The Bed and the Banks

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Research Team

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Central Question

- How have the bed and riverside alluvial deposits of Glen and Grand Canyons changed during the twentieth century?
  - What was the variability in size of these deposits during the pre-dam and post-dam eras?
  - Are there temporal trends in bar condition or bar response?
  - Are there longitudinal trends of bar condition or bar response?
  - How are these changes related to sediment transport?

Previous Studies

- Laursen et al. (1976)
- Pemberton (1976)
- Dolan et al. (1974)
- Howard et al. (1975, 1976, 1979, 1981)
- Beus et al. (1985, 1993)
- Schmidt et al. (1990, 1993, 1995)
- campsite monitoring (Brian and Thomas, 1984; Kearsley et al., 1994, 1999)
- Hazel and Kaplinski (1991 - present)

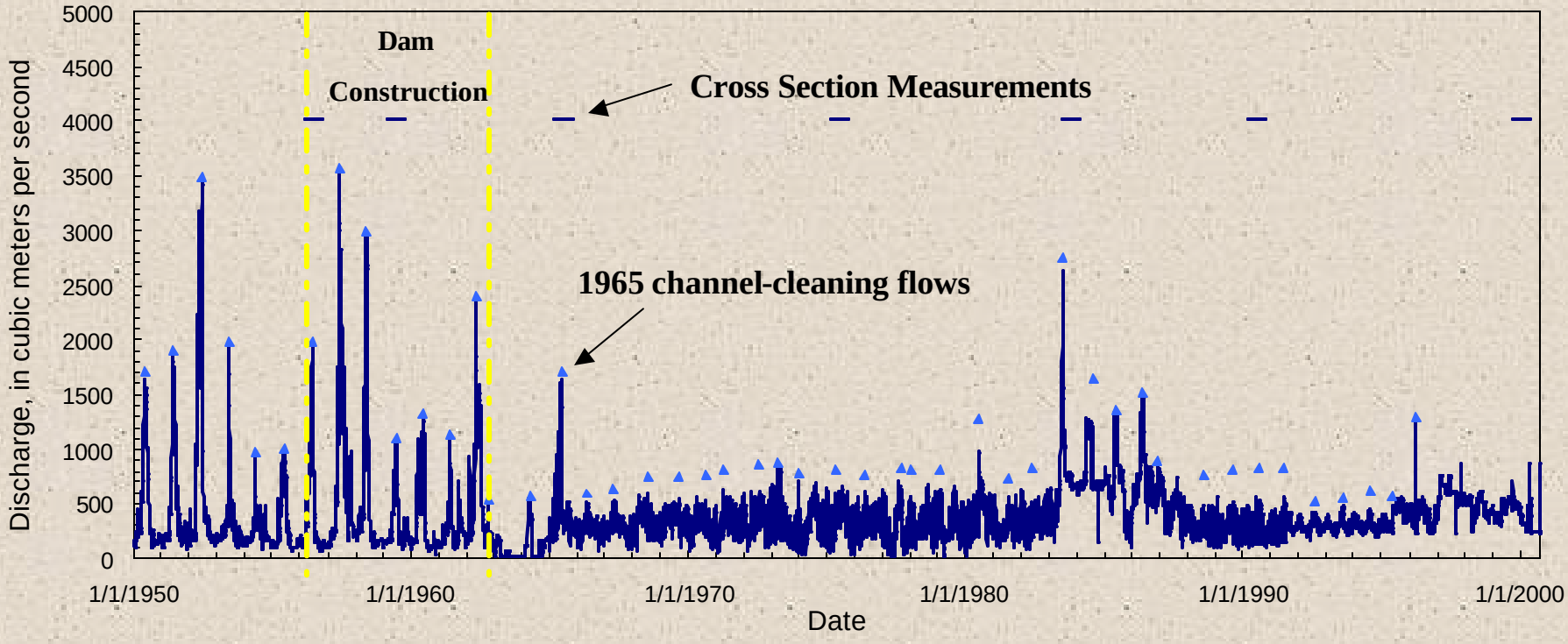
Alternative Paradigms

- Progressive and continuing loss everywhere?
- Establishment of a new equilibrium?
- Different conditions in different parts of the canyon (longitudinal trends indicating more erosion closer to the dam)?

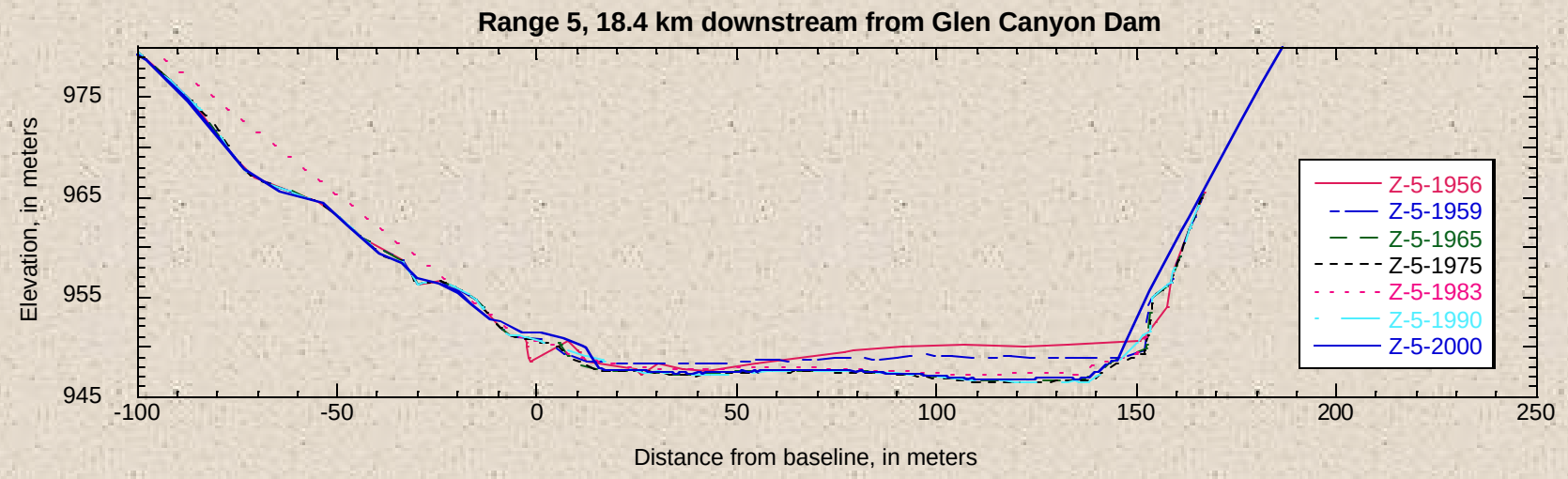
Bed and Bank Changes in Glen Canyon

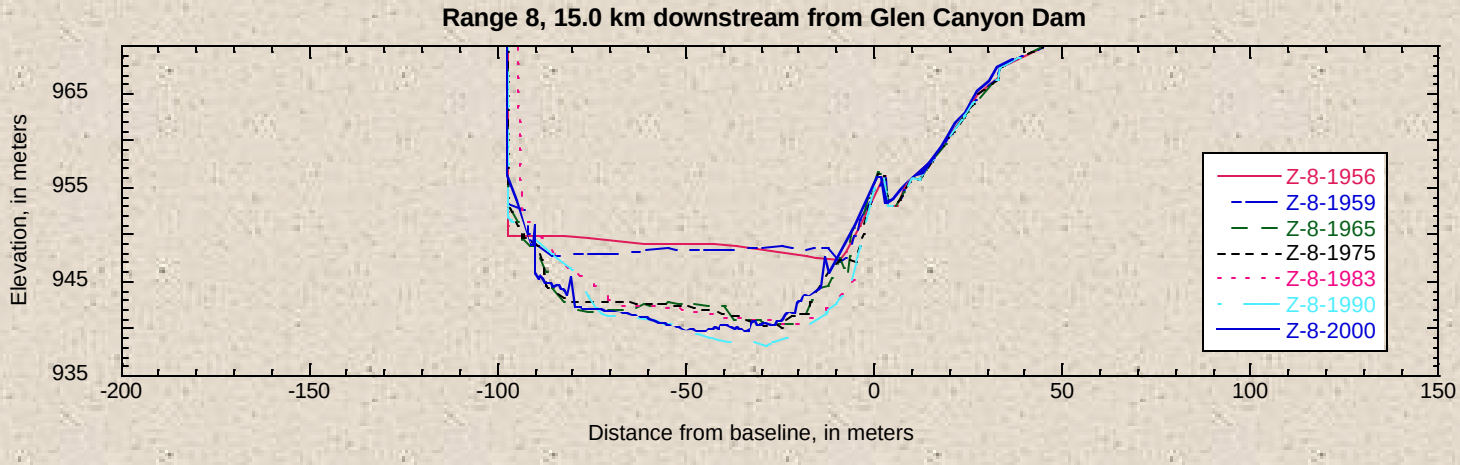
- Channel cross-section resurveys
- Bed material size data
- Deep bore-hole data
- Aerial photograph analysis

Lees Ferry Mean Daily Discharge, 1950 to 2000

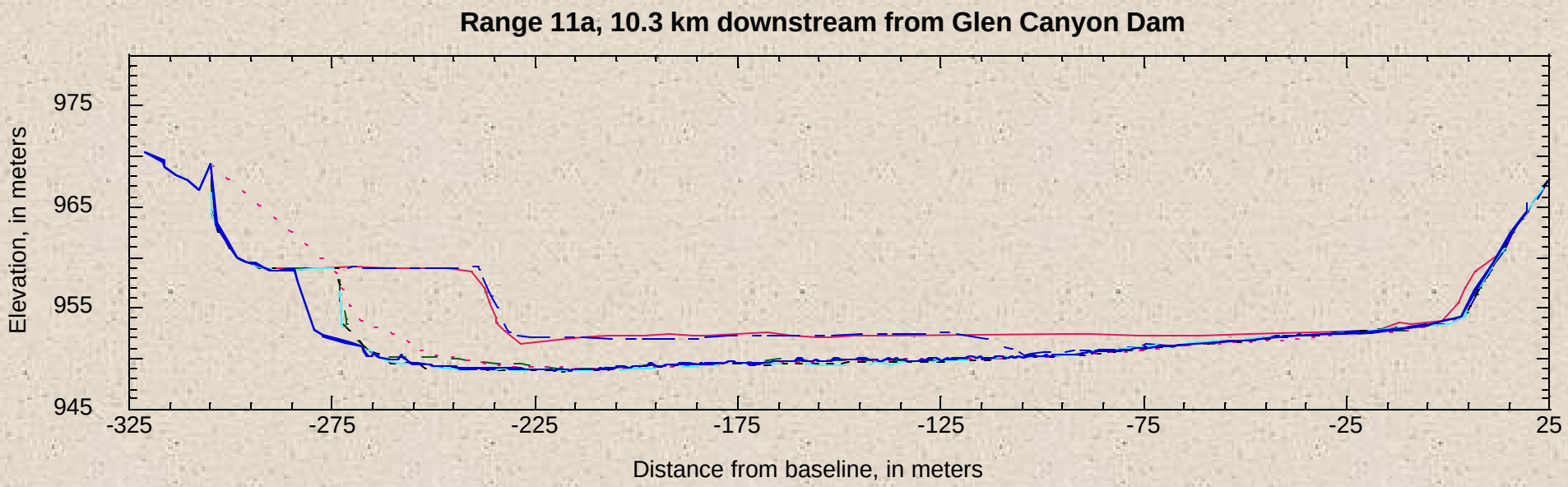


Glen Canyon Cross Sections 5 and 8

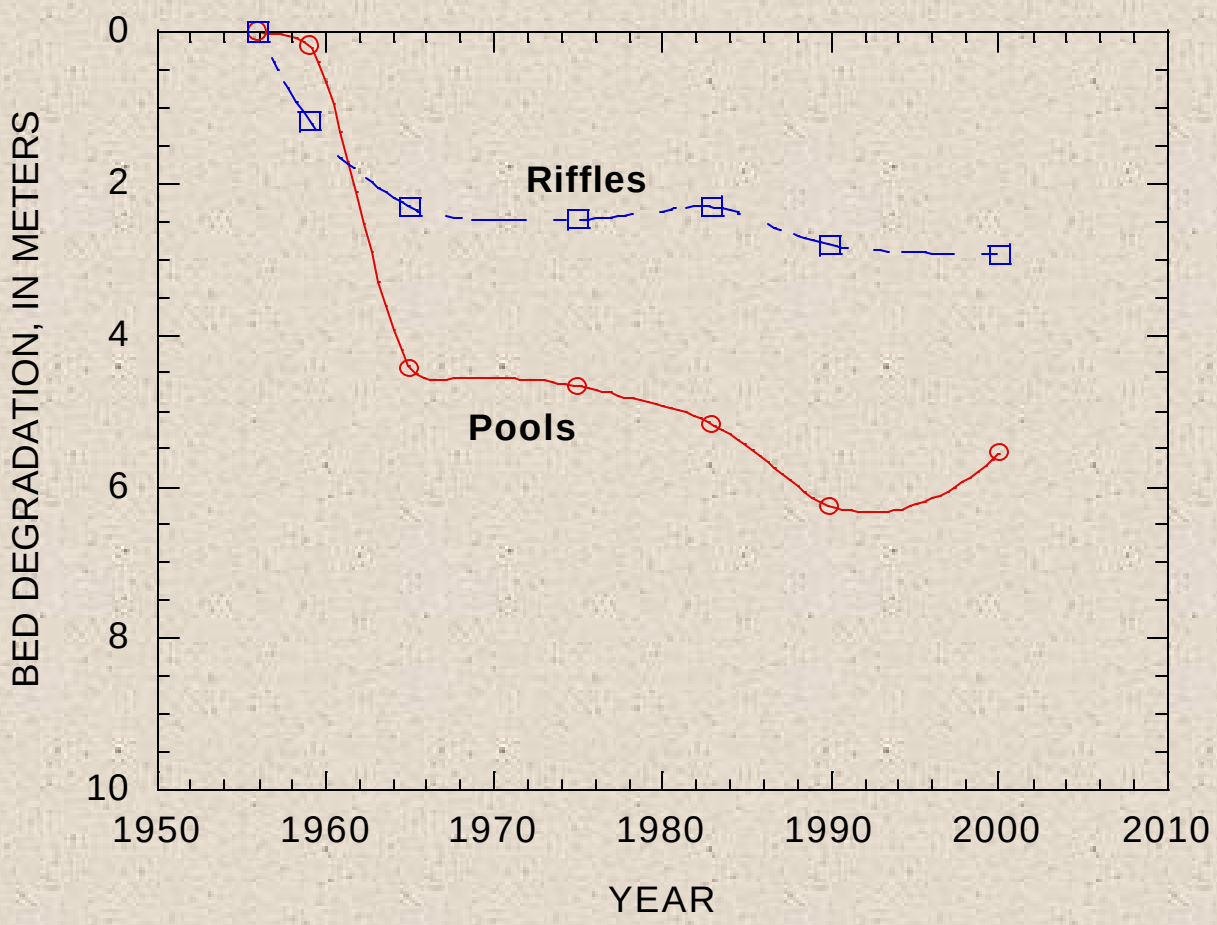




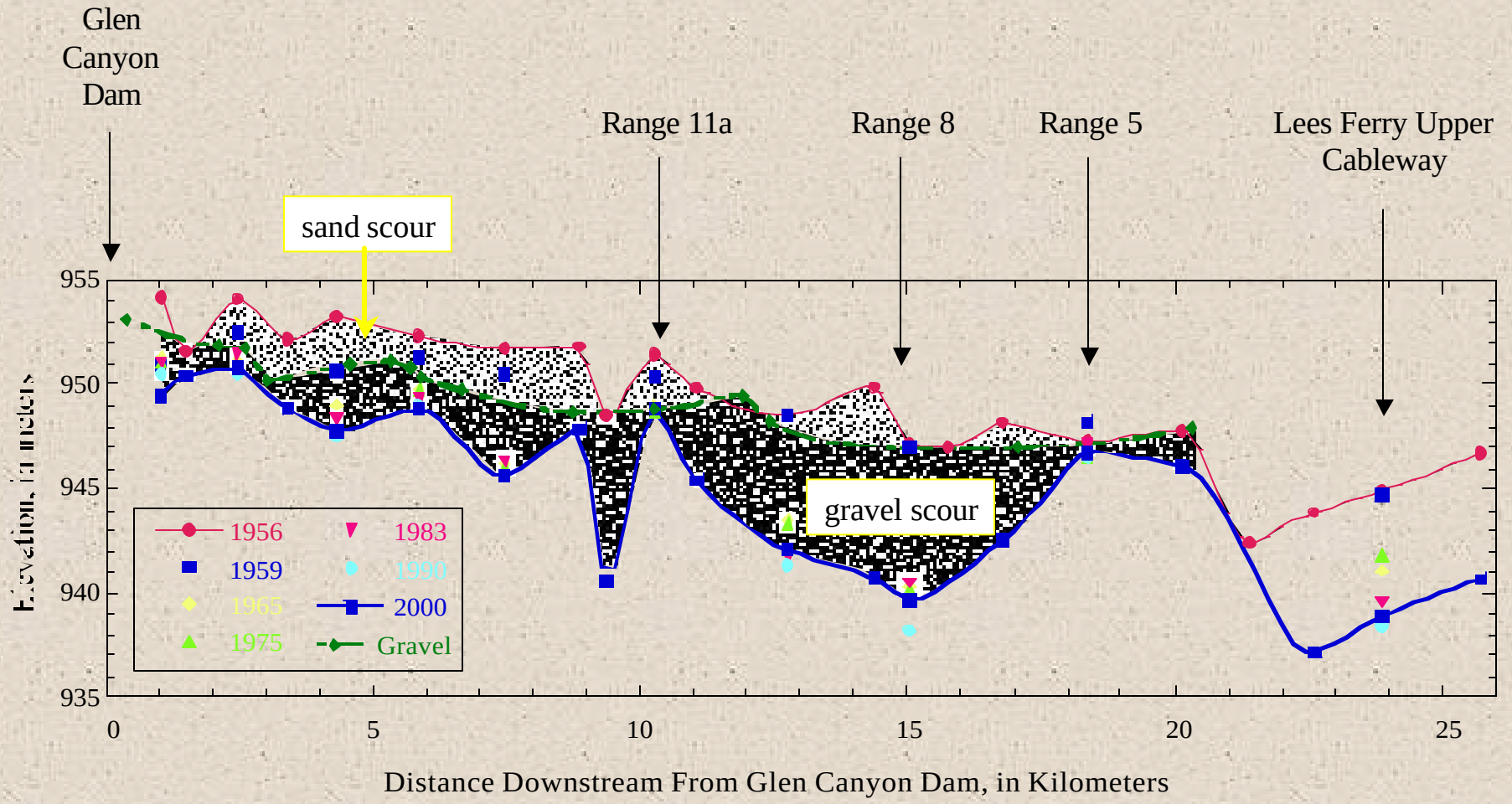
Glen Canyon Cross Section 11a



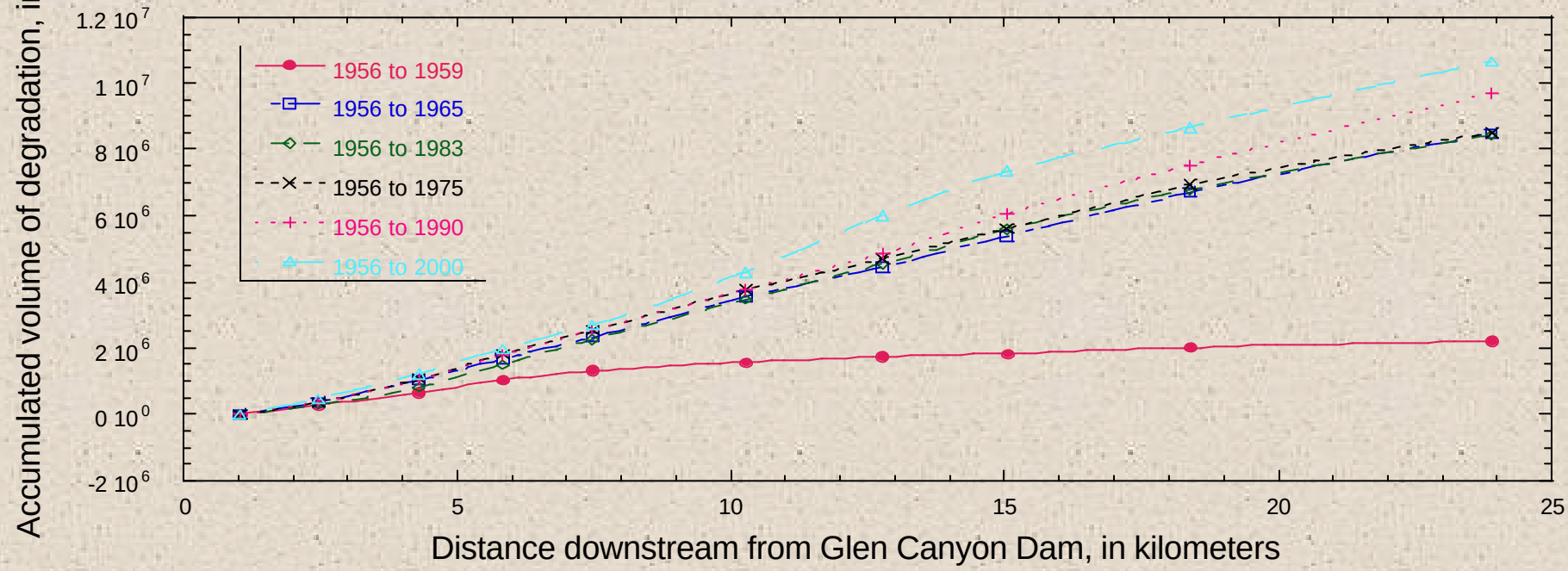
Average Degradation between Glen Canyon Dam and Lees Ferry in Pools and Riffles



Longitudinal Profile, Glen Canyon Dam to Lees Ferry

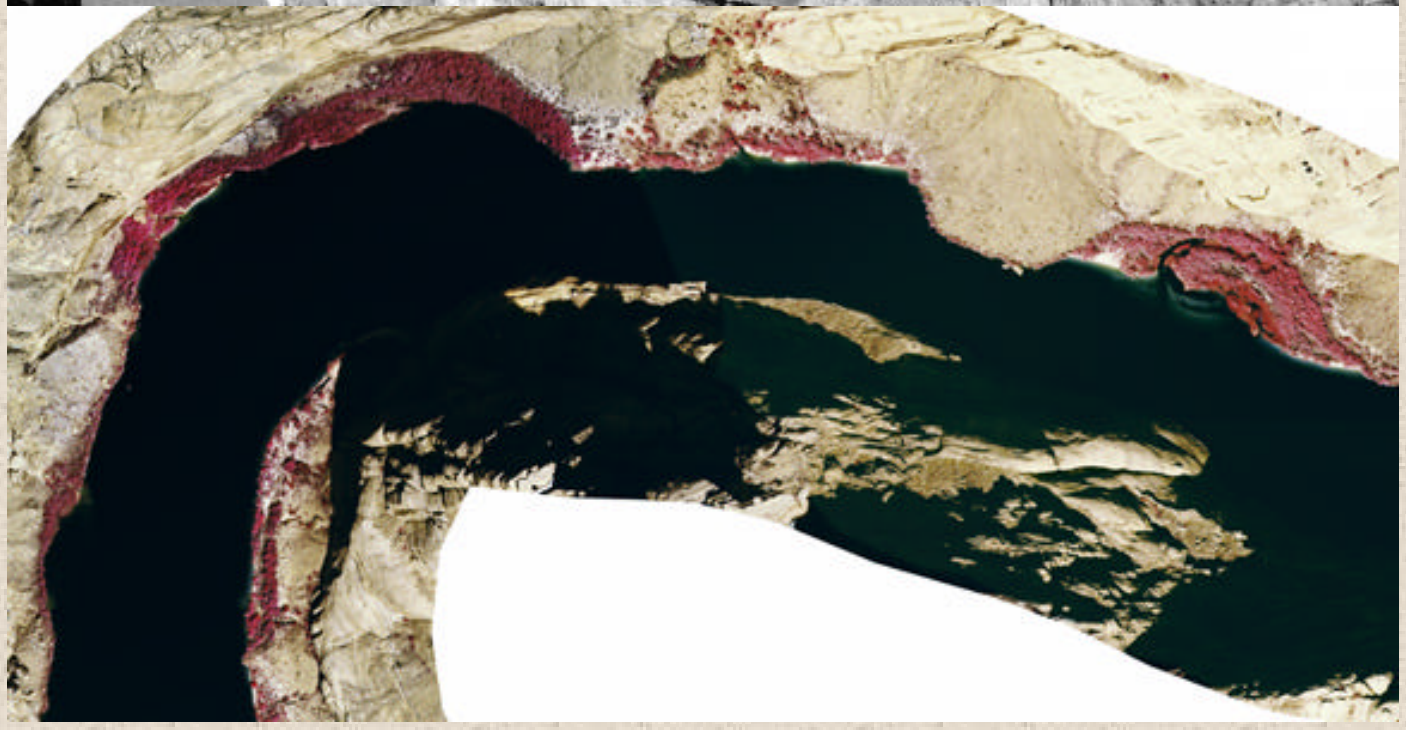


Accumulated Volume of Bed Degradation, 1956 to 2000

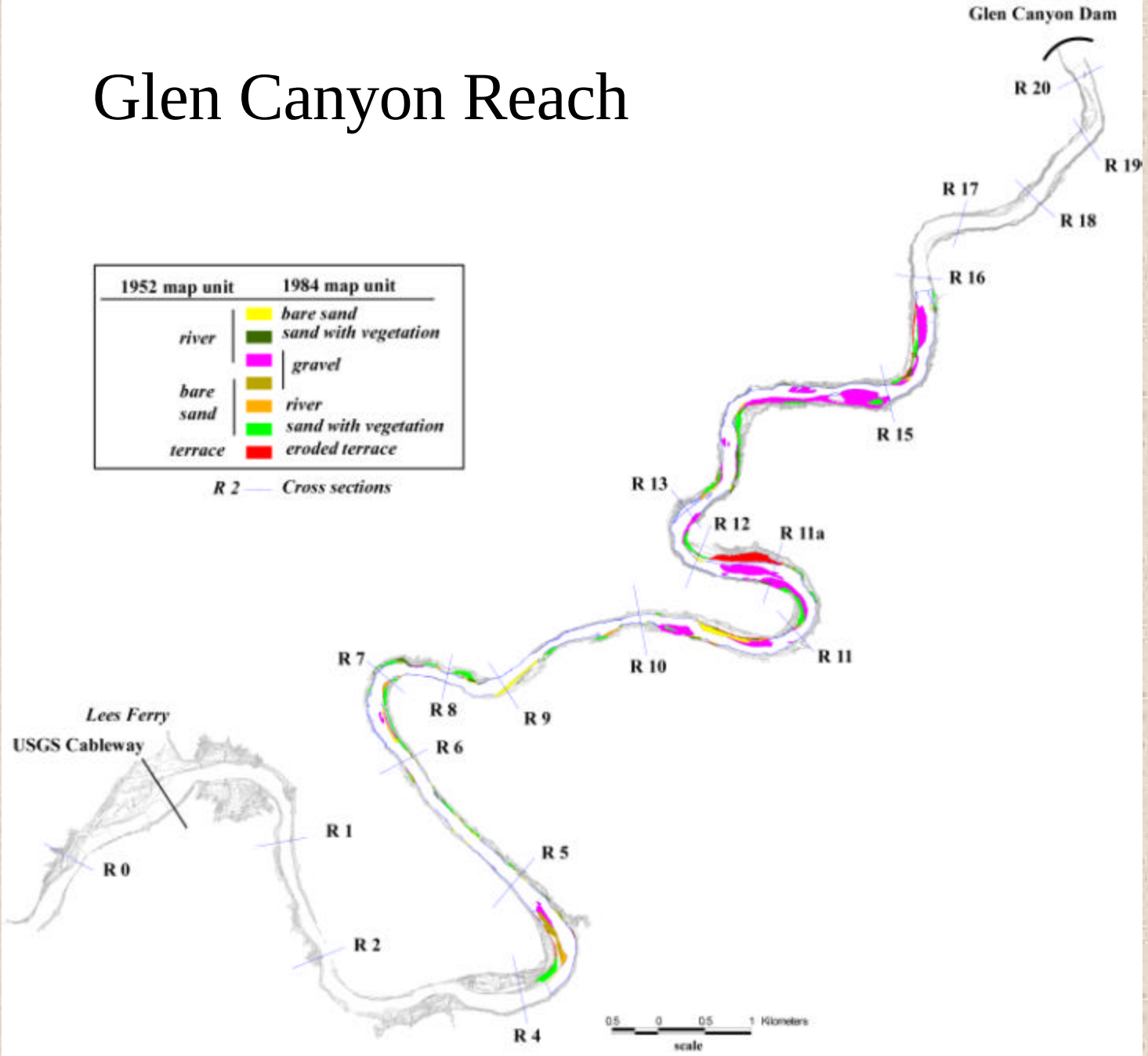


1952

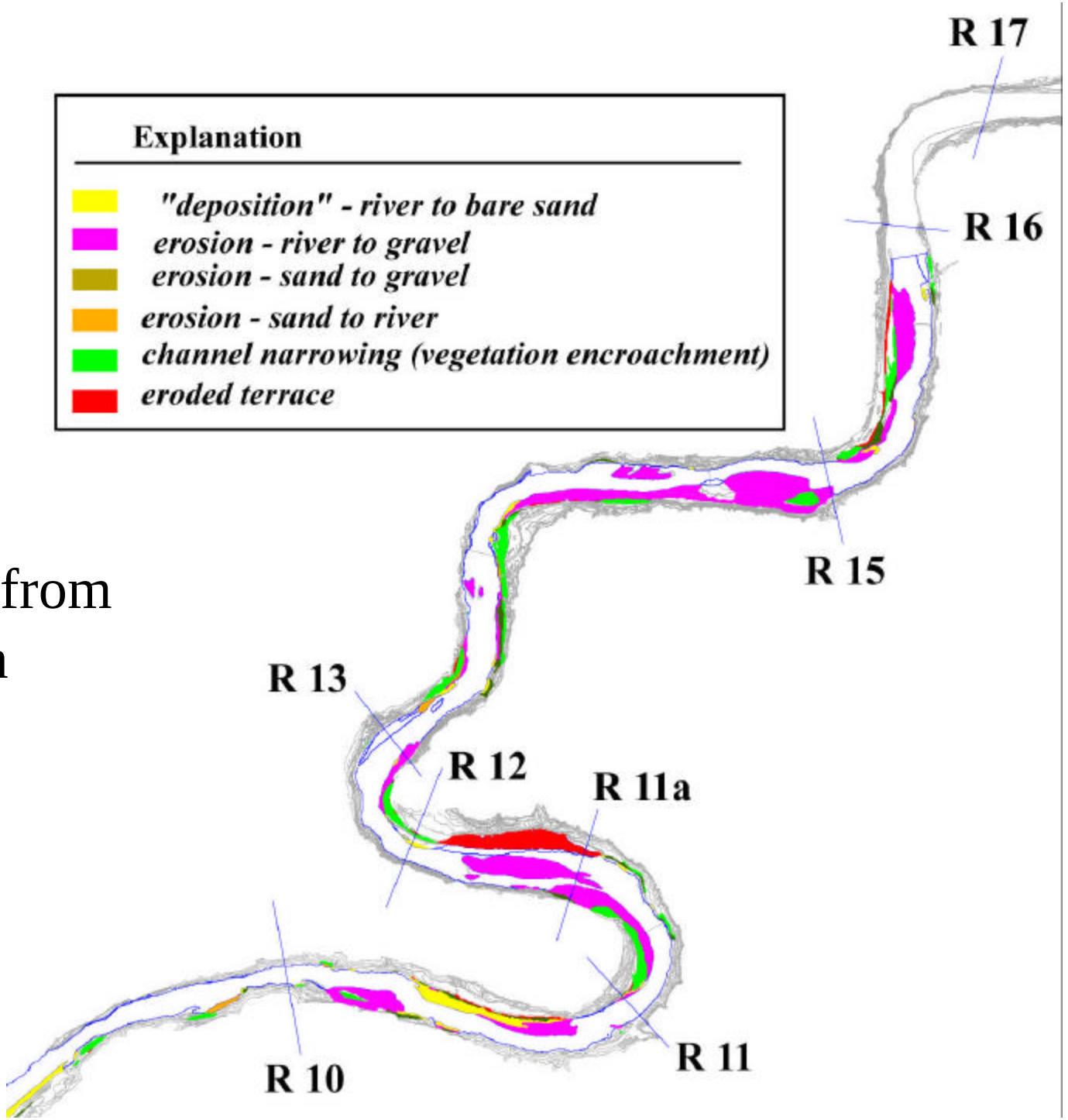
1998



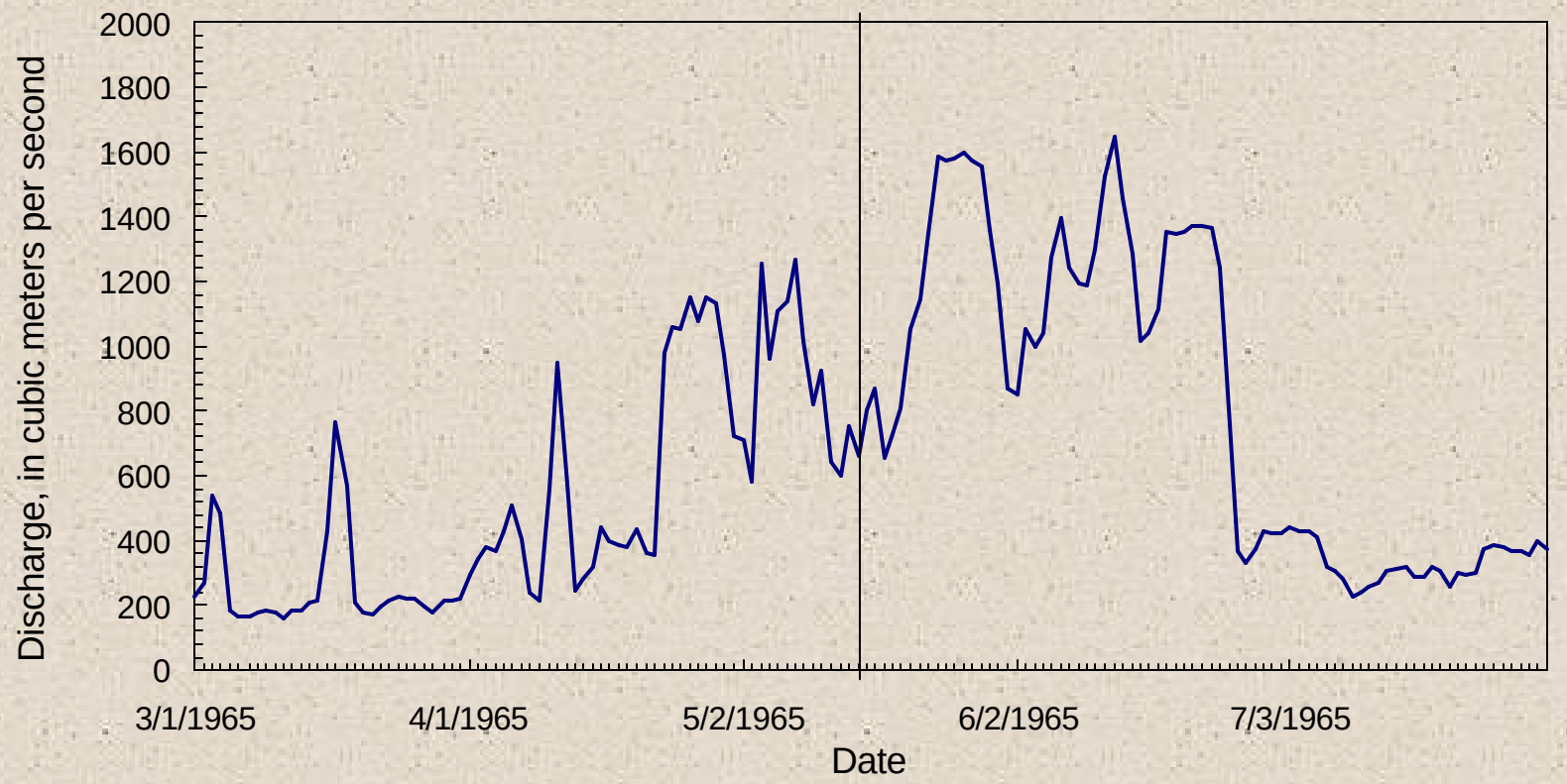
Glen Canyon Reach



2 to 14 km downstream from Glen Canyon Dam



Lees Ferry Mean Daily Discharge, Spring 1965



Channel Cleaning Flows

COMPUTATION SHEET

BY _____ DATE _____ PROJECT Upper Colo River SHEET No. _____

CHKD BY _____ DATE _____ FEATURE Glen Canyon

OFFICE _____ DETAIL Tailwater. FILE No. _____

n_s = Specific Speed = 27.6 at Full Head

℄ of ~~Runner~~ Scroll Case @ 3140 $b = 54\frac{1}{2} = 4.53$

H_s measured from (3140.0 − 4.53) 3135.47'

H_b = 26.7" H_g = 30.2' of water

Assume Q = 10000' @ Min Head of 345

TW El. Lowered to 3133.0 @ min Head = 345

$$\sigma = \frac{30.2 - 2.47}{345} = \frac{28.7}{345} = .083$$

@ Design 510

$$\sigma = \frac{28.7}{510} = .056$$

See Engr Monograph #20 PP 19 and F Ruud's Paper

Critical σ = .055 for n_s = 27.5

At Present TW el = 3137.0 for 10000 c.f.s.

With Cross Weir at El. 3132. TW el should be 3135.5

Tailwater 1.5' Higher than design called for.

Lowering TW el to 3133.0 and improving conditions is equivalent to lowering cross weir 2.5' in design or to 3129.5

Thus TWel. would be lowered 4' (1.5 + 2.5)

For Single Unit Q = 3035 Min Head = 345

$$\sigma = \frac{30.2 - 4.00}{345} = \frac{29.2}{345}$$

TW el = 3134

3135.5
3134.0
1.0

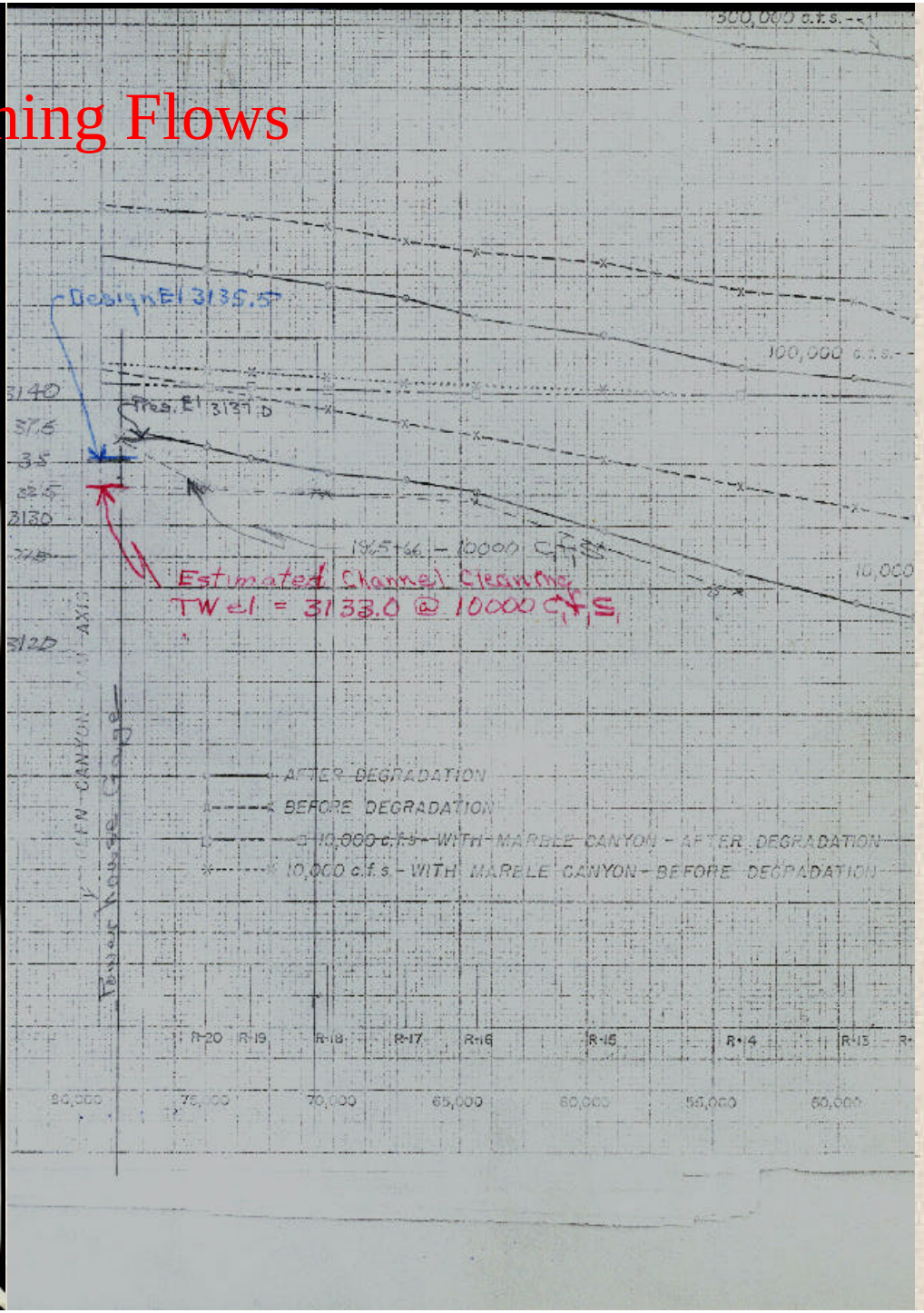
σ = .085

For Single Unit @ Design Head Q 3984 H_d = 510

$$\sigma = \frac{30.2 - (3135.47 - 3134.7)}{510} = \frac{29.6}{510} = .086$$

With Lowering Single Unit at min Head = Twel = 3130.0

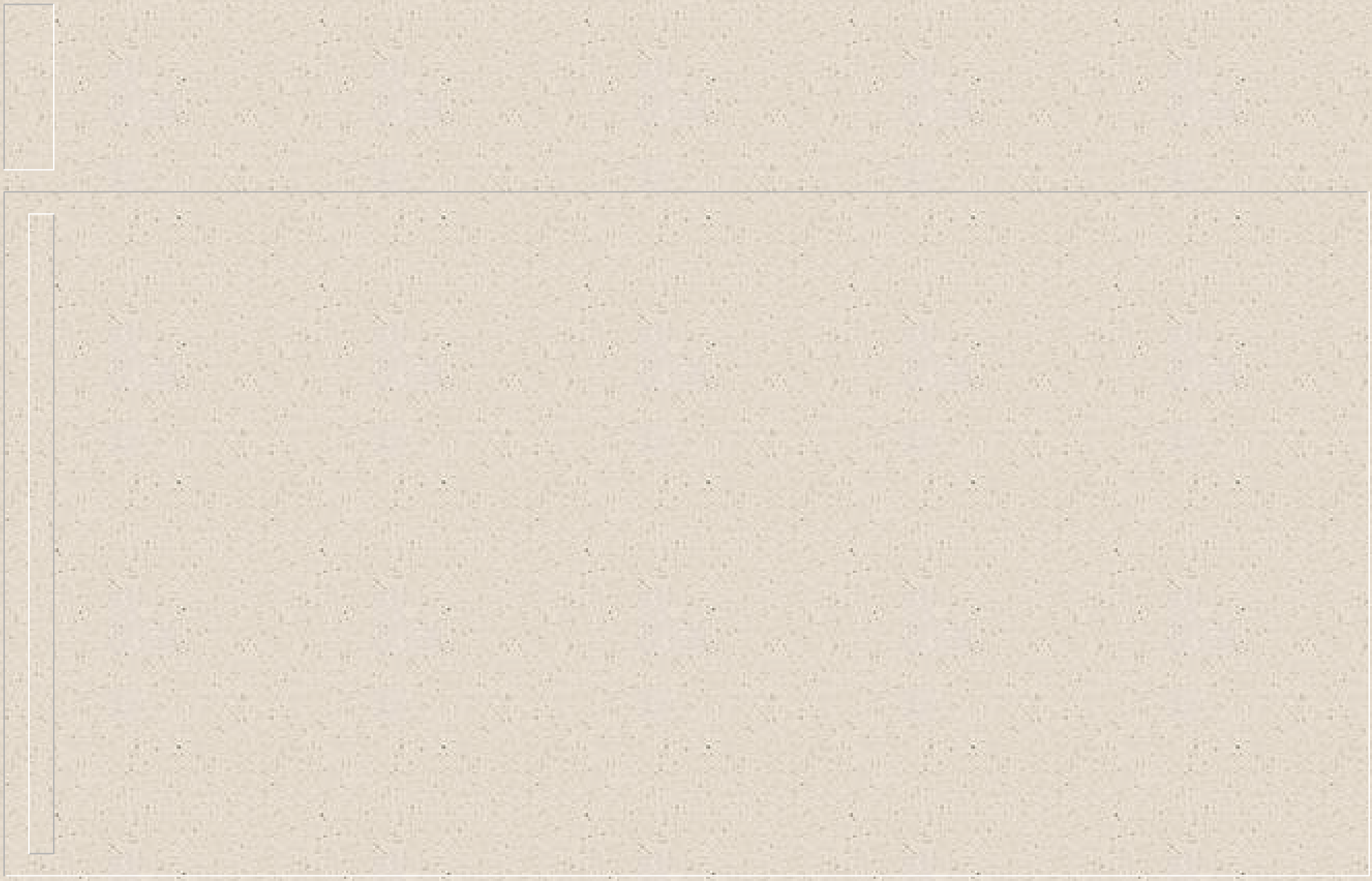
$$\sigma = \frac{30.2 - 5.5}{345} = \frac{24.7}{345} = .072$$



Bed Changes Downstream from Lees Ferry

- Resurvey of the Marble Canyon Dam cross-sections
- Changes at Grand Canyon gage

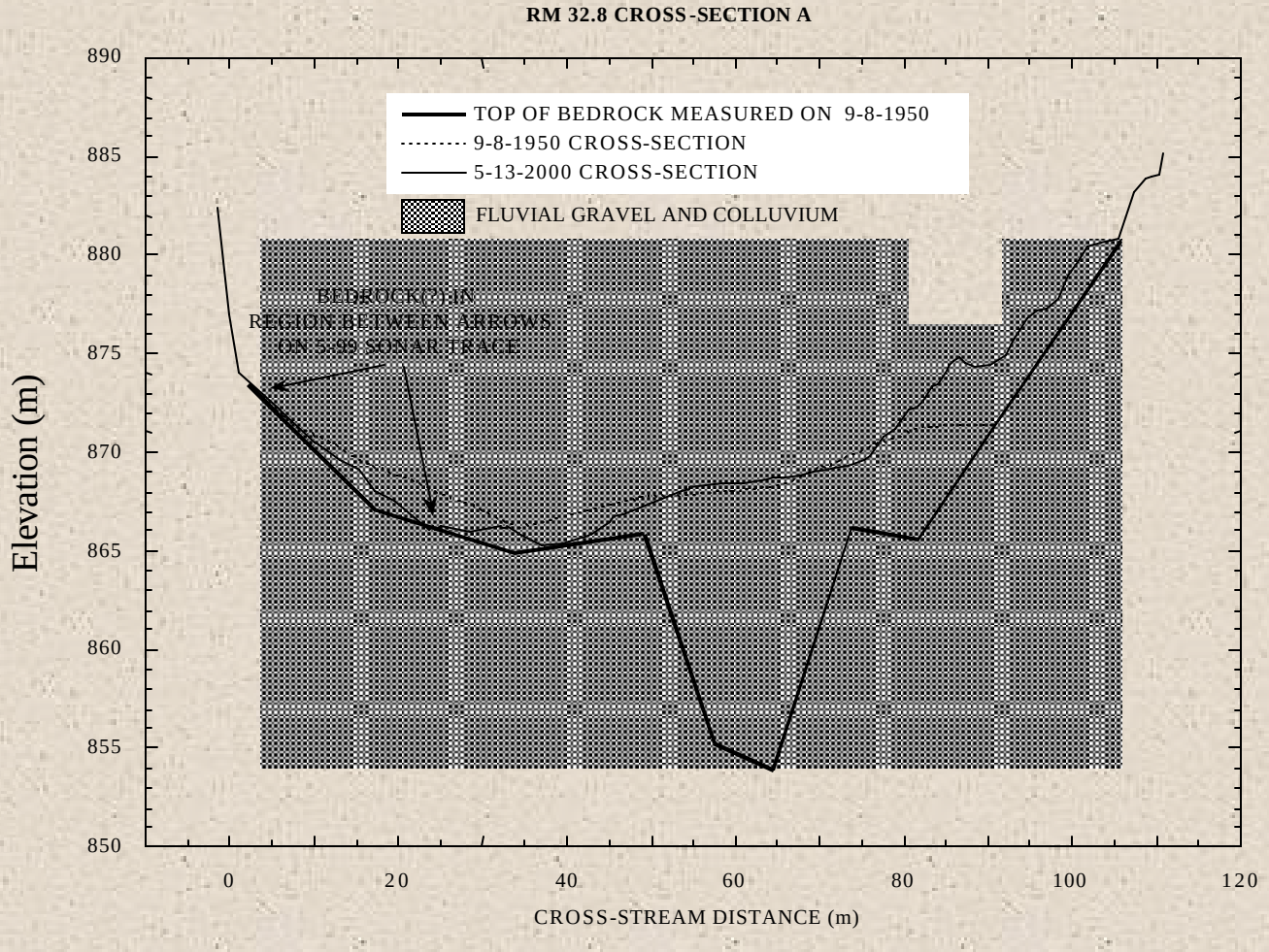
Bed behavior at Grand Canyon gage



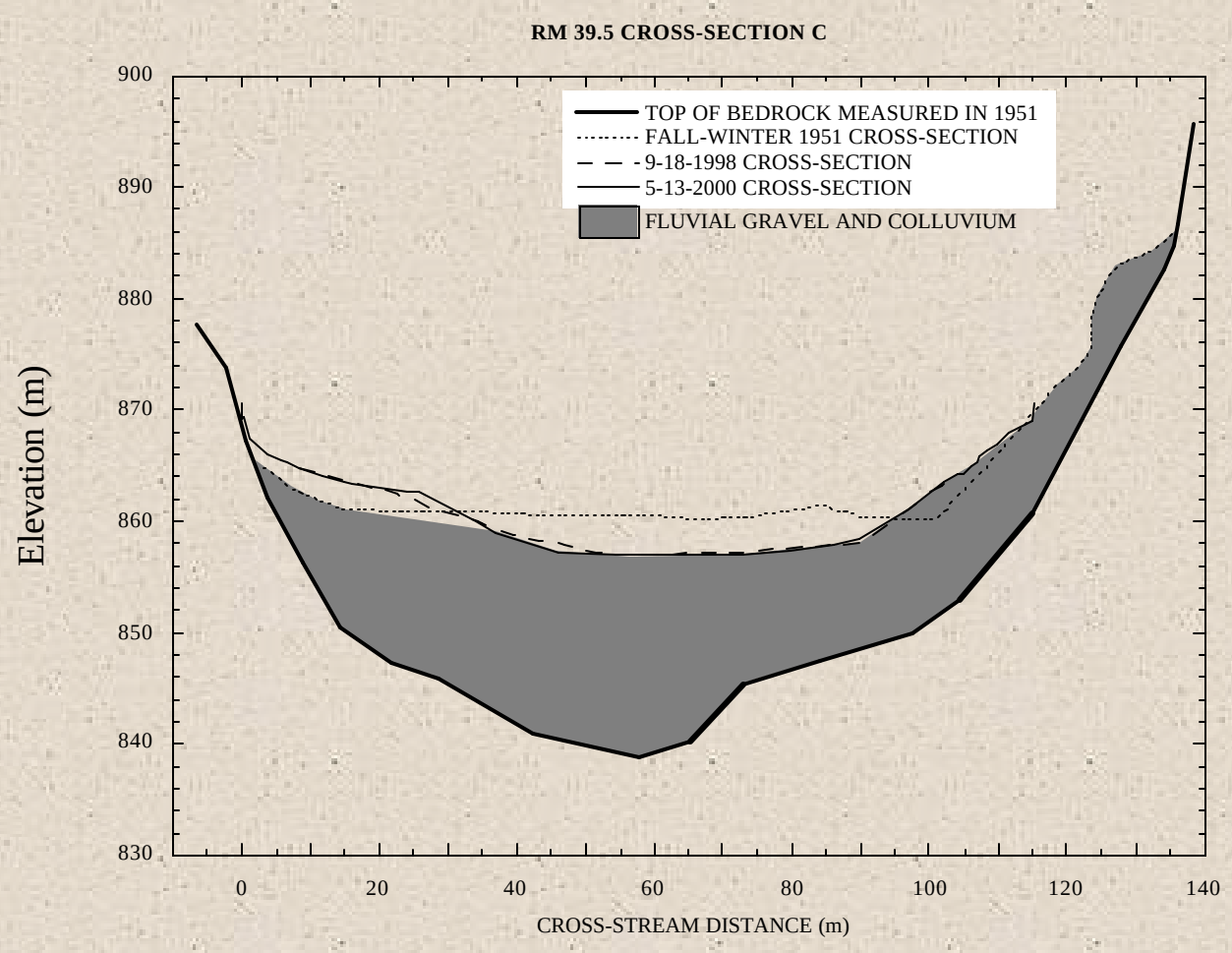
Bed degradation in Marble Canyon

Location	Change, 1950-2000 (m^2)	Change, 1998-2000 (m^2)
RM 32.8 A	0	
RM 32.8 B	+8	
RM 39.5 A	-92	
RM 39.5 B	-95	0
RM 39.5 C	-101	-3
RM 39.5 D	-43	+10

Bed degradation in Marble Canyon, 80 km downstream from dam

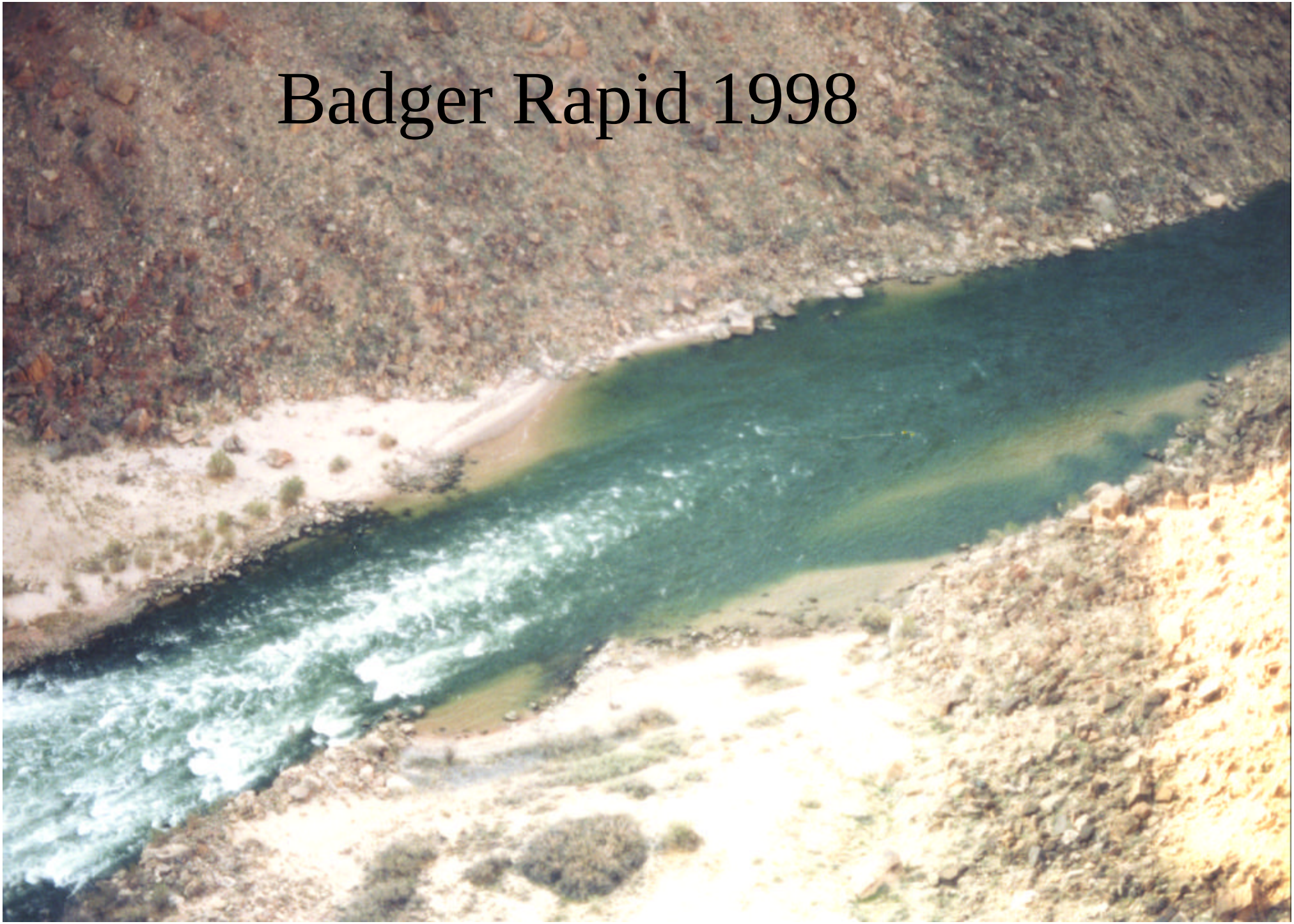


Bed degradation at the Marble Canyon Dam site, 91 km downstream from dam

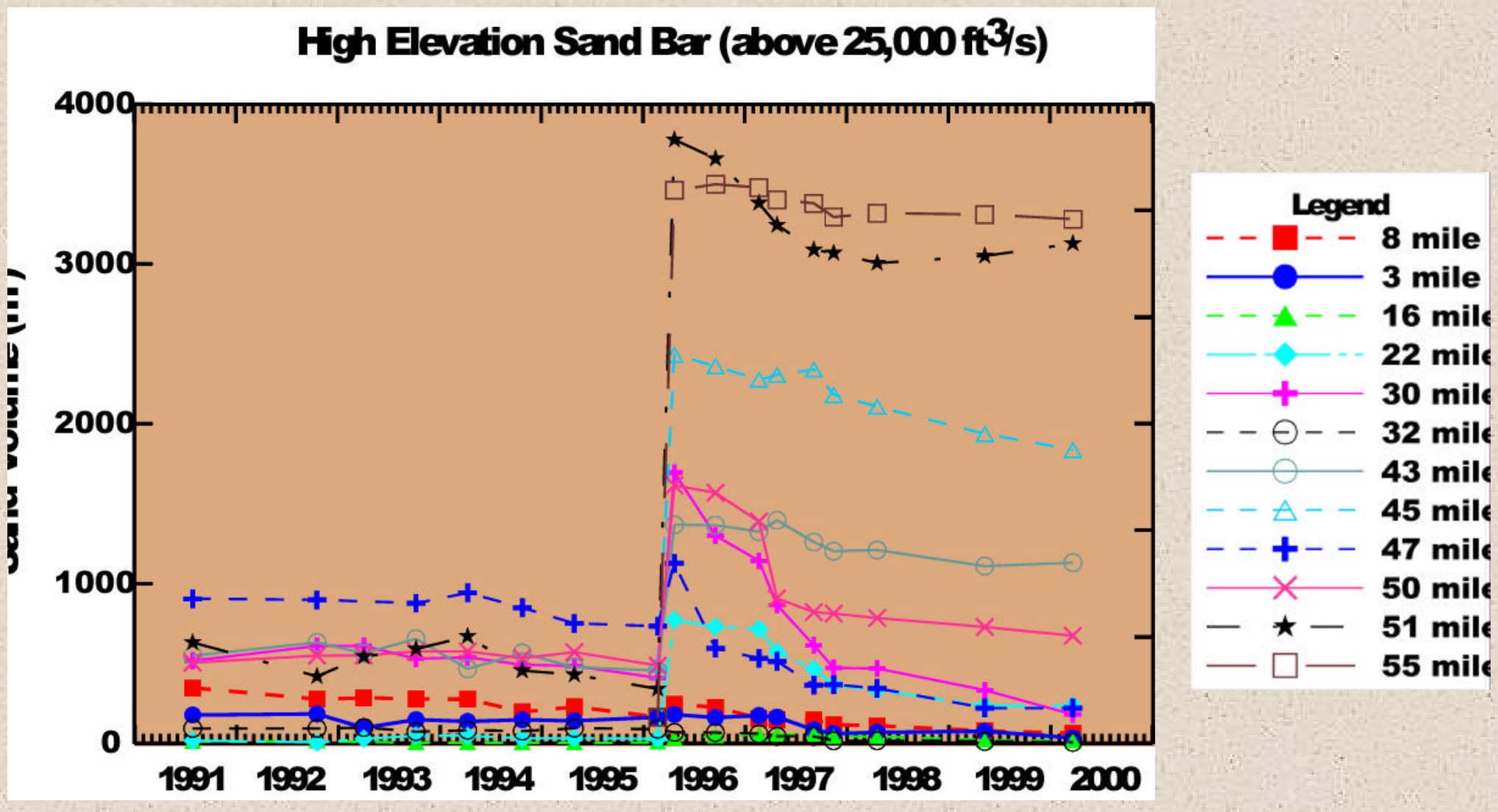


Changes in Alluvial Bars and Banks Downstream from Lees Ferry

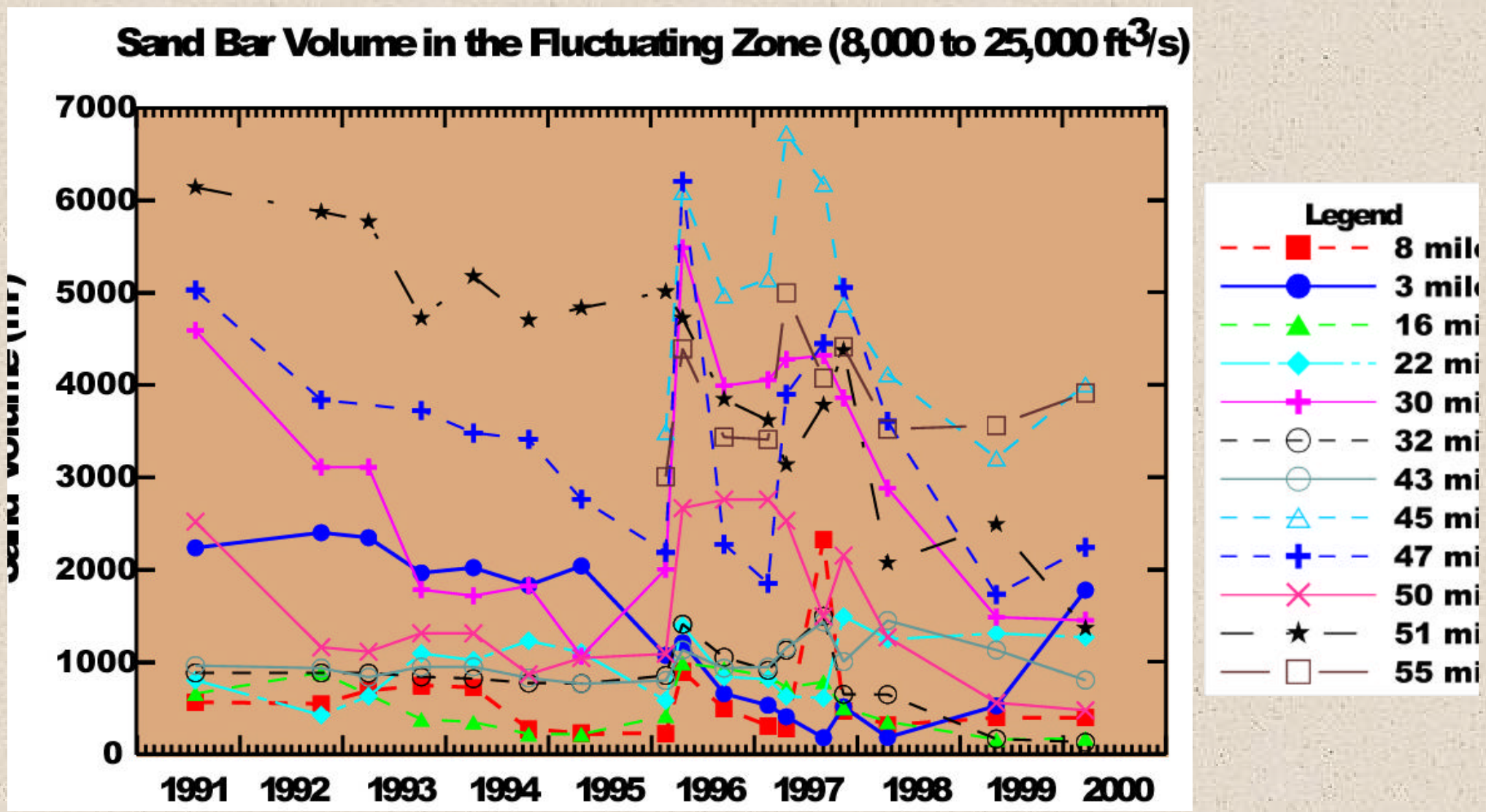
- Repeat oblique photographs
- Aerial photographs
- Inventories of campsites
- Profile and topographic surveys of sand bars and channel-margin deposits
- Sediment budgets (influx = efflux $\pm$ δS)


Badger Rapid 1998

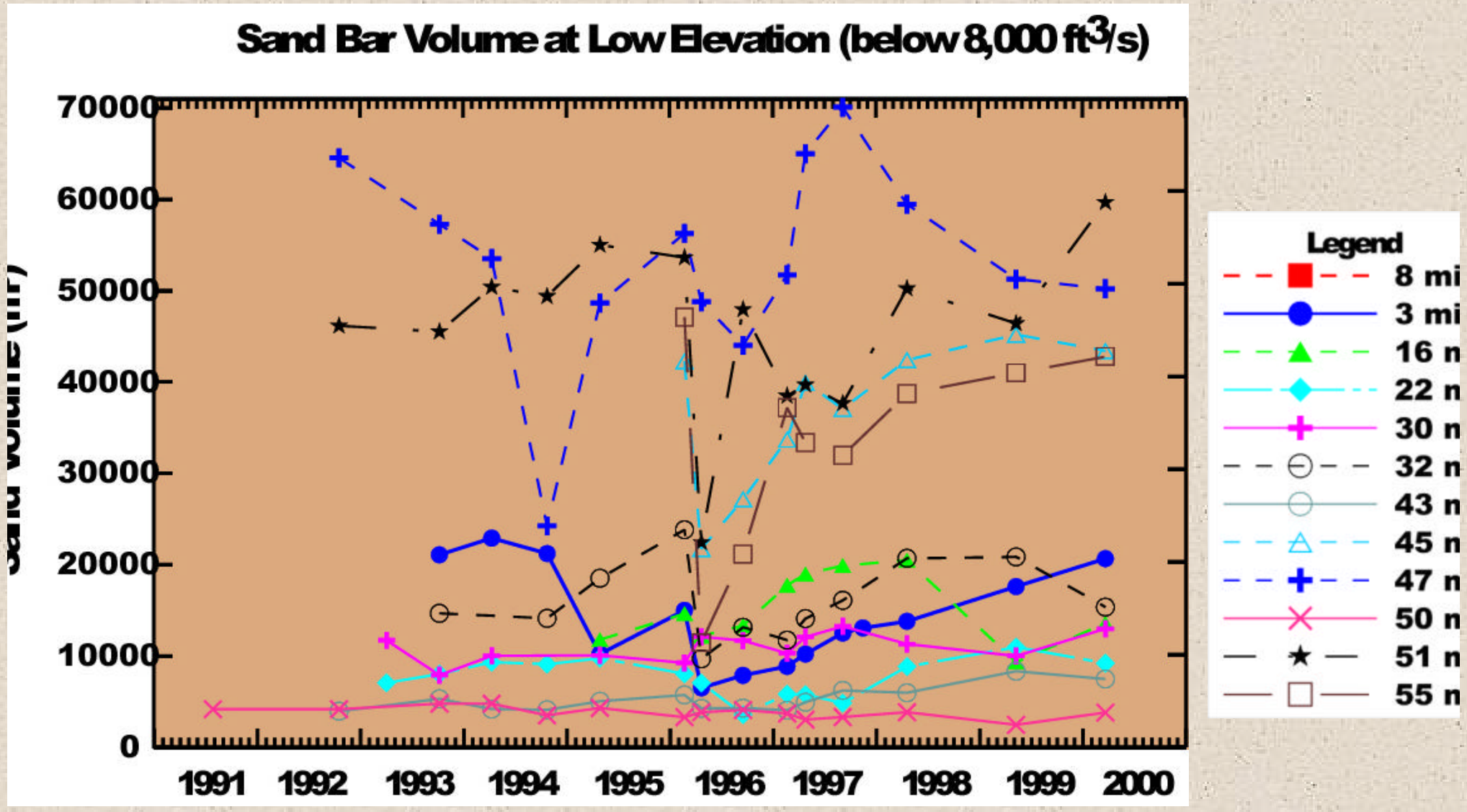
Volume changes at NAU sites above LCR



Volume changes at NAU sites above LCR

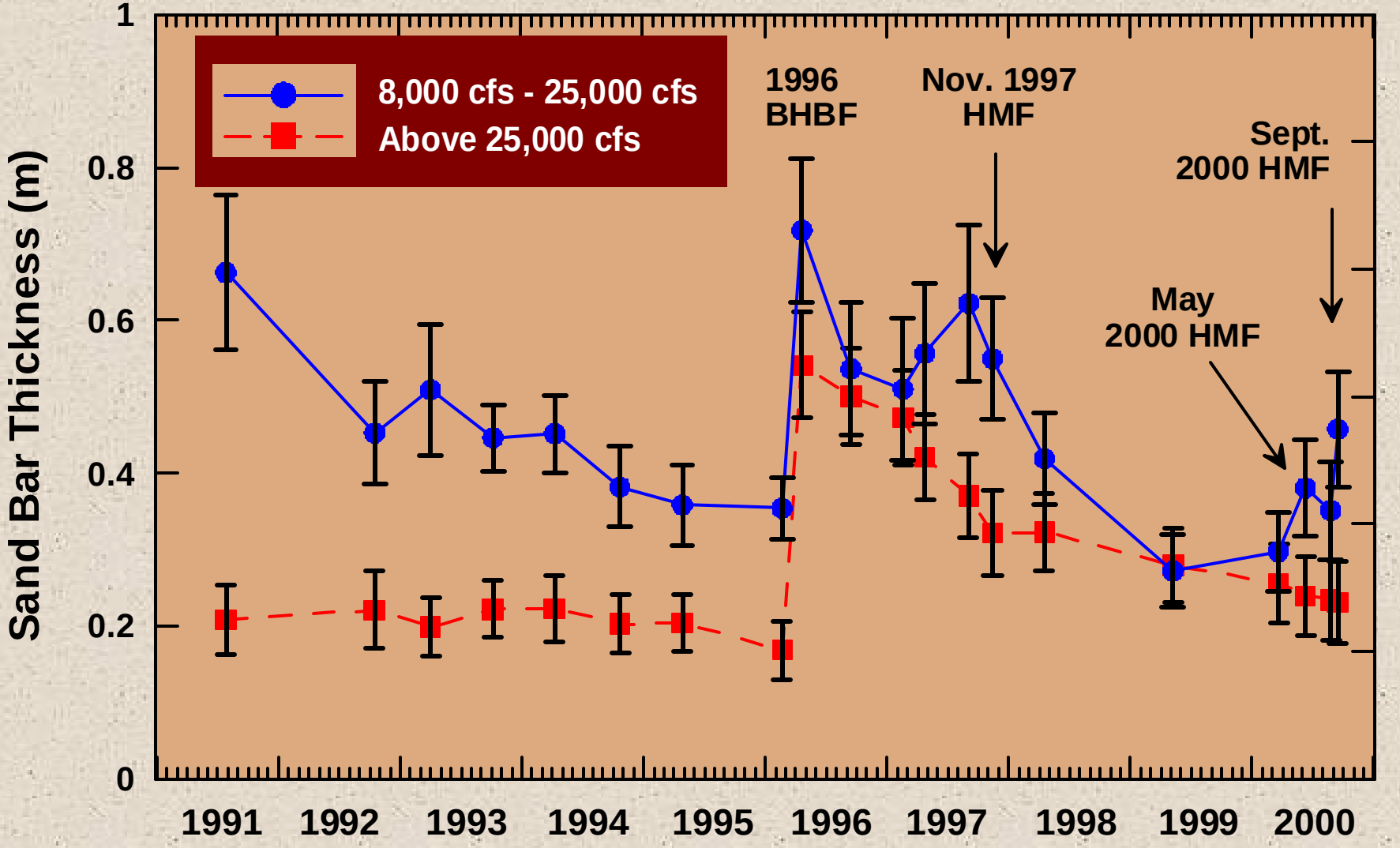


Volume changes at NAU sites above LCR



Sand Bar Thickness in Marble Canyon, 1991 - 2000

(Hazel and Kaplinski, written commun.)



Sand Bar Thickness in Marble Canyon, 1996 - 2000

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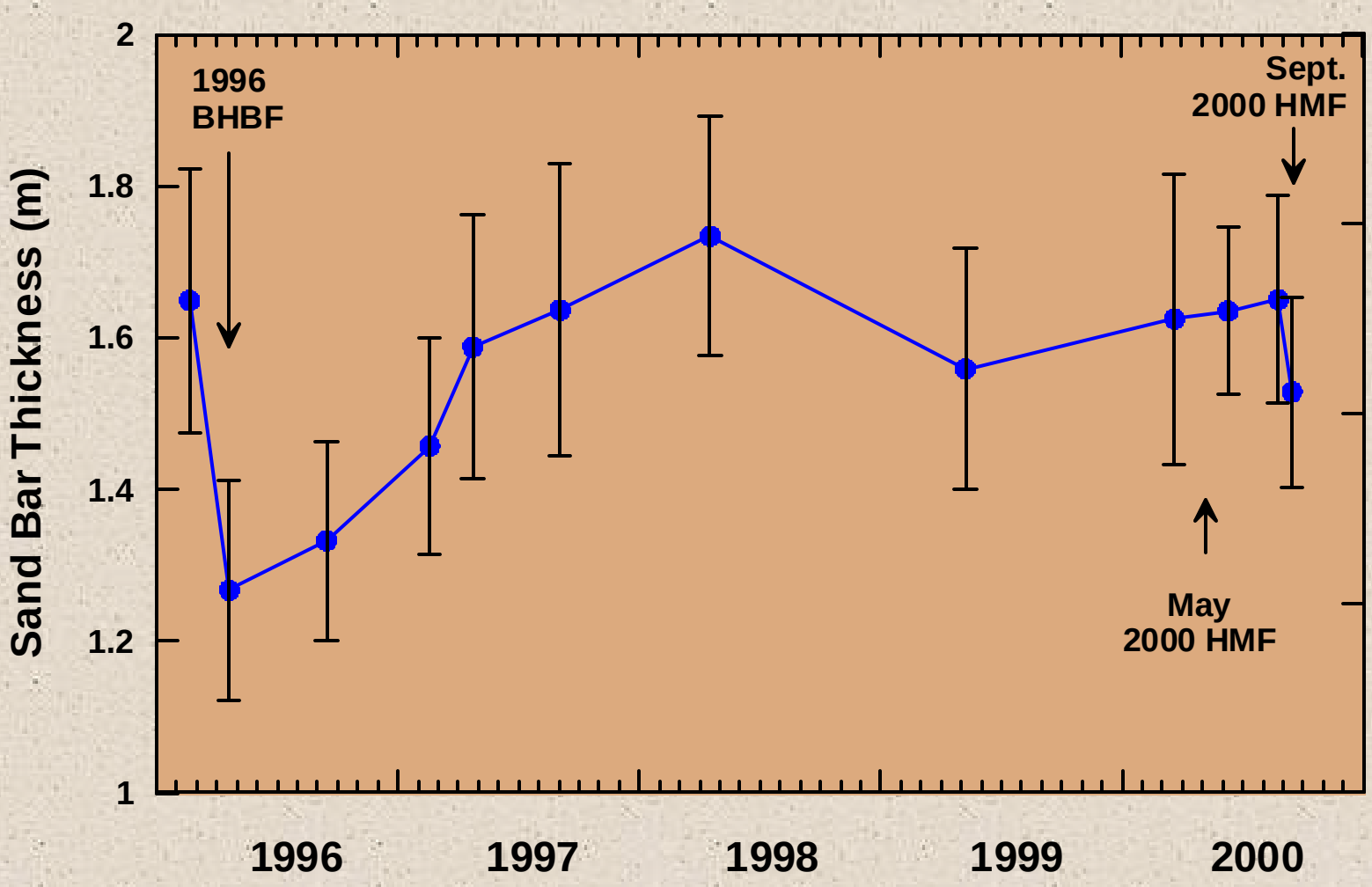
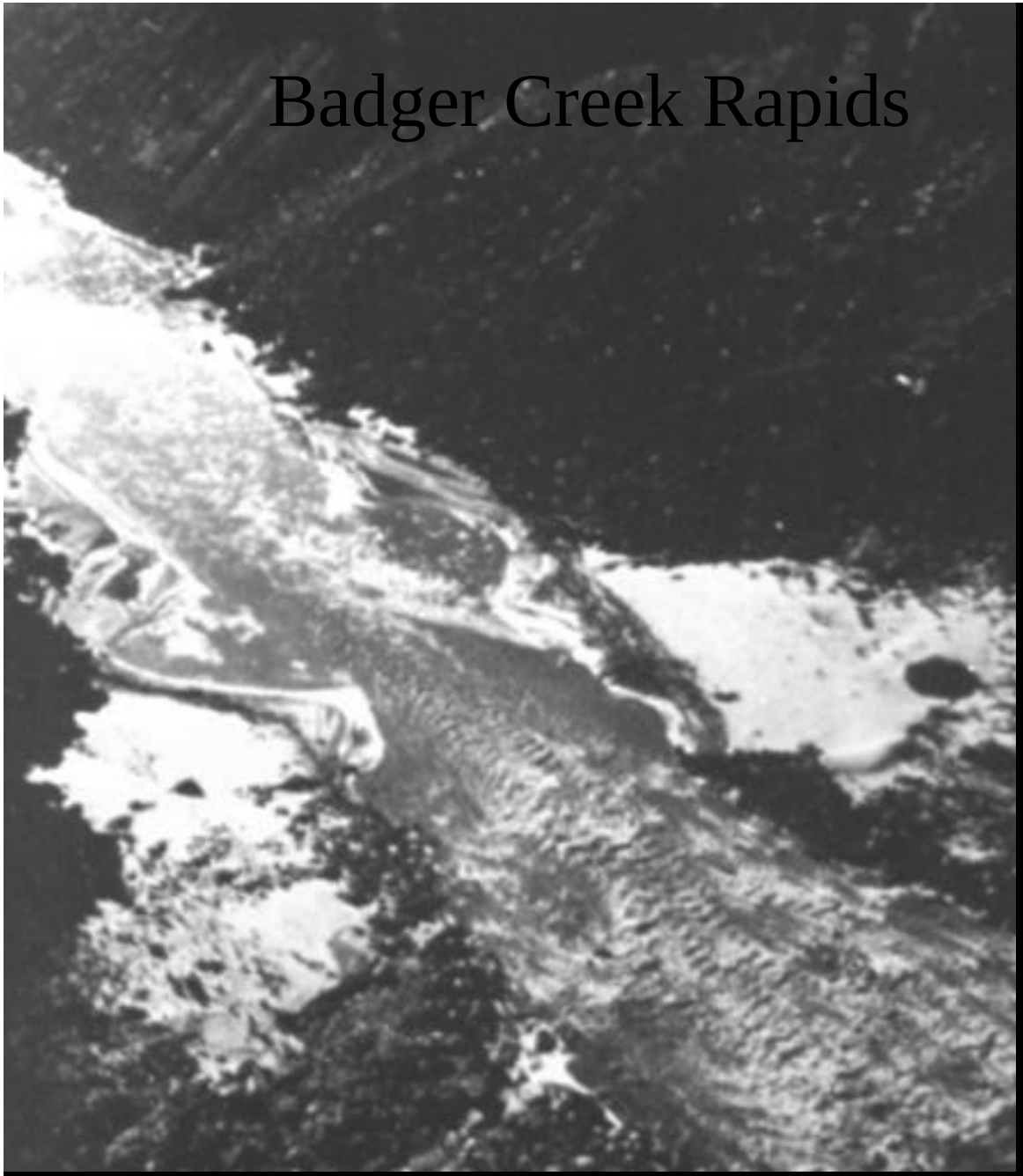


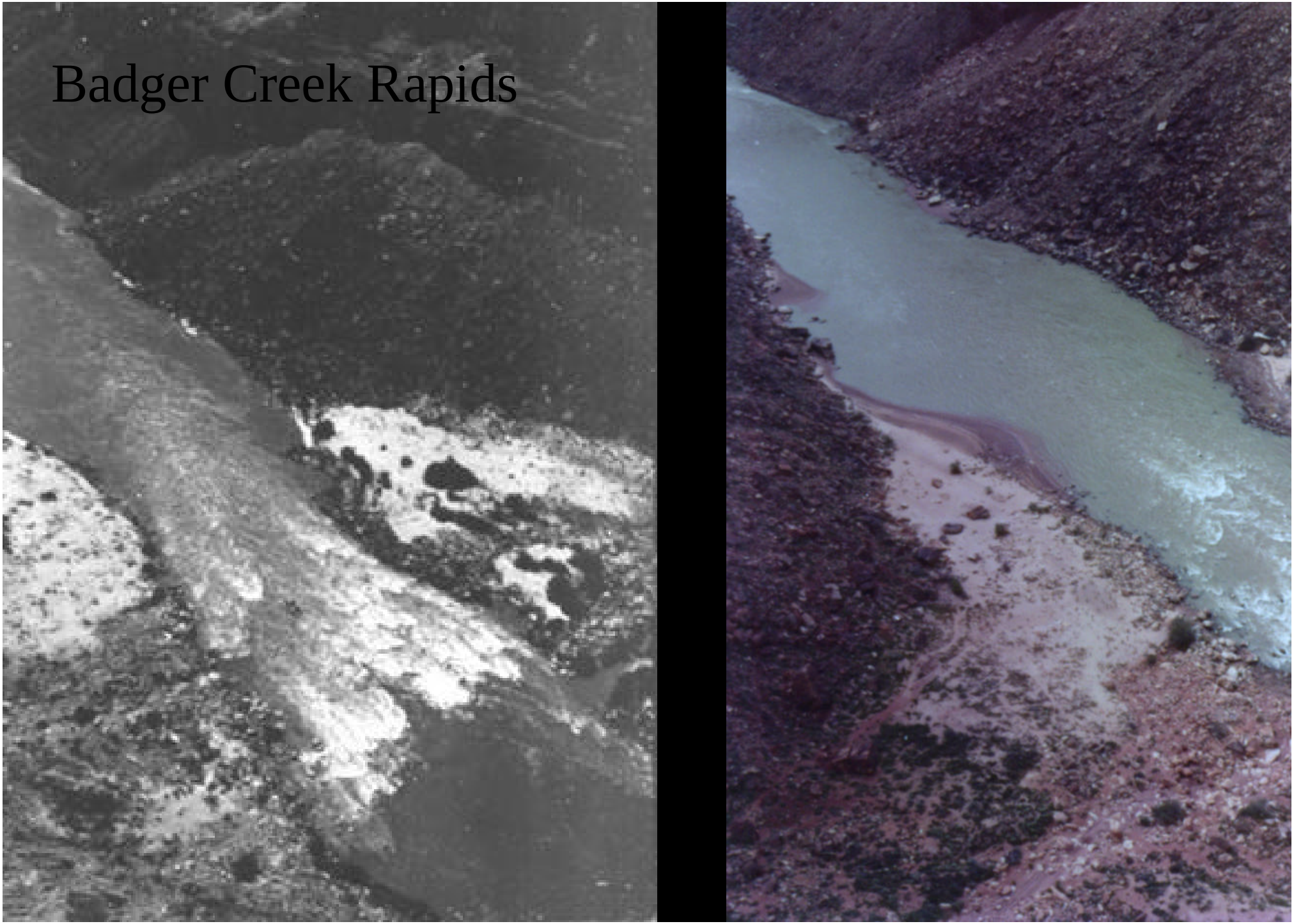
Conclusions

- High-flow and flood sands (>25,000 ft^3/s) were constructed by 1996 controlled flood and now are being progressively eroded
- Lower-elevation sands (8000-25,000 ft^3/s) were deposited by 1996 flood and 1997 and 2000 maximum power plant flows)
- Very low sands (< 8000 ft^3/s) were eroded by floods and power plant flows
- Variability in bar response increases at lower elevations

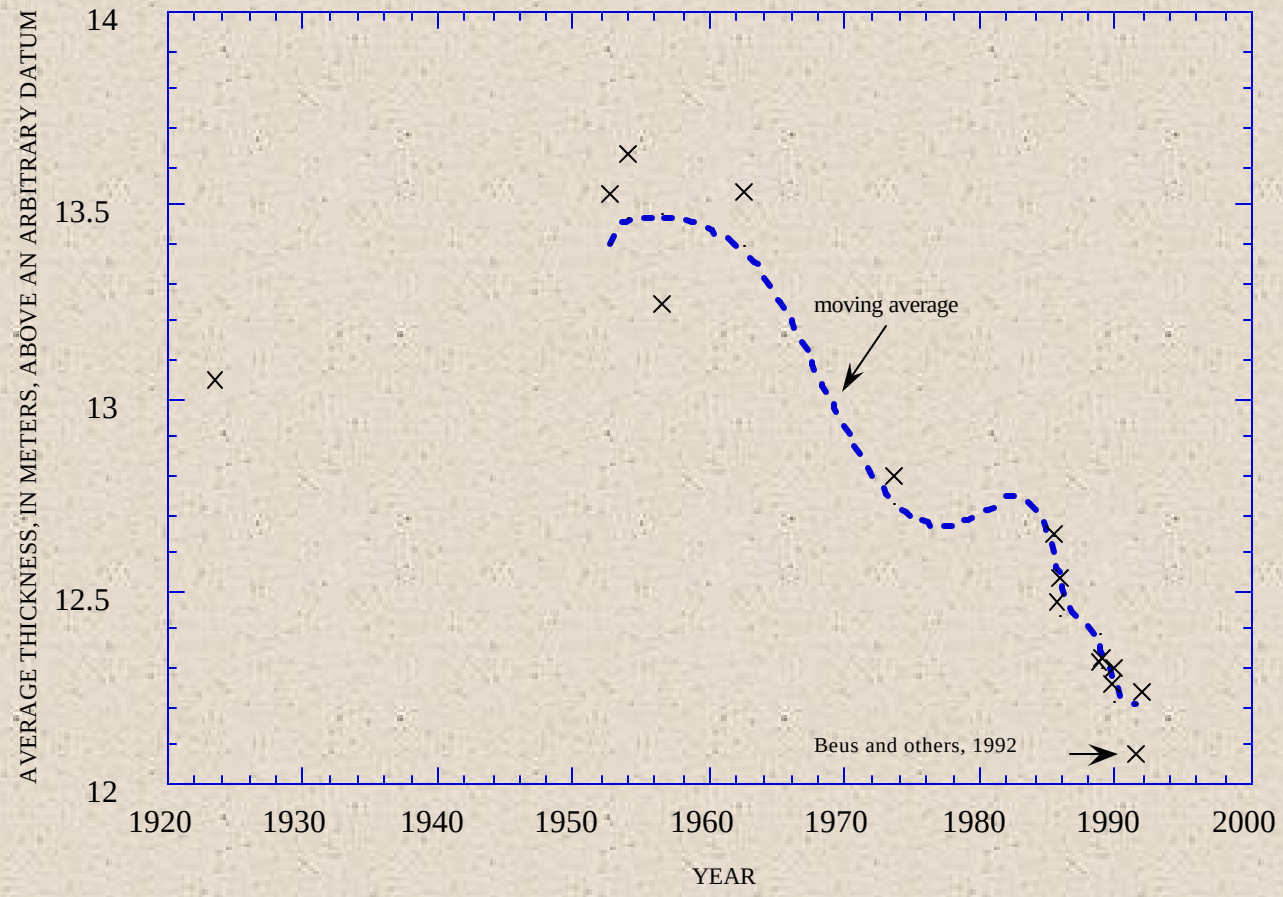
The Historic Record - Temporal Variation at Specific Sites

- Badger Creek Rapids
- other sites

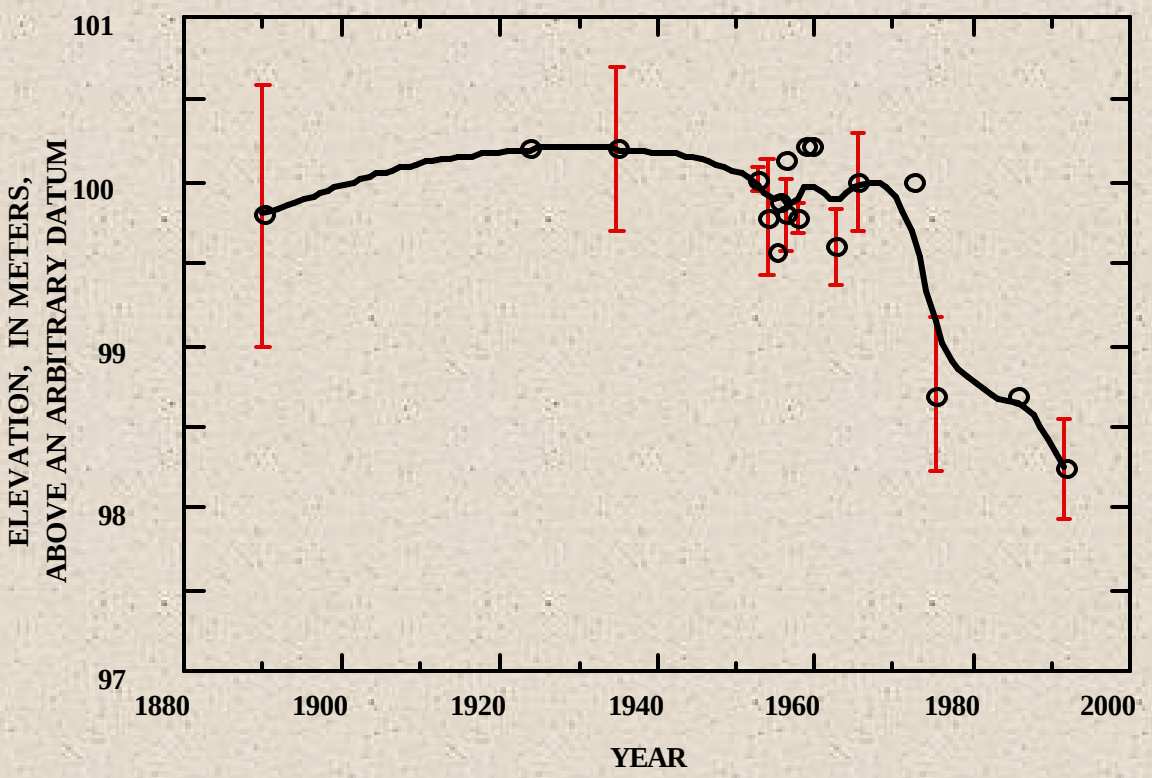

Badger Creek Rapids


Badger Creek Rapids

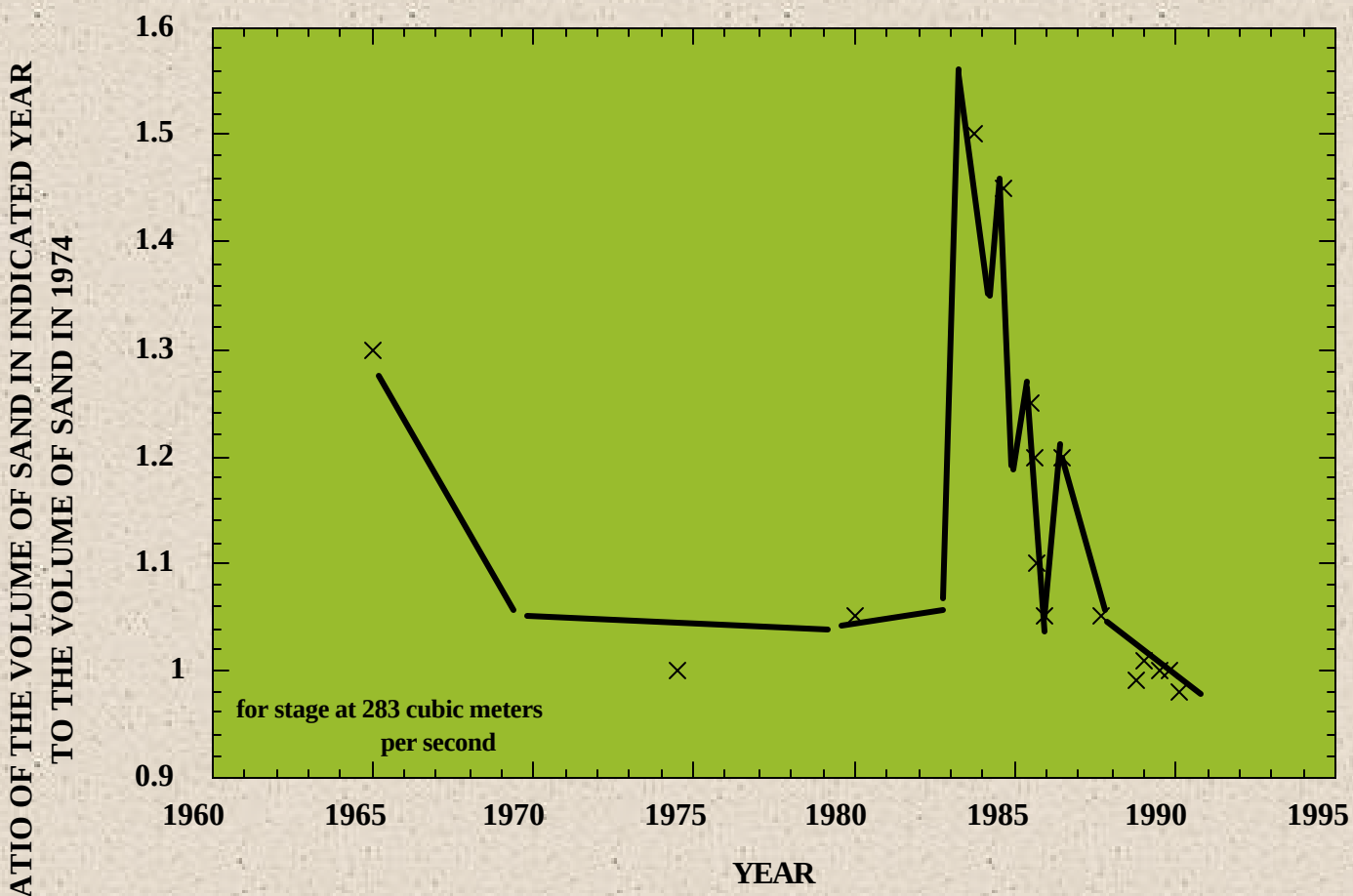
Changes in the Volume of Sand above 25,000 ft^3/s at Jackass Beach



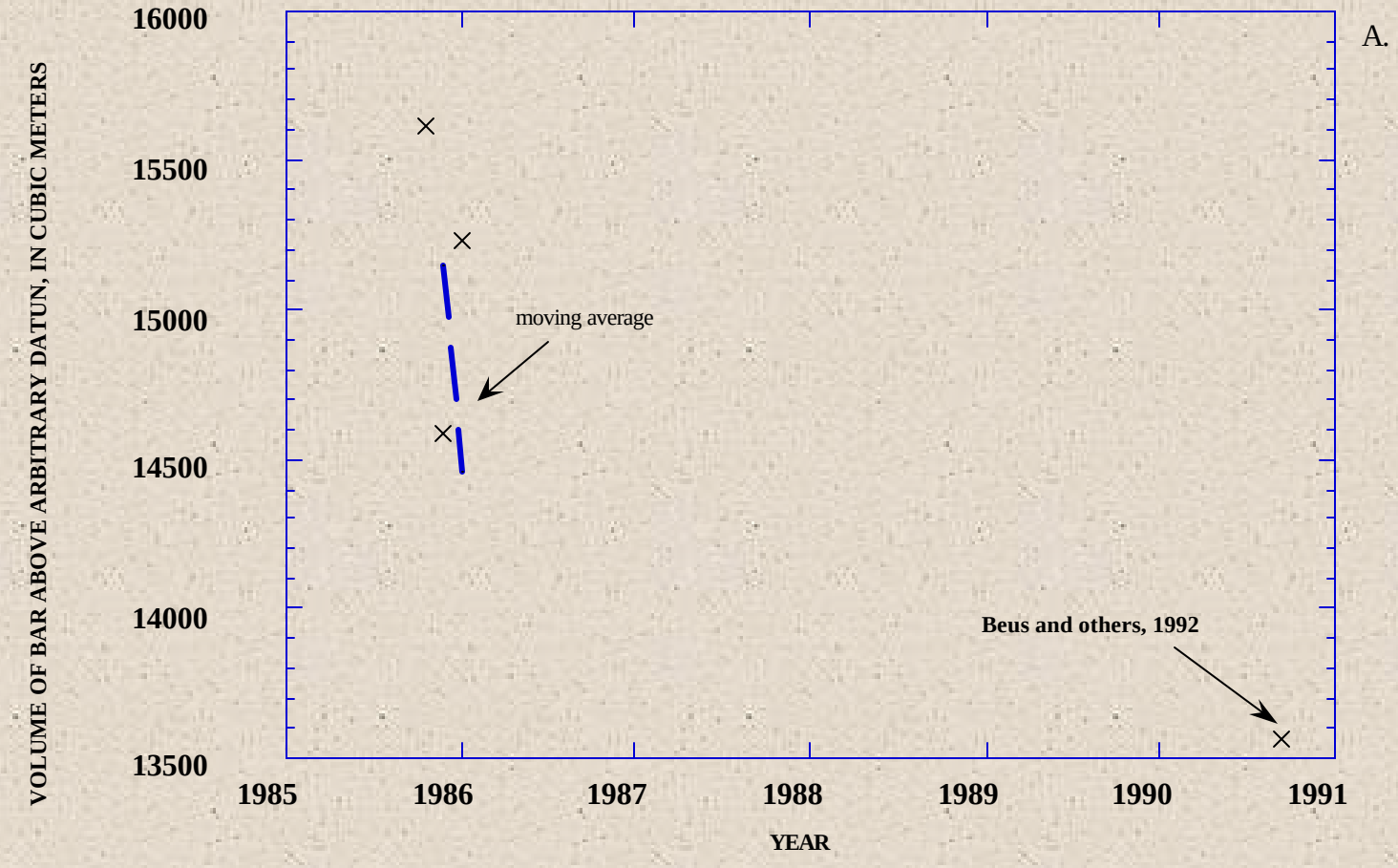
Elevation Changes at Jackass Beach at High Elevation (Turret rock)



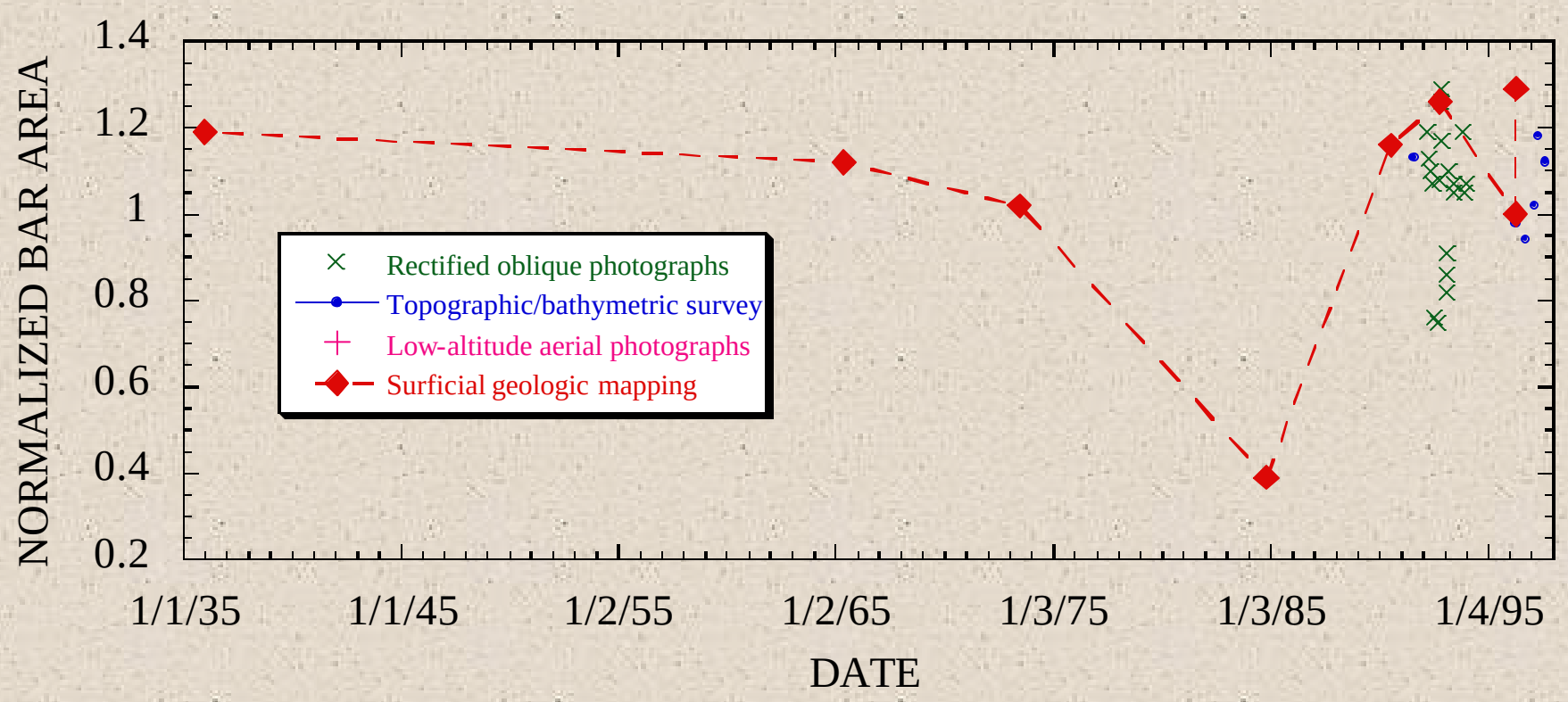
Volume Changes at Grapevine Reattachment Bar

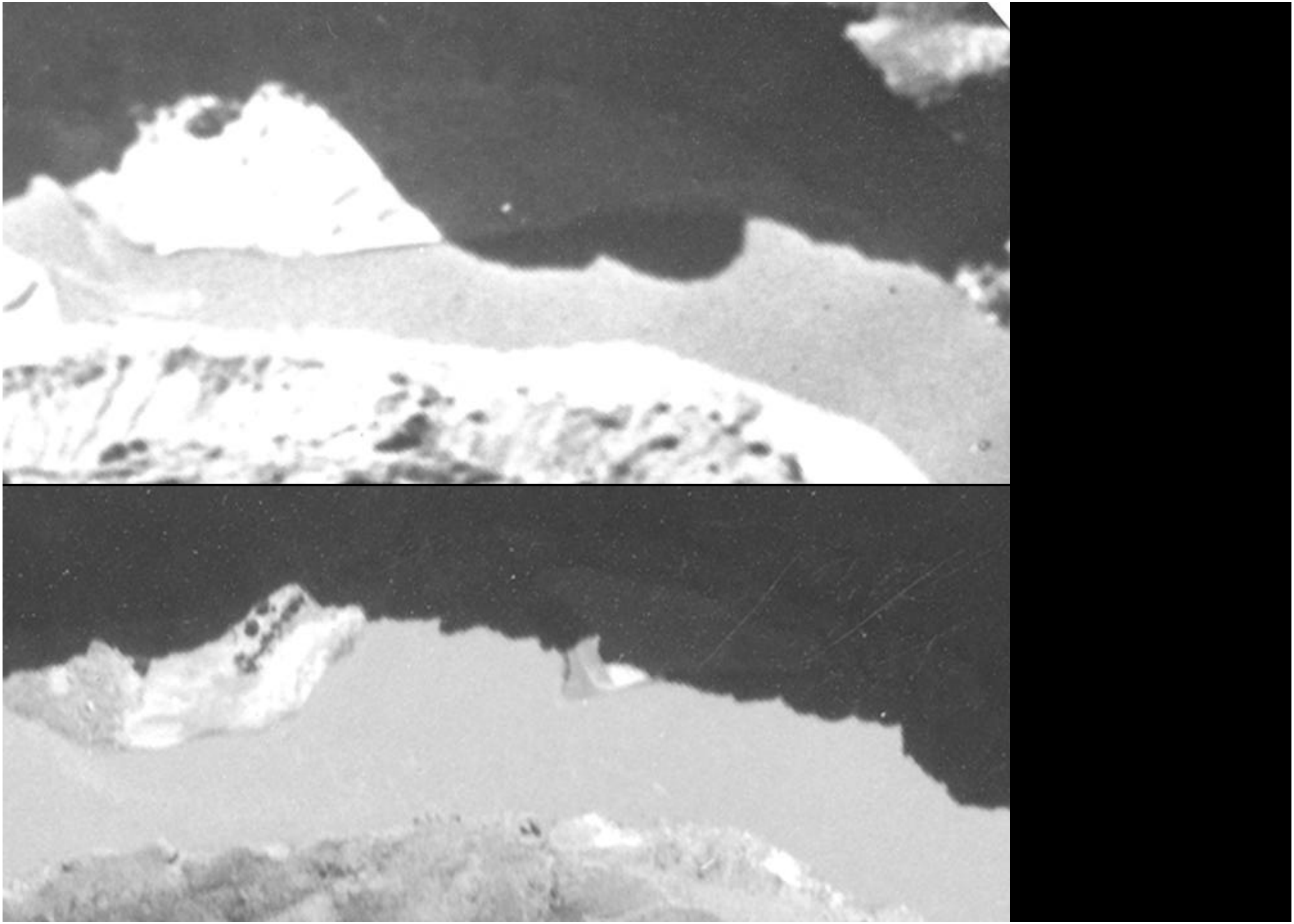


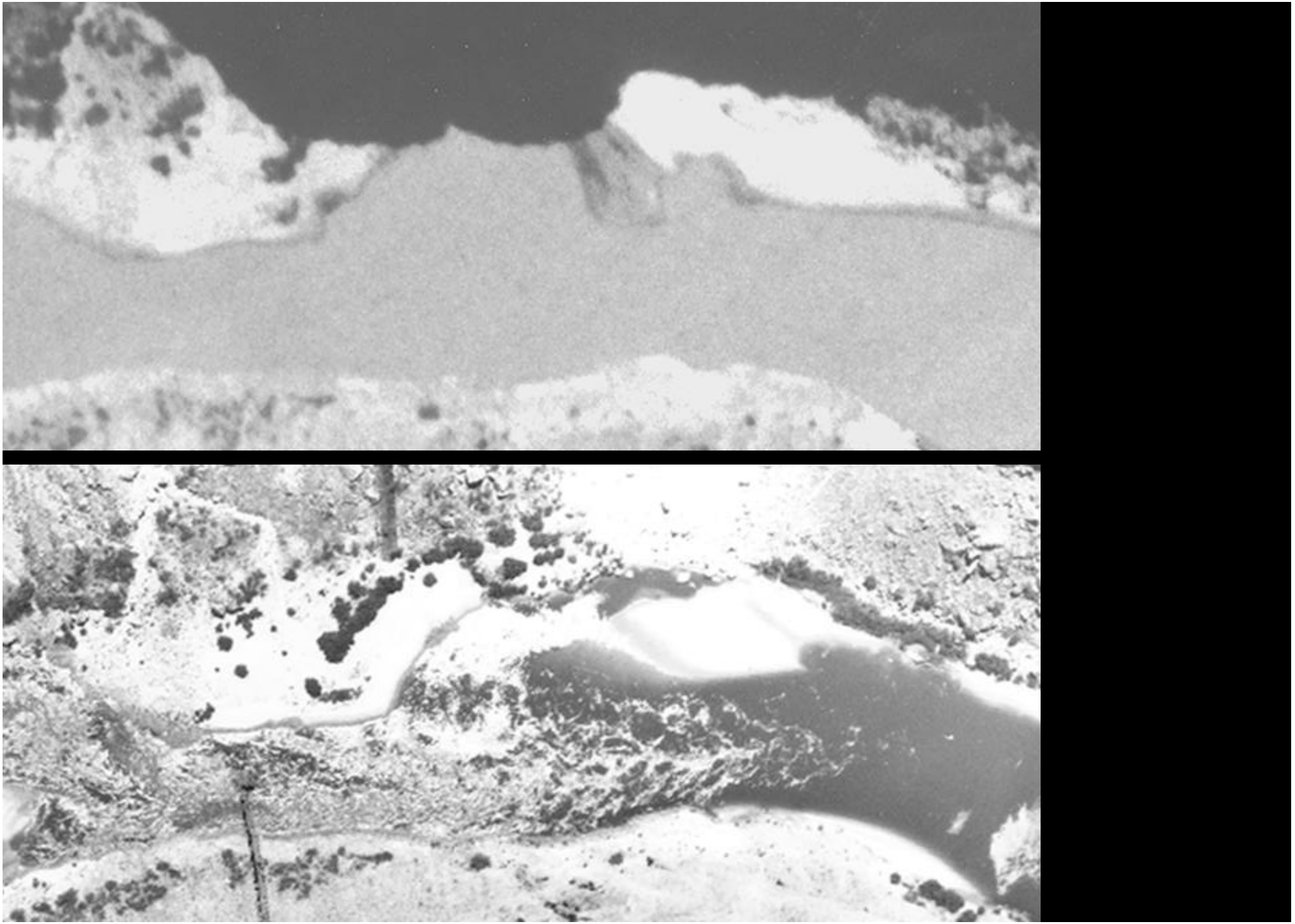
Above Cathedral Rapids



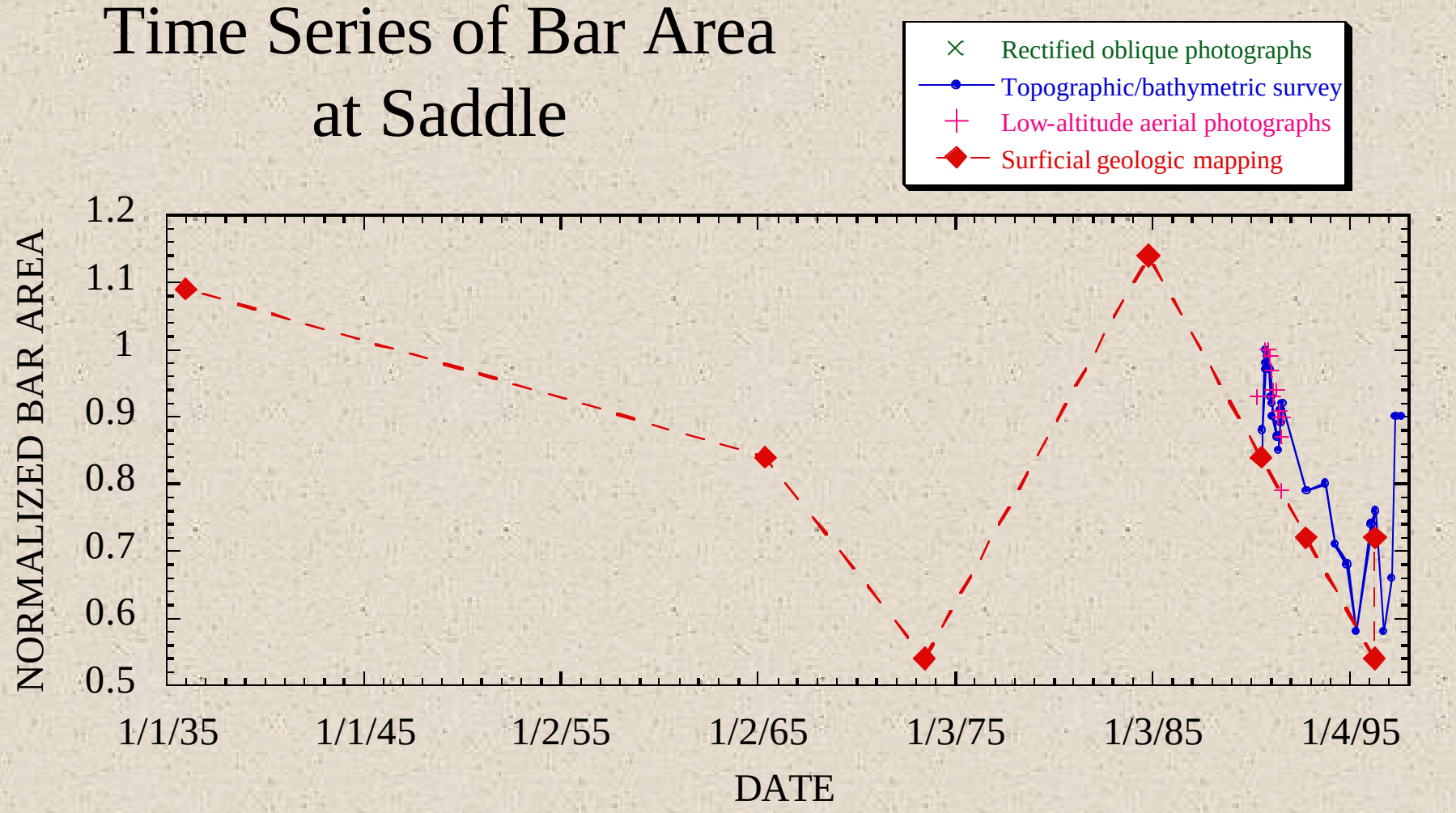
Time Series of Bar Area at Eminence

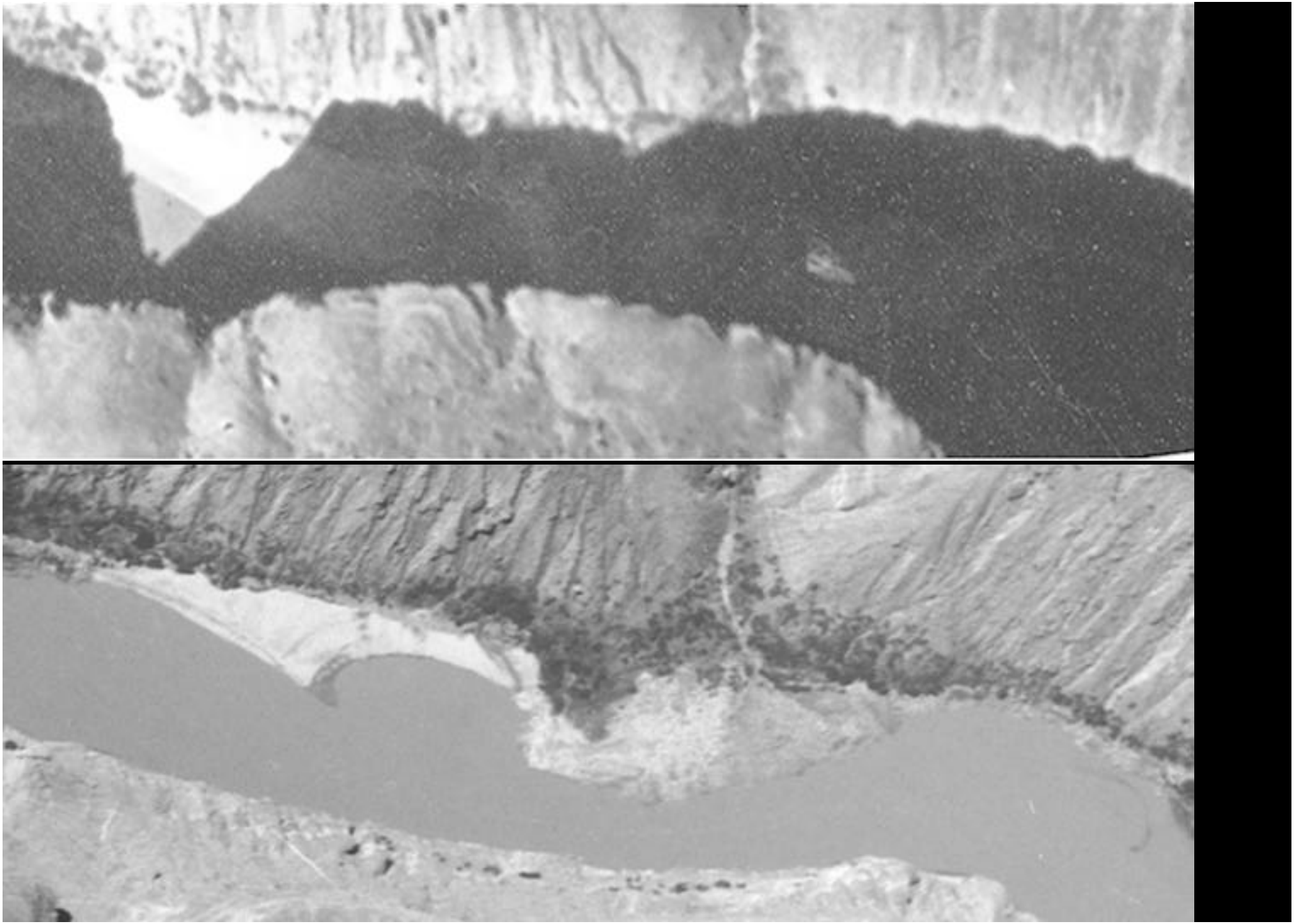


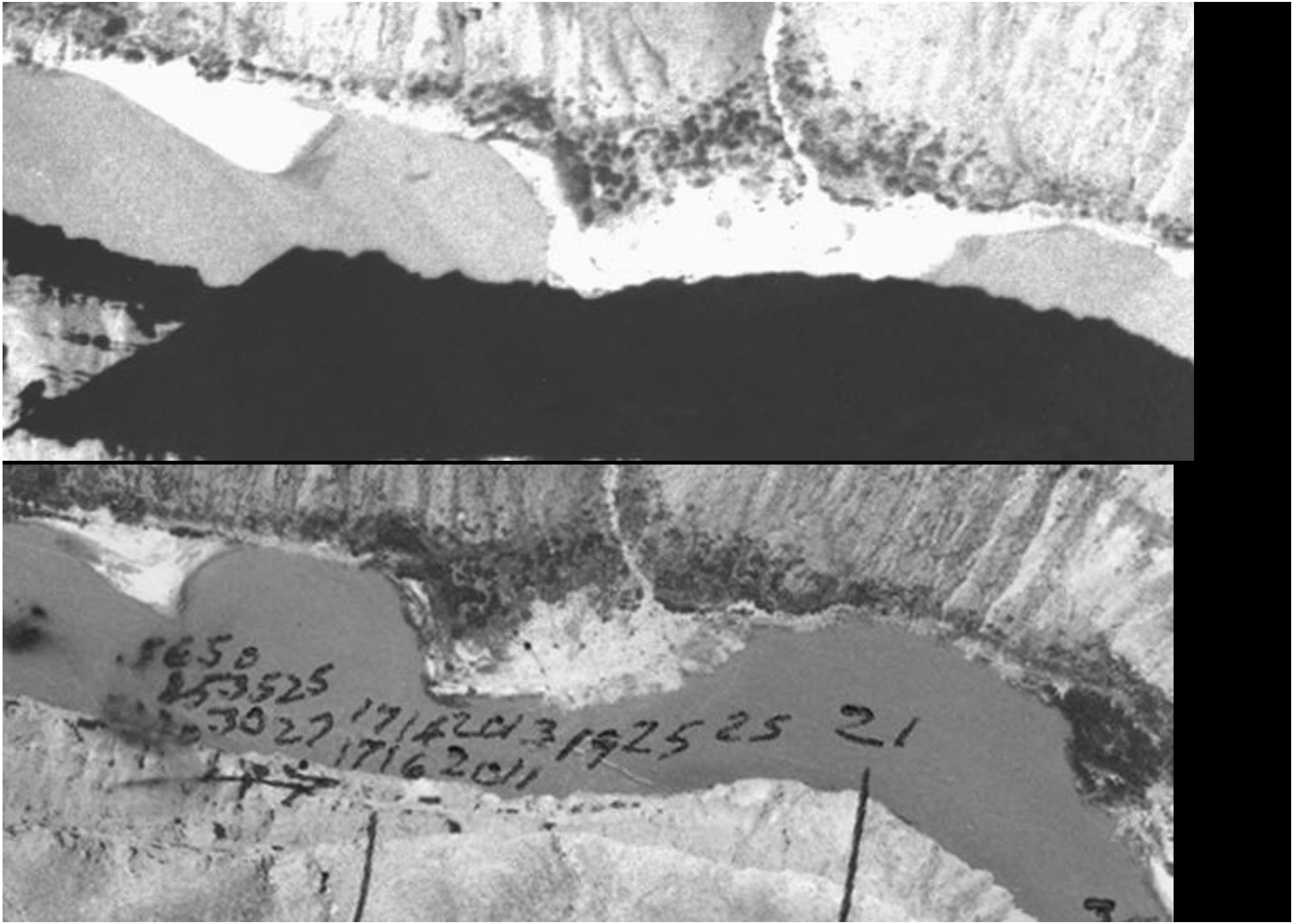


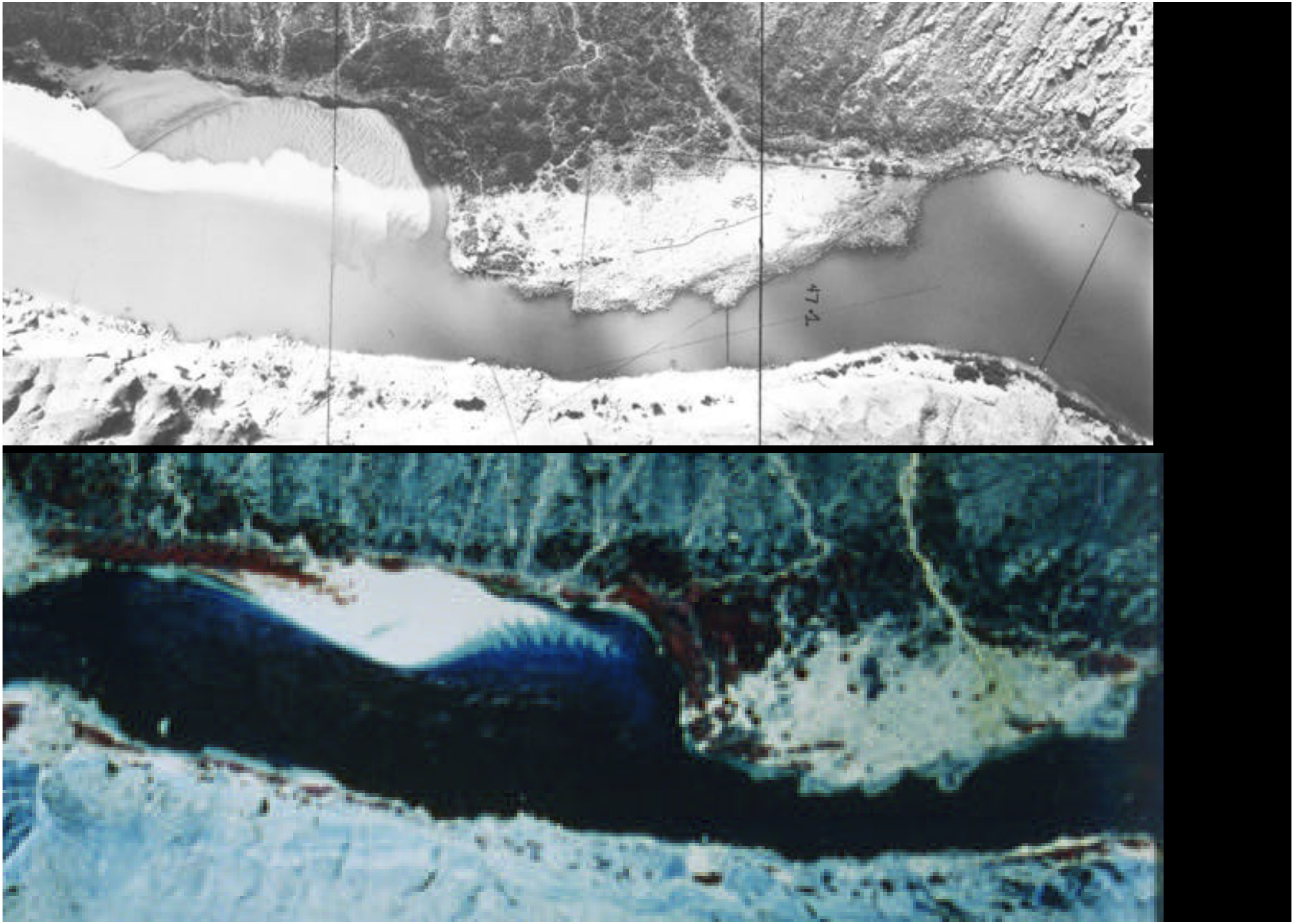


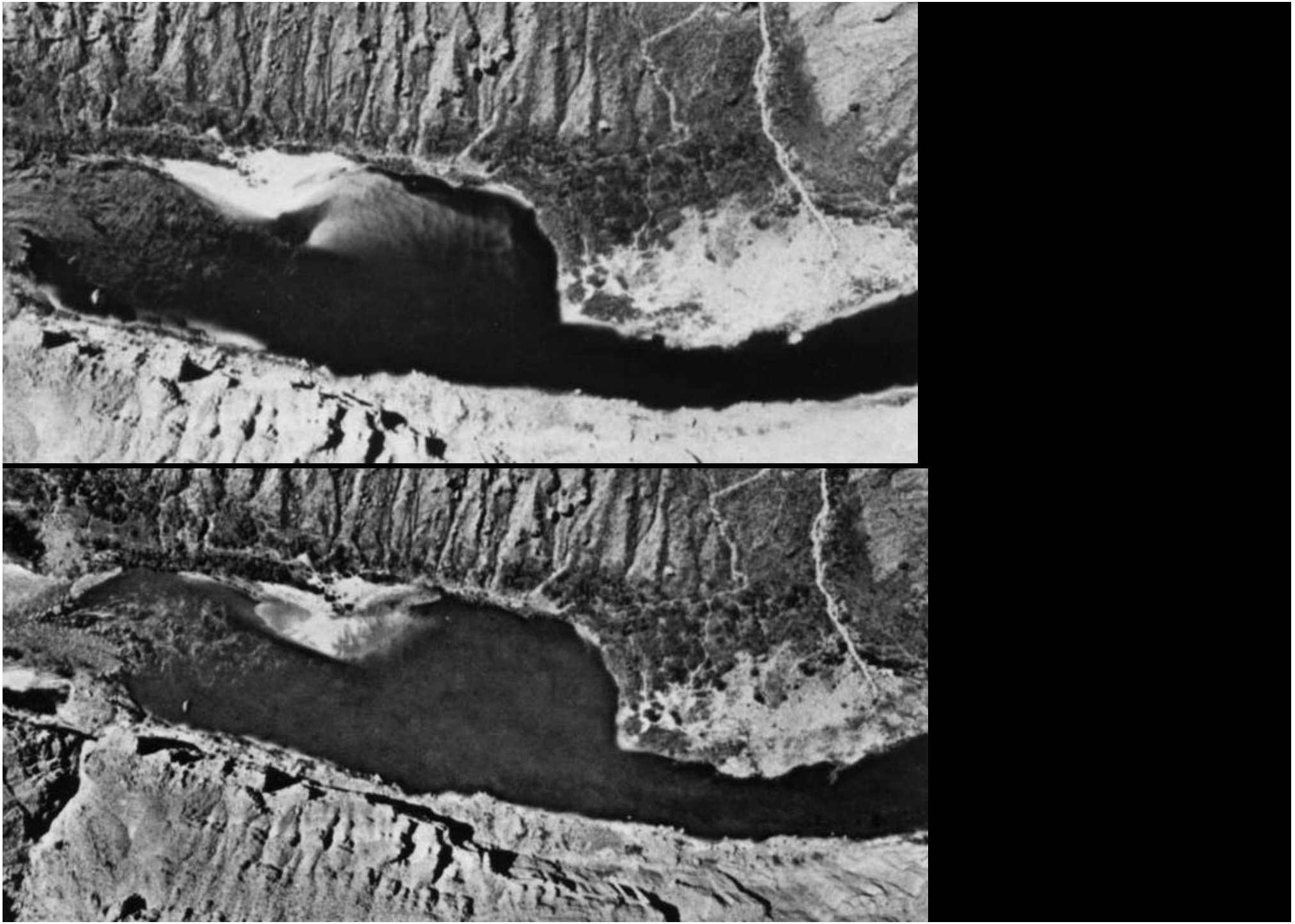
Time Series of Bar Area at Saddle






1650
1716201


47 A



Conclusions

- Large variability at-a-site and site-to-site when considering the entire eddy (very-low, low, and higher deposits)
- Long-term trend of degradation when considering only higher deposits
  - High-flow and flood sand levels were thicker in pre-dam era at Jackass Beach
  - High and mid-elevation sands were thicker in mid-1980's than now at Above Cathedral and Grapevine

Spatially-Robust Data Sets

- Developed from historical aerial photographs
- Photogeologic interpretation and analysis within geographic information systems

Analyses

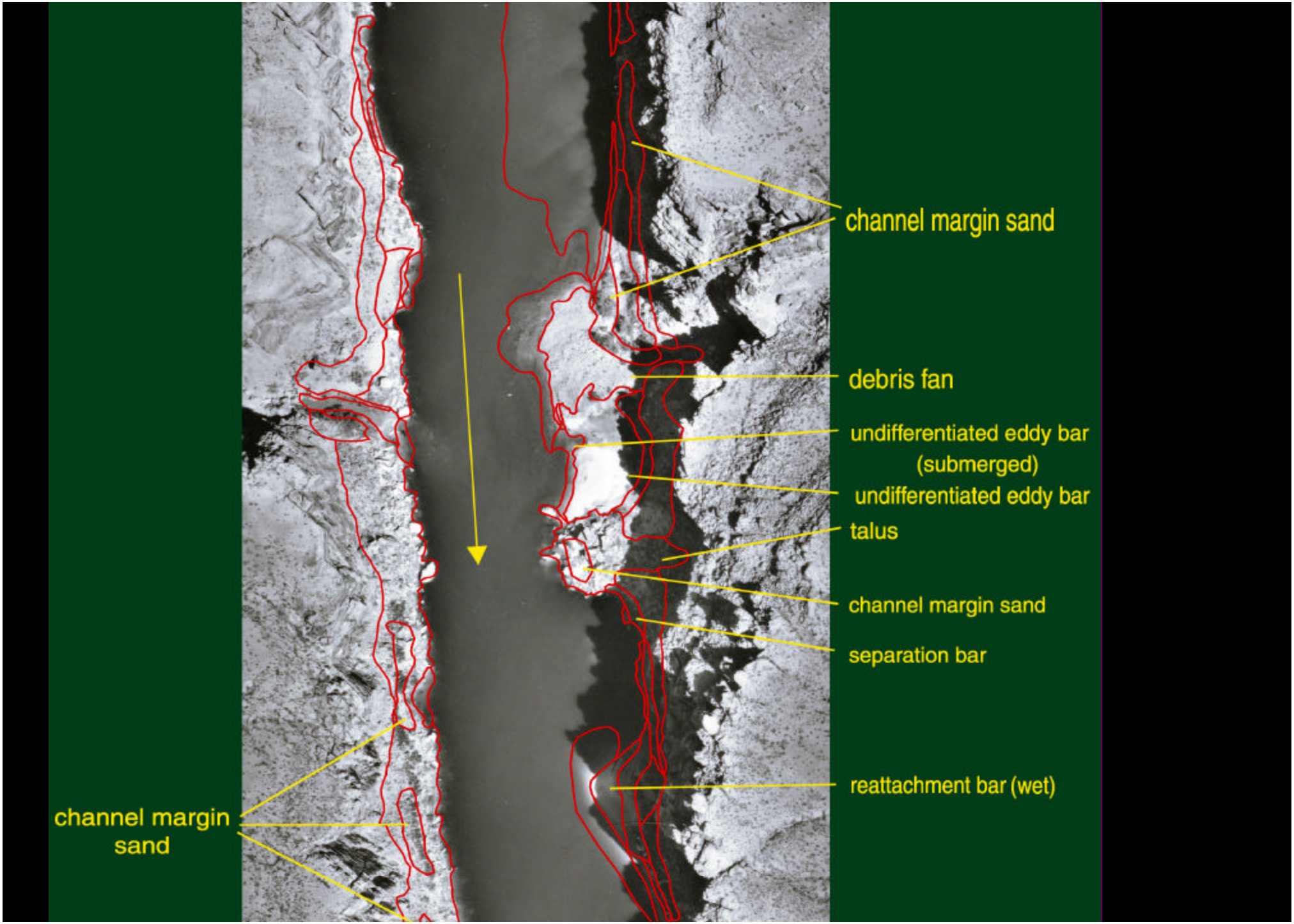
- Long-term trends
- Longitudinal patterns of response to a specific flow event

Aerial Photograph Analysis

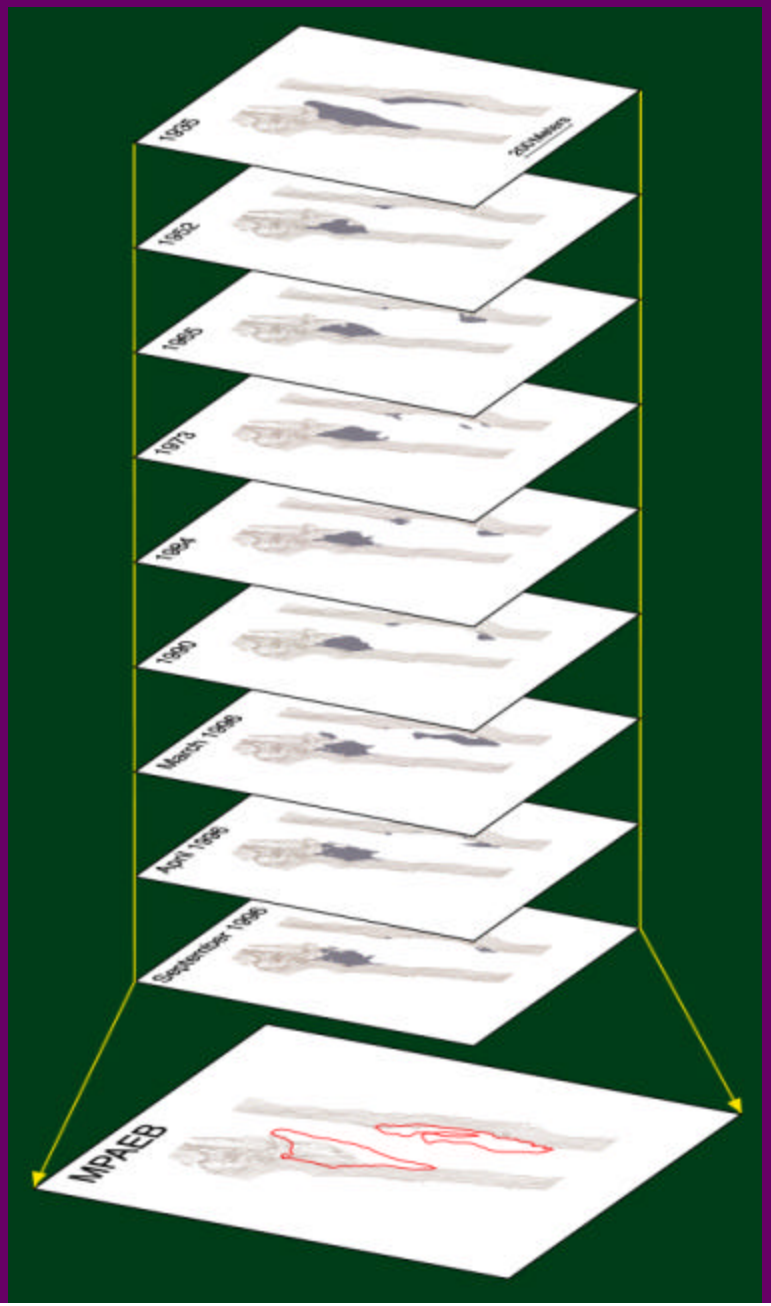
- Define total area where sand bars have been exposed in the past (maximum potential area of eddy bar [MPAEB])
- compute the ratio of area of emergent sand in each year to the MPAEB
- compute the ratio of the area of sand at high-elevation, or low-elevation, to the MPAEB

Aerial Photograph Analysis (cont.)

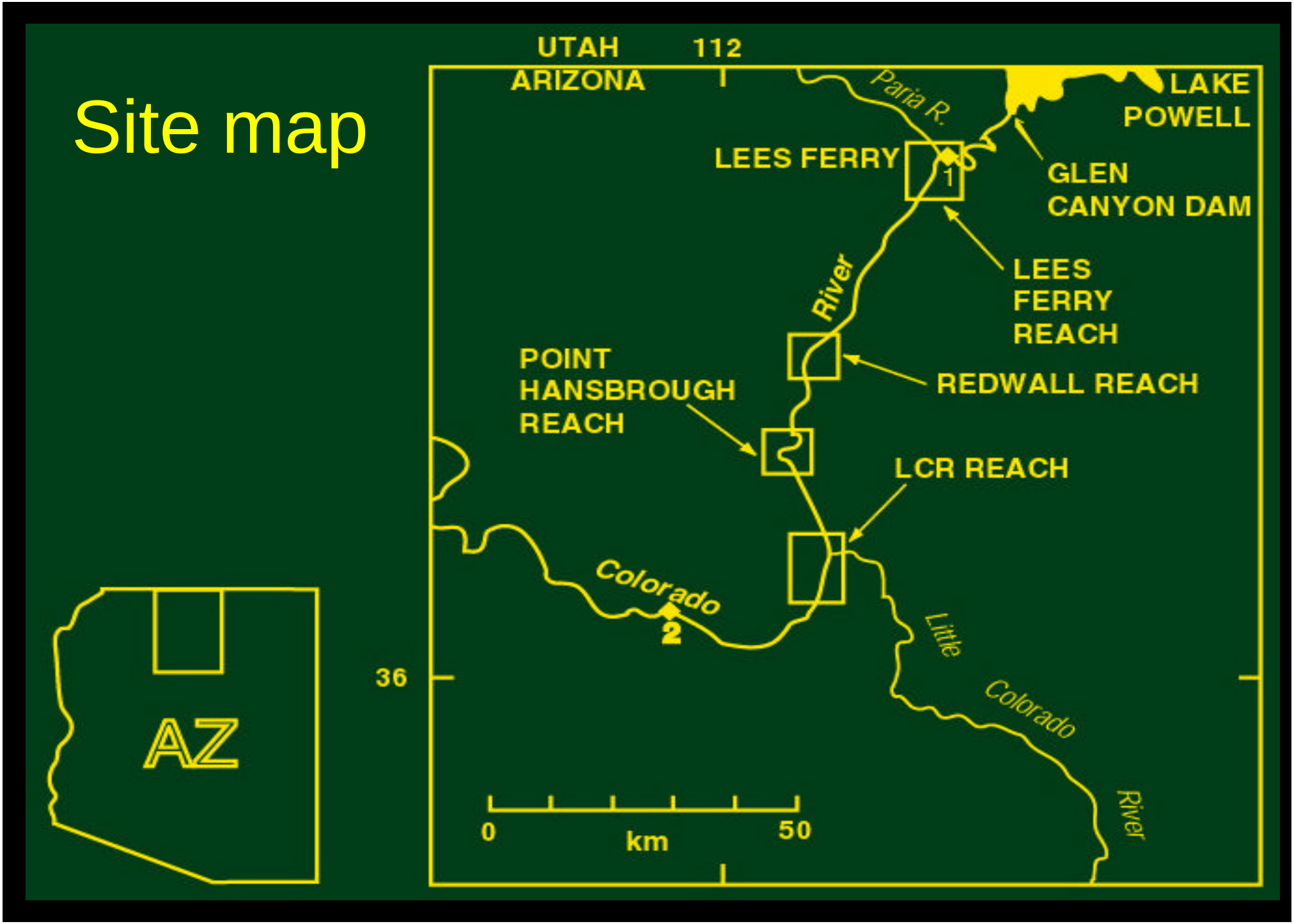
- Compute the proportion the area of significant deposition to the area of significant erosion in each MPAEB


channel margin sand
debris fan
undifferentiated eddy bar (submerged)
undifferentiated eddy bar
talus
channel margin sand
separation bar
reattachment bar (wet)
channel margin sand

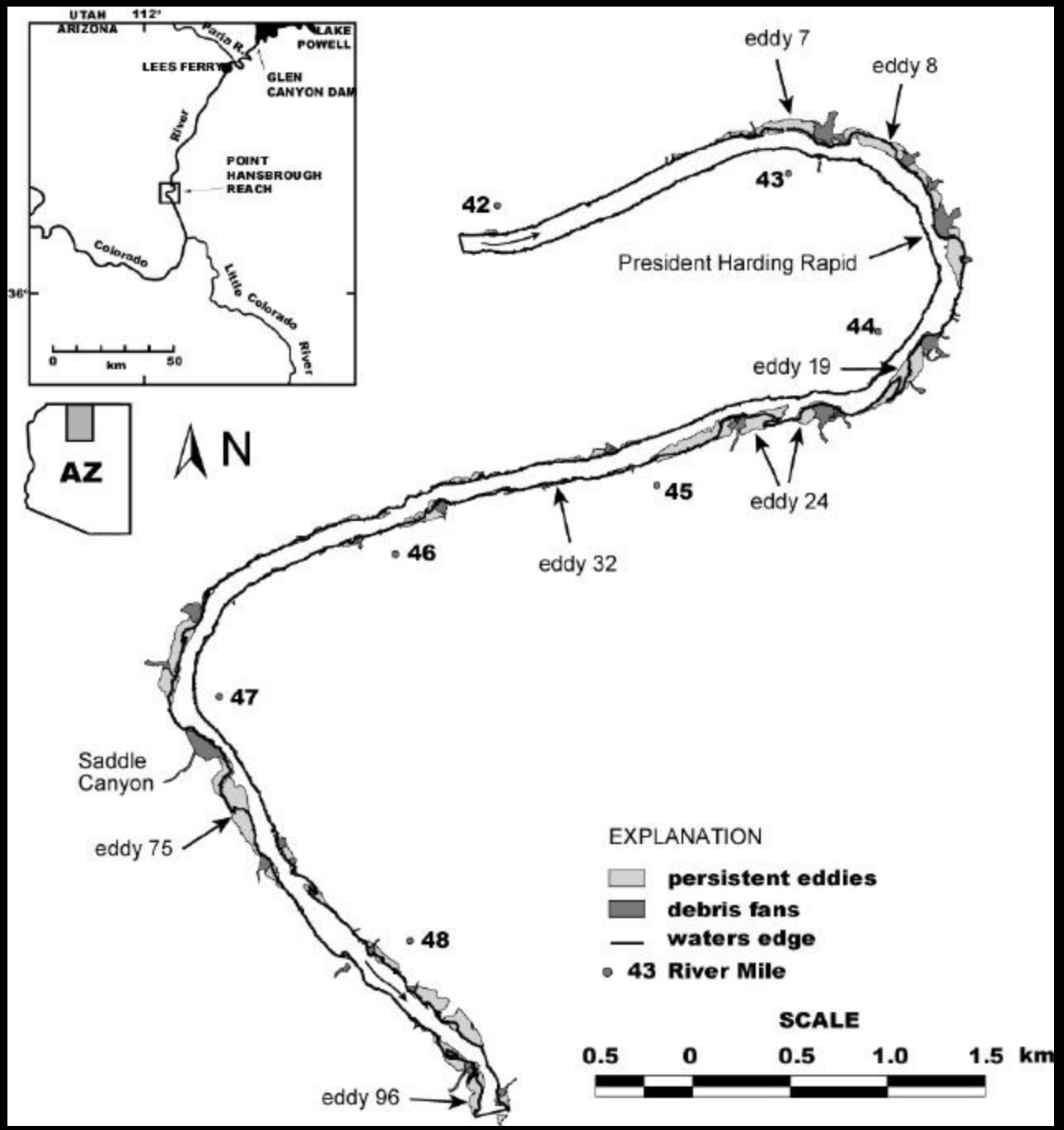
Maximum potential area of eddy bar (MPAEB)



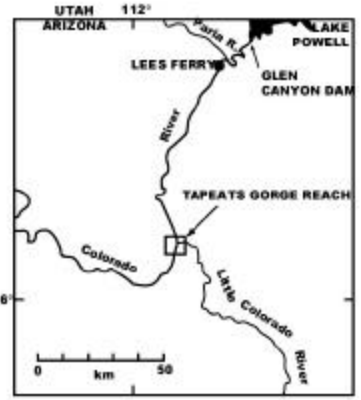
Site map

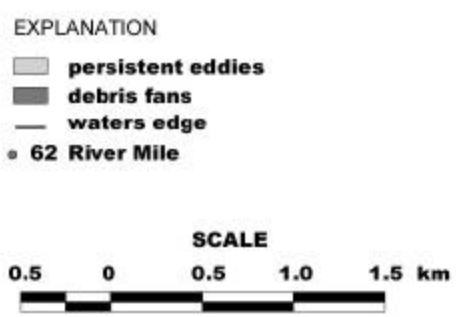

UTAH
ARIZONA
112
Paria R.
LAKE
POWELL
LEES FERRY
1
GLEN
CANYON DAM
River
LEES
FERRY
REACH
POINT
HANSBROUGH
REACH
REDWALL REACH
LCR REACH
Colorado
2
Little
Colorado
River
36
AZ
0
km
50

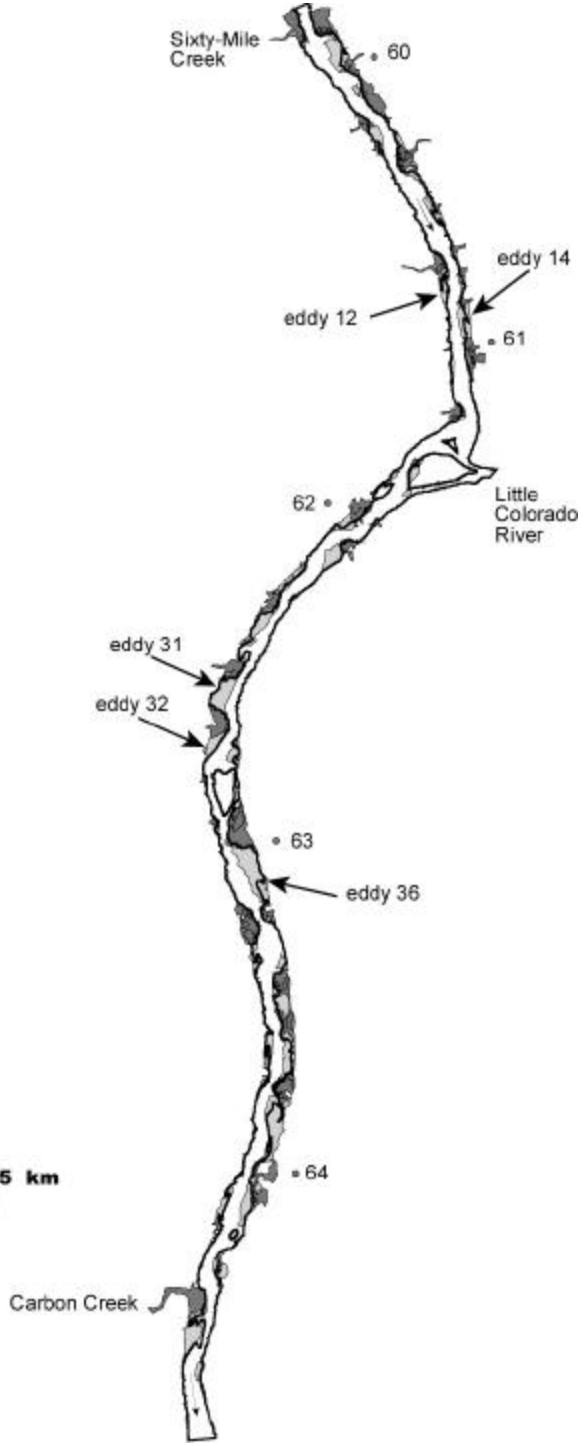
Point Hansbrough Reach

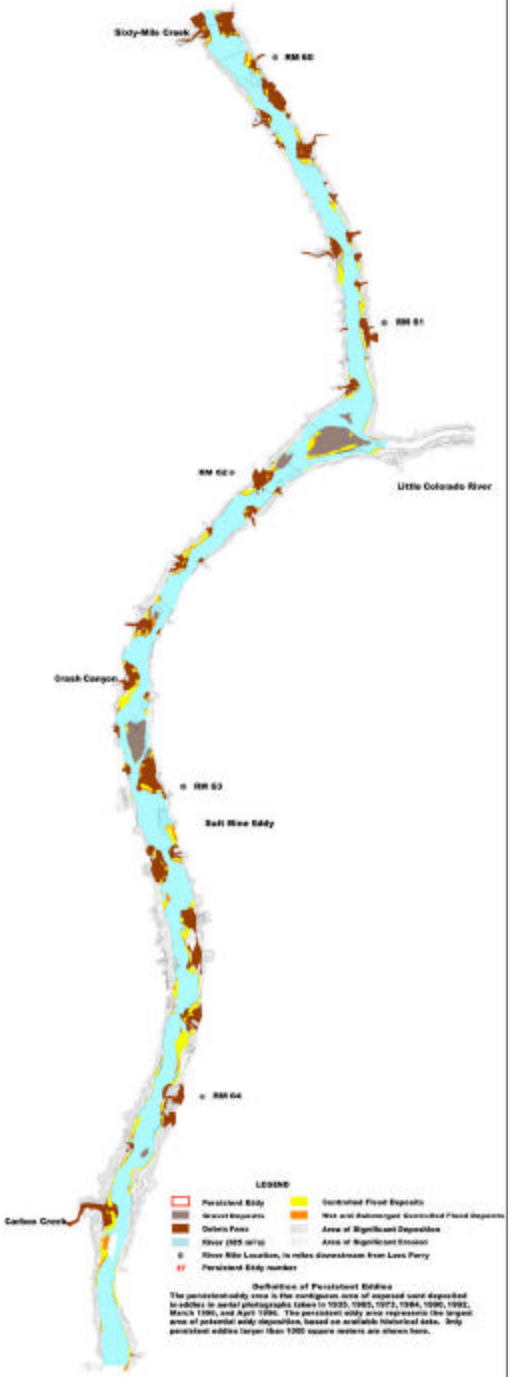


Tapeats Gorge Reach

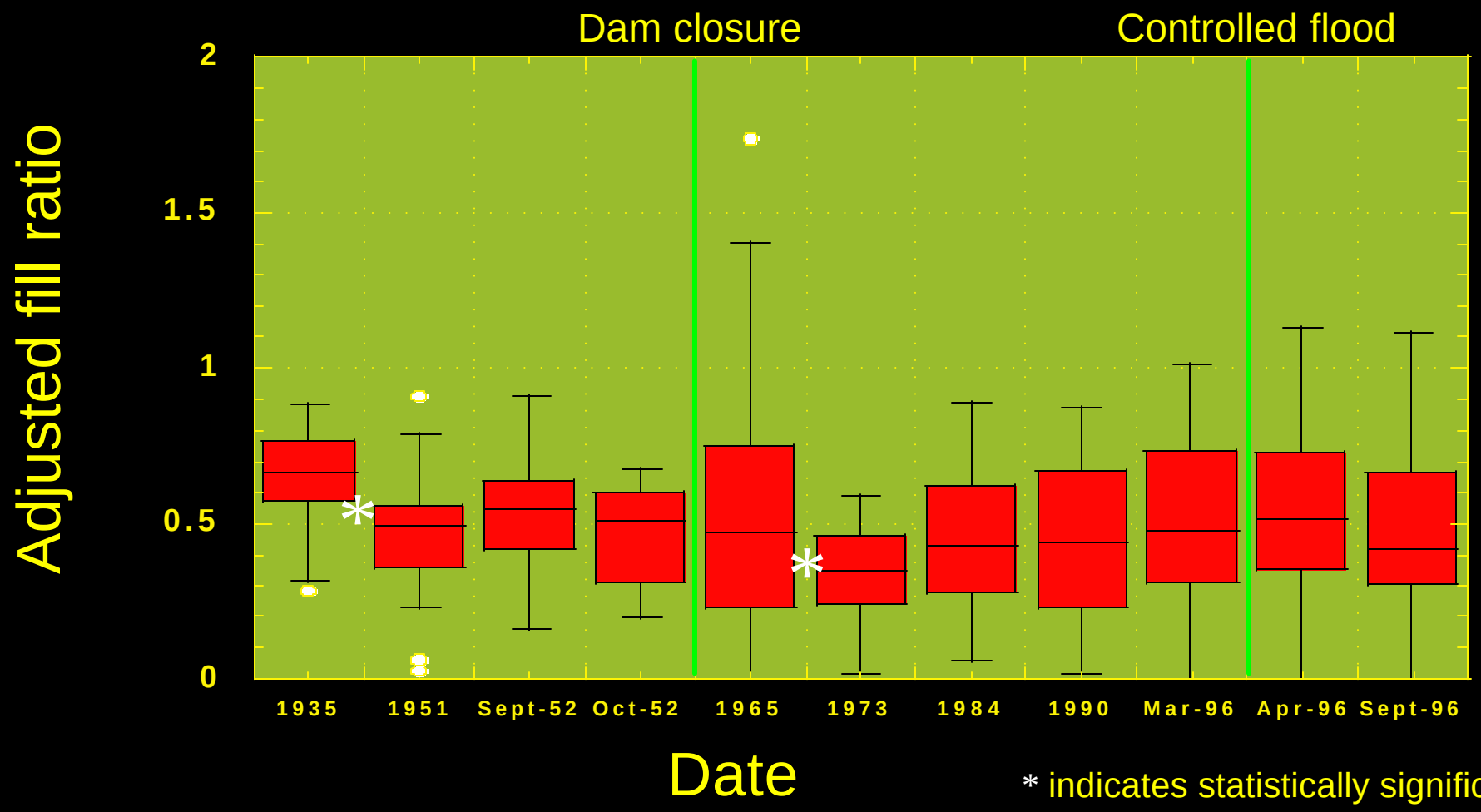






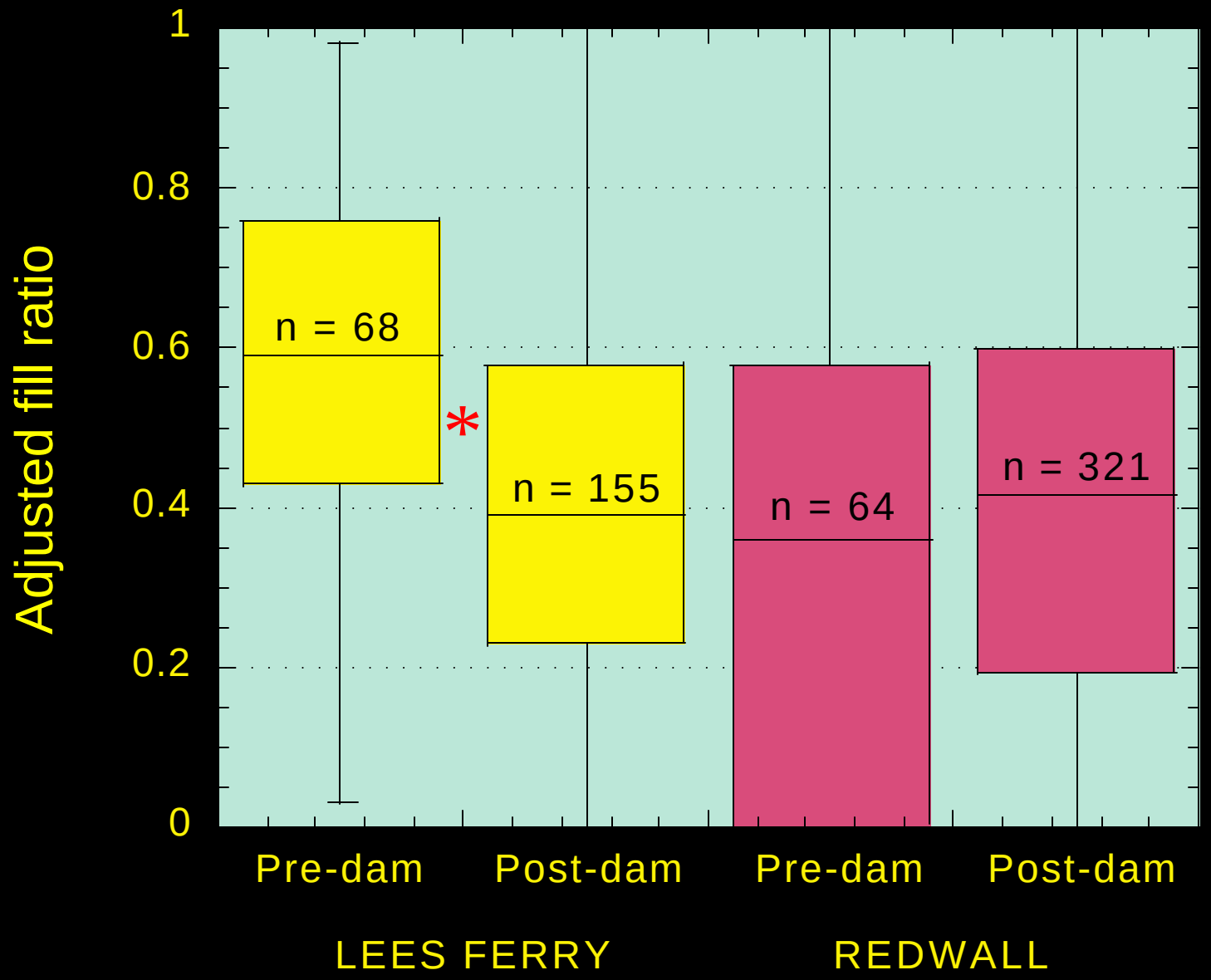


Sand bars in Lees Ferry reach through time

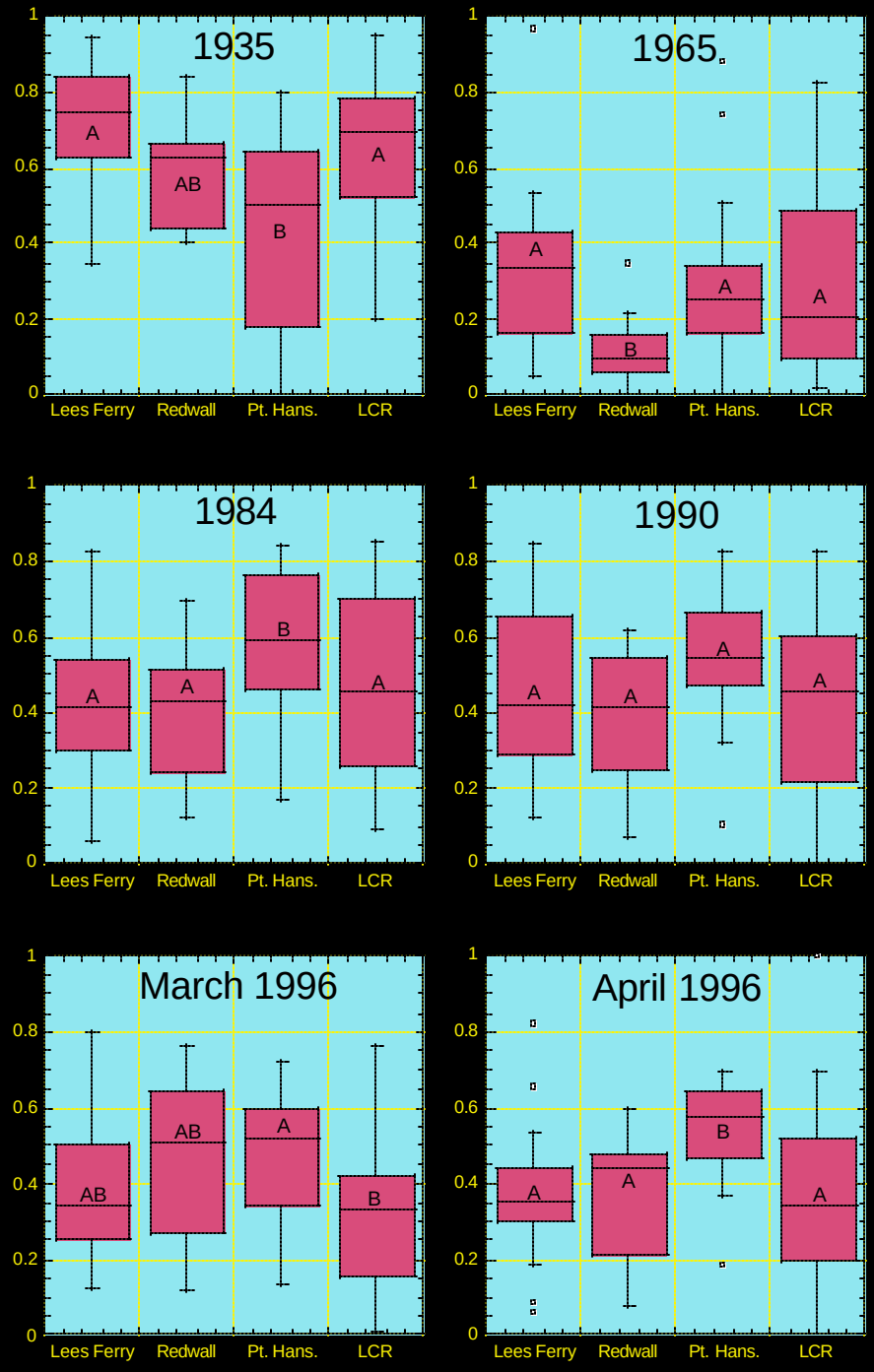


* indicates statistically significant differences between data sets.

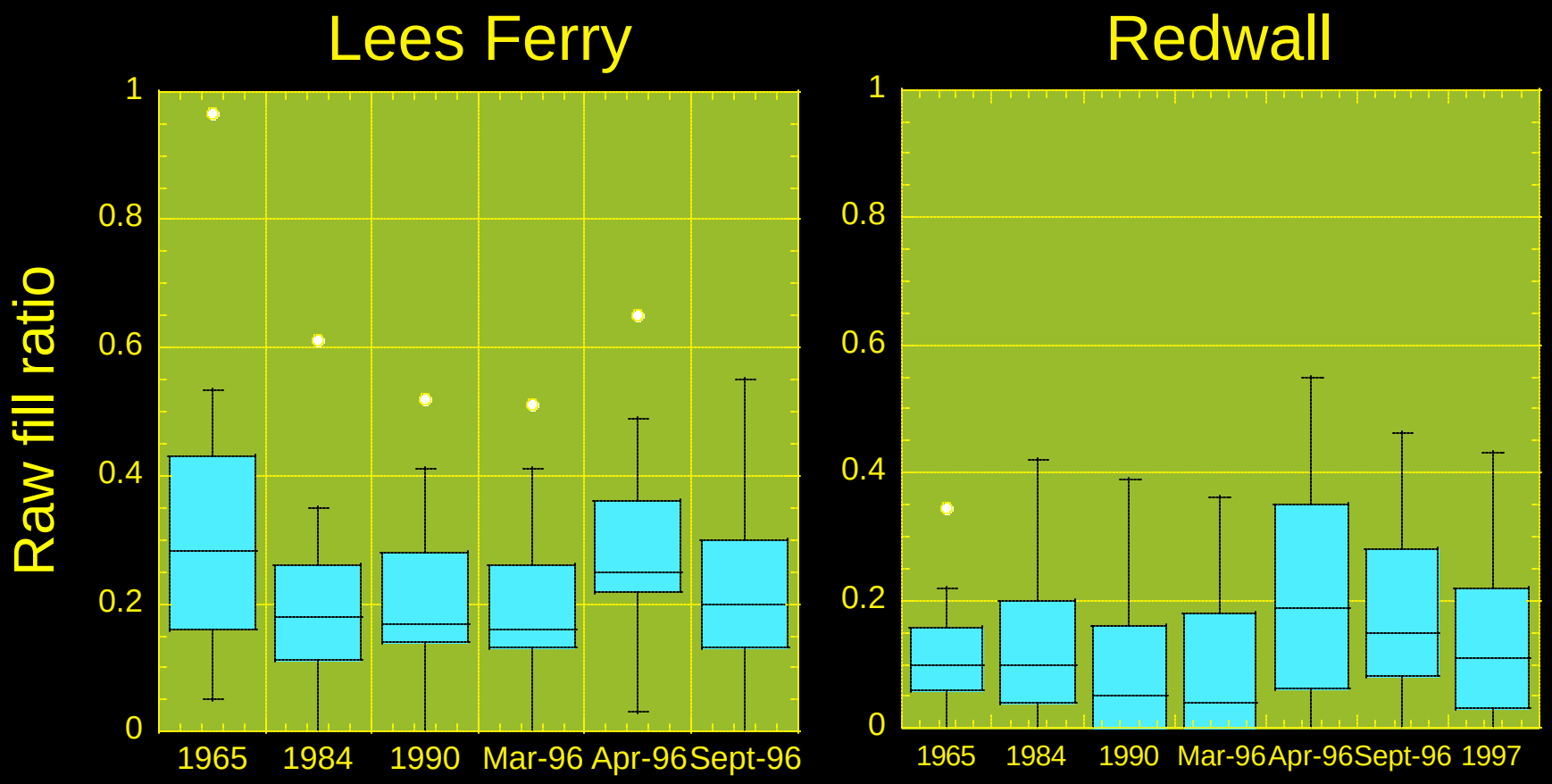
otal fill ratios for all pre-dam and all post-dam era data



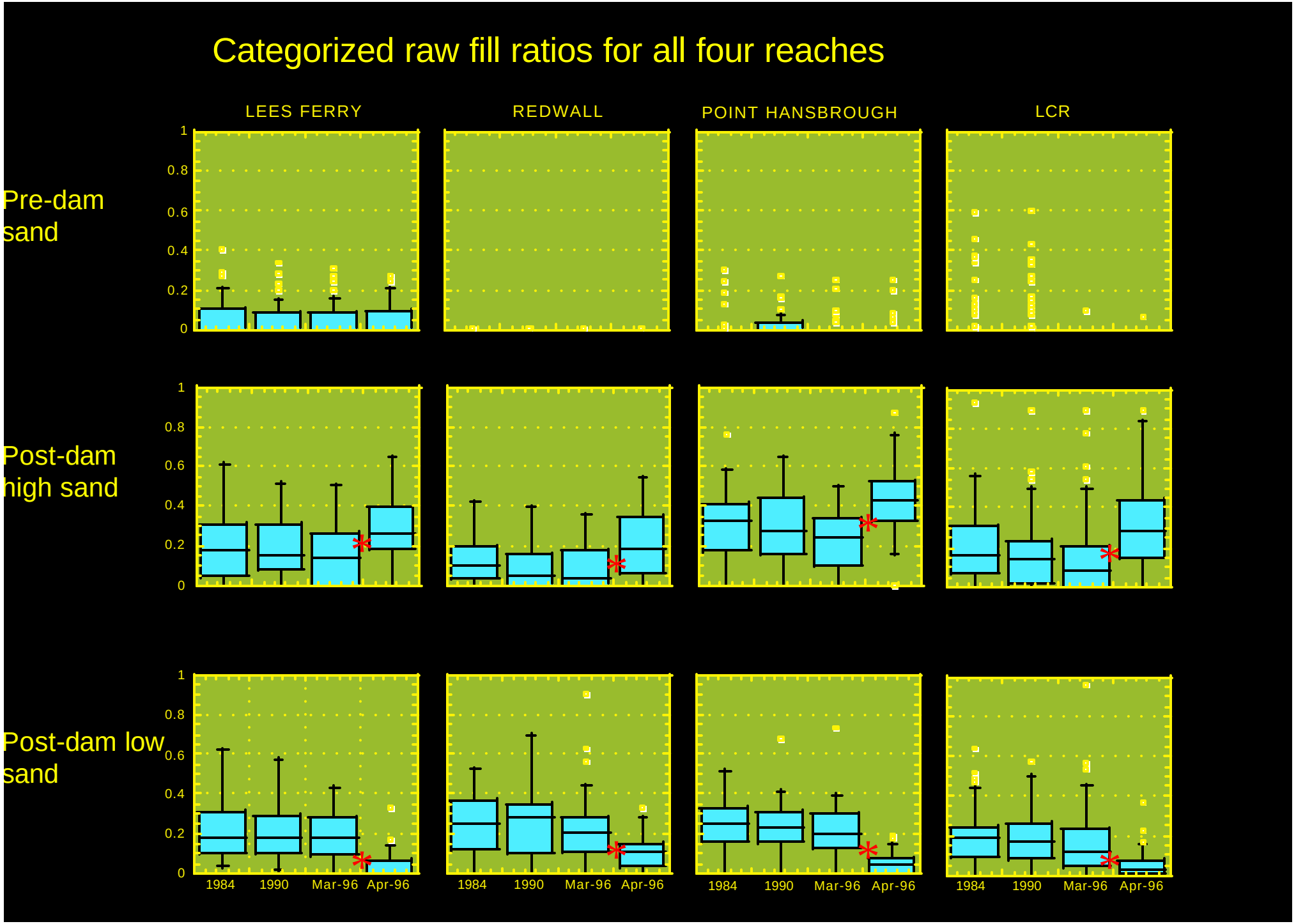
Corrected total fill ratios for all reaches 1935-1996



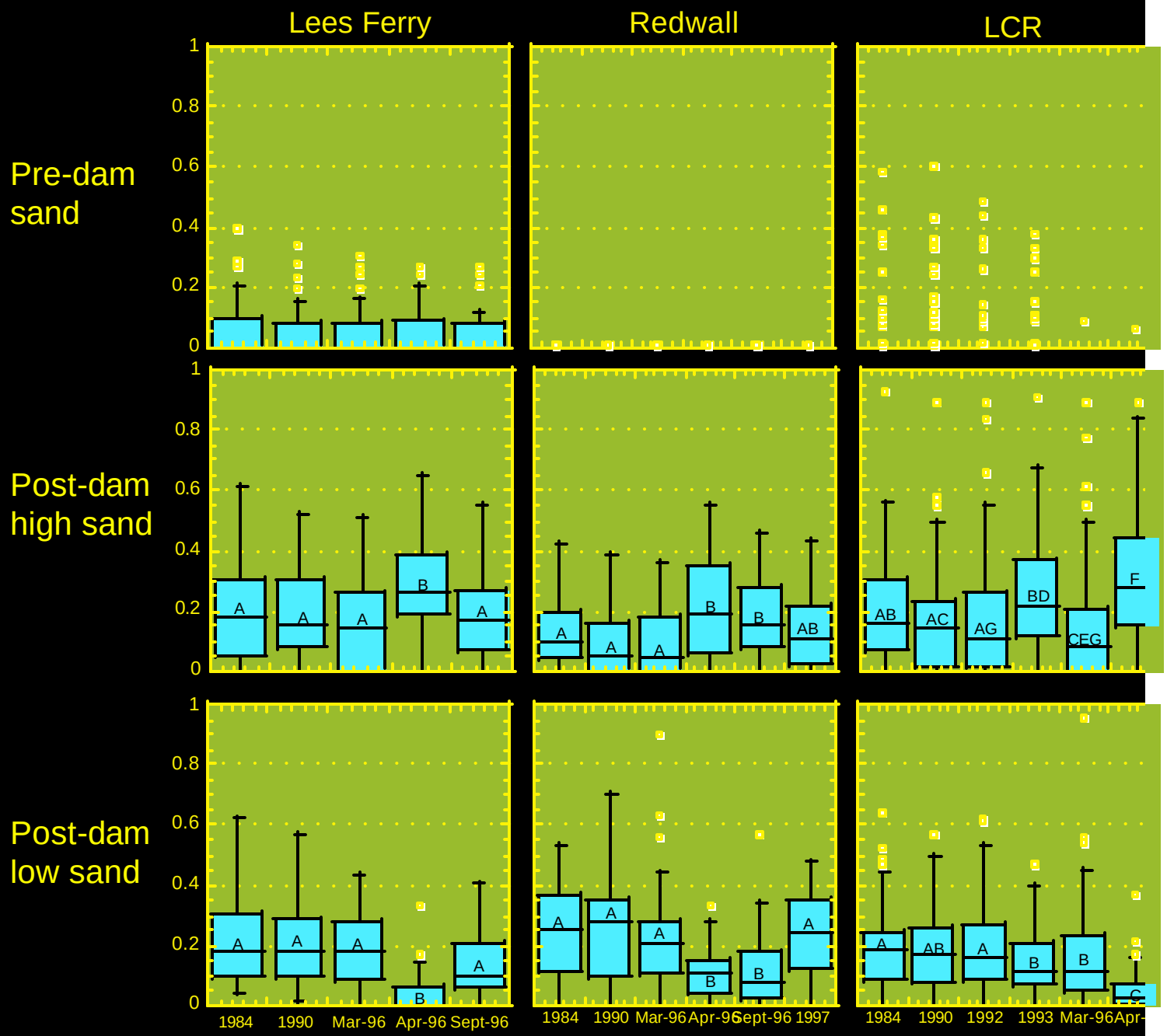
Fill ratios of post-dam flood deposits in the Lees Ferry and Redwall reaches between 1965 and September 1996, for MPAEBs larger than 5000 m^2



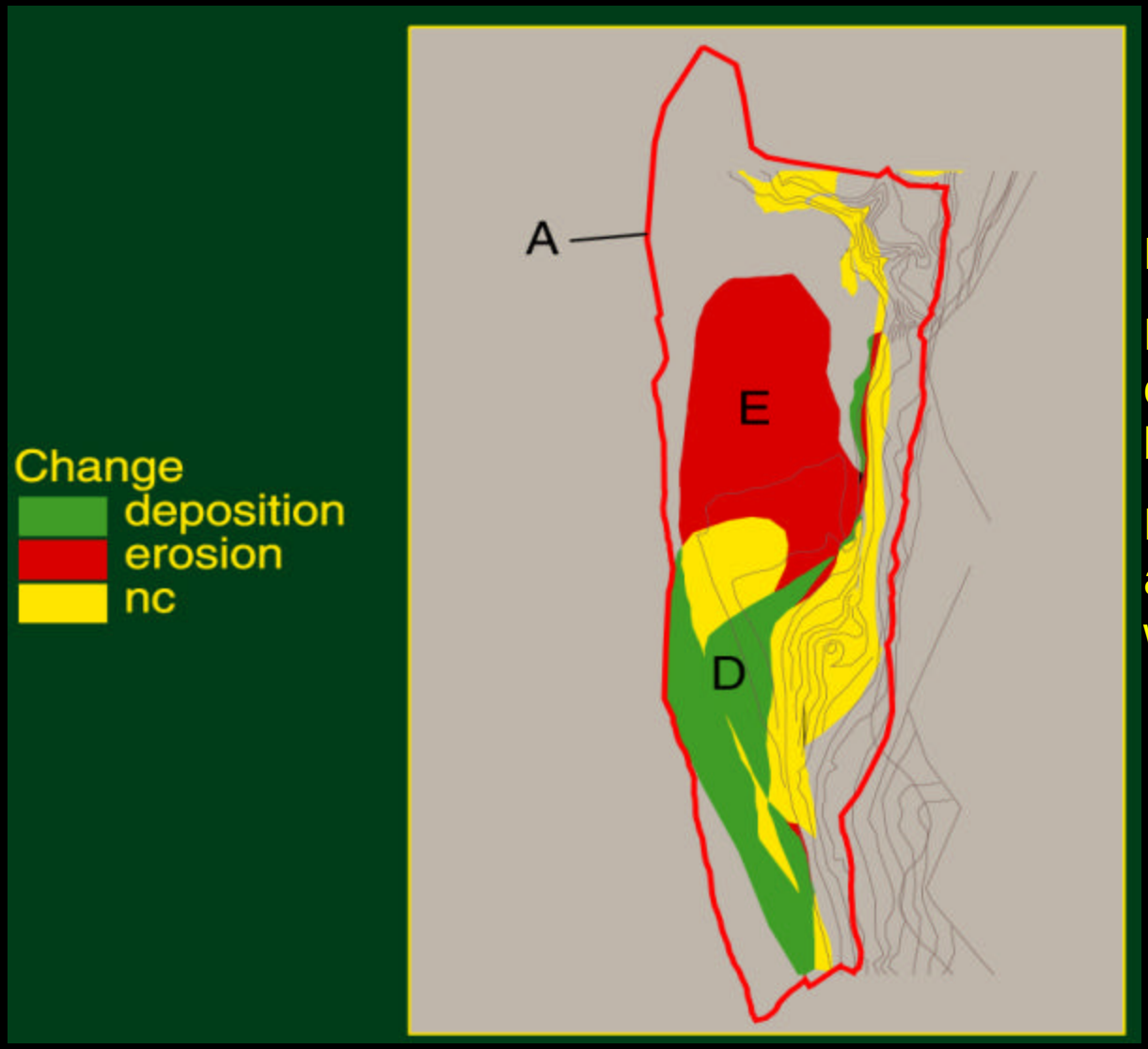
Categorized raw fill ratios for all four reaches



Categorized raw fill ratios for Lees Ferry, Redwall, and LCR reaches, for all available data between 1984 and 1997



Net normalized aggradation (NNA) is calculated by comparing the total area of deposition to the total area of erosion in each MPAEB

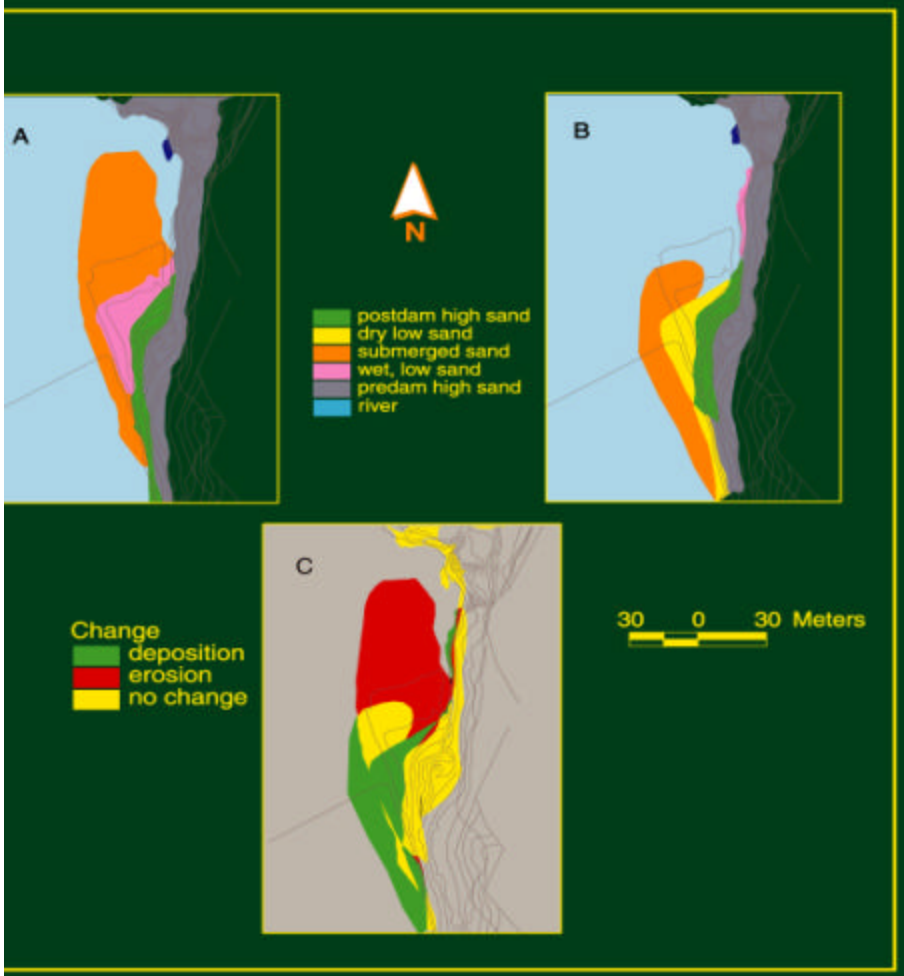


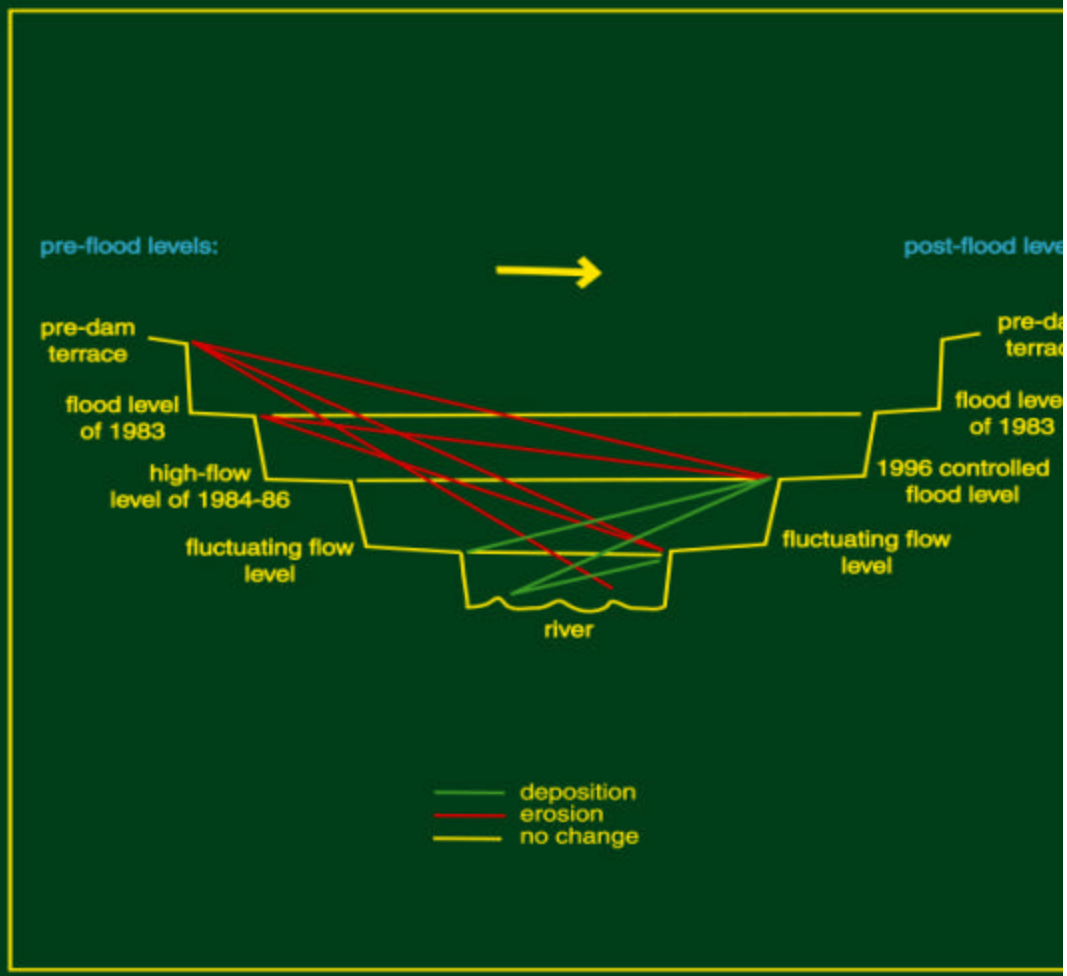
NNA = (D – E) / A

Positive value indicates greater area of deposition than erosion within the boundary of the MPAEB

Negative value indicates greater area of erosion than deposition within this boundary

Automated generation of areas of erosion and deposition is based on changes in topography

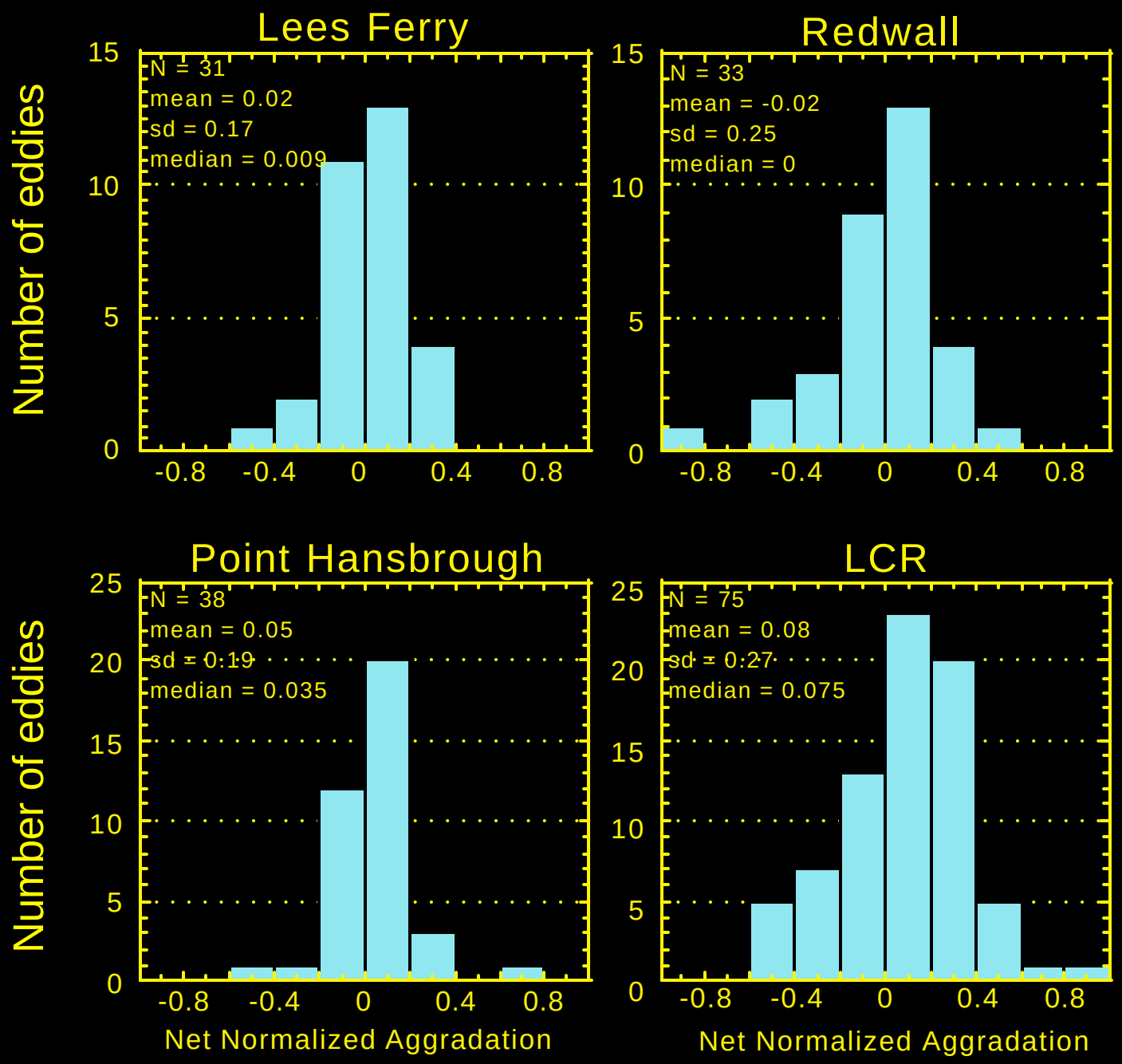




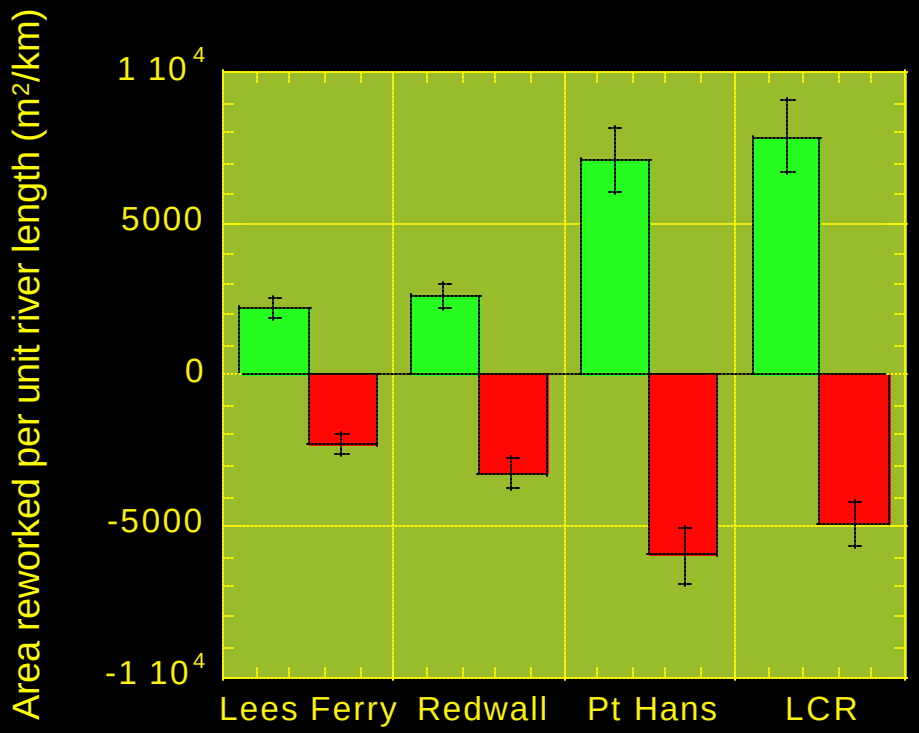
Error matrix comparing GIS data to ground surveys for all reaches

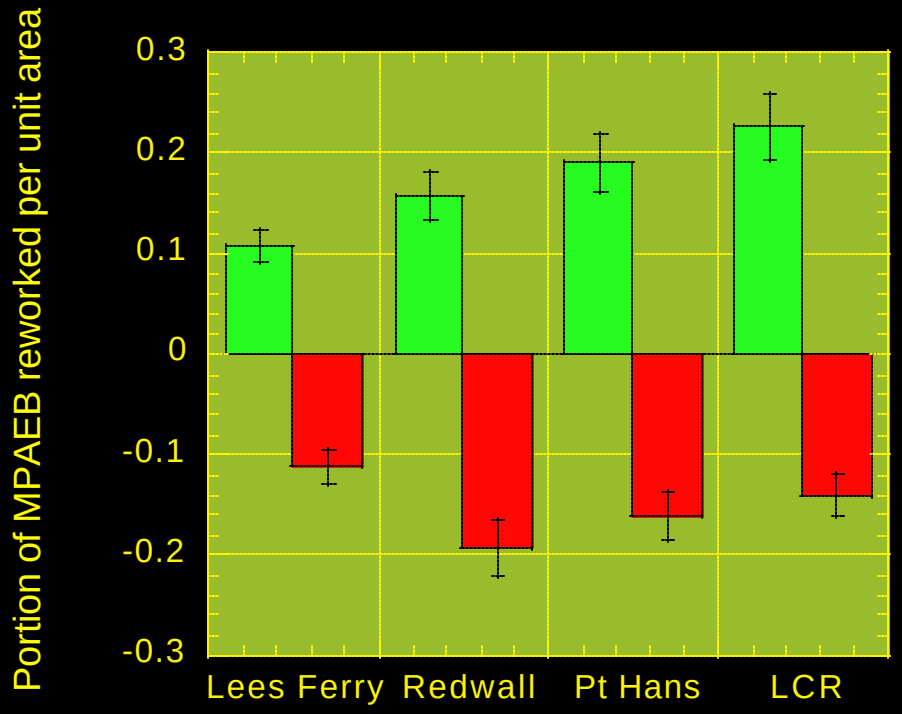
	Complete agreement	Unclear or indistinguishable	Complete disagreement
Lees Ferry (2 sites)	72.0%	25.6%	2.4%
Redwall (2 sites)	57.2%	39.3%	3.6%
Point Hansbrough (3 sites)	70.9%	24.3%	4.8%
Tapeats Gorge (1 sites)	52.7%	44.3%	2.9%
Big Bend (2 sites)	56.7%	33.9%	9.3%
All Sites (10 sites)	**65.8%**	**28.9%**	**5.4%**

Net Normalized Aggradation for all reaches



Reworking of eddies in all reaches as a result of the 1996 controlled flood





Conclusions: Temporal Variability

- The total area of sand above base flow has been highly variable and it is difficult to detect changes between the pre-dam and post-dam eras
- The total area of sand above the normal range of powerplant operations has not changed significantly since 1965 in upper Marble Canyon, despite field measurements of vertical degradation of some of these deposits

Conclusions: longitudinal variation during discrete flow events

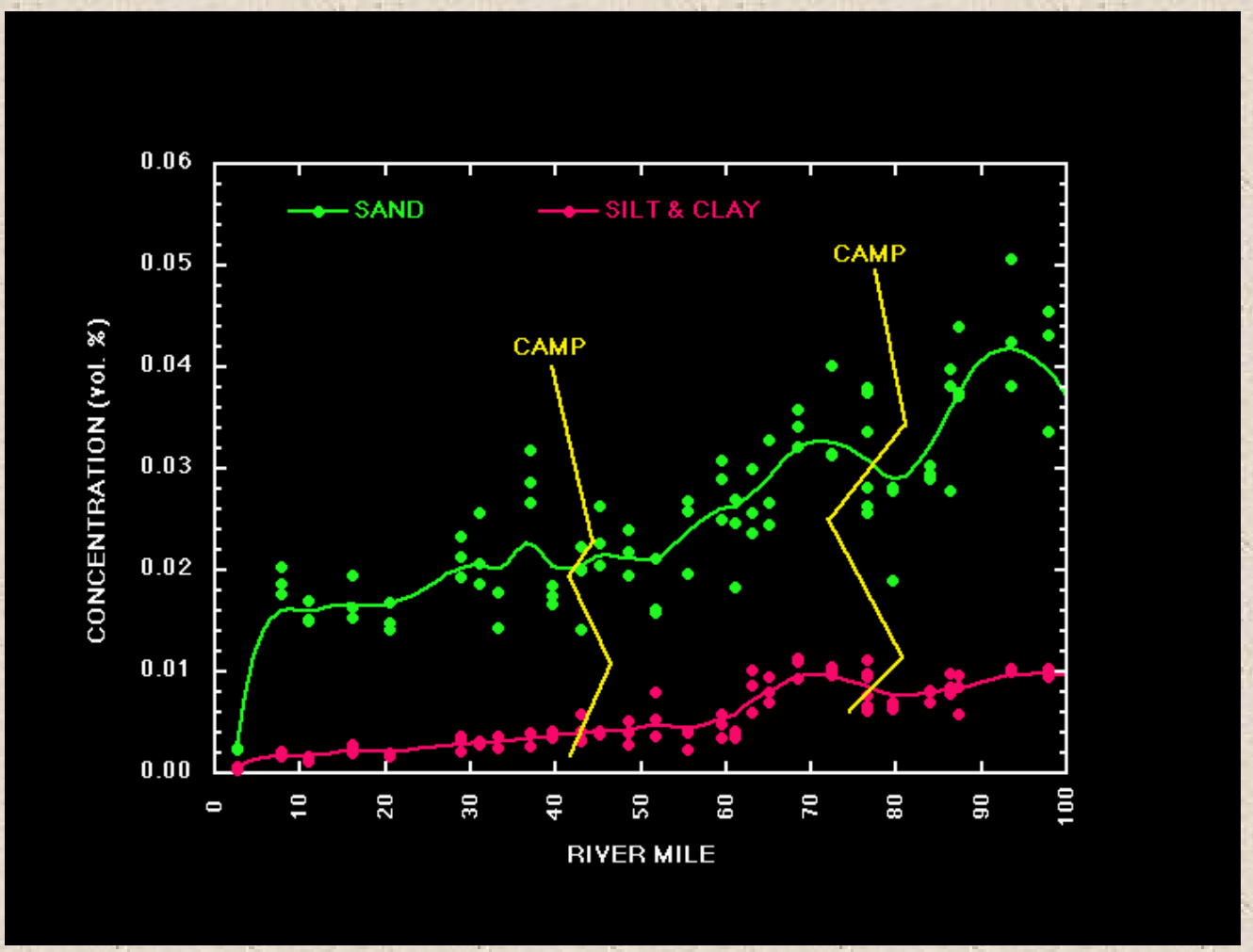
- The style of response to the flow regimes between 1984 and 1997, including the 1996 controlled flood, was similar in all reaches between Lees Ferry and Unkar Rapids
- The relative proportion of each eddy where significant aggradation exceeded significant degradation was greater in lower Marble Canyon than further upstream during the 1996 controlled flood
- The total area of reworking increased in the downstream direction during the 1996 controlled flood

Relation to sediment budgets: longitudinal trends

Sand budget for 1996 controlled flood shows evidence for longitudinal differences in sources and sinks

	Marble Canyon	Downstream from LCR
Inflow	0	800,000
High-elevation eddy sand	760,000	330,000
High-elevation channel margin sand	120,000	90,000
Low-elevation eddy sand	-1,400,0000	0
Channel sand	-920,000	-1,250,000
Outflow	800,000.	1,600,000
High-elevation deposits/outflow	1.1	0.25

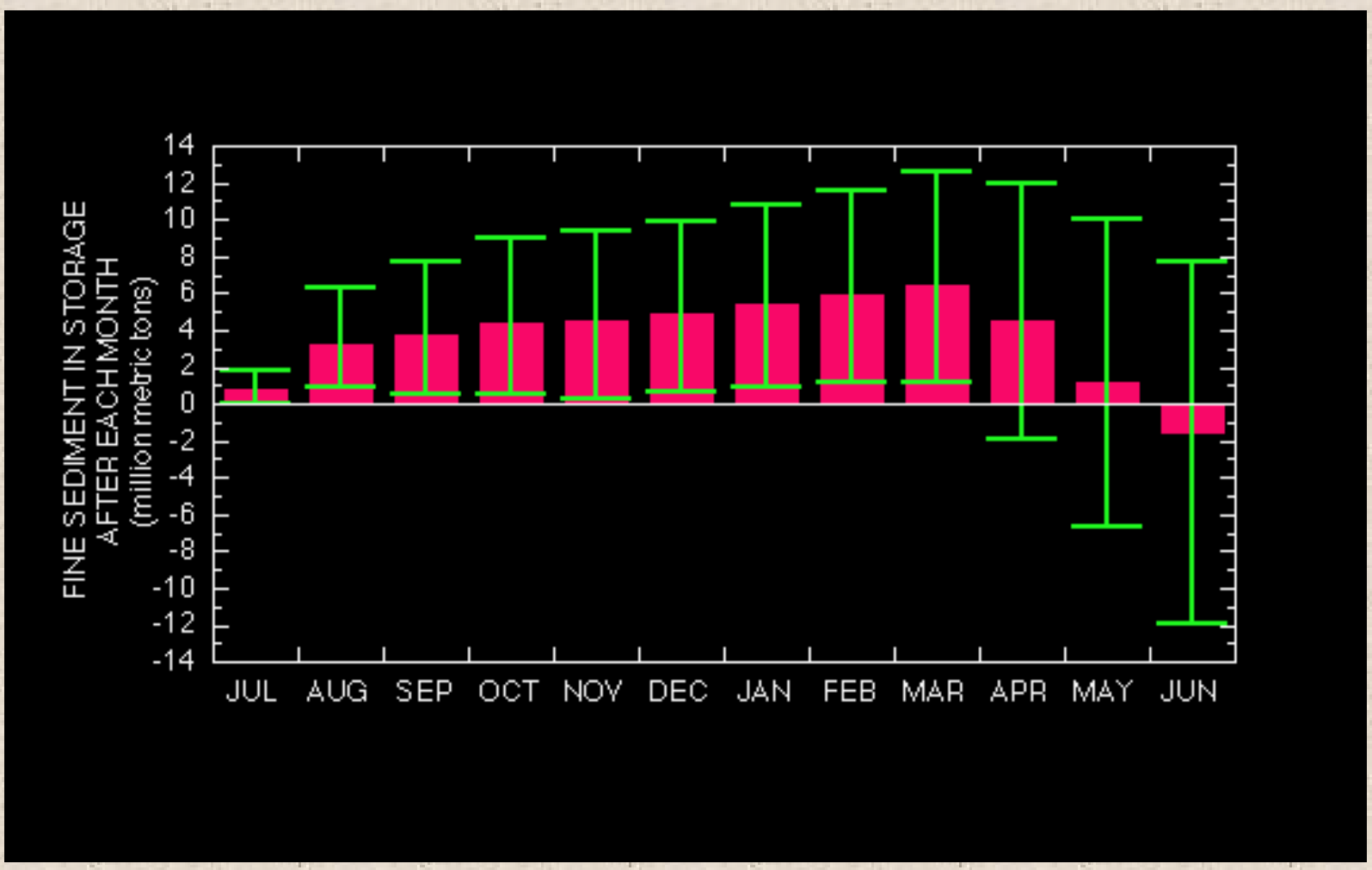
There were longitudinal trends in transport during the Sept. 2000 spike flow (Topping and Rubin, unpubl.)



Relation to sediment budgets: temporal trends

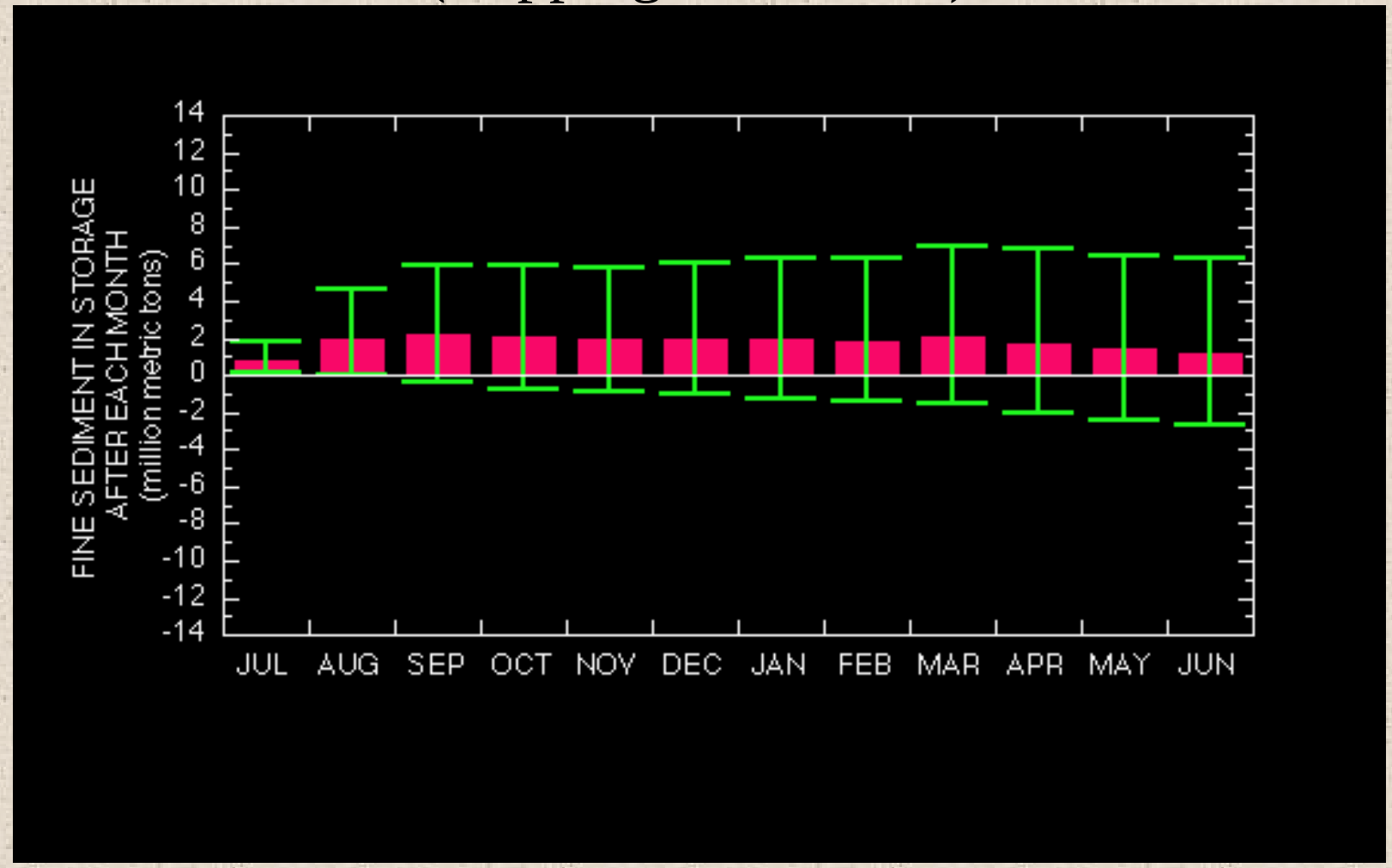
The pre-dam era included a 9-mth period of fine sediment accumulation and a 3-mth period of evacuation

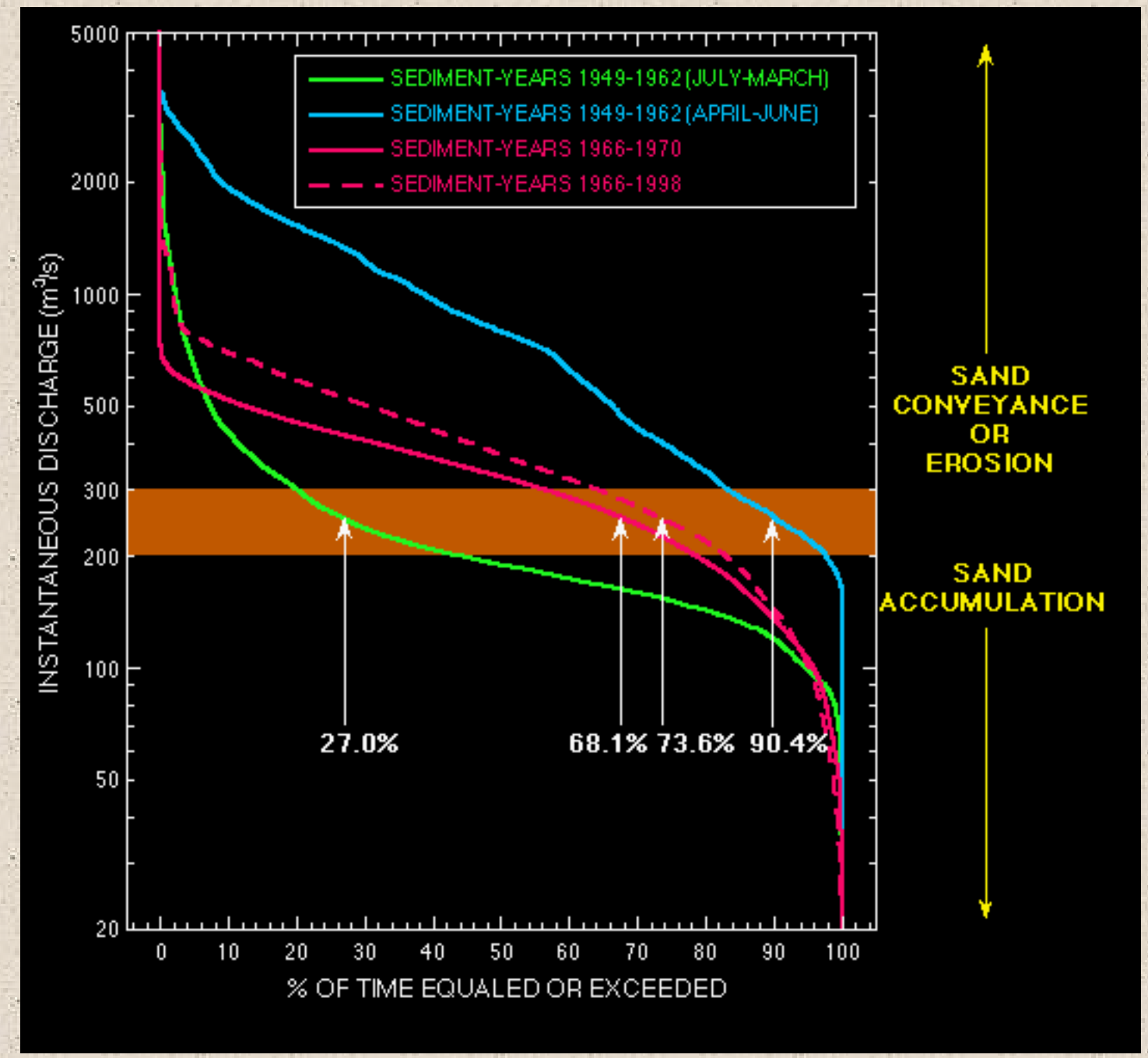
(Topping et al., 2000)



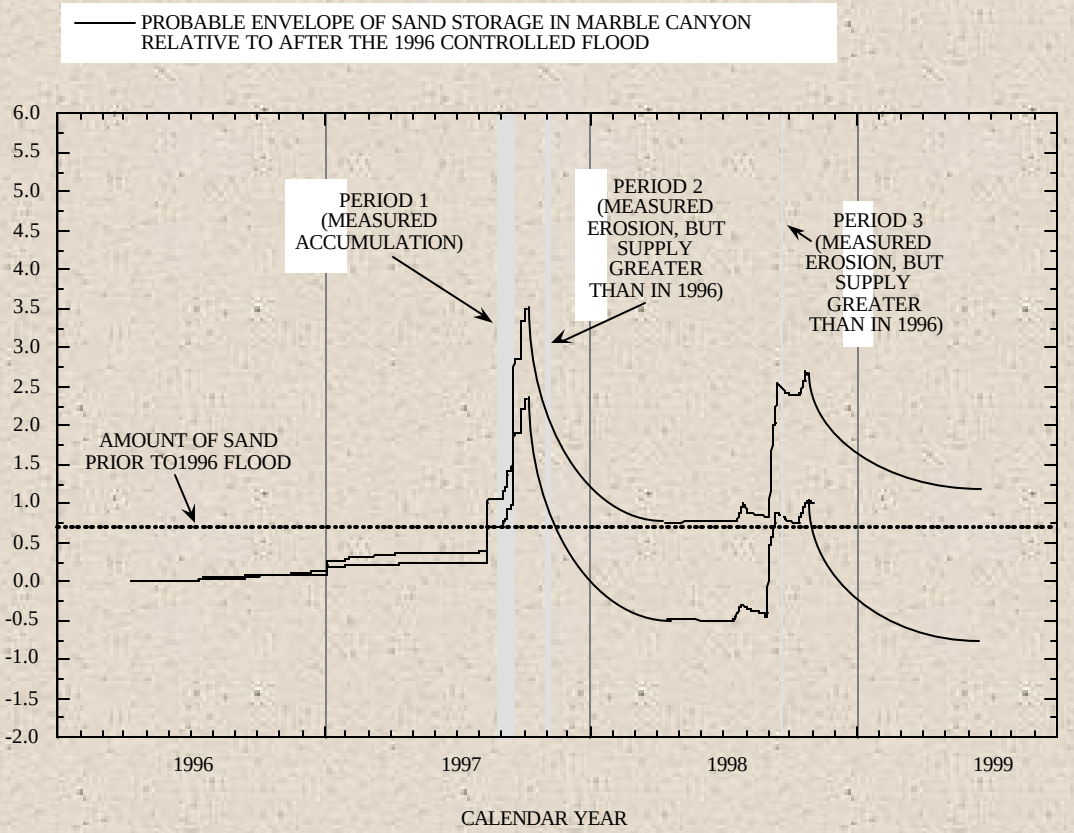
It is difficult to detect multi-month sediment accumulation in the post-dam era

(Topping et al. 2000)




SEDIMENT-YEARS 1949-1962 (JULY-MARCH)
SEDIMENT-YEARS 1949-1962 (APRIL-JUNE)
SEDIMENT-YEARS 1966-1970
SEDIMENT-YEARS 1966-1998
INSTANTANEOUS DISCHARGE (m³/s)
5000
2000
1000
500
300
200
100
50
20
0
10
20
30
40
50
60
70
80
90
100
% OF TIME EQUALED OR EXCEEDED
27.0%
68.1%
73.6%
90.4%
SAND CONVEYANCE OR EROSION
SAND ACCUMULATION

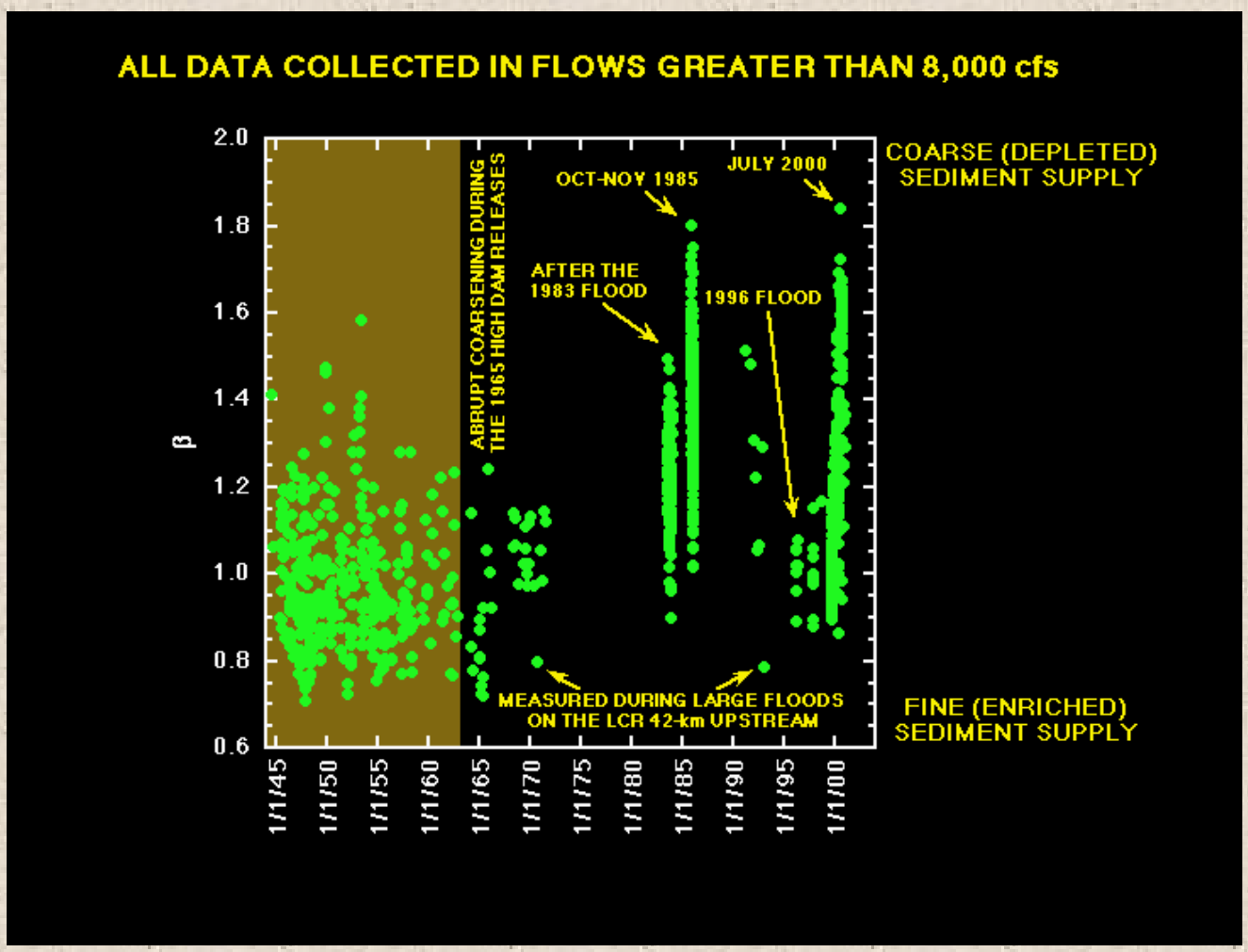
Fine sediment accumulates only for short periods



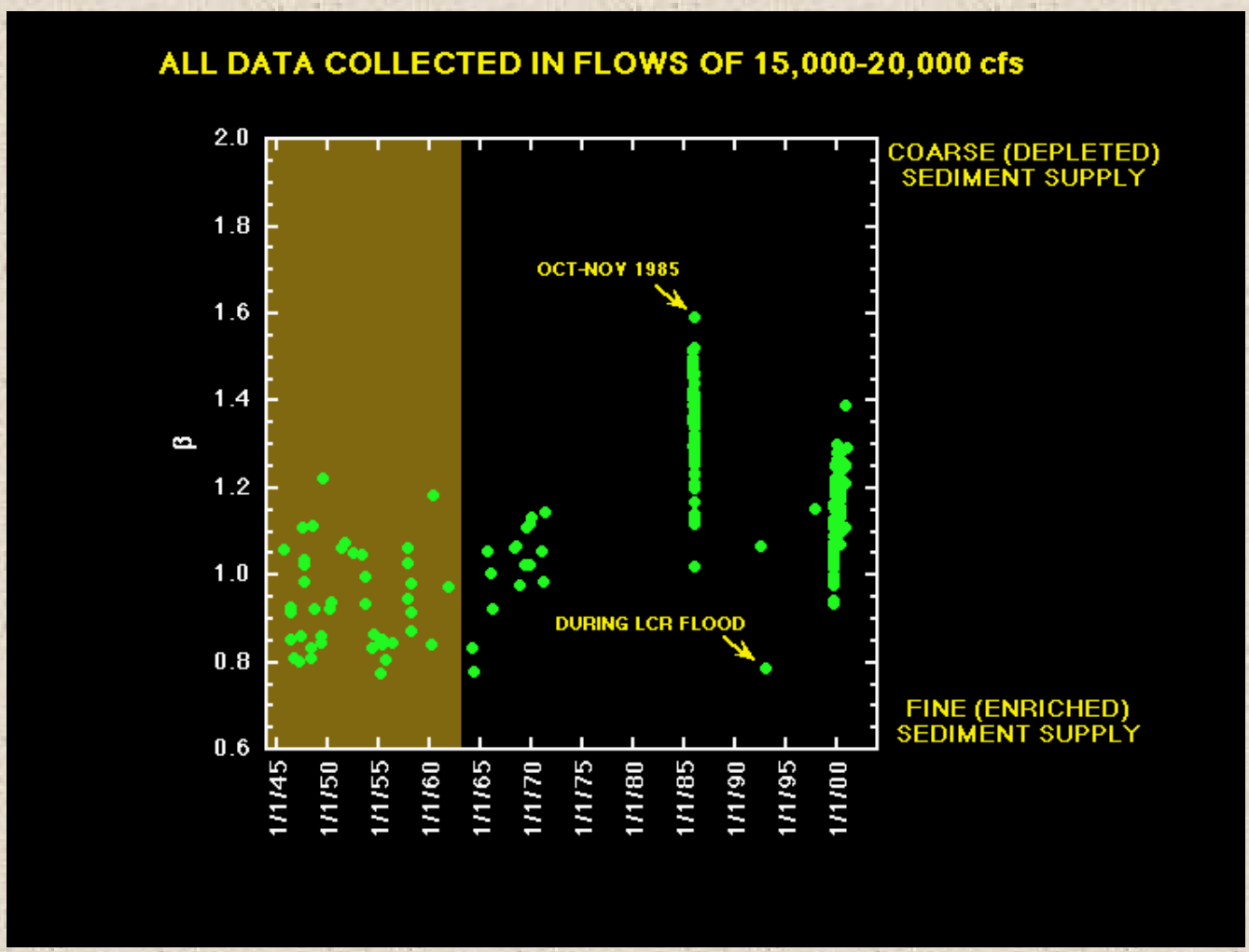
Effect of Sediment Accumulation on Sand Bar Sizes

- Accumulation of fine sediment can only occur below the water surface. Accumulation is associated with finer bed material, higher concentrations of entrained fine sediment, and higher deposition rates when floods occur

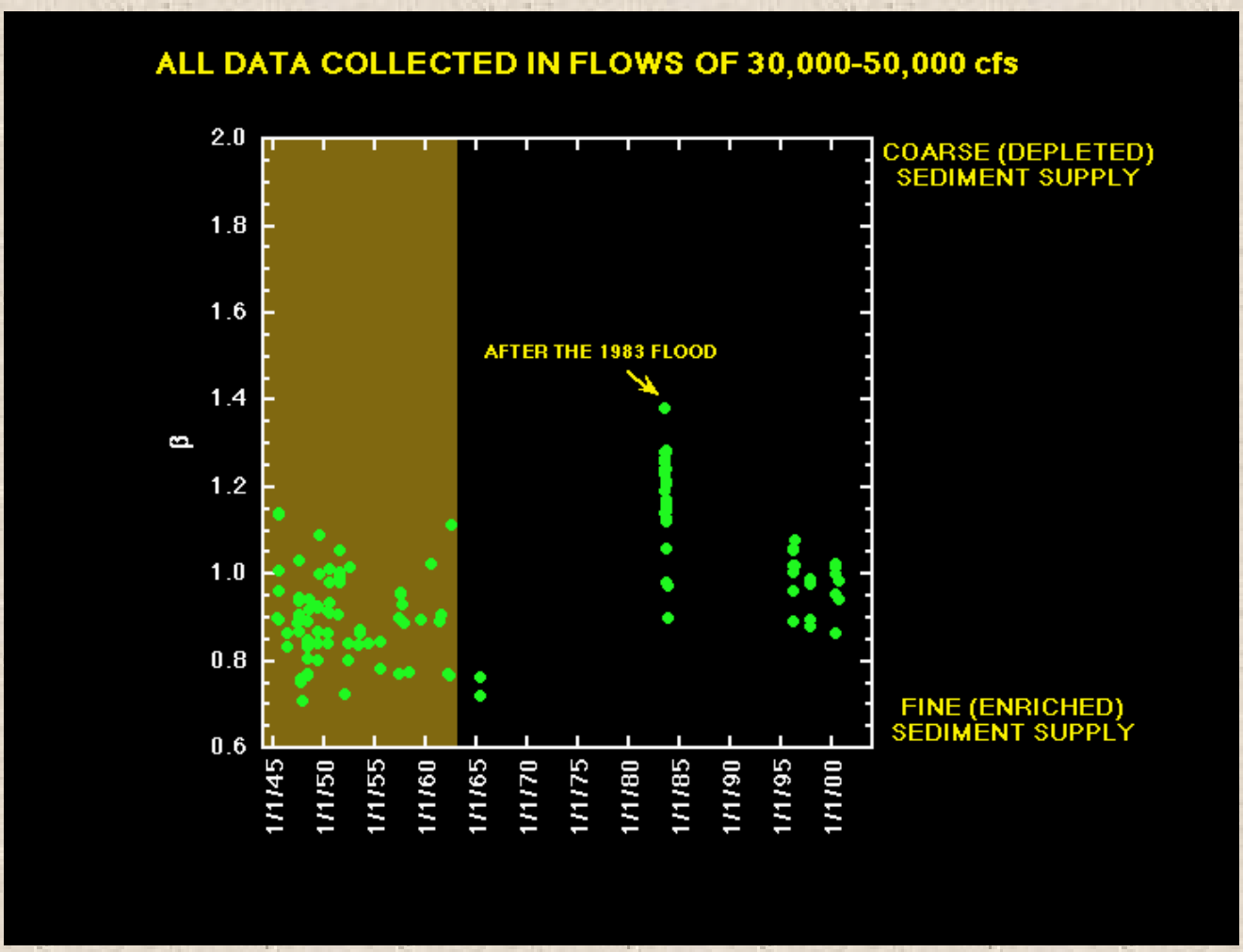
The system has generally been coarser in the post-dam era



Flows that build bars at the level of high powerplant flows have also been coarser, except for the 1993 LCR flood

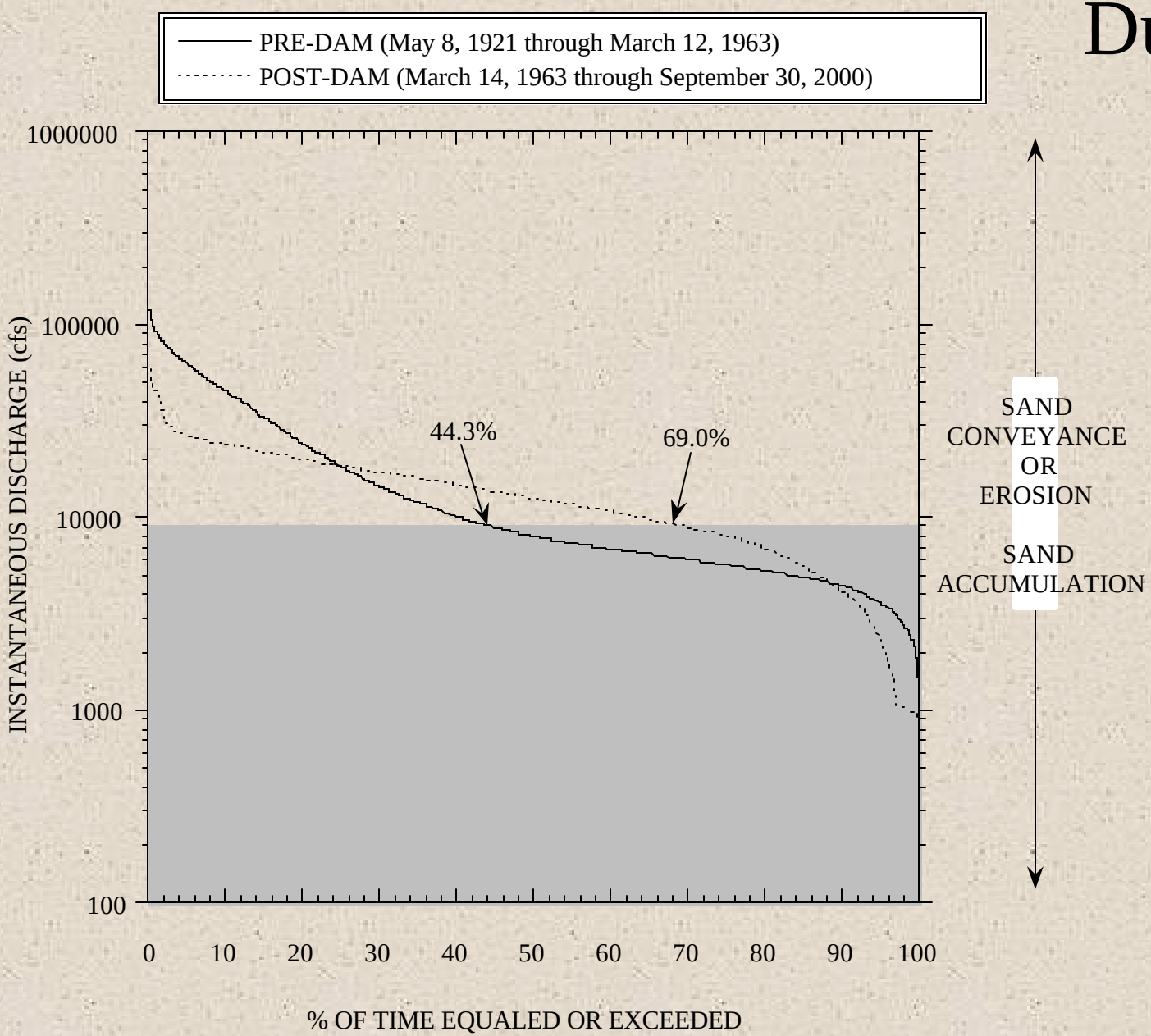


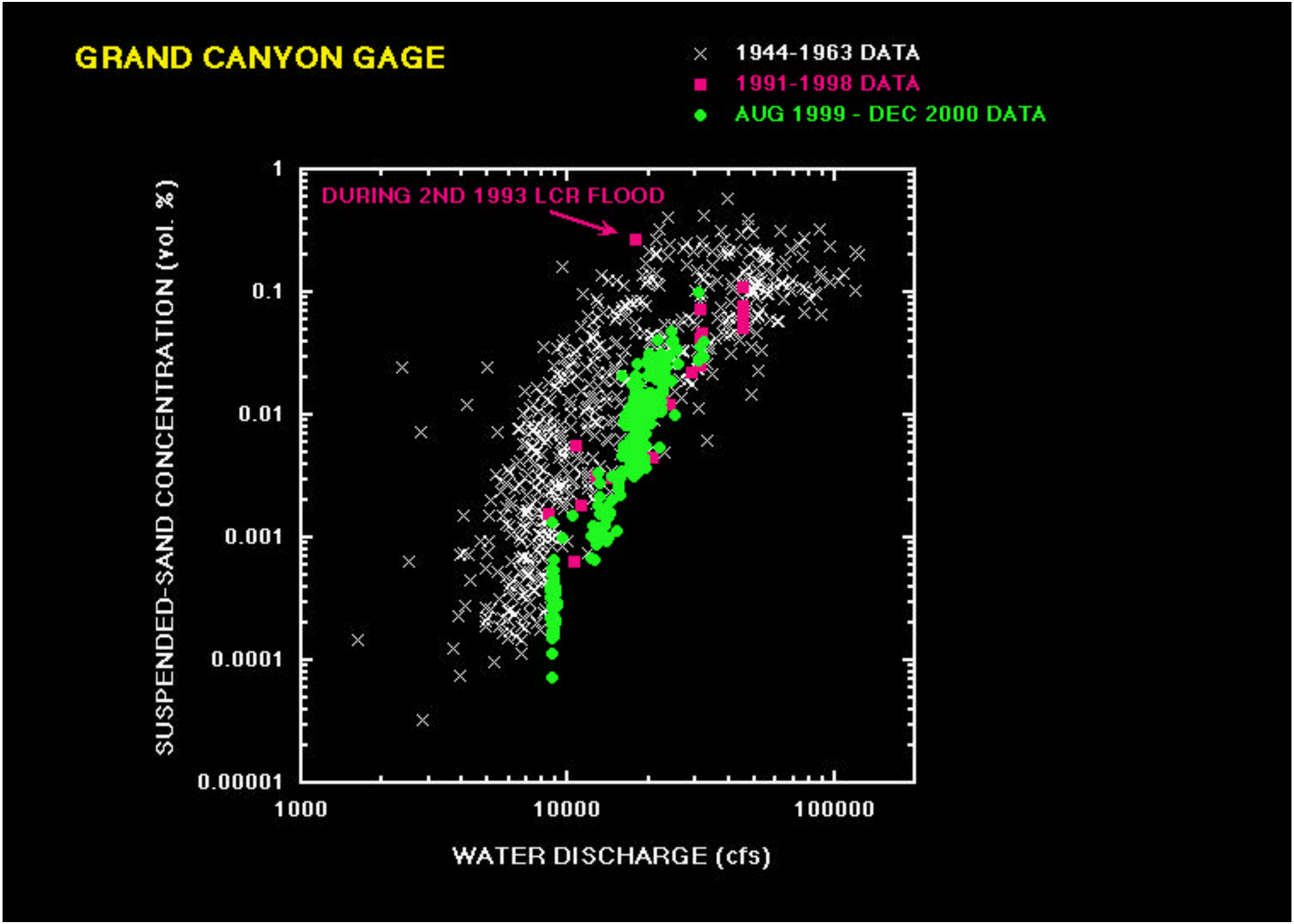
Flows that build the high elevation parts of bars have had lower concentrations than in the pre-dam era

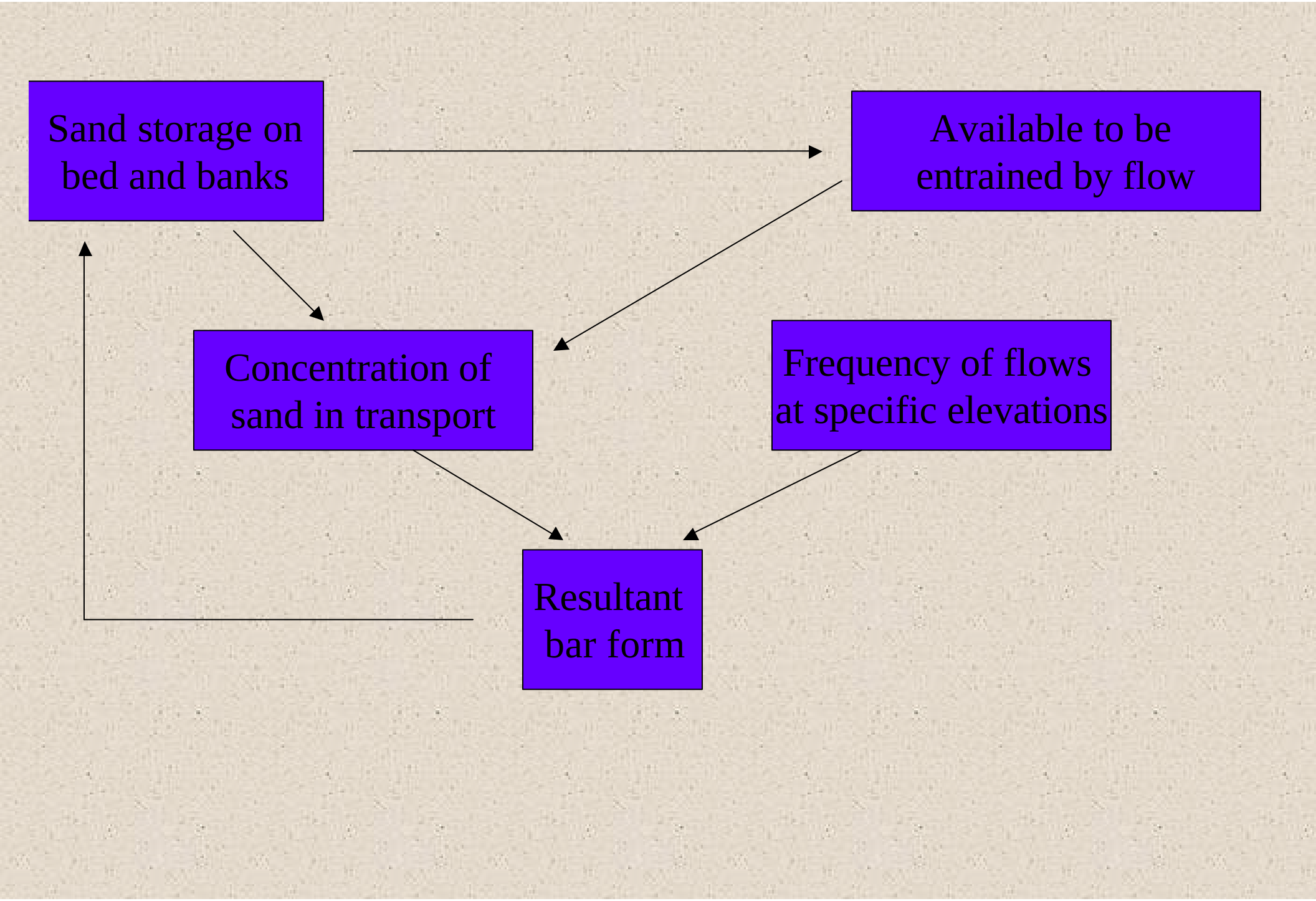


Magnitude, frequency, concentration, and resulting bar form

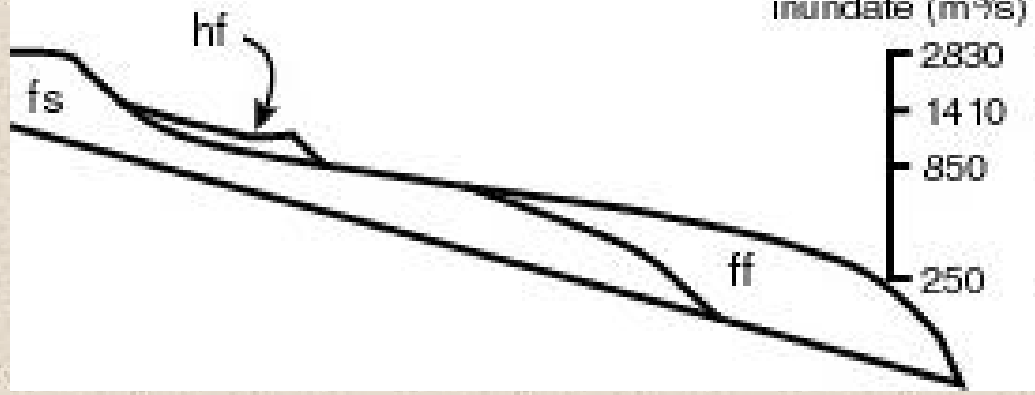
Duration


PRE-DAM (May 8, 1921 through March 12, 1963)
POST-DAM (March 14, 1963 through September 30, 2000)
1000000
100000
10000
1000
100
INSTANTANEOUS DISCHARGE (cfs)
44.3%
69.0%
SAND CONVEYANCE OR EROSION
SAND ACCUMULATION
0
10
20
30
40
50
60
70
80
90
100
% OF TIME EQUALED OR EXCEEDED


GRAND CANYON GAGE
1944-1963 DATA
1991-1998 DATA
AUG 1999 - DEC 2000 DATA
DURING 2ND 1993 LCR FLOOD
SUSPENDED-SAND CONCENTRATION (vol. %)
1
0.1
0.01
0.001
0.0001
0.00001
1000
10000
100000
WATER DISCHARGE (cfs)


Sand storage on bed and banks
Available to be entrained by flow
Concentration of sand in transport
Frequency of flows at specific elevations
Resultant bar form

Conceptual Model



Duration		Concentration		Effecti Elevati	
pre	post	pre	post	pre	p
9	0.1	0.05 - 0.4	?	X	
12	12	0.02 - 0.3	0.02 - 0.1	X	
22	59	0.0002 - 0.1	0.0001 - 0.001		

fine-sediment storage occurs below this stage

Synthesis Findings

-Degradation of pools and riffles in Glen Canyon has been significant and continues, although at a much slower rate
-Bed degradation of the riffles has caused an overall decrease in the stage of specific flows
-This decrease has caused alluvial deposits in Glen Canyon to be inundated less frequently than in the pre-dam era
-Although there are many vertical cutbanks in Glen Canyon, bank erosion has been localized

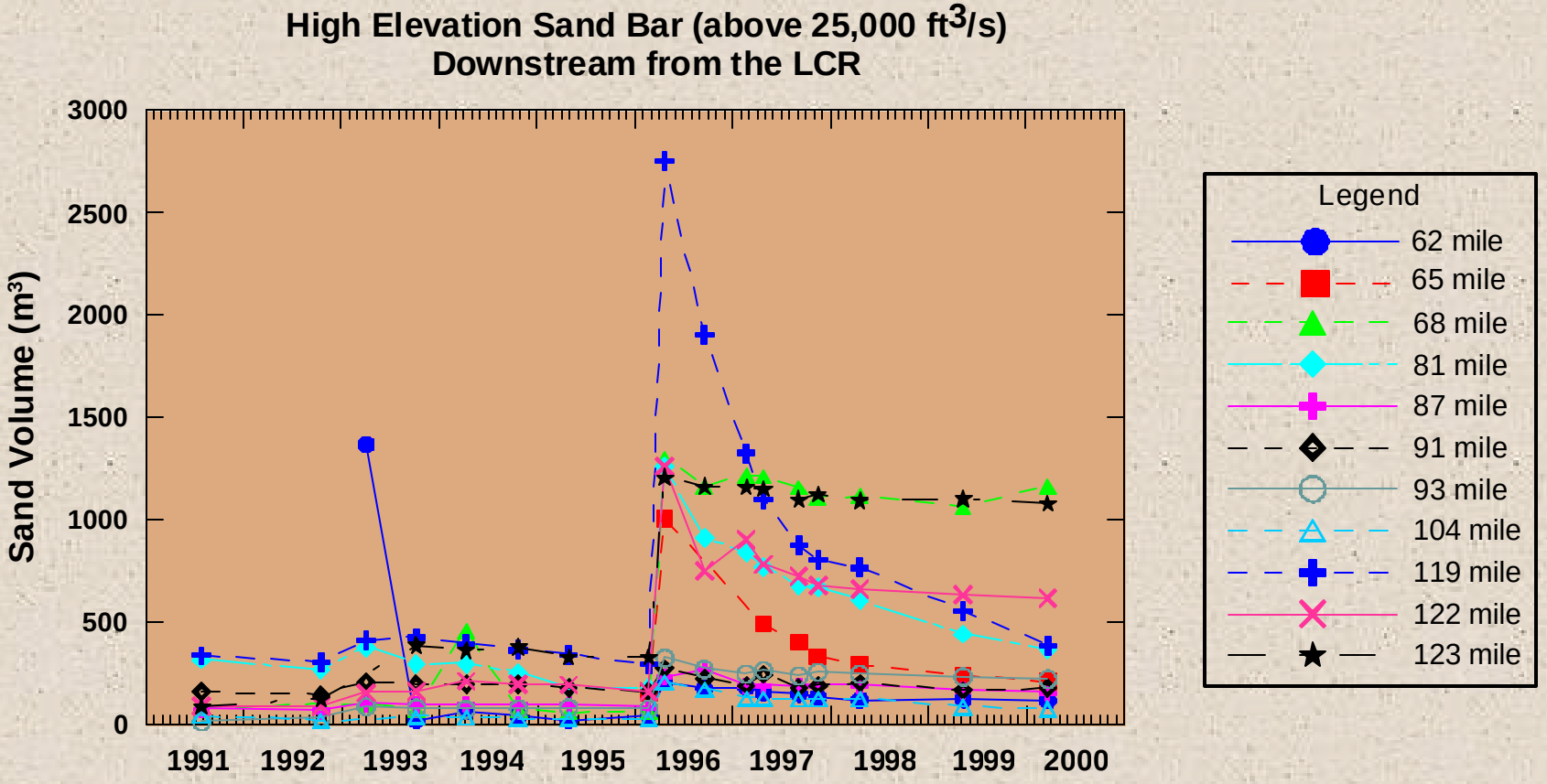
Synthesis Findings

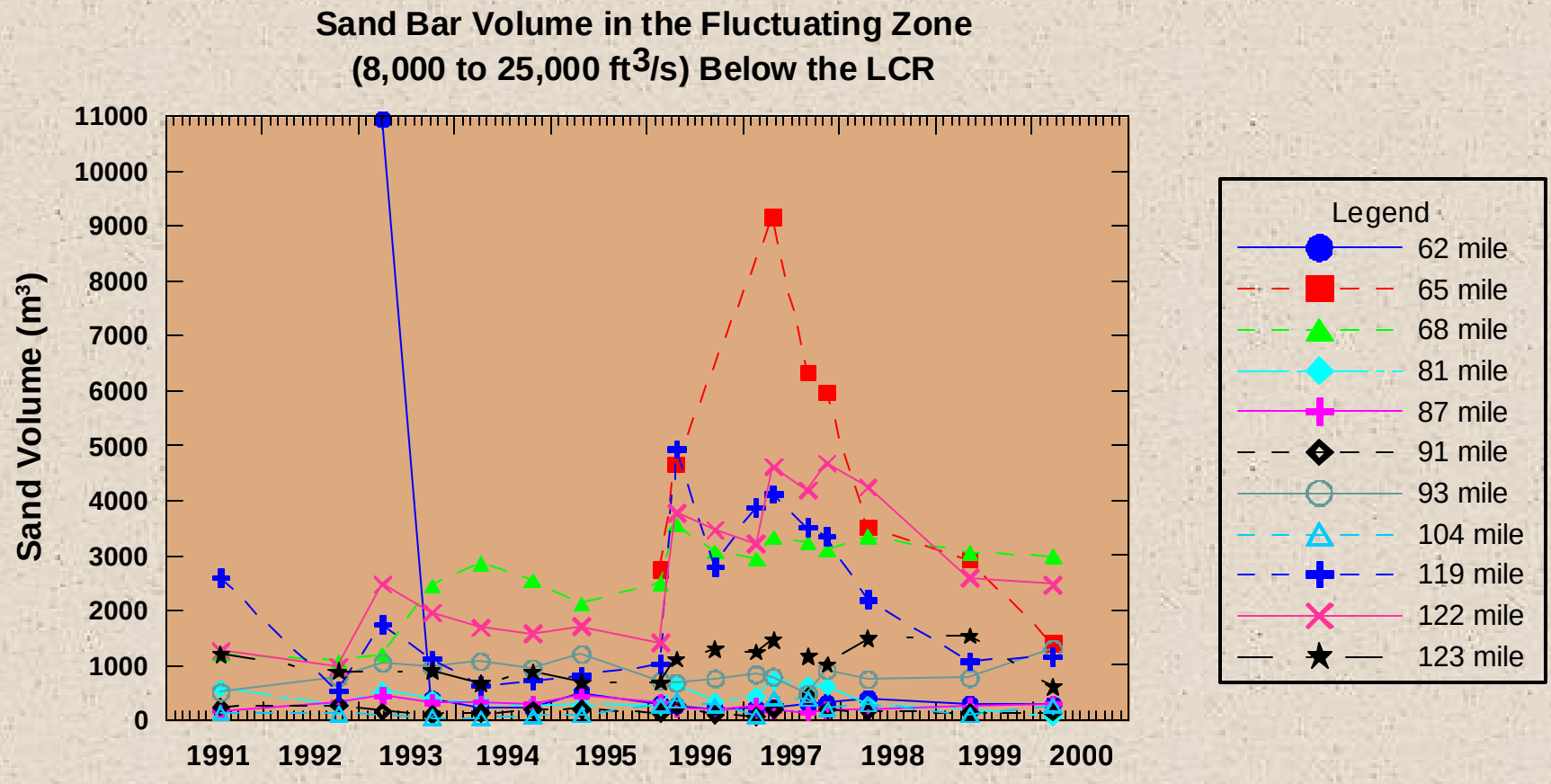
- Degradation of some pools in Marble Canyon has occurred; it is unlikely that any riffles or rapids have been degraded. Thus, there have not been any systematic changes in stage-discharge relations in Marble or Grand Canyons
- High-elevation sand areas are built by floods and are eroded during intervening periods; the characteristics of these deposits is determined by the sediment transport characteristics of the flows that occur at these elevations and not the average canyon-wide sediment budget of the intervening times

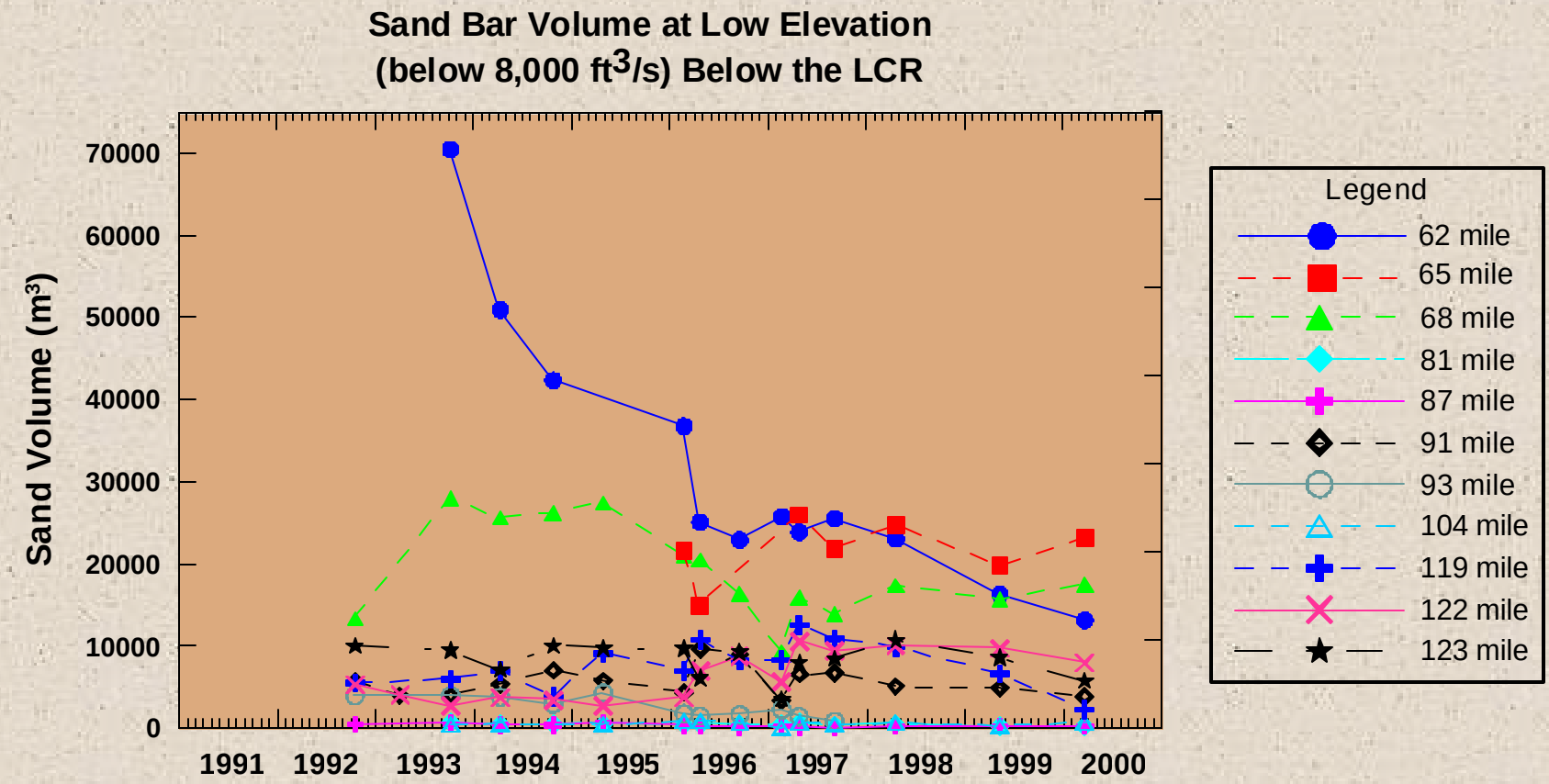
Synthesis Findings

- Low-elevation sand areas are subject to aggradation if there is a canyon-wide accumulation of fine sediment and the bars are inundated
- Low-elevation sand areas are subject to degradation if there is a canyon-wide loss of sediment and the bars are inundated
- Low-elevation sand areas are subject to mass failures during periods of high deposition rates (Andrews et al., 1999) and at other times (Cluer, 1995)
- Variability in the distribution and characteristics of low-elevation sand make the detection of long-term trends in the total area of sand difficult to detect

- extras


High Elevation Sand Bar (above 25,000 ft3/s)
Downstream from the LCR
Sand Volume (m3)
3000
2500
2000
1500
1000
500
0
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Legend
62 mile
65 mile
68 mile
81 mile
87 mile
91 mile
93 mile
104 mile
119 mile
122 mile
123 mile


Sand Bar Volume in the Fluctuating Zone
(8,000 to 25,000 ft3/s) Below the LCR
Sand Volume (m3)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Legend
62 mile
65 mile
68 mile
81 mile
87 mile
91 mile
93 mile
104 mile
119 mile
122 mile
123 mile


Sand Bar Volume at Low Elevation
(below 8,000 ft3/s) Below the LCR
Sand Volume (m3)
70000
60000
50000
40000
30000
20000
10000
0
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Legend
62 mile
65 mile
68 mile
81 mile
87 mile
91 mile
93 mile
104 mile
119 mile
122 mile
123 mile