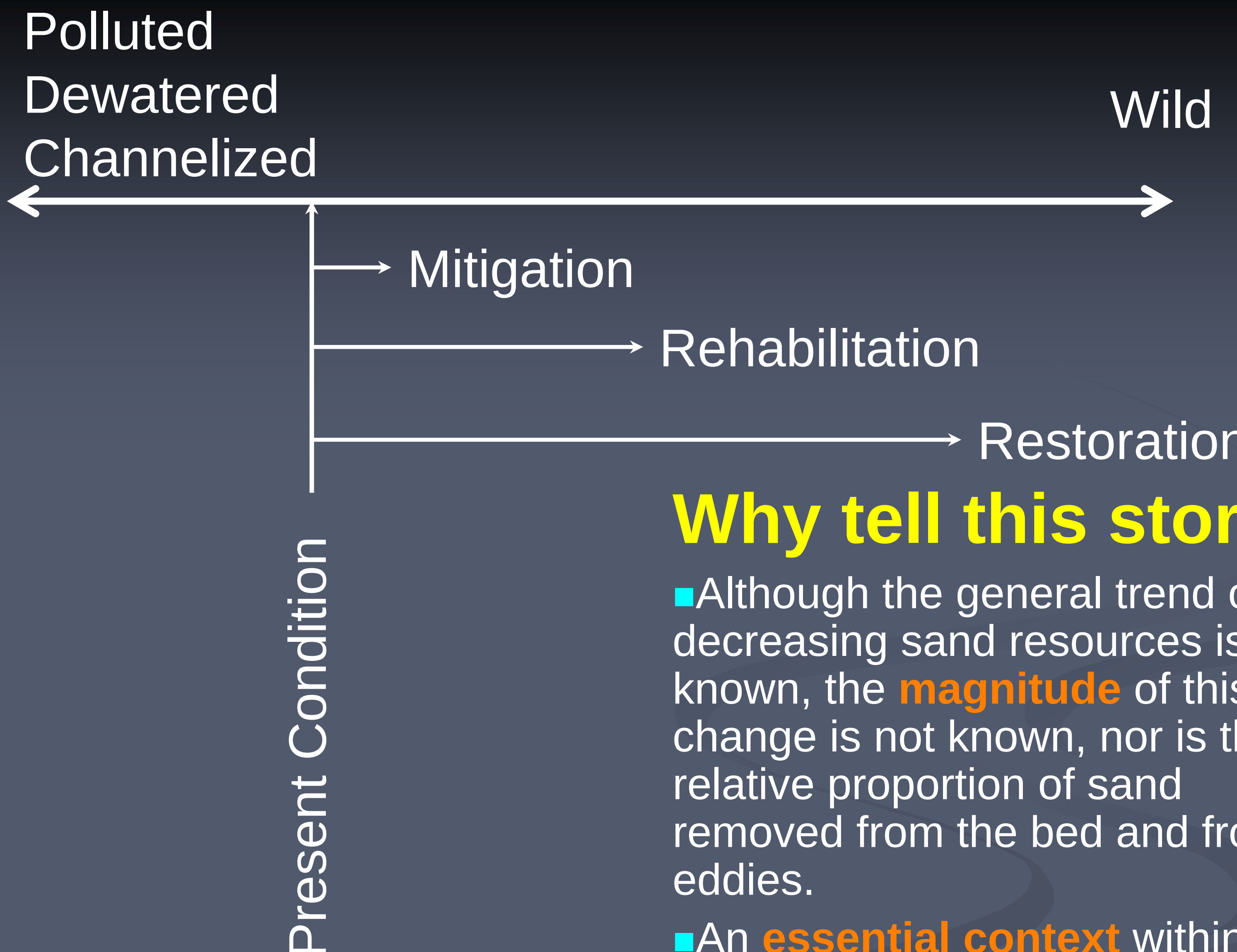
upper Marble Canyon

lower Marble Canyon

upper Grand Canyon

Significance of fine-sediment deposits to resource management

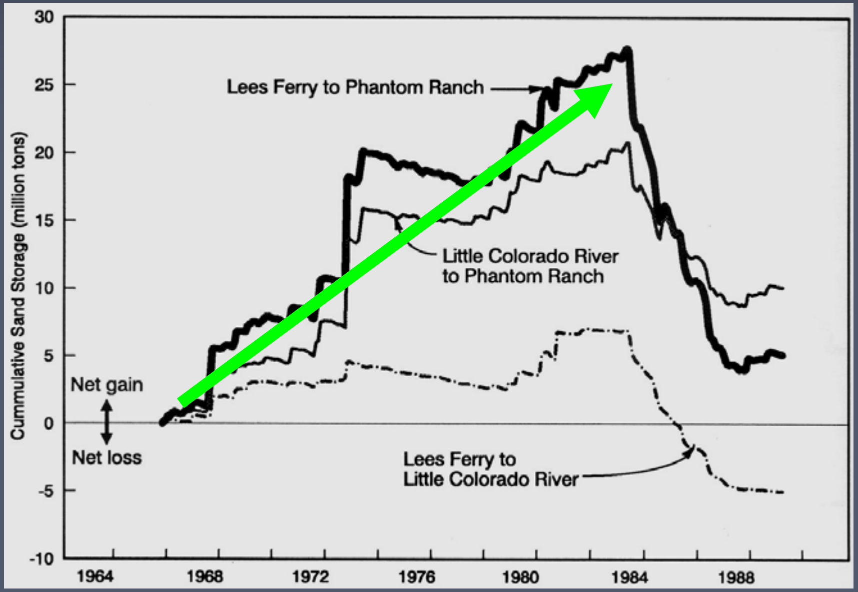
- **Distinctive attribute** of the pre-dam riverscape
- **Campsites**
- Architecture that creates stagnant flow and **backwater habitat** at some discharges
- Substrate for **riparian ecosystem**
- Deposits contain **archaeological resources** or contribute to stability of those resources
- Transport creates **turbidity**



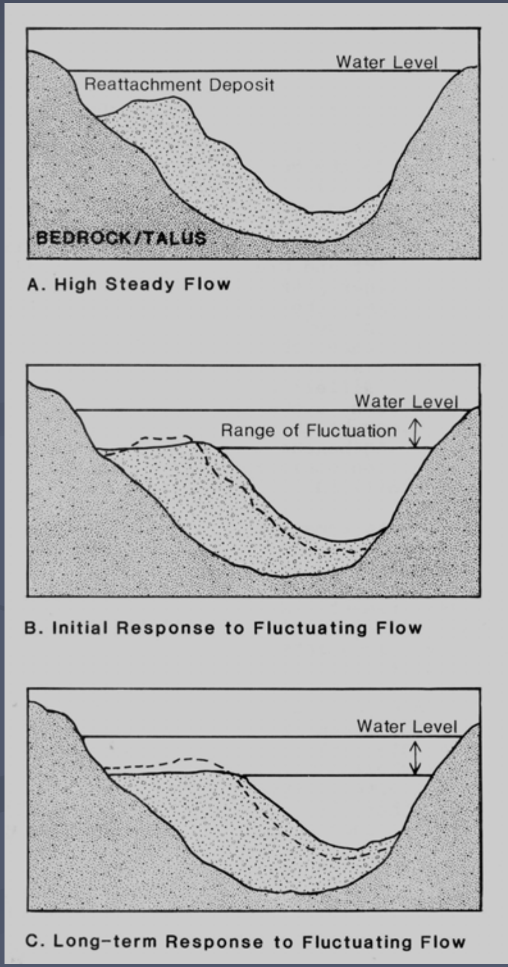
Why tell this story?

- Although the general trend of decreasing sand resources is known, the **magnitude** of this change is not known, nor is the relative proportion of sand removed from the bed and from eddies.
- An **essential context** within which to understand restoration efforts and i**nform discussion** about managing Glen Canyon Dam.

The hypothesis of sediment surplus led to the hope that fine sediment can be accumulated and managed



Final GCD EIS, 1995



- **"Greatly reduced flood peaks since completion of Glen Canyon Dam have decreased the turbulence generated by rapids and hence transport capacity to the extent that an average of more than 1.5 m of sand has accumulated on the bed of the Upper Grand Canyon.**" (Howard and Dolan, 1981)

Where might sand accumulate?

Main channel pools

channel-margin deposits

eddies

“If eddies are the primary storage site, then eddies in upstream part of Marble Canyon will be progressively eliminated in the face of a long-term and progressive negative sediment budget” *(Rubin et al. 1994)*

- Bed
  - Estimates of the proportion of the bed covered by sand
    - 75%: post-dam estimate (Howard and Dolan, 1981)
    - 33%: post-dam estimate (Smith and Wiele, unpubl., ~1988)
    - 25%: post-dam estimate at Grand Canyon gage (Topping, based on Anima data)

The Questions

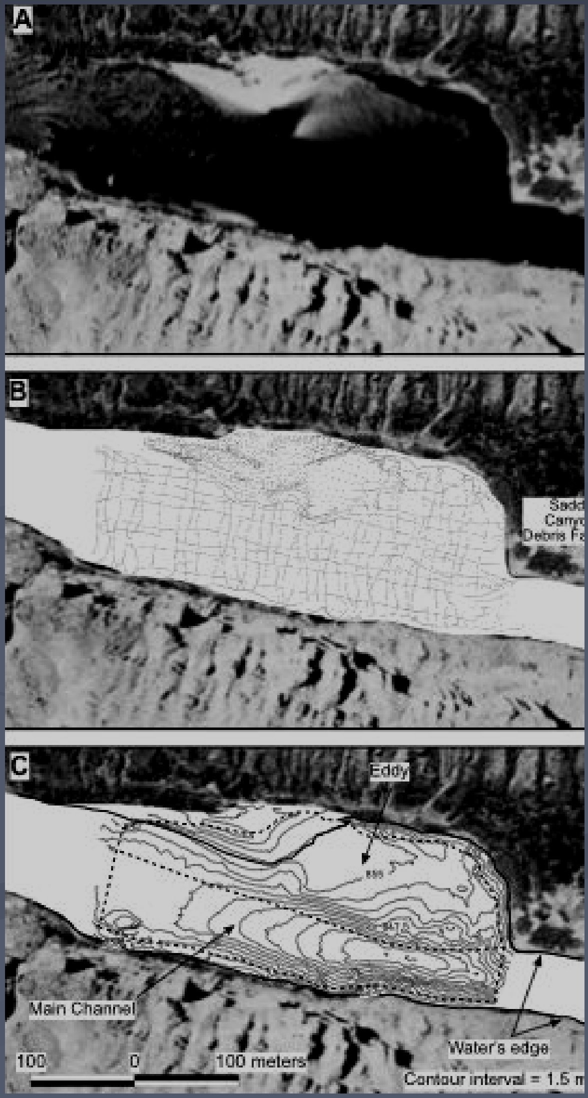
- Is there evidence for sustained accumulation of fine sediment on the bed?
- What has been the system-wide average loss of sand in eddies?
- Are present management efforts returning the eddy bars to their pre-dam condition?

Data Sources - Bed

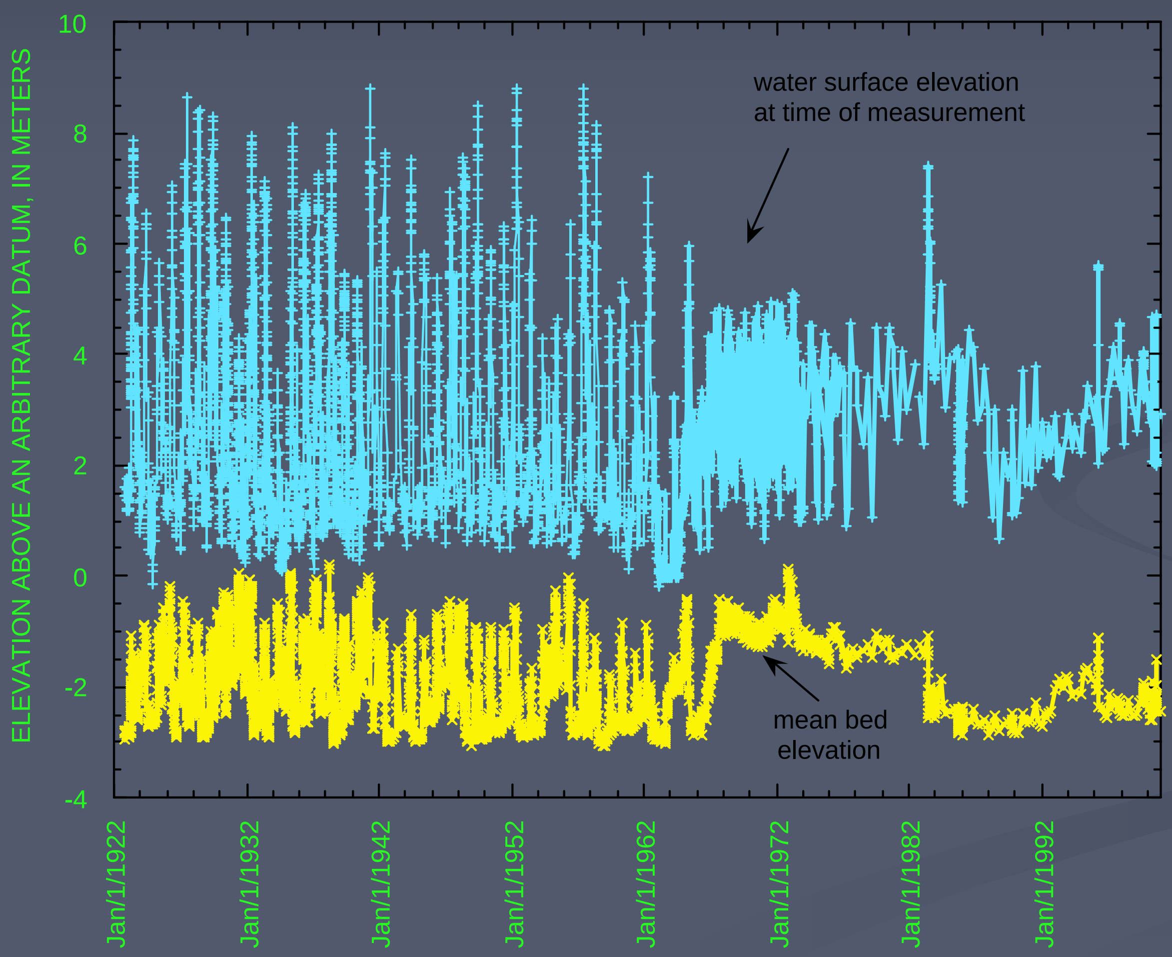
- Discharge measurements at 2 gaging stations (USGS)
  - Grand Canyon gage (1922-present)
  - Lower Marble Canyon gage (1983-present)
- Bed surveys at proposed dam sites (BoR, GCMRC)
  - 6 cross-sections in Marble Canyon (1950-2000)
- Monitoring at cr0ss-section
  - Annual resurvey of 57 cross-sections (1992-1999) (USGS)
  - Annual resurveys in 16 pools (1992-2000) (NAU)

Data Sources - Eddy Bars and Banks

- Matched ground-level photography (USGS)
  - 79 matches
- Aerial photography (USU)
  - 5 reaches (8-14 km long; 15 series 1930s-1997; ~60,000 polygons)
- Resurvey of subaerial and subaqueous topography (1975-present) (GCMRC, NAU, et al.)
  - 17 eddy bars (1990-present)



Long-term (1922-1962) degradation of bed of pool = 1.6 cm/yr due to long-term decrease in sediment delivery (Topping et al. 2000)



bouldery
rapid

Scenarios of the likely distribution of sand on main channel bed and in eddies based on known area of main channel and of eddies, seasonal fine sediment accumulation, and likely fluctuations in thickness of deposits.

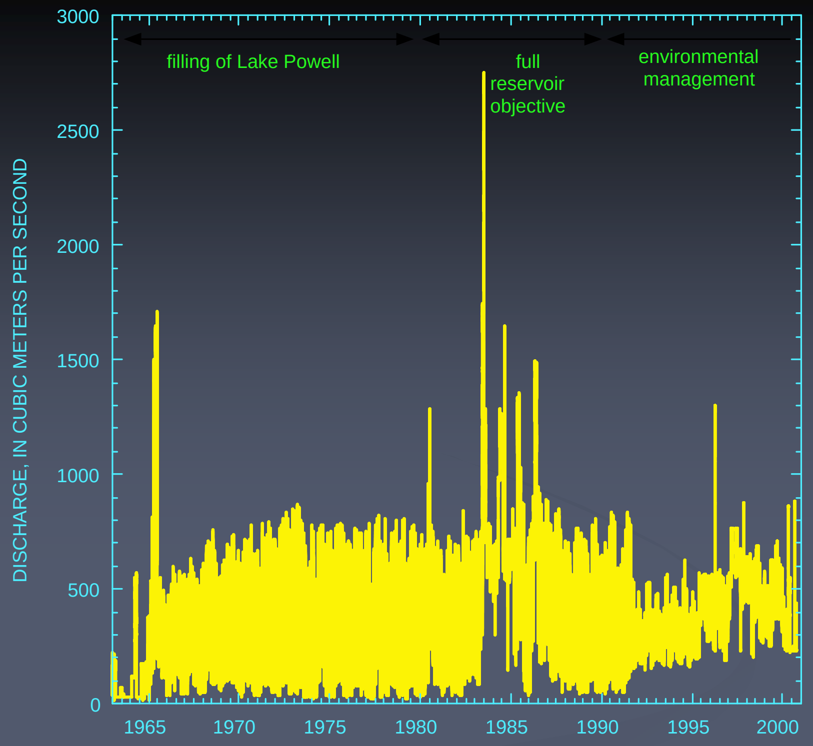
Seasonal sediment accumulation, in metric tons	Equivalent volume, in cubic meters[1]	Equivalent thickness, in meters, under three assumptions about the relative proportion of fine sediment stored in eddies and in the main channel and two assumptions about the proportion of the channel that can store fine sediment[2]					
		eddies	channel	eddies	channel	eddies	channel
proportion of the channel that can store fine sediment			[0.9] (0.3)		[0.9] **(0.3)**		[0.9] (0.3)
relative proportion stored in eddies and the main channel		0.1	0.9	**0.5**	**0.5**	0.9	0.1
1,000000	640,000	0.02	[0.04] (0.13)	**0.08**	[0.02] **(0.07)**	0.15	[0.00] (0.01)
7,000,000	4,460,000	0.11	[0.30] (0.91)	**0.57**	[0.17] **(0.51)**	1.03	[0.03] (0.10)
13,000,000	8,280,000	0.21	[0.56] (1.69)	**1.06**	[0.31] **(0.94)**	1.91	[0.06] (0.19)

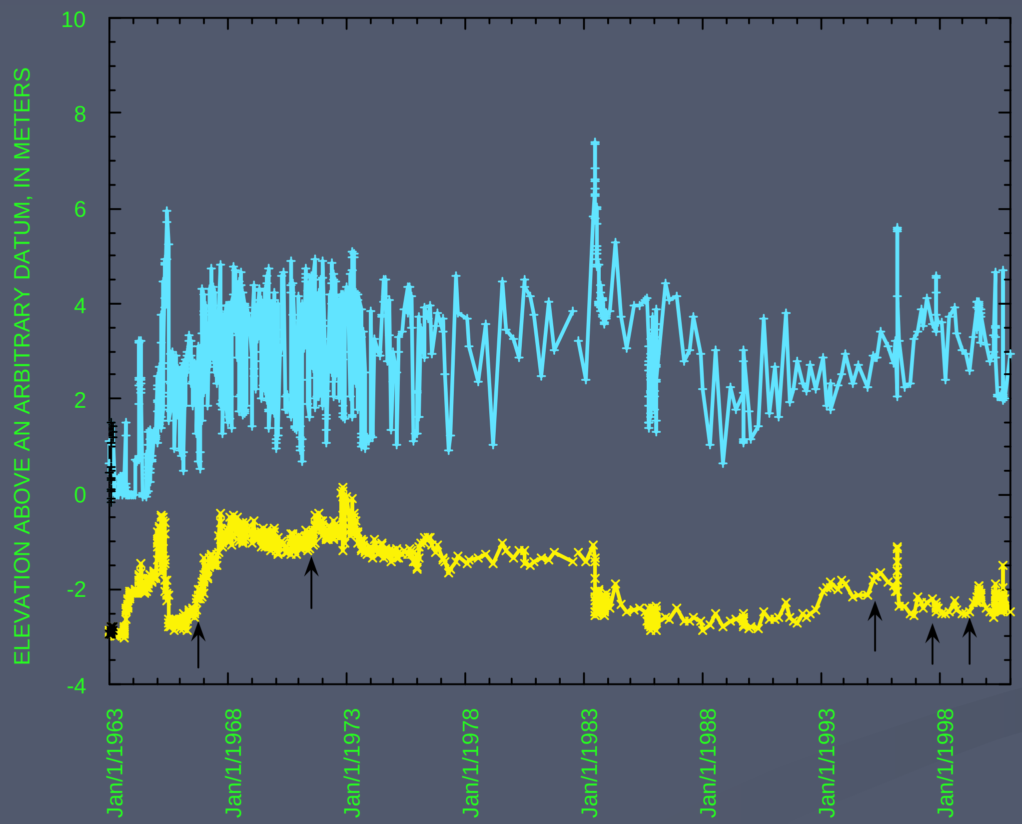
[1] assumes bulk specific weight of fine sediment is 1570 kg/m^3

[2] assumes area of eddies is 3.9 x 10^6 m^2, and area of channel is 14.7 x 10^6 m^2

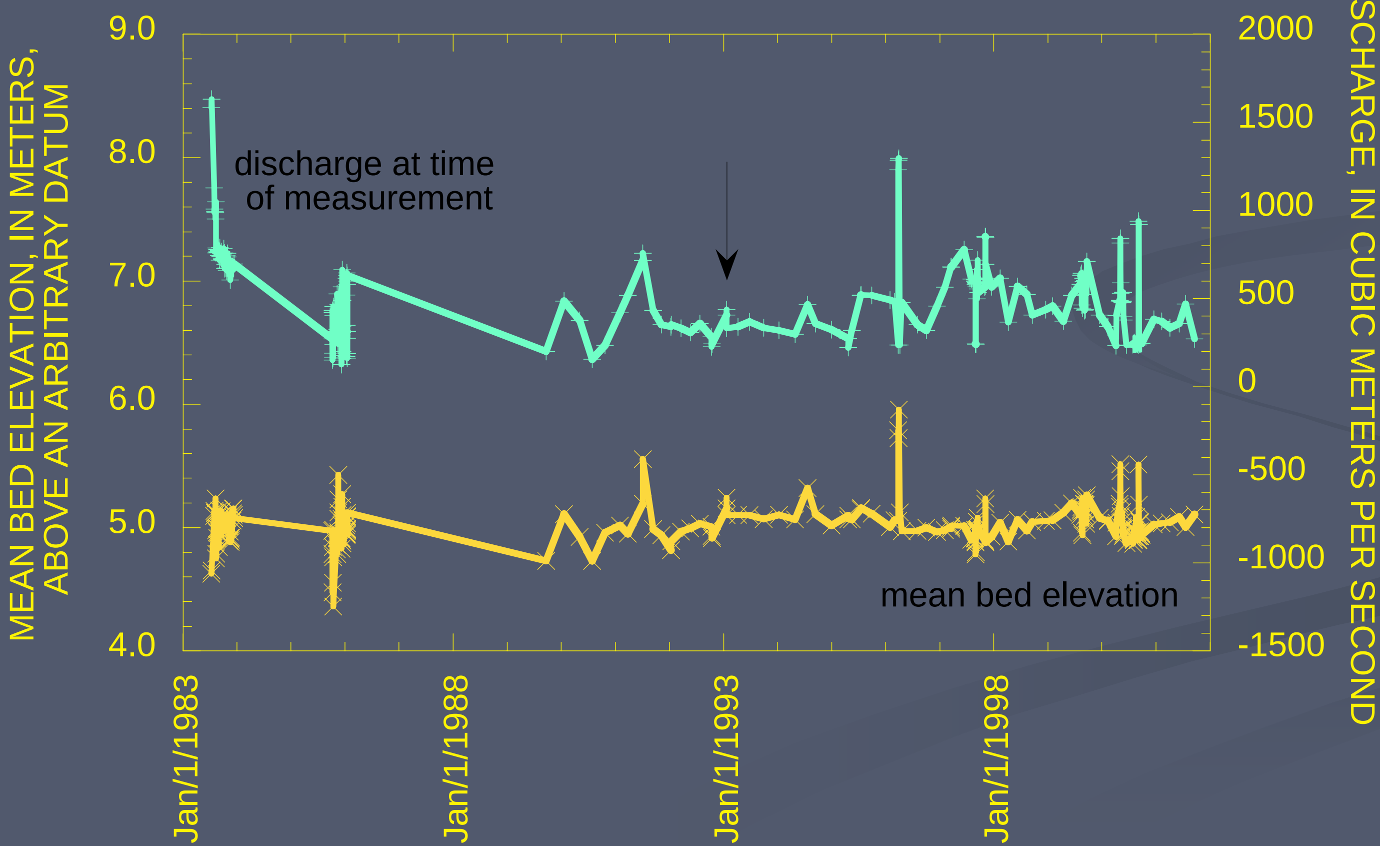
No progressive change in bed elevation since GCD.

Short-term changes associated with changes in boulder deposits at rapid.

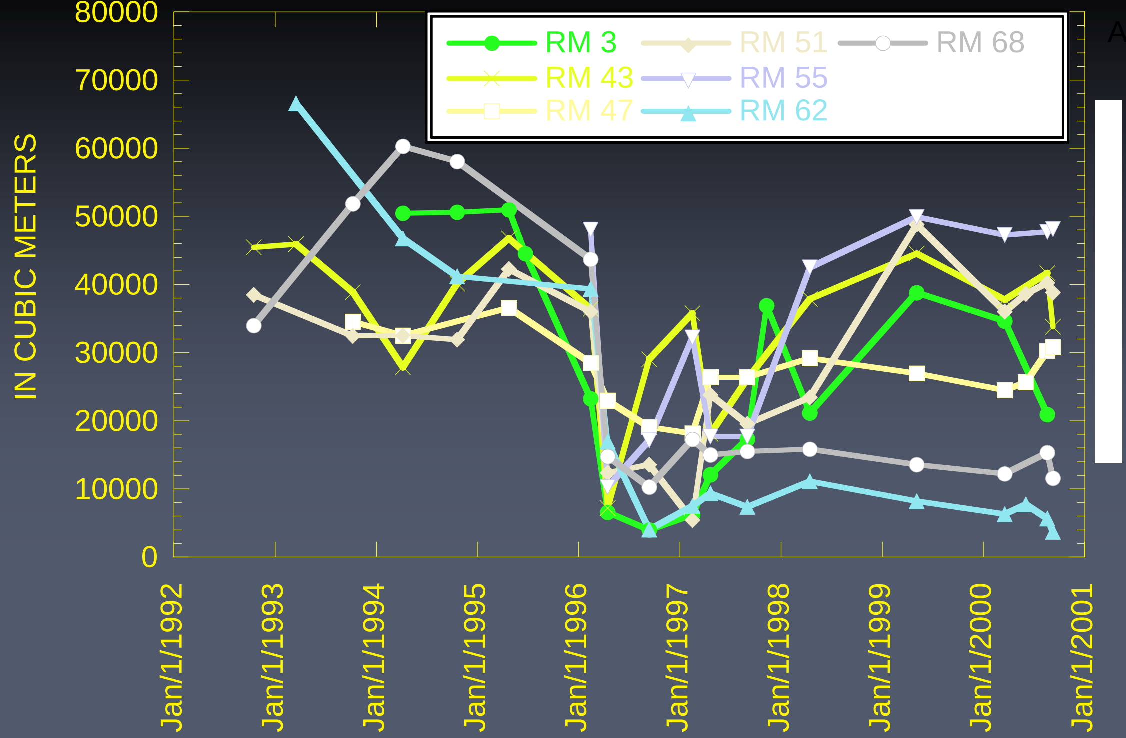




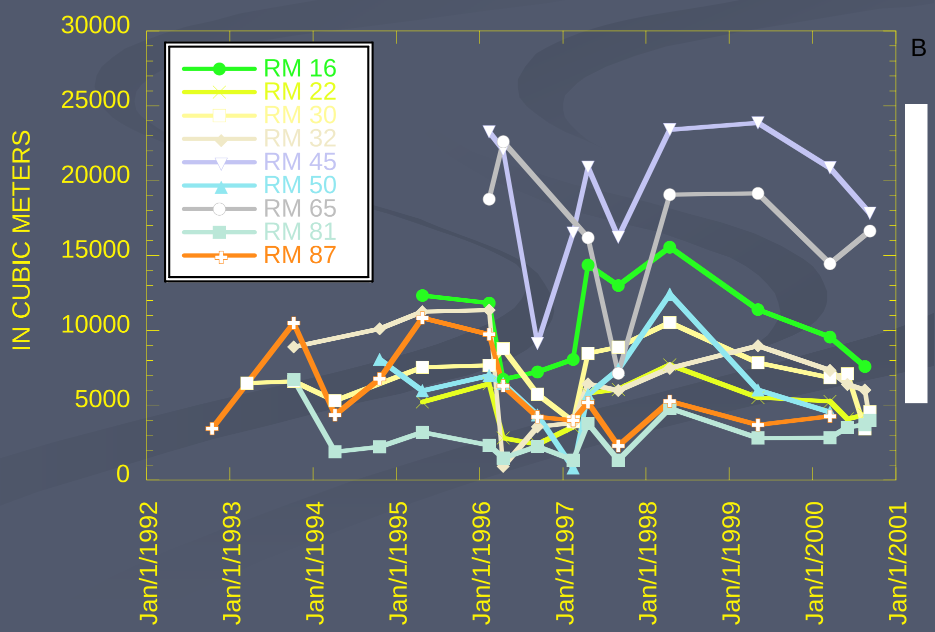
No evidence of bed aggradation at the lower Marble Canyon gage since 1983. Short-term aggradation when stage increased by tributary inflow.



no aggradation in channel pools since 1990

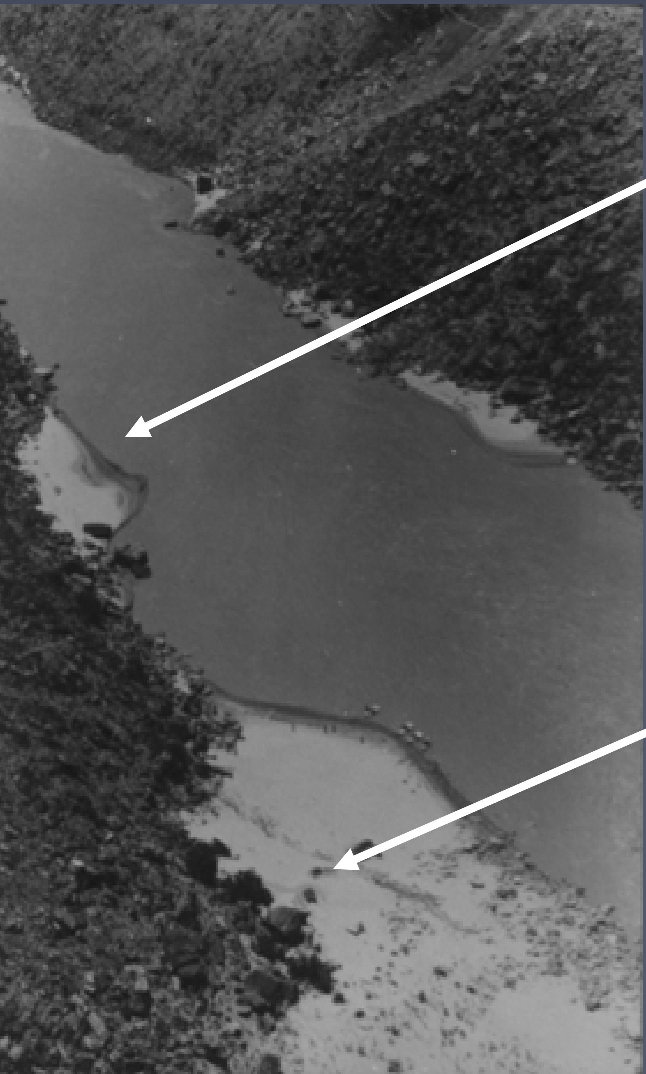


main channel pools offshore from eddies (NAU data)



Flynn and Hornewer (2003) surveys 1992-1999 did not show any fine sediment accumulation

The general pattern of eddy bar change

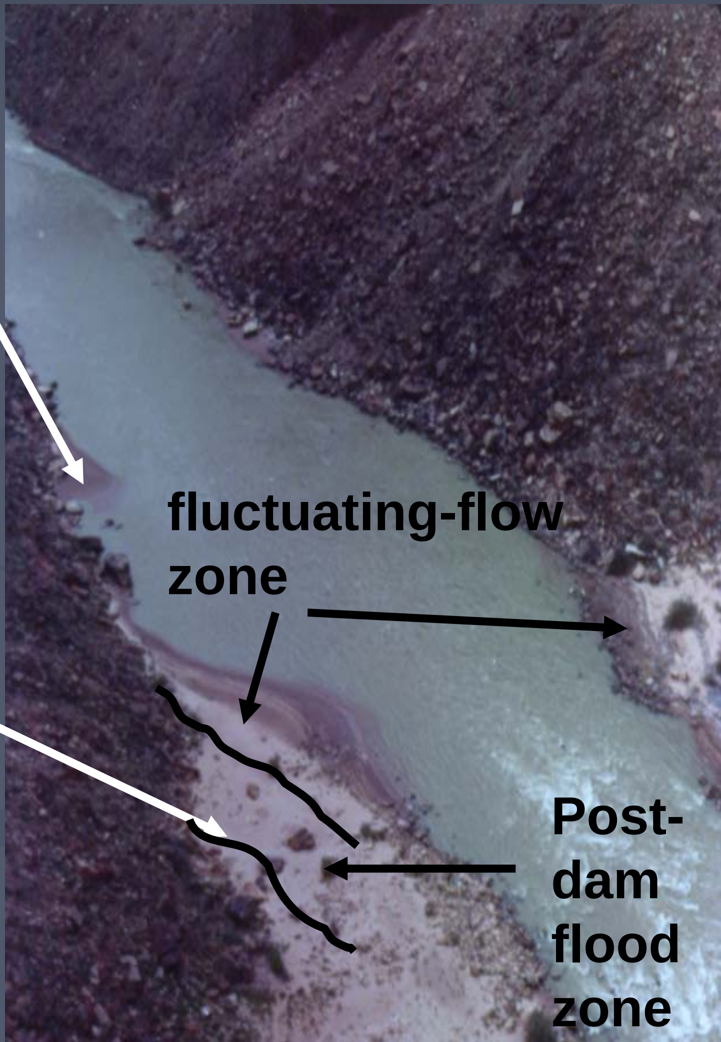


… sand eroded from eddies …

… and eroded by wind and not replaced by flood deposition

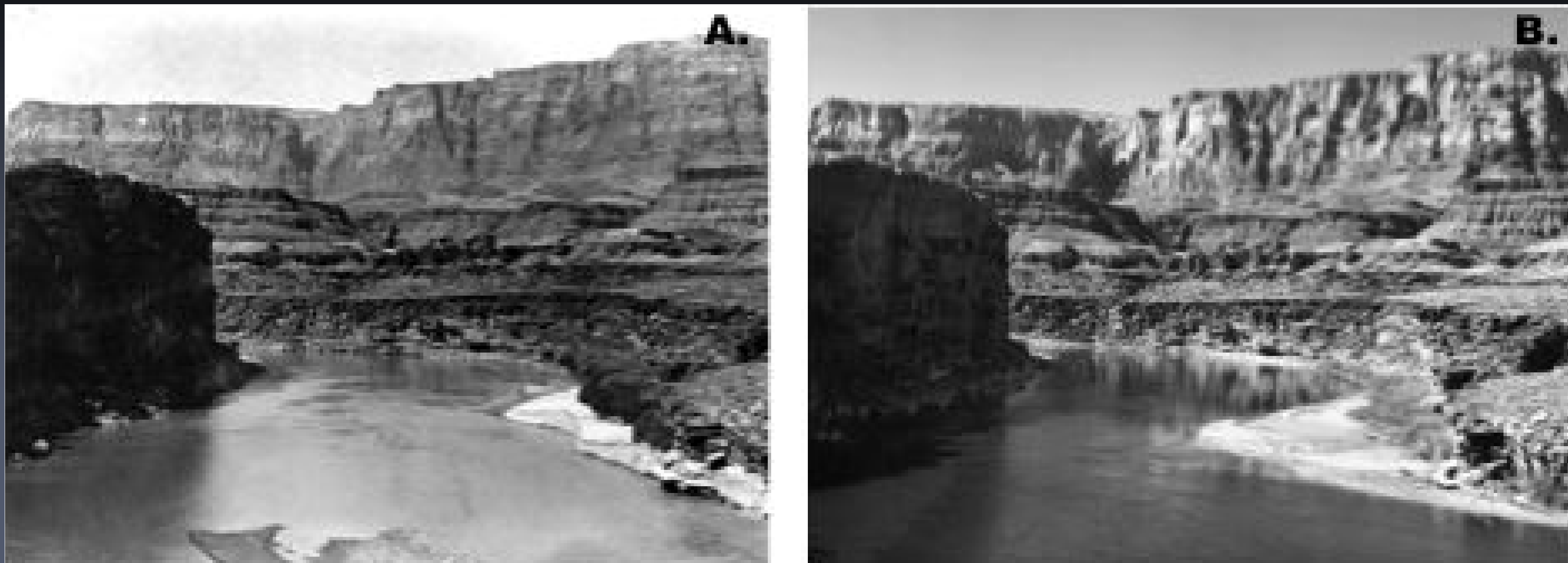
1956

1999



Badger Creek Rapids

1897 1994



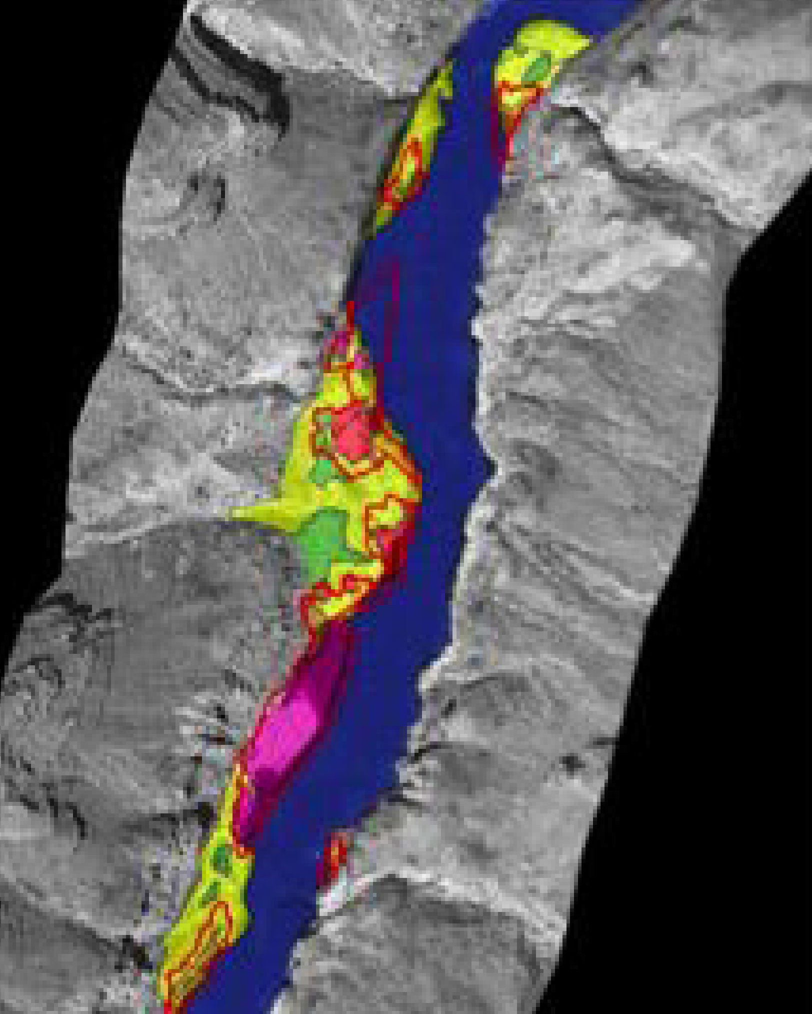
<u>Pre-dam/post-dam photo match comparisons:</u>

In post-dam flood zone

2 increase, 16 decreased, 33 no change (n=51)

In fluctuating flow zone

3 increase, 31 decreased, 24 no change (n=58)



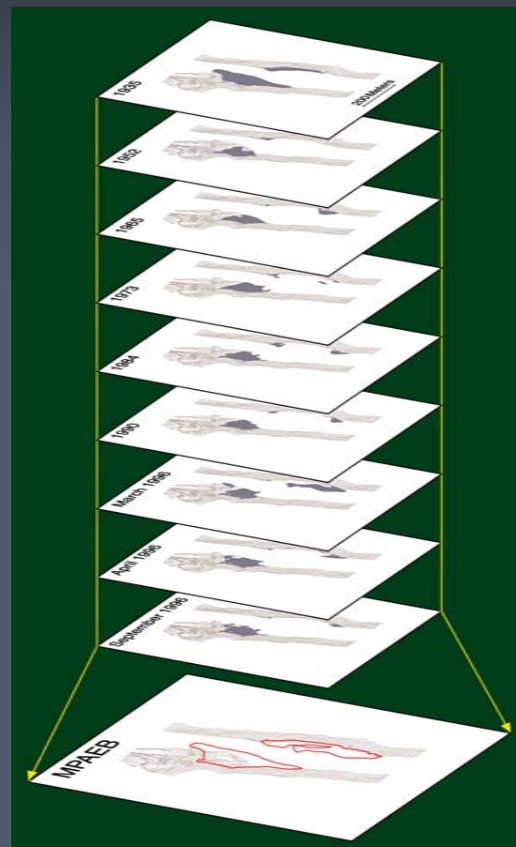
Geomorphic features

Formative discharges

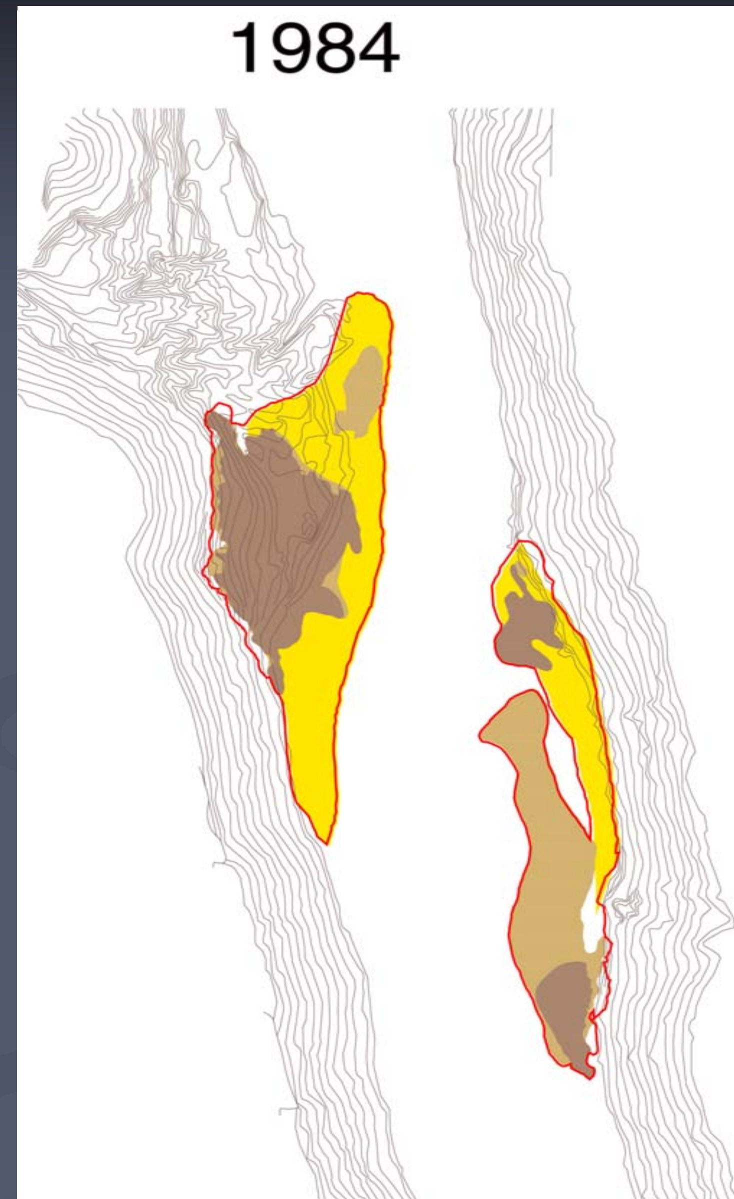
Fluctuating flow zone

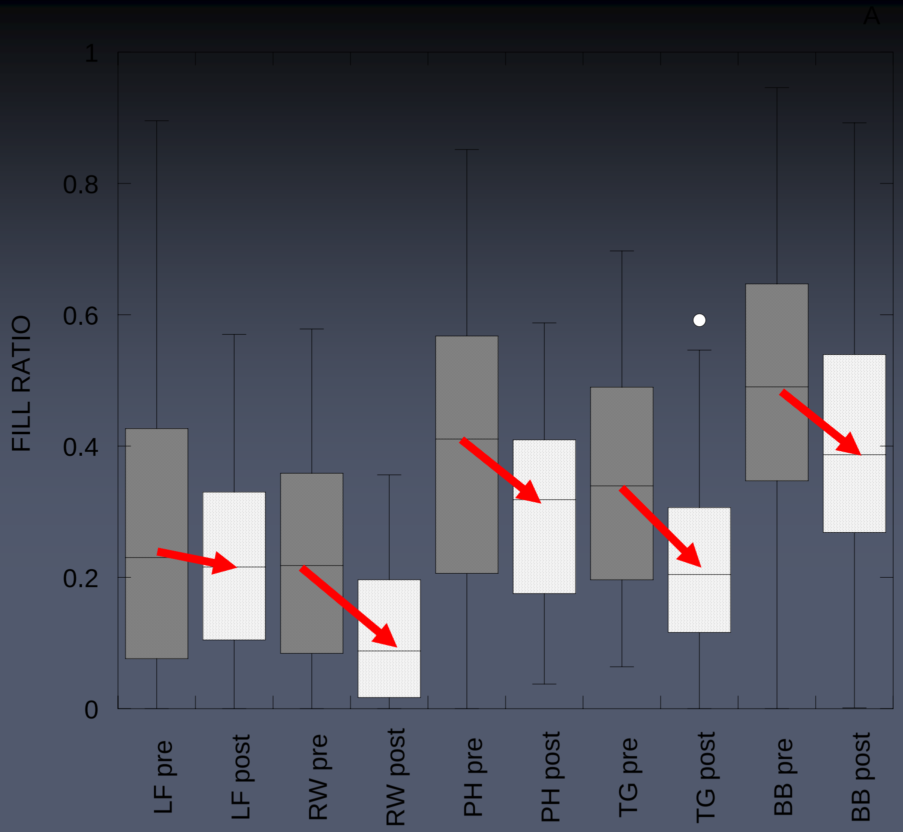
Post-dam flood zone

Changes in the area of fine-grained alluvial deposits determined by aerial photograph analysis



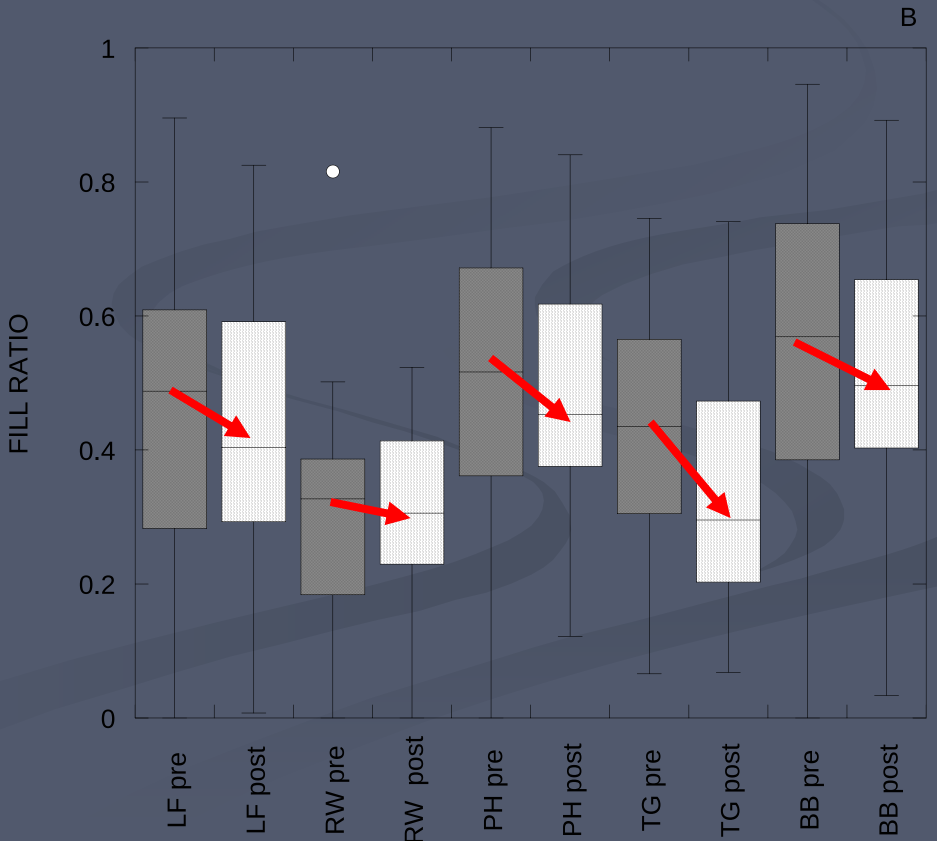
Eddy deposition zone (EDZ)



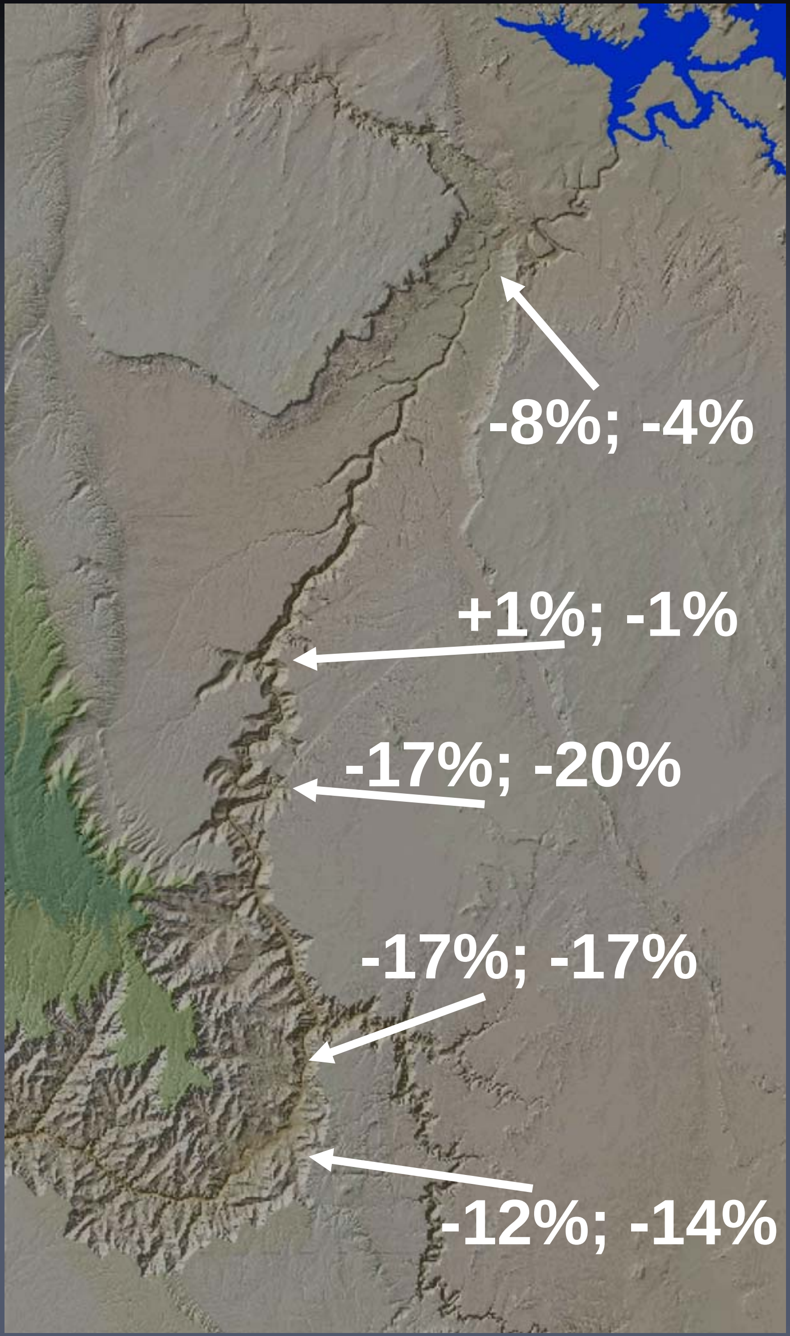


Sand in the post-dam flood zone

All sand above base flow



Proportion of EDZs filled by sand in each reach

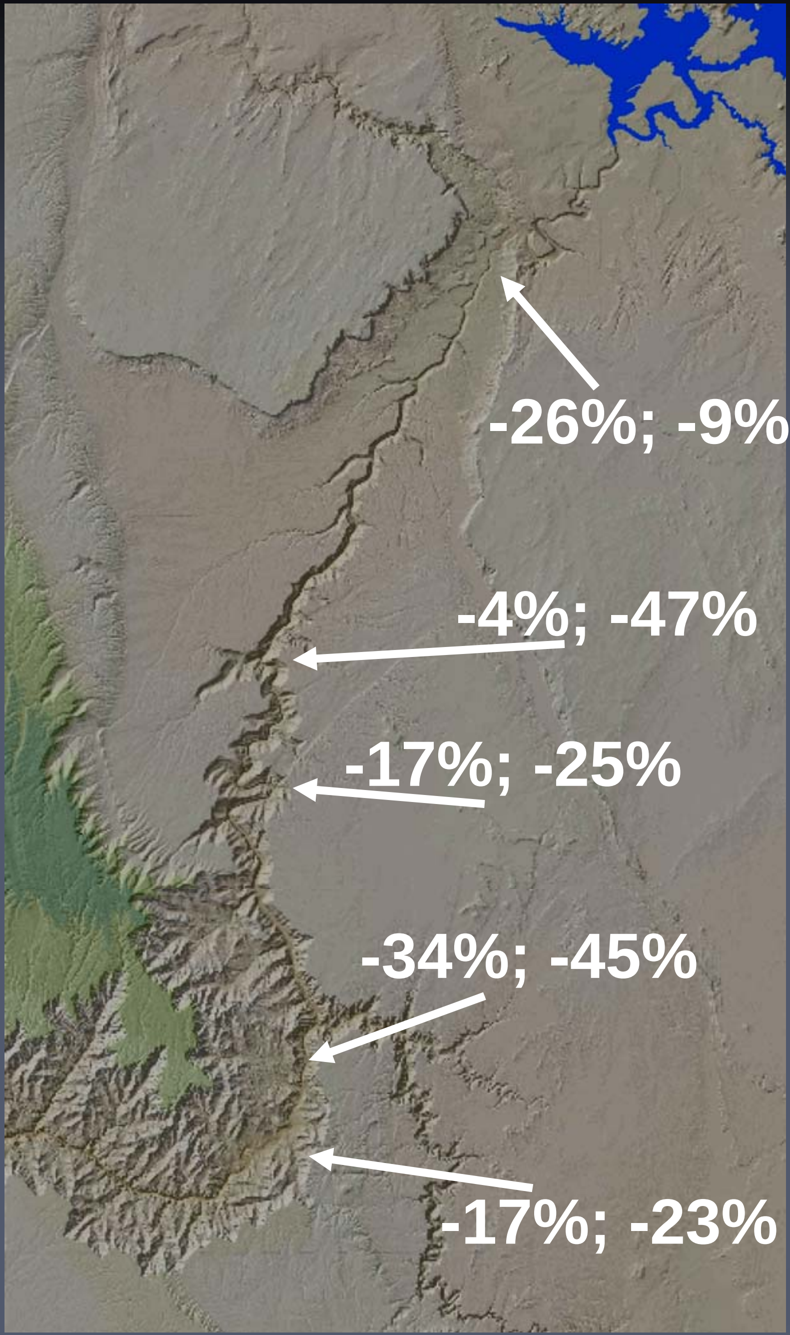


EDZ inventory method: a conservative metric of bar change

- Comparison of average pre-dam conditions (1930s, 1950s) to average of conditions in 1990s (1990, 3/1996, 4/1996)

- change must exceed 1 se of measurements
  - i.e. erosion if A_{pre} - SE > A_{90s} + SE
  - deposition if A_{pre} + SE < A_{90s} - SE

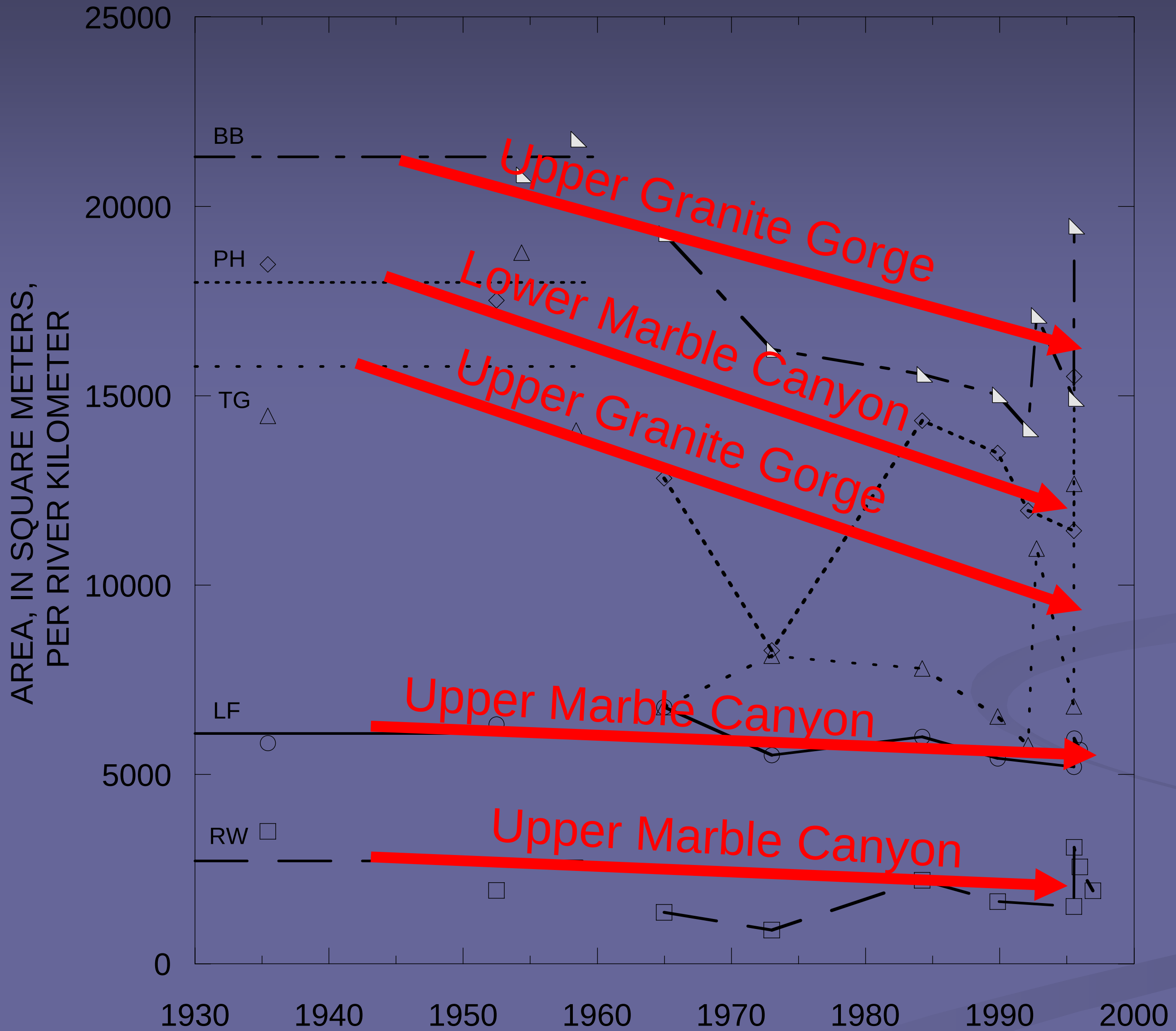
- change in the area of all sand above base flow; change in sand at the elevation of the post-dam



Changes in mean bar size

- Comparison of average pre-dam conditions to average of conditions in 1990s

- change in the area of all sand above base flow; change in sand at the elevation of the post-dam flood zone

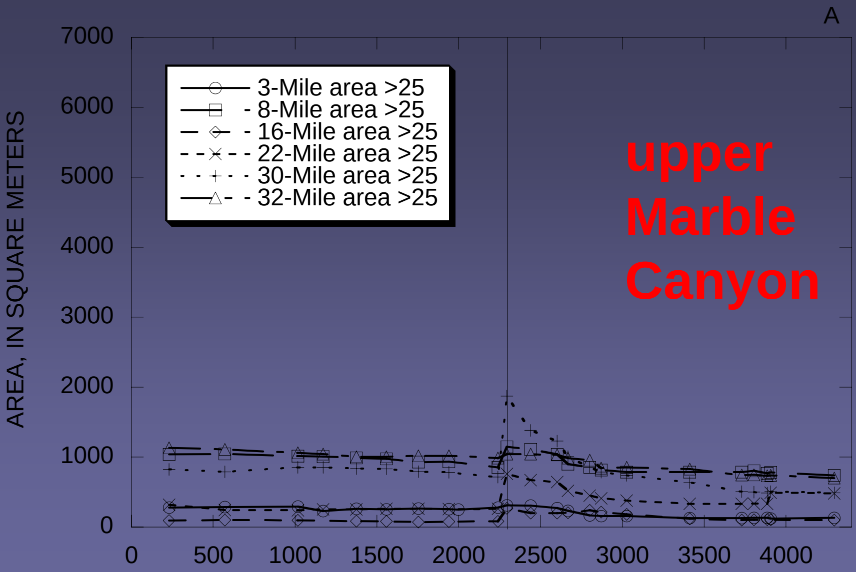


Area of eddy bars is now ~ 25% smaller than in average pre-dam conditions.

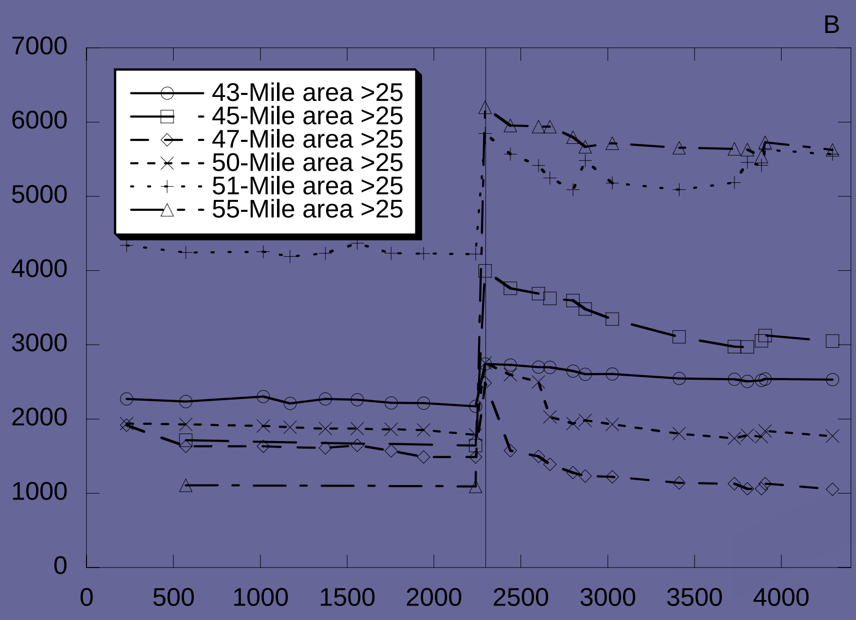
Comparison of survey data and conservative estimates of the average volume of eddy sand in the pre-dam era indicates 1.8 - 6.2 m of sand has been eroded away.

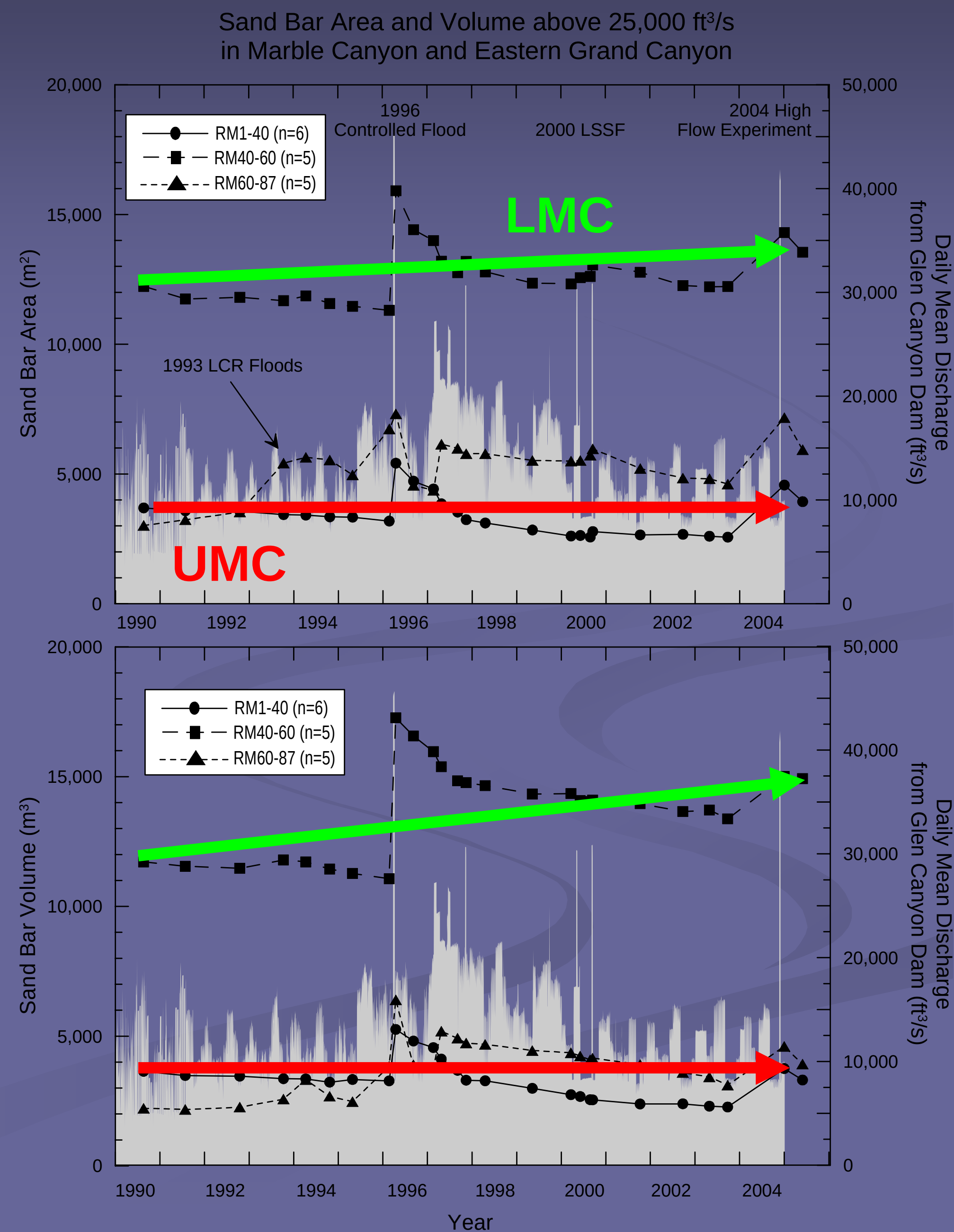
EDZ name	EDZ area, in square meters	Area surveyed by NAU, in square meters	Area of comparison, in square meters	Void volume between the stage of 100 m^3/s and the minimum elevations surveyed by NAU, in cubic meters	Percent overlap between EDZ and area surveyed by NAU	Thickness of void volume, in meters
Cathedral	11658	8392	7124	25122	72	3.53
Fence Fault	11479	9448	4954	8949	82	1.81
South Canyon	10837	9536	4316	11877	88	2.75
Anasazi Bridge	25348	11318	4545	12412	45	2.73
Eminence break	80259	30377	12884	34776	38	2.70
Saddle canyon	44977	29935	21831	92797	67	4.25
Crash Canyon	20103	17816	14878	92787	89	6.24
Carbon	20253	18123	10971	24451	89	2.23
Tanner	11476	9422	4269	11822	82	2.77

The 1990s: post-dam flood zone



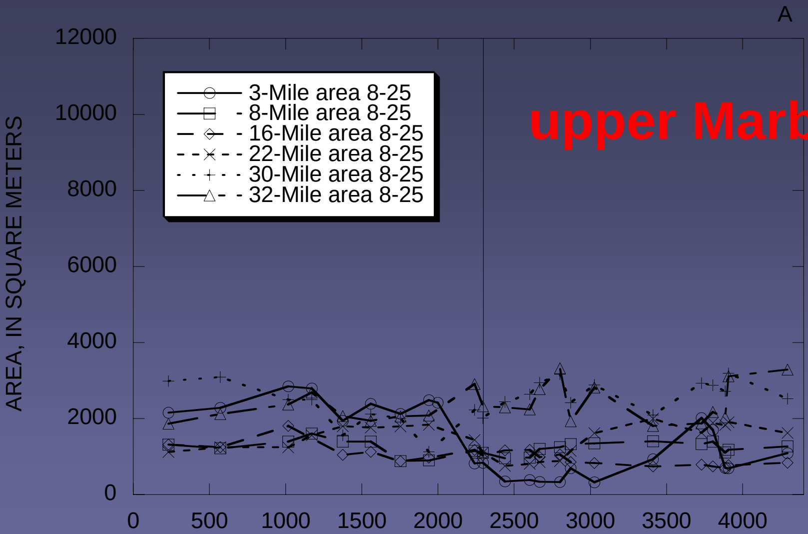
lower Marble Canyon

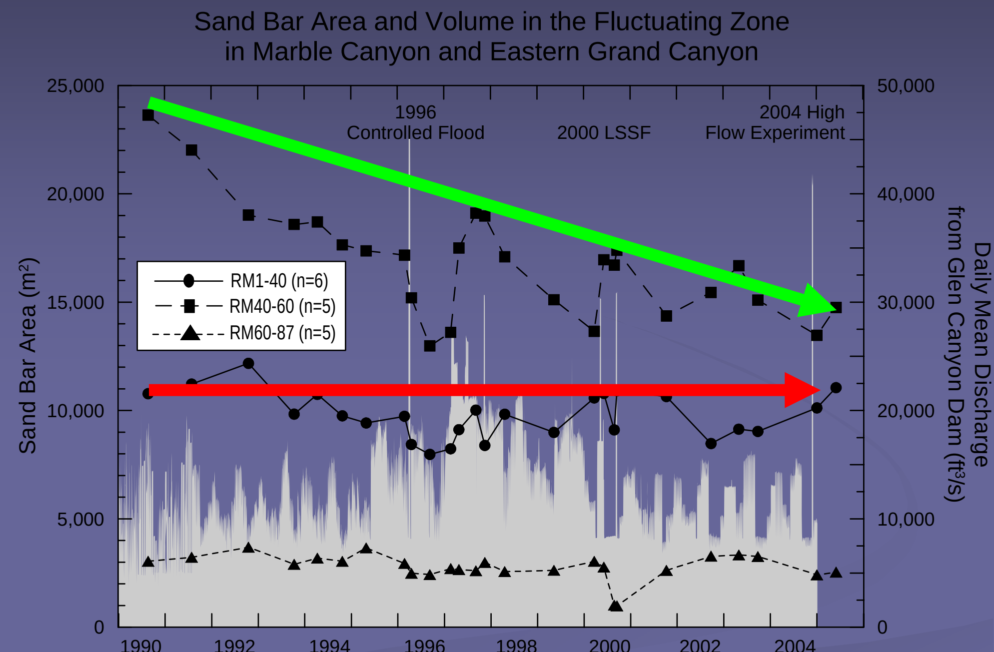




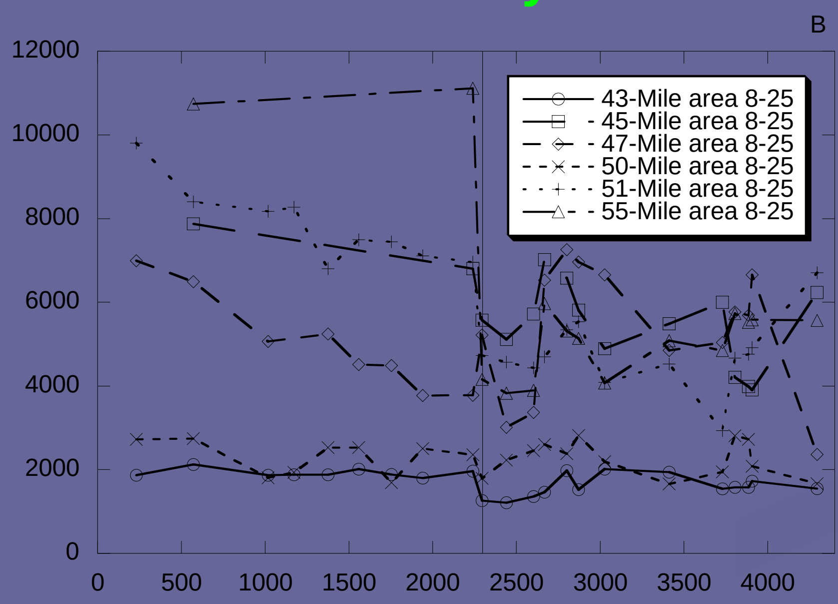
Fluctuating flow zone

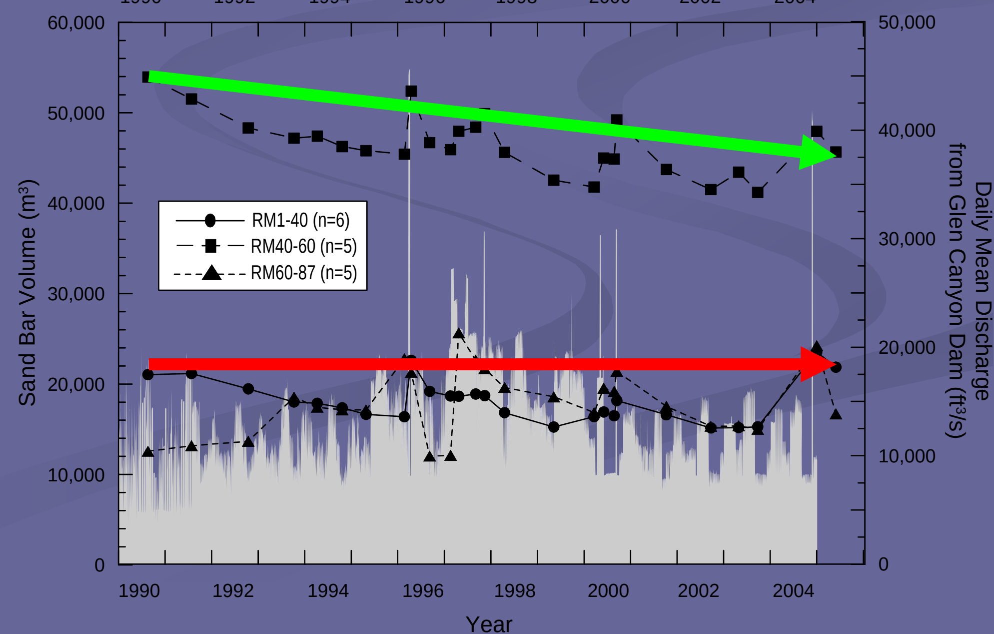
upper Marble Canyon



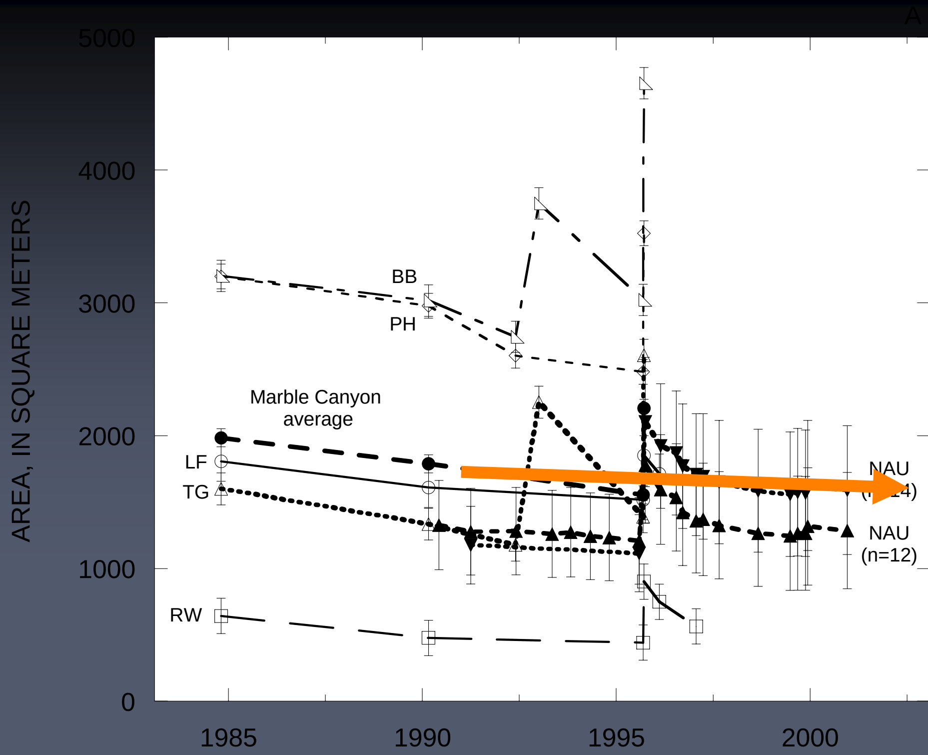


lower Marble Canyon



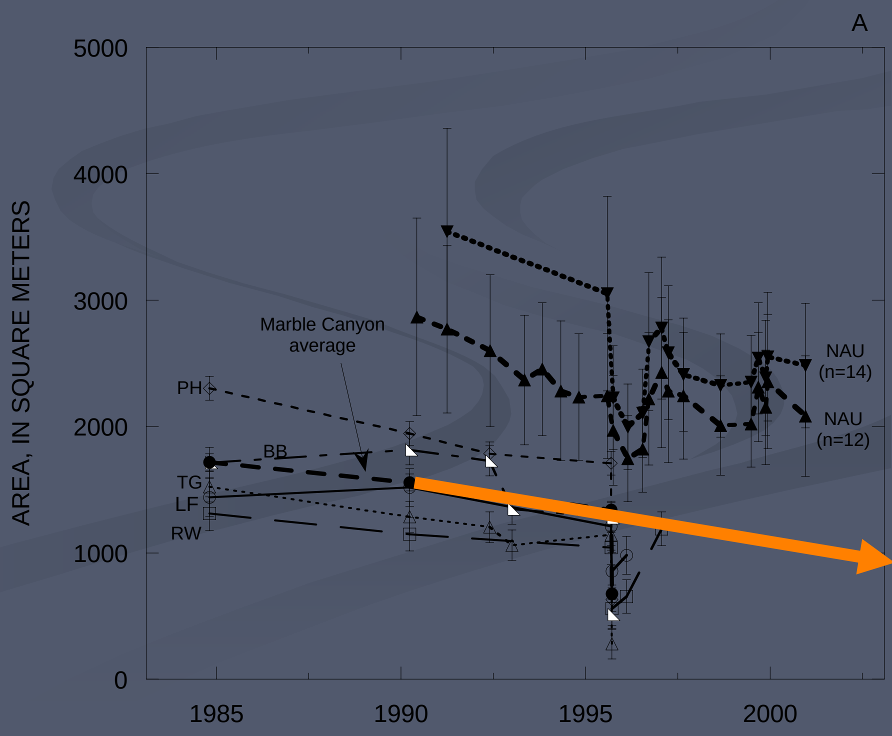


Integrated history: 1984-2005



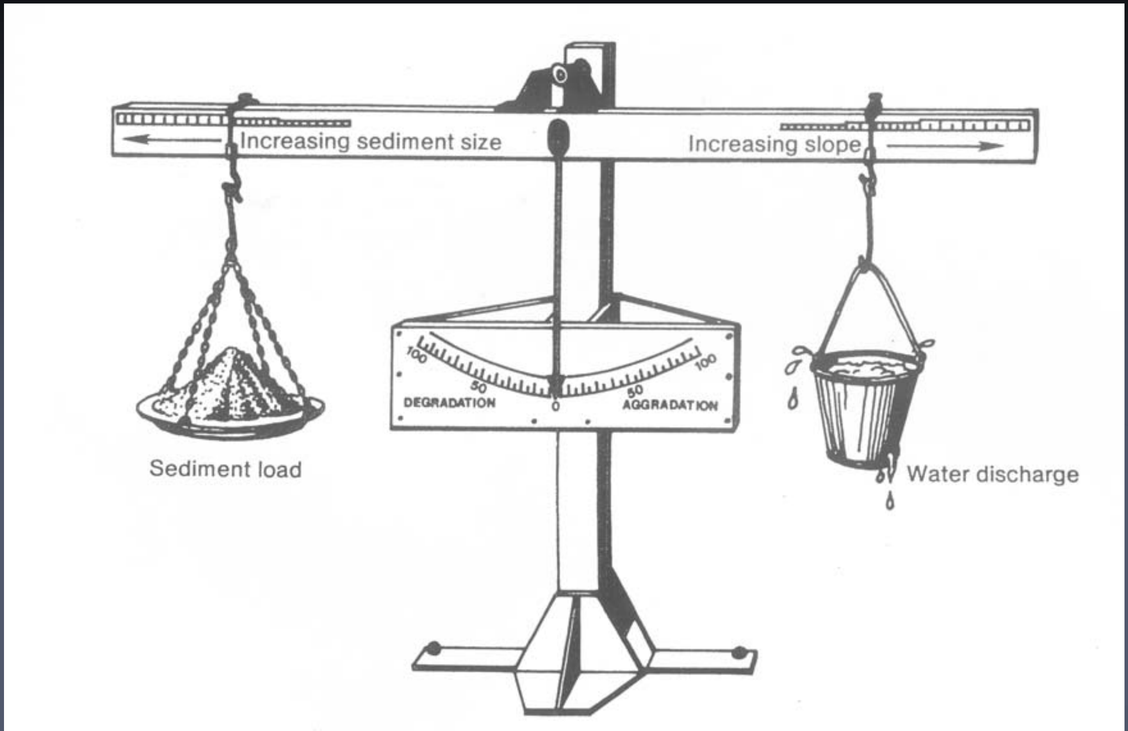
Post-dam flood zone

Fluctuating flow zone



Thus …

- **It is likely that ~50% of the seasonal accumulation of fine sediment occurred over ~30% of the main channel bed.**
- **Today, ~10% of the fine sediment is stored on the main channel bed. Sand is primarily stored in the eddies.**
- **There is no evidence for multi-year accumulation of fine sediment on the bed.**
- All evidence points to smaller deposits, and decrease is not entirely due to tamarisk
- Post-dam flood zone area is ~ 25% less than average pre-dam; **thickness of degradation of eddy bars 1-6 m**
- Sand is less since 1984; sand is less than 1990
- Sand is less at low elevation as well as at high elevation



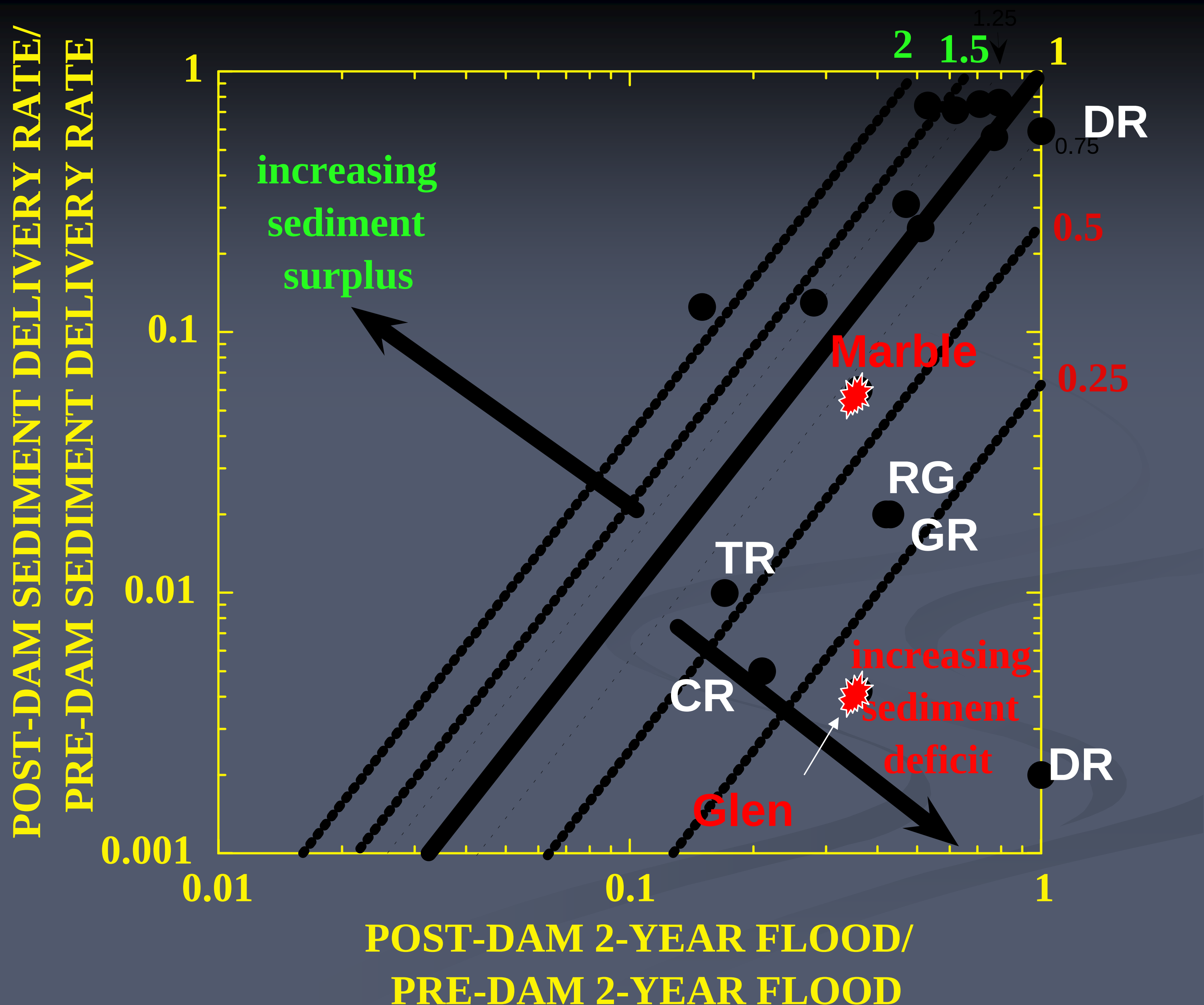
Quantifying Lane's (1955) mass balance:

$$S_{post}/S_{pre} = (Qs_{post}/Qs_{pre})^{0.5}\,(D_{post}/D_{pre})^{0.75}\,(Q_{pre}/Q_{post})$$

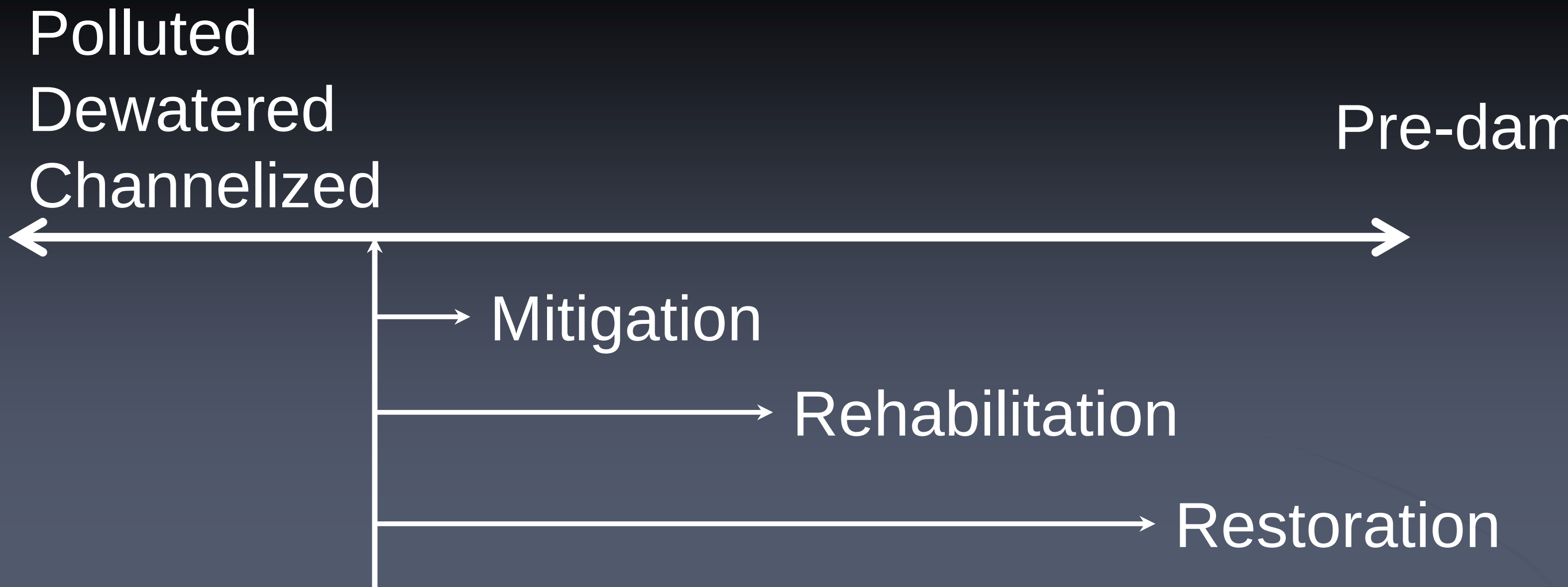
deficit likely: $S_{post}/S_{pre} < 1$

surplus likely: $S_{post}/S_{pre} > 1$

(Schmidt and Wilcock, adapted from Henderson, 1966)



POST-DAM SEDIMENT DELIVERY RATE/
PRE-DAM SEDIMENT DELIVERY RATE
POST-DAM 2-YEAR FLOOD/
PRE-DAM 2-YEAR FLOOD
0.001
0.01
0.1
1
2
1.5
1.25
1
0.75
0.5
0.25
increasing
sediment
surplus
increasing
sediment
deficit
Marble
Glen
DR
RG
GR
TR
CR
DR



- **What is possible?**
- **At what cost?**

- **What is our goal?**
  - **restoration? rehabilitation? mitigation?**