Historic Changes in Fine Sediment Storage Downstream from Lees Ferry

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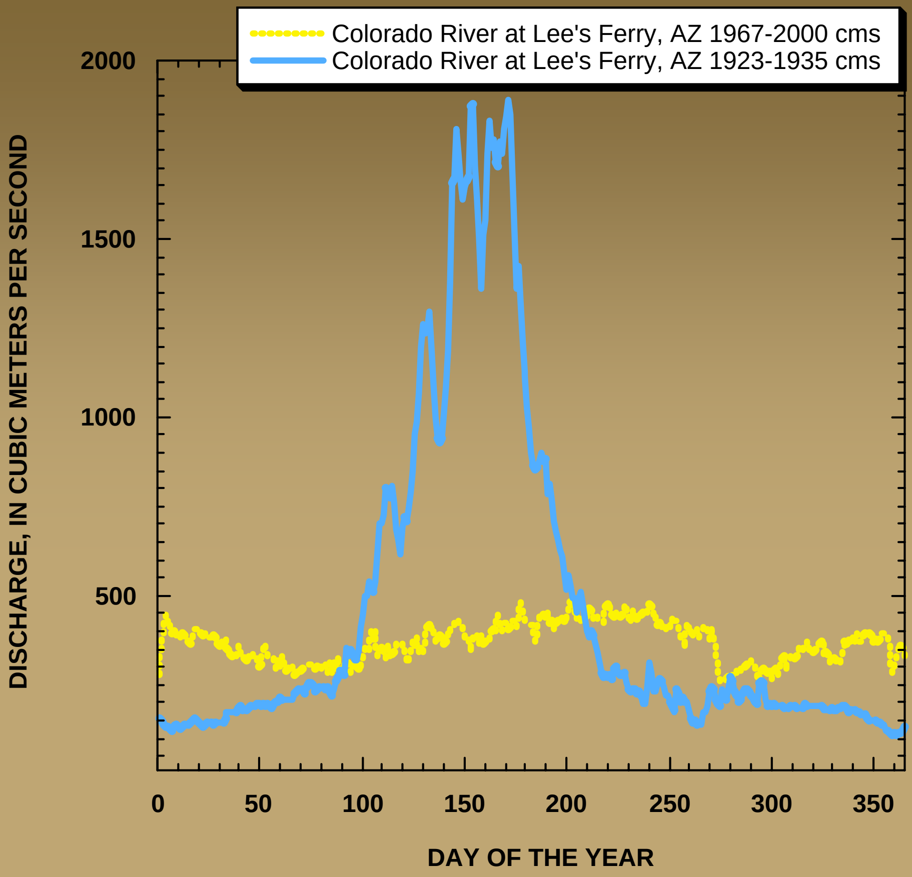
Water and Fine Sediment Fluxes

~60% decrease in flood magnitude

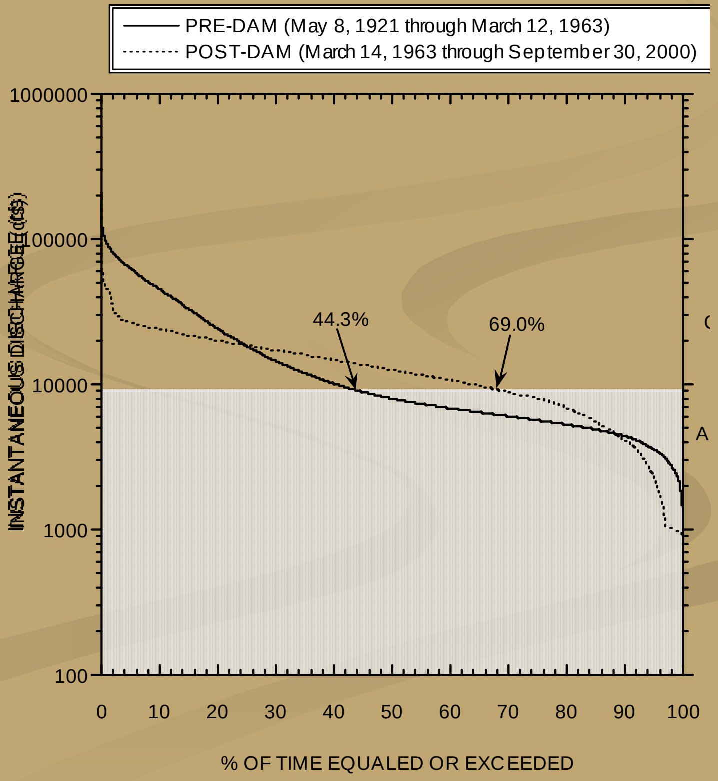
Increase in base flow

85-95% reduction in fine sediment delivery



Lees Ferry gage

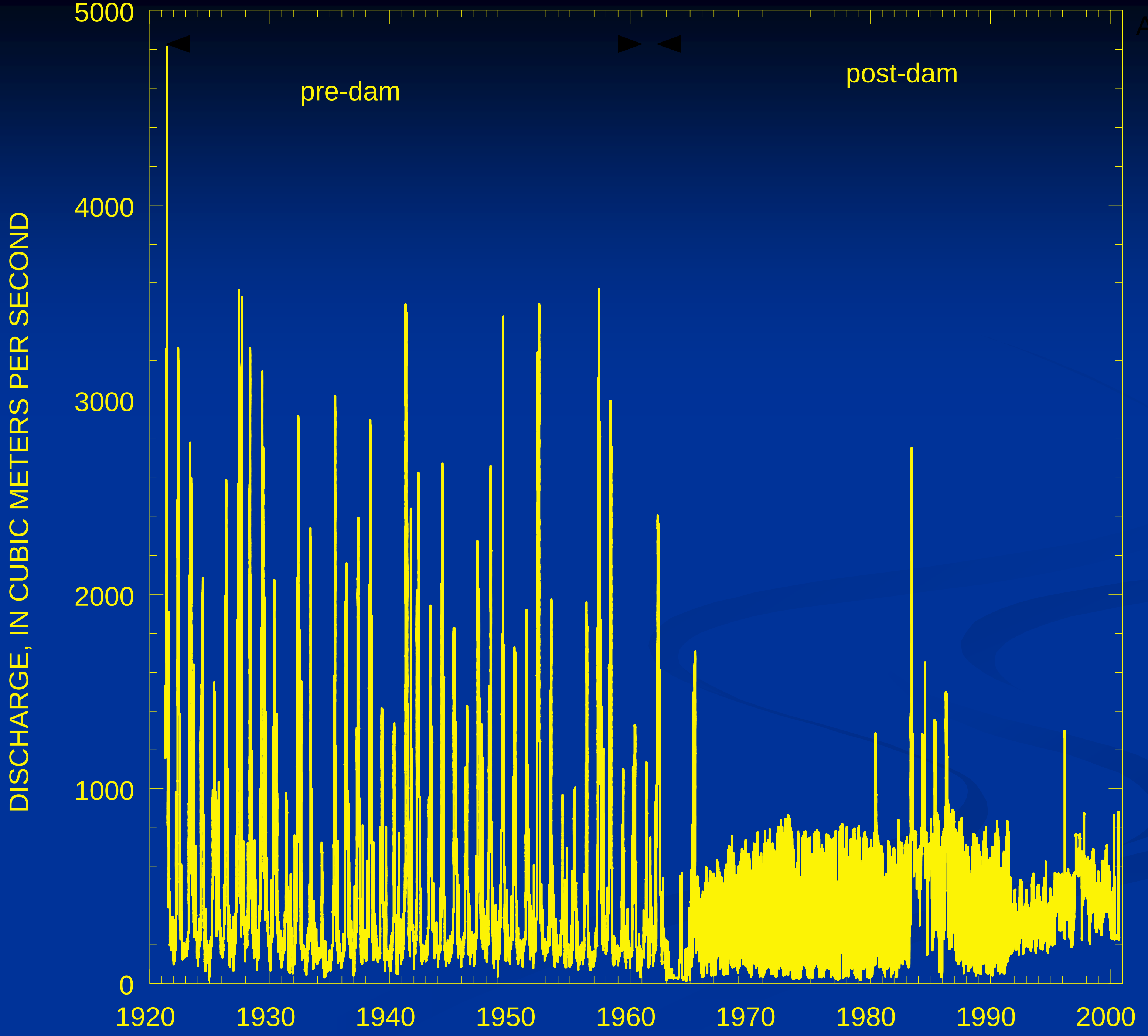
Changes in duration of low flows



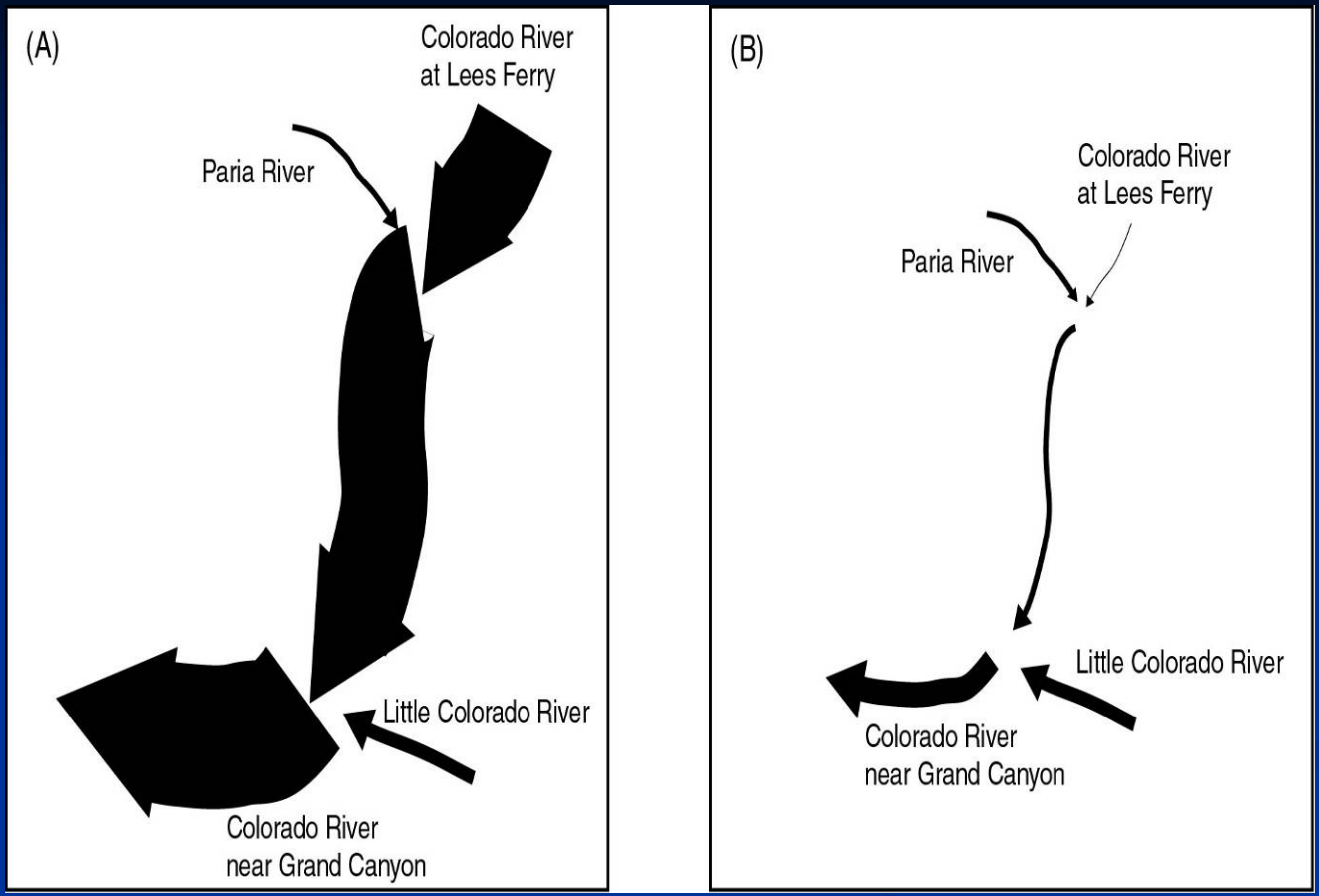
10%: 1359 --> 708

50%: 227 --> 395

90%: 127 --> 125

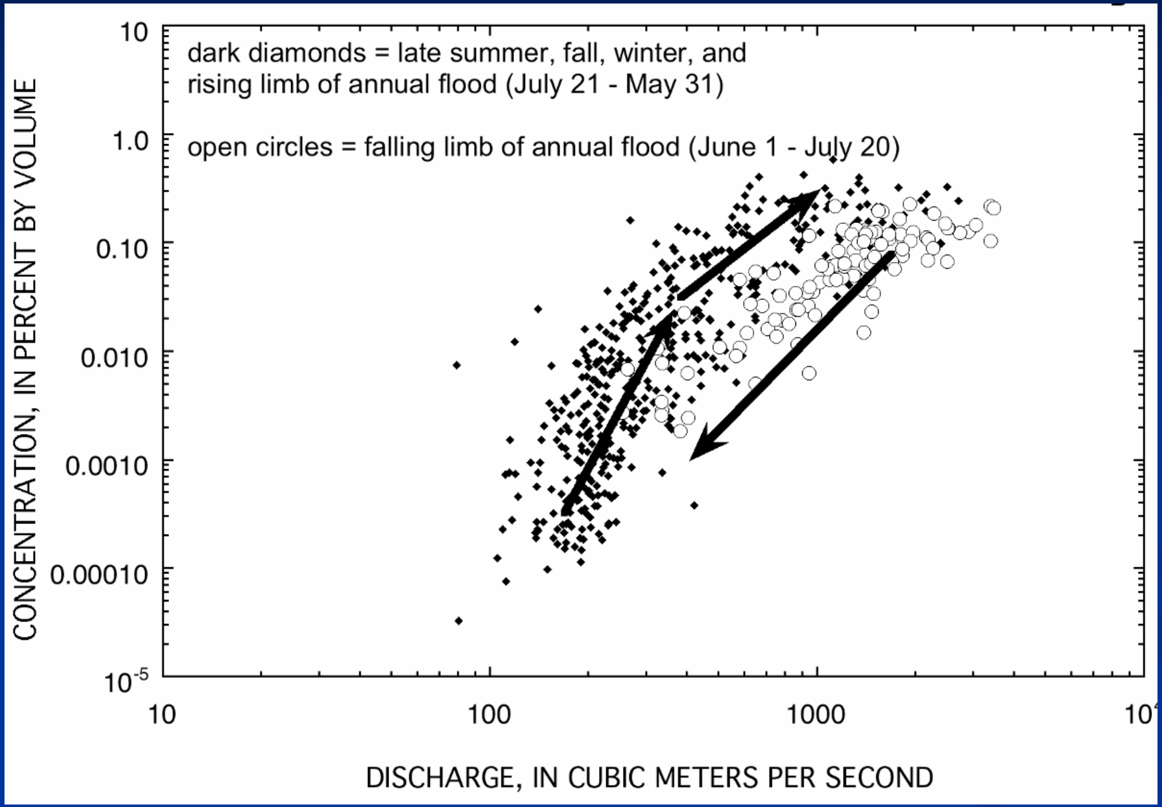


A
pre-dam
post-dam
DISCHARGE, IN CUBIC METERS PER SECOND
5000
4000
3000
2000
1000
0
1920
1930
1940
1950
1960
1970
1980
1990
2000

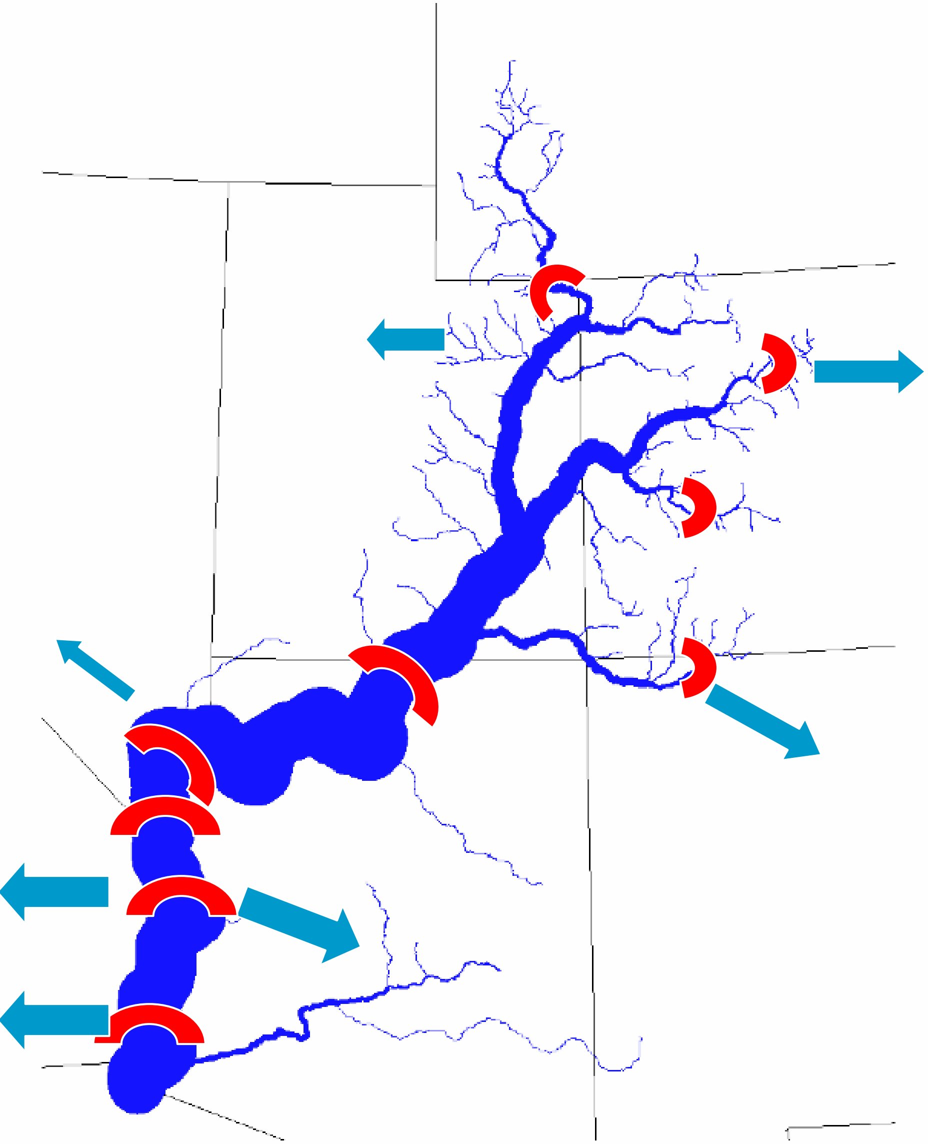


- Annual fine-sediment load
  - 57 --> 0.3 mmt (25 km blw dam)
  - 83 --> 14 mmt (170 km blw dam)
- Pre-dam loads were 35-40% sand

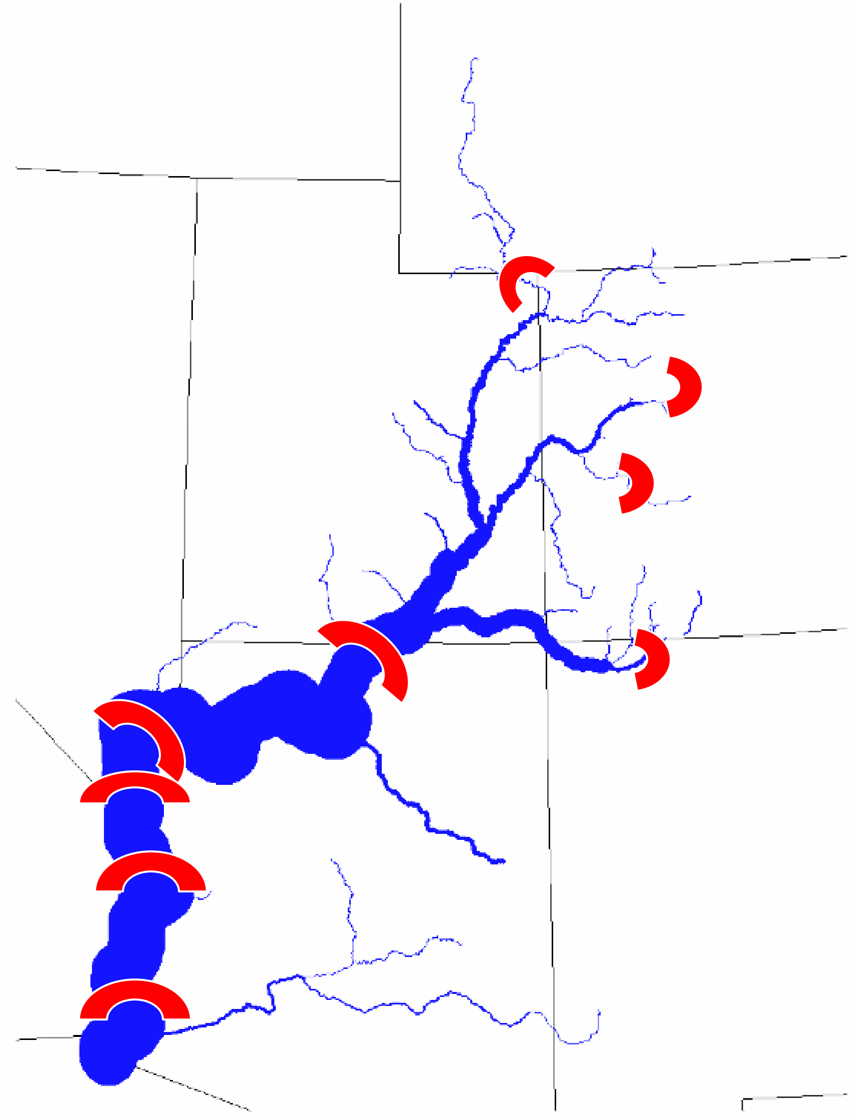
(Topping et al., 2000)



dark diamonds = late summer, fall, winter, and rising limb of annual flood (July 21 - May 31)
open circles = falling limb of annual flood (June 1 - July 20)
CONCENTRATION, IN PERCENT BY VOLUME
10
1.0
0.10
0.010
0.0010
0.00010
10^{-5}
10
100
1000
DISCHARGE, IN CUBIC METERS PER SECOND



water



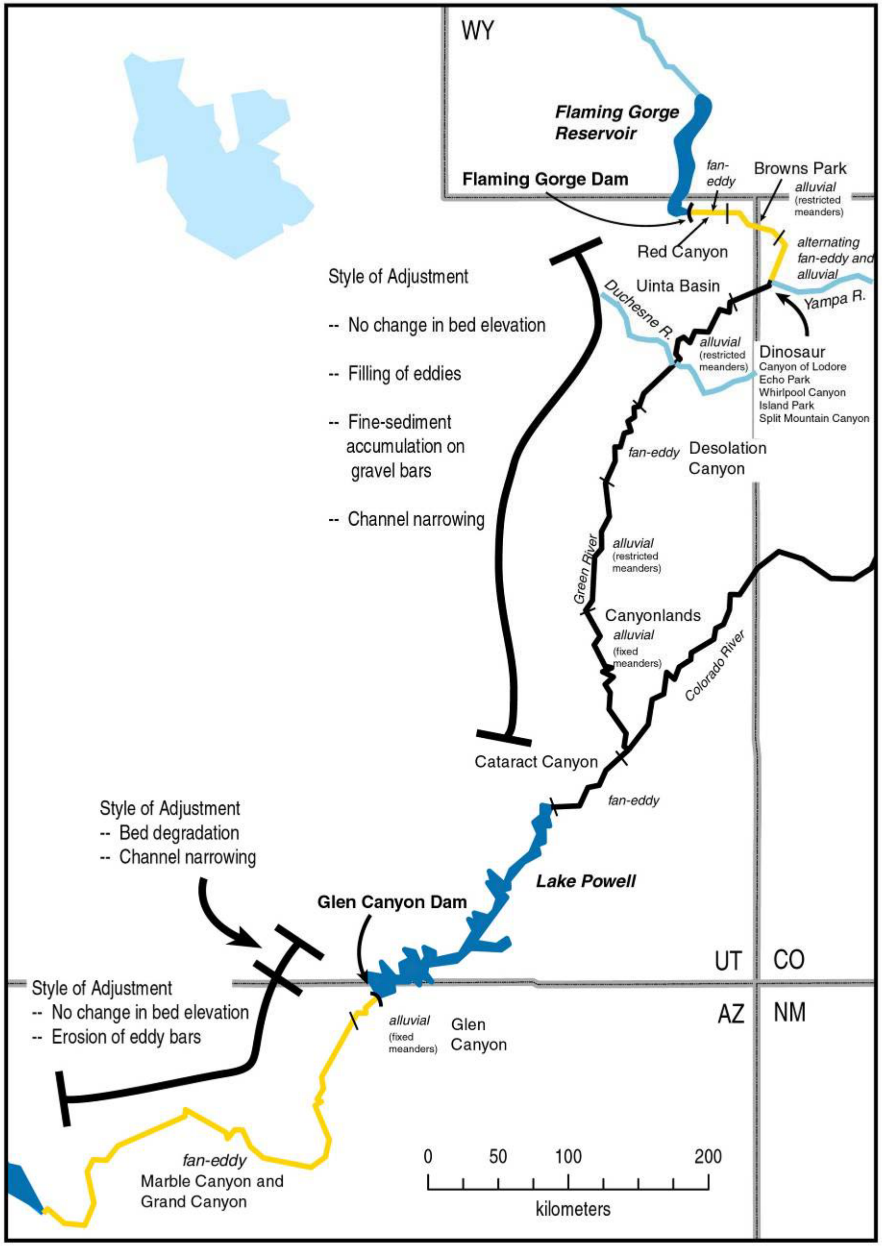
sediment

Sediment deficit reaches

immediately downstream from dams

Sediment surplus reaches

further downstream



The Valley of the Colorado River

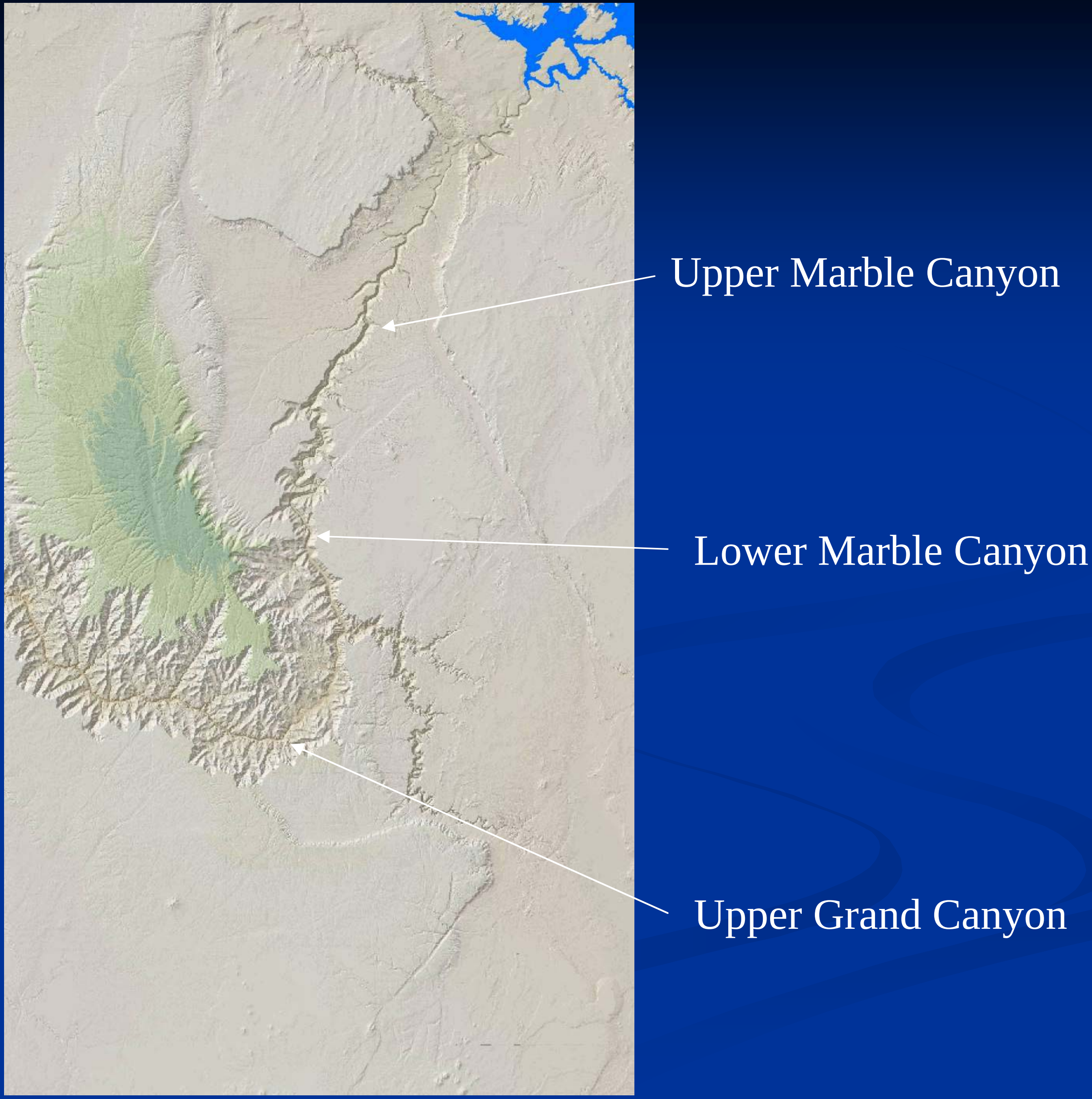
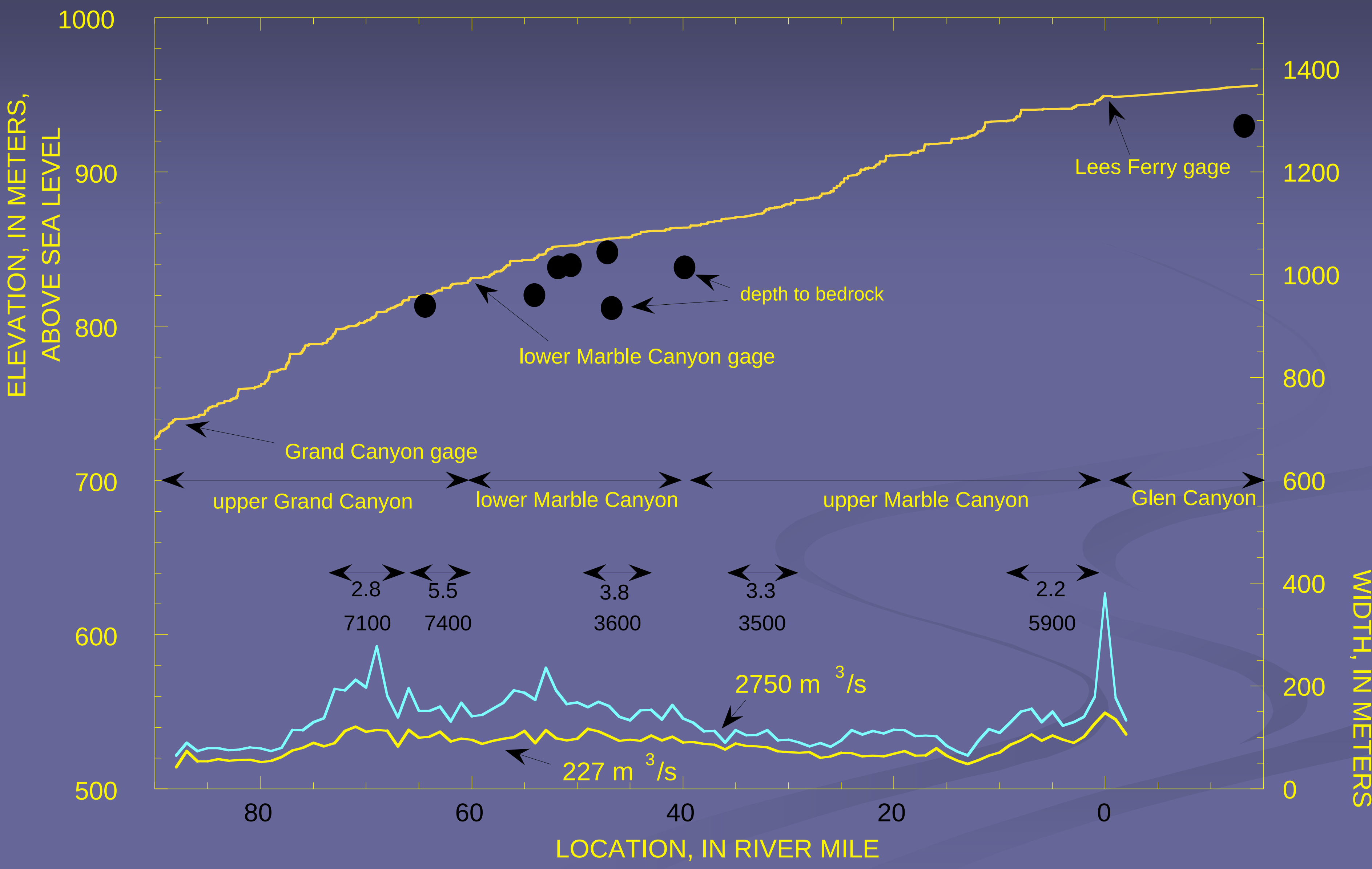

Upper Marble Canyon
Lower Marble Canyon
Upper Grand Canyon

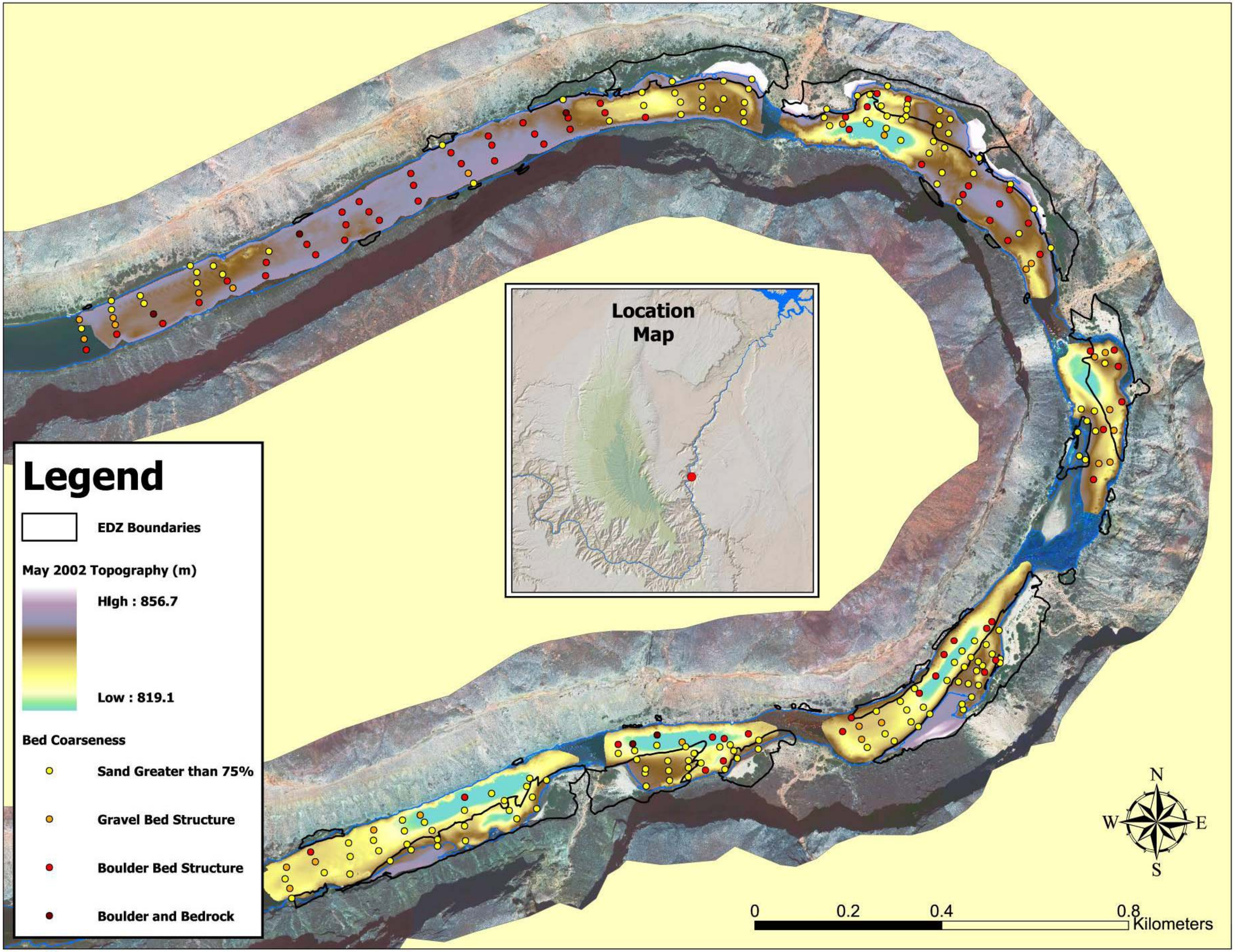
Table 1. Segment characteristics of the Colorado River in Marble and upper Grand Canyons

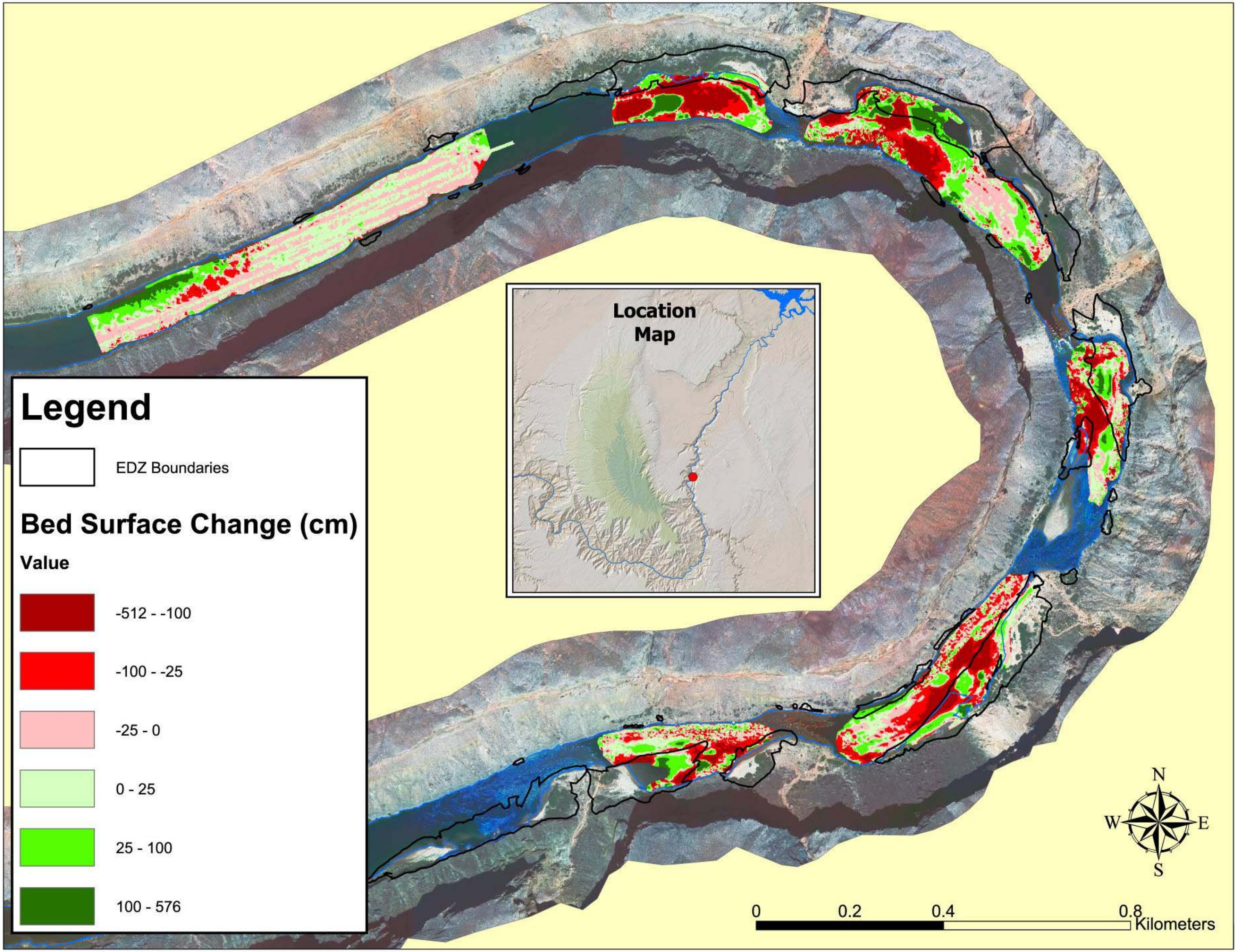
River Mile	Reach-average channel width at base flow (227 m^3/s), in meters[1]	Reach-average channel width at flood stage (2746 m^3/s), in meters[1]	Ratio of base flow channel to flood channel width
Upper Marble Canyon (RM 1-40)	78.1	111.5	0.71
Lower Marble Canyon (RM 40-61)	99.9	164.7	0.61
Upper Grand Canyon			
Tapeats Gorge and Big Bend (RM 61-77)	101.1	171.0	0.61
Upper Granite Gorge (RM 77-87)	59.3	82.1	0.72

[1] Reach-average width determined from maps of water's edge at indicated discharge. Water surface area at indicated discharge was divided by reach length to determine average width.

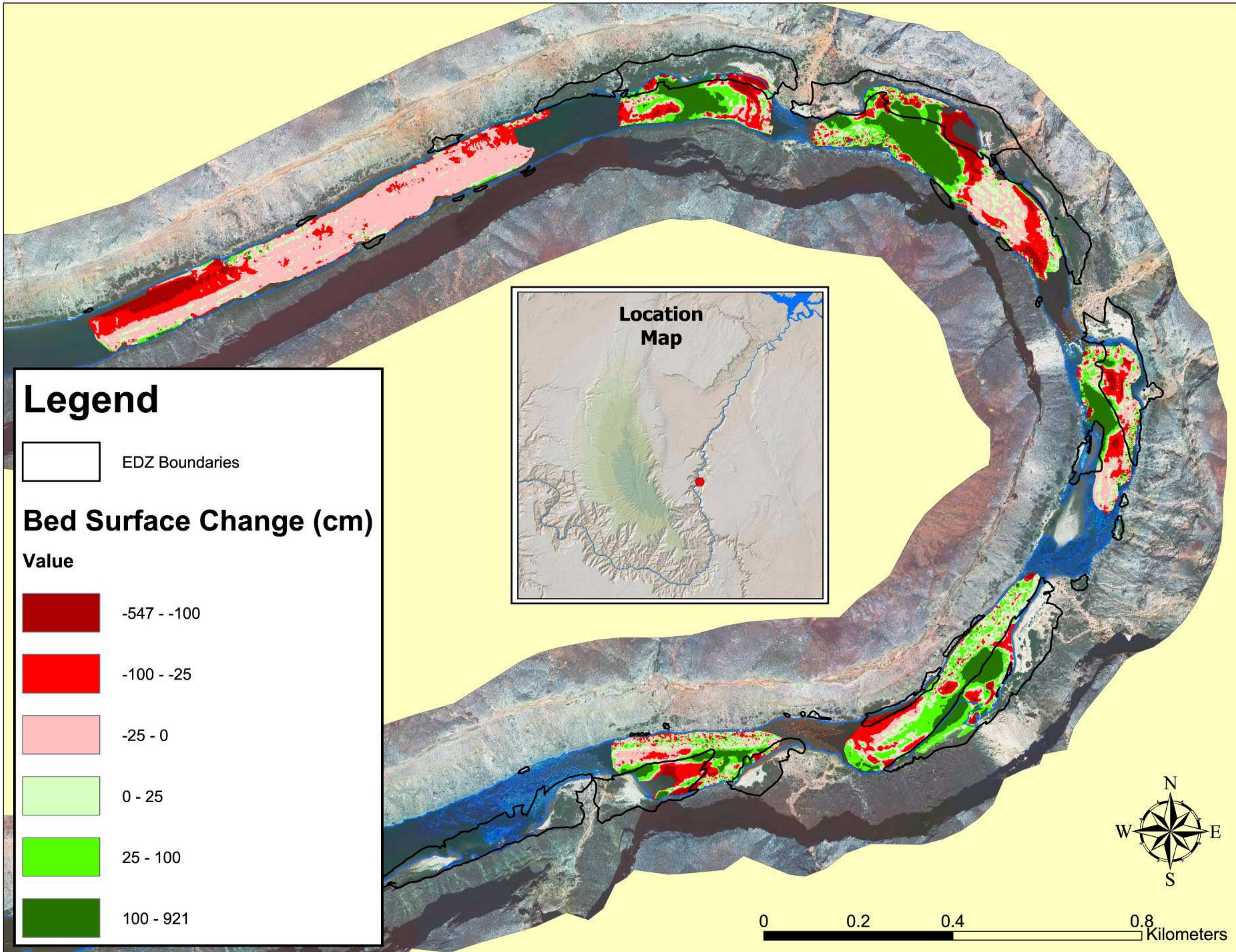


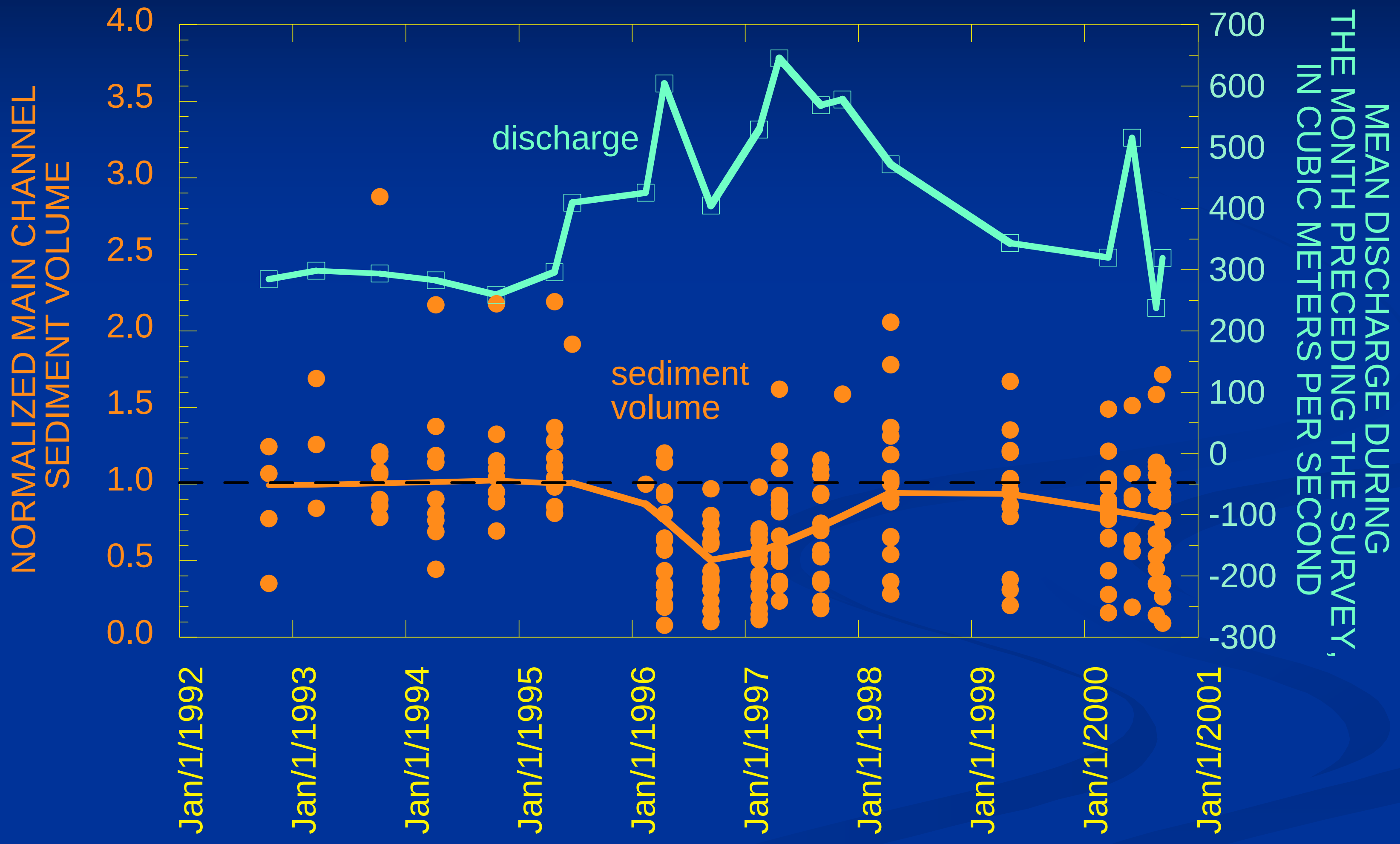
ELEVATION, IN METERS, ABOVE SEA LEVEL
1000
900
800
700
600
500
1400
1200
1000
800
600
400
200
0
WIDTH, IN METERS
Lees Ferry gage
depth to bedrock
lower Marble Canyon gage
Grand Canyon gage
upper Grand Canyon
lower Marble Canyon
upper Marble Canyon
Glen Canyon
2.8
5.5
3.8
3.3
2.2
7100
7400
3600
3500
5900
2750 m 3/s
227 m 3/s
80
60
40
20
0
LOCATION, IN RIVER MILE



Legend
EDZ Boundaries
May 2002 Topography (m)
HIgh : 856.7
Low : 819.1
Bed Coarseness
Sand Greater than 75%
Gravel Bed Structure
Boulder Bed Structure
Boulder and Bedrock
Location Map
N
W
E
S
0
0.2
0.4
0.8
Kilometers



Location Map
Legend
EDZ Boundaries
Bed Surface Change (cm)
Value
-512 - -100
-100 - -25
-25 - 0
0 - 25
25 - 100
100 - 576
N
W
E
S
0
0.2
0.4
0.8
Kilometers


Legend
EDZ Boundaries
Bed Surface Change (cm)
Value
-547 - -100
-100 - -25
-25 - 0
0 - 25
25 - 100
100 - 921
Location Map
N
W
E
S
0
0.2
0.4
0.8
Kilometers

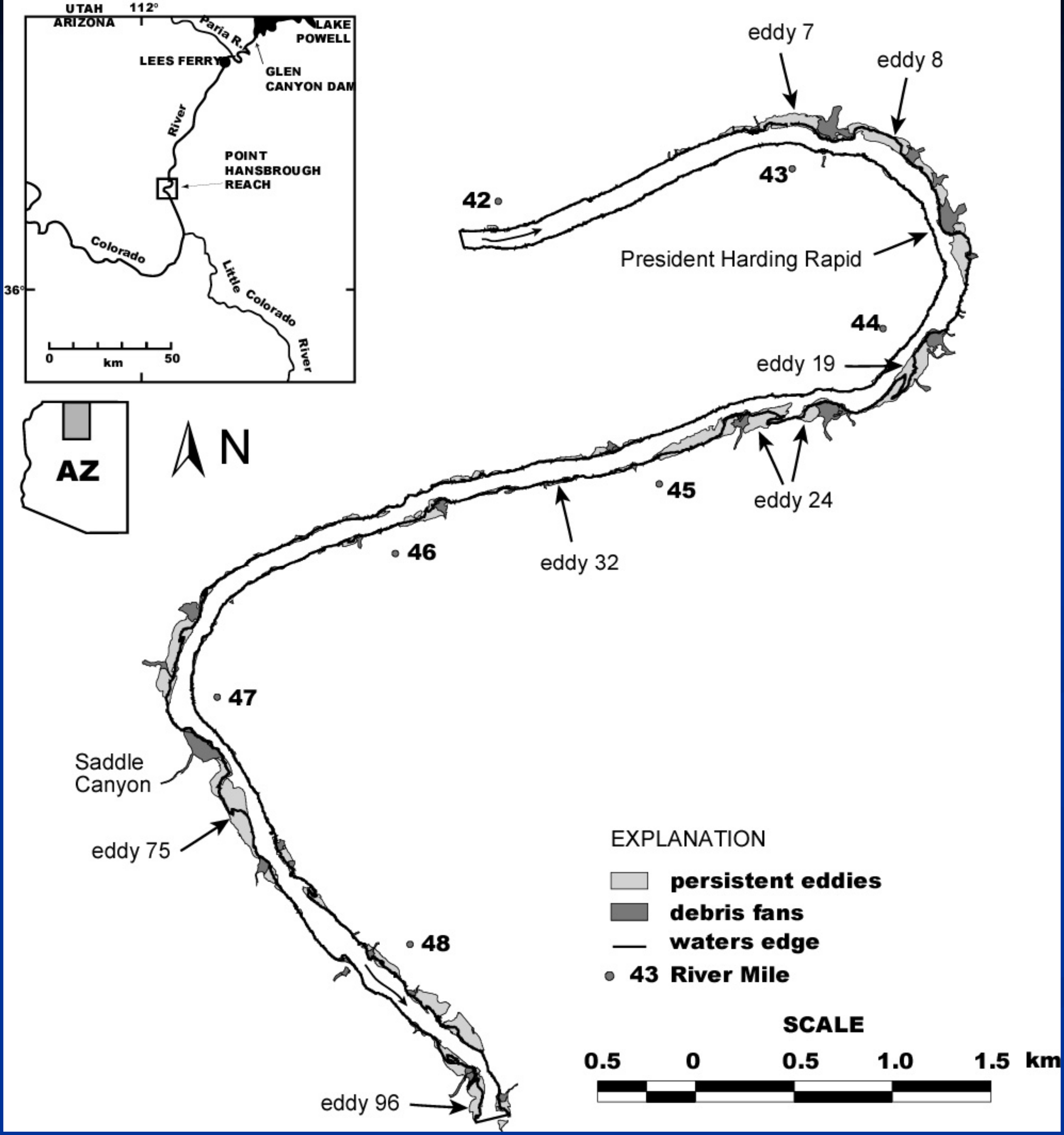


NORMALIZED MAIN CHANNEL SEDIMENT VOLUME
MEAN DISCHARGE DURING THE MONTH PRECEDING THE SURVEY, IN CUBIC METERS PER SECOND
discharge
sediment volume
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
700
600
500
400
300
200
100
0
-100
-200
-300
Jan/1/1992
Jan/1/1993
Jan/1/1994
Jan/1/1995
Jan/1/1996
Jan/1/1997
Jan/1/1998
Jan/1/1999
Jan/1/2000
Jan/1/2001

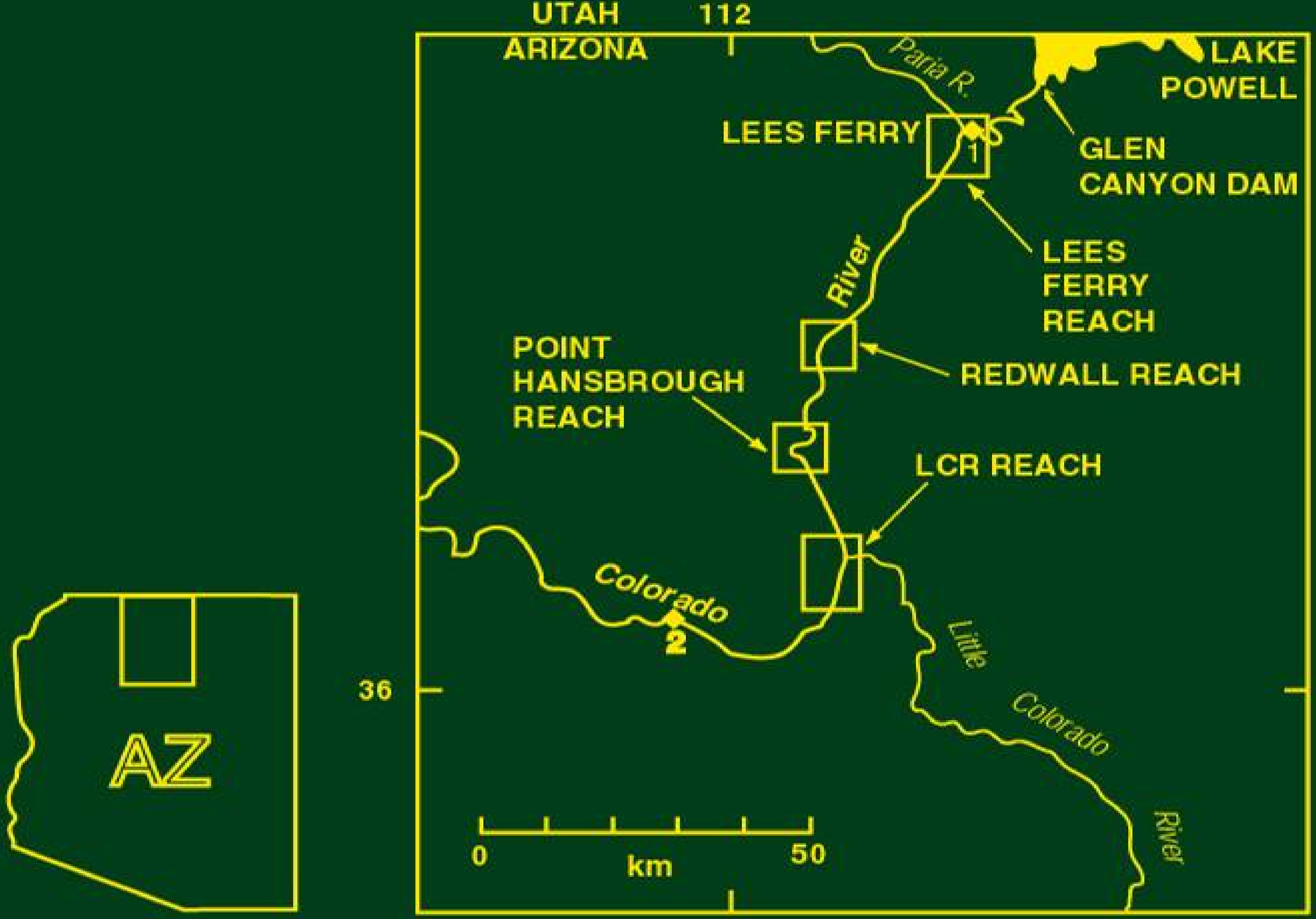
Fan-Eddy Complex

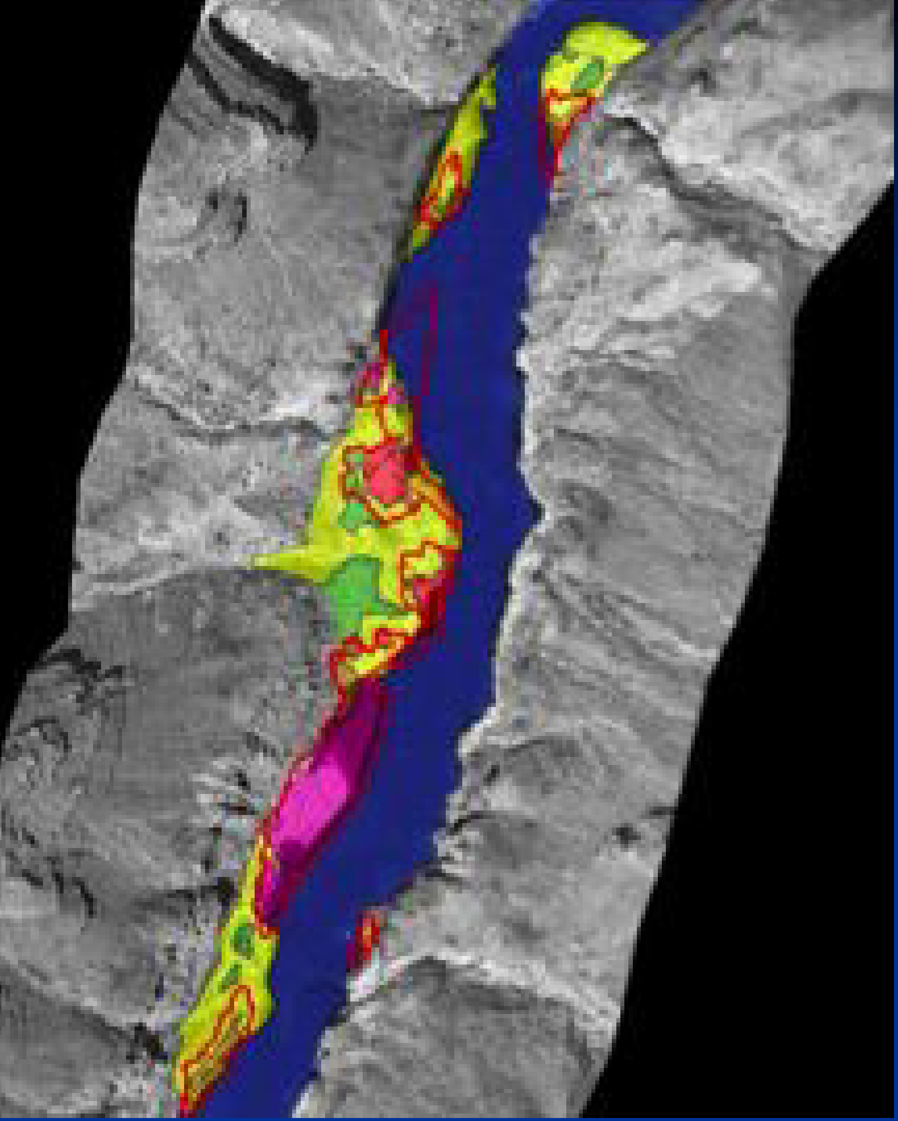
(Schmidt and Rubin 1995)

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.



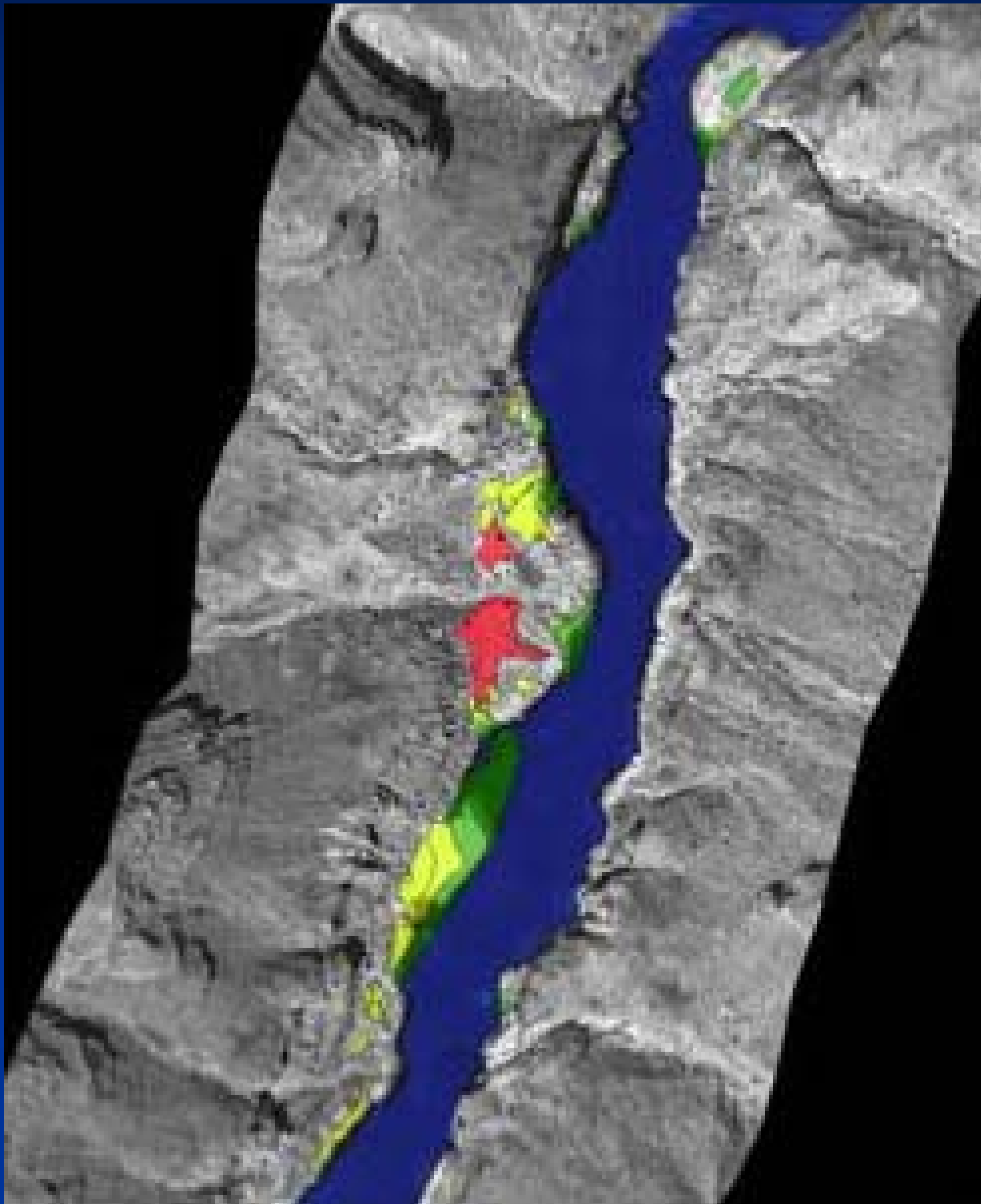
UTAH
ARIZONA
112°
Paria R.
LAKE POWELL
LEES FERRY
GLEN CANYON DAM
River
POINT HANSBROUGH REACH
Colorado
36°
Little Colorado River
0 km 50
AZ
N
eddy 7
eddy 8
42
43
President Harding Rapid
44
eddy 19
45
eddy 24
46
eddy 32
47
Saddle Canyon
eddy 75
48
eddy 96
EXPLANATION
persistent eddies
debris fans
waters edge
43 River Mile
SCALE
0.5 0 0.5 1.0 1.5 km


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

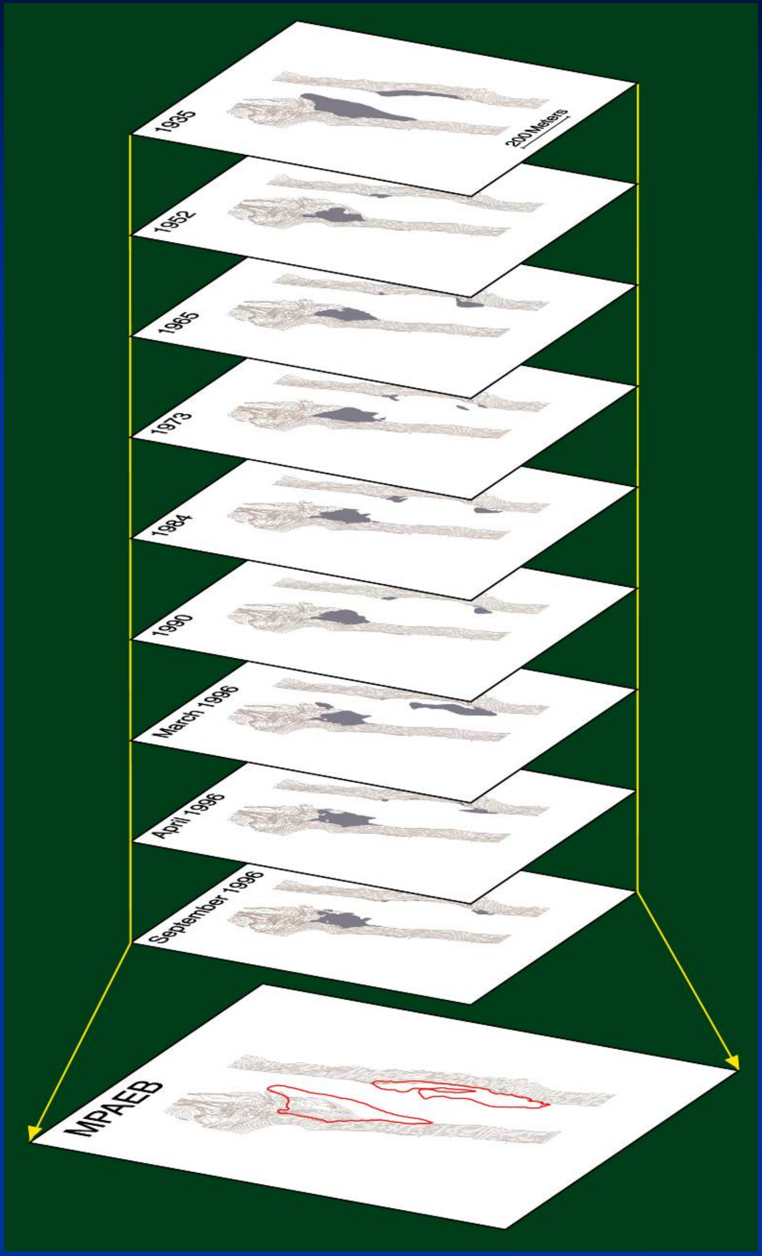


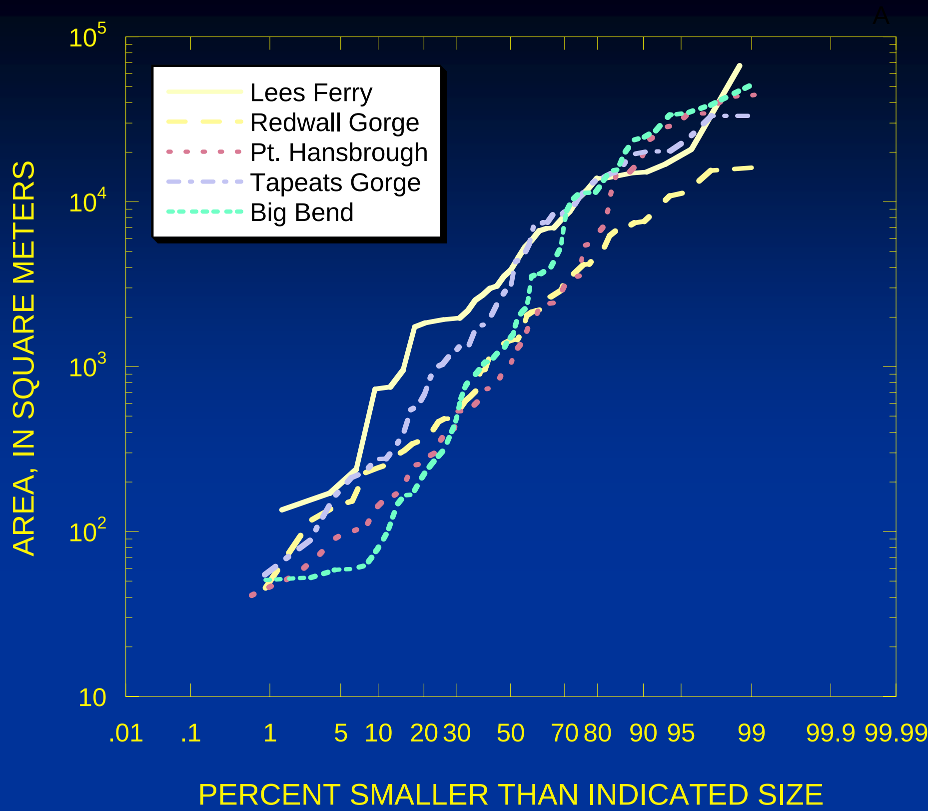
Geomorphic features

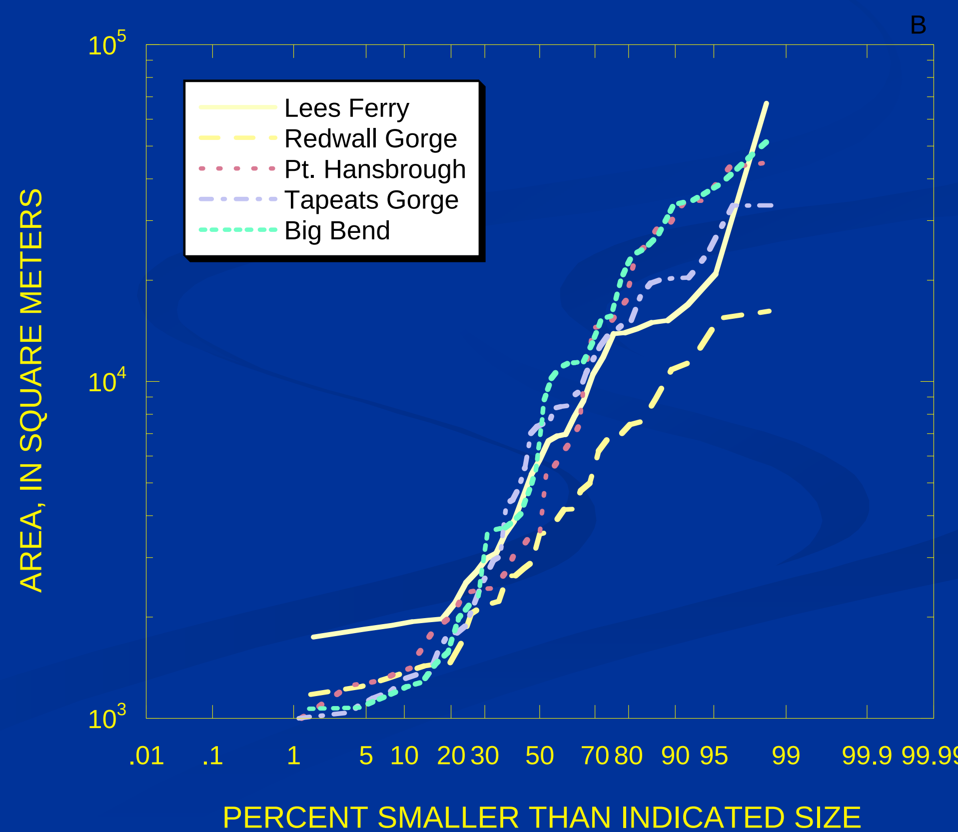
Formative discharges



Eddy Deposition Zone (EDZ)




A
AREA, IN SQUARE METERS
10^5
10^4
10^3
10^2
10
Lees Ferry
Redwall Gorge
Pt. Hansbrough
Tapeats Gorge
Big Bend
.01 .1 1 5 10 20 30 50 70 80 90 95 99 99.9 99.99
PERCENT SMALLER THAN INDICATED SIZE


B
AREA, IN SQUARE METERS
10^5
10^4
10^3
Lees Ferry
Redwall Gorge
Pt. Hansbrough
Tapeats Gorge
Big Bend
.01 .1 1 5 10 20 30 50 70 80 90 95 99 99.9 99.99
PERCENT SMALLER THAN INDICATED SIZE

		Lees Ferry Reach (RM 0-8)	Redwall Gorge Reach (RM 29-35)	Point Hansborough Reach (RM 42-50)	Tapeats Gorge Reach (RM 60-65)	Big Bend Reach (RM 65-72)
Reach length, in kilometers		14	10	10.8	8.0	12.1
Total number of EDZs	all	37	56	81	57	56
	> 1000 m^2	31	33	41	44	34
EDZ frequency, in number per kilometer	all	2.6	5.6	7.5	7.1	4.6
	> 1000 m^2	2.2	3.3	3.8	5.5	2.8
Total area of EDZs	all	287,400	167,100	453,460	406,930	414,630
	> 1000 m^2	284,430	157,450	437,120	402,230	407,410
Total EDZ area per kilometer	all	20,500	16,700	42,000	50,900	34,300
	> 1000 m^2	20,300	15,700	40,500	50,300	33,700
Mean size	all	7800	3000	5600	7100	7400
	> 1000 m^2	9200	4800	10,700	9100	12,000
Median size	all	3900	1400	1000	3000	1500
	> 1000 m^2	5900	3500	3600	7400	7100
Notabley large EDZs (location in River Mile and size in square meters)		1.2R: 67,000		43.6L: 34,300 44.5L: 34,400 47.1R: 43,300 47.6R: 45,000	63.5L: 33,300 64.4L: 34,300	66.1L: 34,500 68.2L: 52,800 71.3L: 38,600 71.7L: 33,500

Back of the envelope calculations

183 EDZs > 1000 m^2 in Marble and upper Grand Canyons

~3 EDZ > per km in Marble Canyon

~300 EDZ in Marble Canyon

Total area of EDZ/km = 26,000 m^2/km

~2,600,000 m^2 in Marble Canyon (20% of water surface at flood stage)

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

More back of the envelope

Mean void volume thickness = 3.2 m

Potential storage volume of eddies = ~8,300,000 m^3

Potential storage mass of eddies = ~13,100,000 metric tons

Previous Studies of Fine-Storage Flux and Storage

An Early Sediment Budget

(Dolan et al. 1974)

- “At Lees Ferry, the median suspended-sediment concentration has been reduced by a factor of about 200. Farther downstream, however, there is less reduction because of additional sediment from tributaries and from the continuing erosion of pre-dam terraces and of the channel bed; at the gauging station near Phantom Ranch the factor of reduction is about 3.5.”
- “Quantification of erosion rates and of the balance between sediment losses and deposition is difficult. Base-line studies have not been made, and there is no systematic measurement program.”

A Bleak Future Prognosis Based on a Sediment Budget *(Laursen et al. 1976)*

- "At present, the mean annual capacity of the river to carry beach-building material is about 12 million metric tons per year. The tributaries supply about 2.7 [million] metric tons of beach-building sediment per year. The difference of about 9 million metric tons per year must be obtained through scour of bed and/or banks."

- "… the beaches … could be in danger of being washed away since the transport capacity of the regulated river is in excess of the amount of beach-building material being supplied from the tributaries … How long they will last cannot as yet be estimated; certainly more than 10 years, probably less than 1000 years; but how much more or less than 100 years is a matter for continued study."

An Optimistic Alternative Future

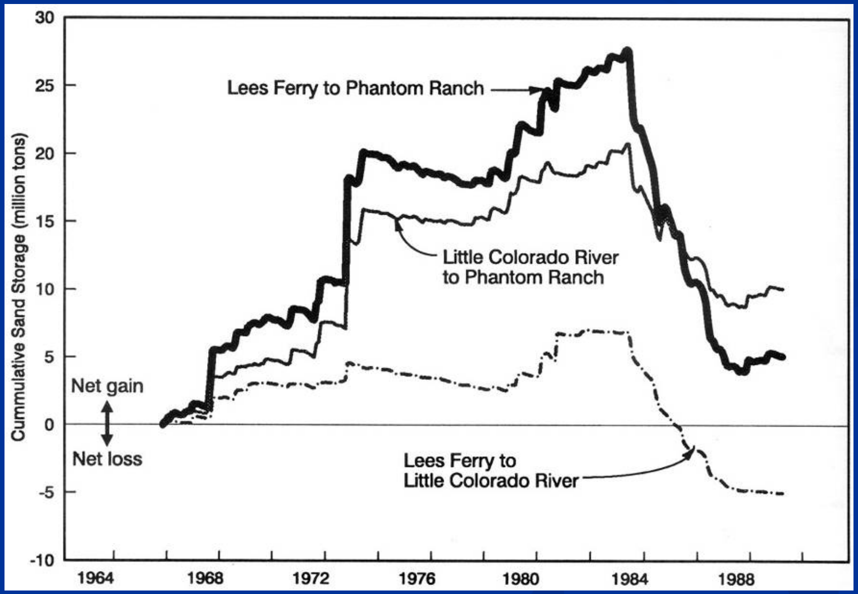
Prognosis Based on a Sediment Budget

(Howard and Dolan 1981)

- "The sand-size and finer sediment transported by the Colorado River is the most important size range both in terms of the extent of deposits and its relative abundance in the sediment load. Furthermore, the fine-grain sizes are the most conspicuously affected by Glen Canyon Dam."
  - $\Delta S = LF + LC + PR + M (LC + PR) - GC$
- Used monthly transport data, assumed that transport relations did not change with time, assumed that bed was the major repository of sand (~75% of bed covered by sand), assumed that only minor changes in banks and eddy bars were occurring.
- "**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**." (based on budget calculation and only calibrated by observations at the Lees Ferry and Grand Canyon gage cross-sections)

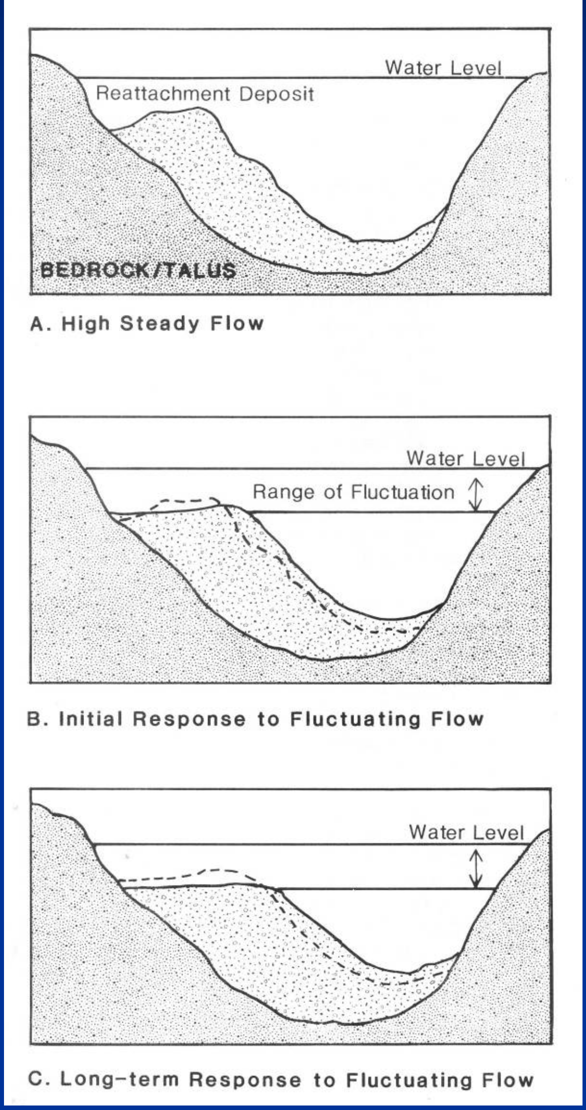
Continued Optimism: Fine Sediment Can Be Accumulated and Managed

- "A three-fold decrease in mean annual peak water discharge, plus the large contribution of sediment by tributaries, results in a surplus rather than a deficit of sediment." *(Andrews, 1990)*
- "… flow fluctuations and corresponding sand transport in the Colorado River can be managed to achieve a balance with long-term average annual sand inputs from the Paria River." *(Smillie et al., 1993)*



Final GCD EIS, 1995

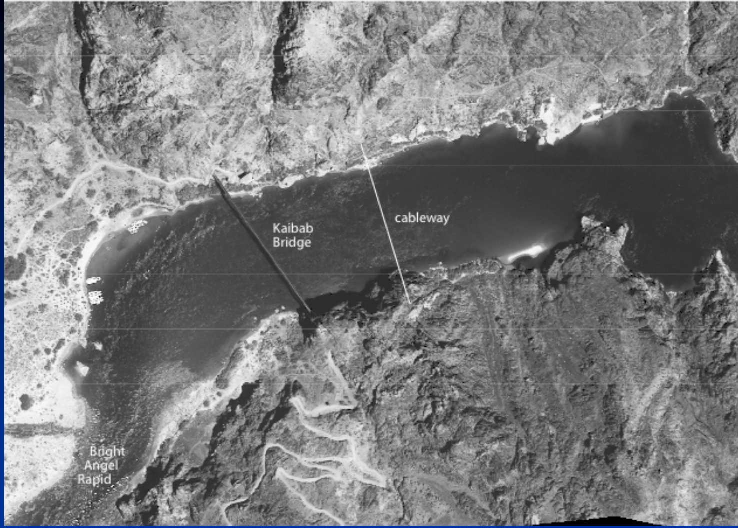
A Conceptual Model of Sediment Storage Unconstrained by Data

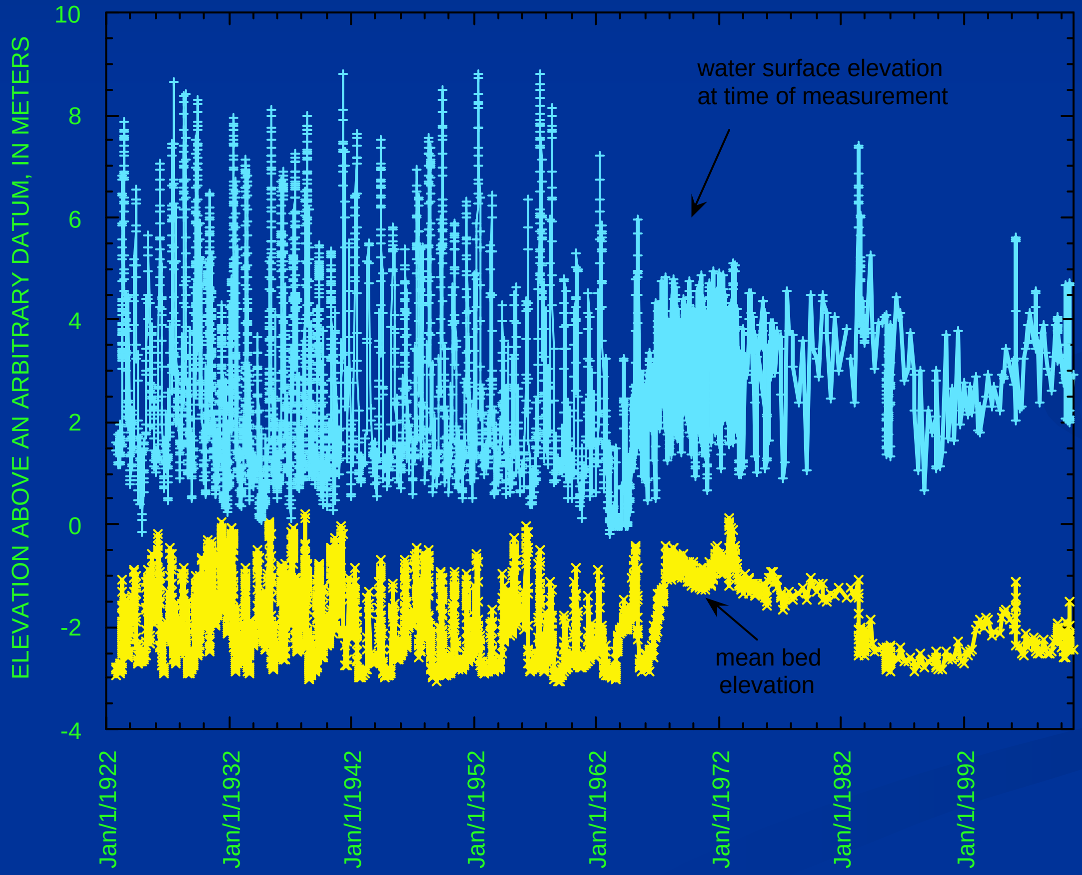


- This model was proposed as consistent with the calculated budget surplus and consistent with field measurements of beach erosion and bed measurements at two gages

(GCES, 1989)

Changes in the Topography of the Main Channel Bed





Long-term (1922-1962) degradation of bed of pool = 1.6 cm/yr

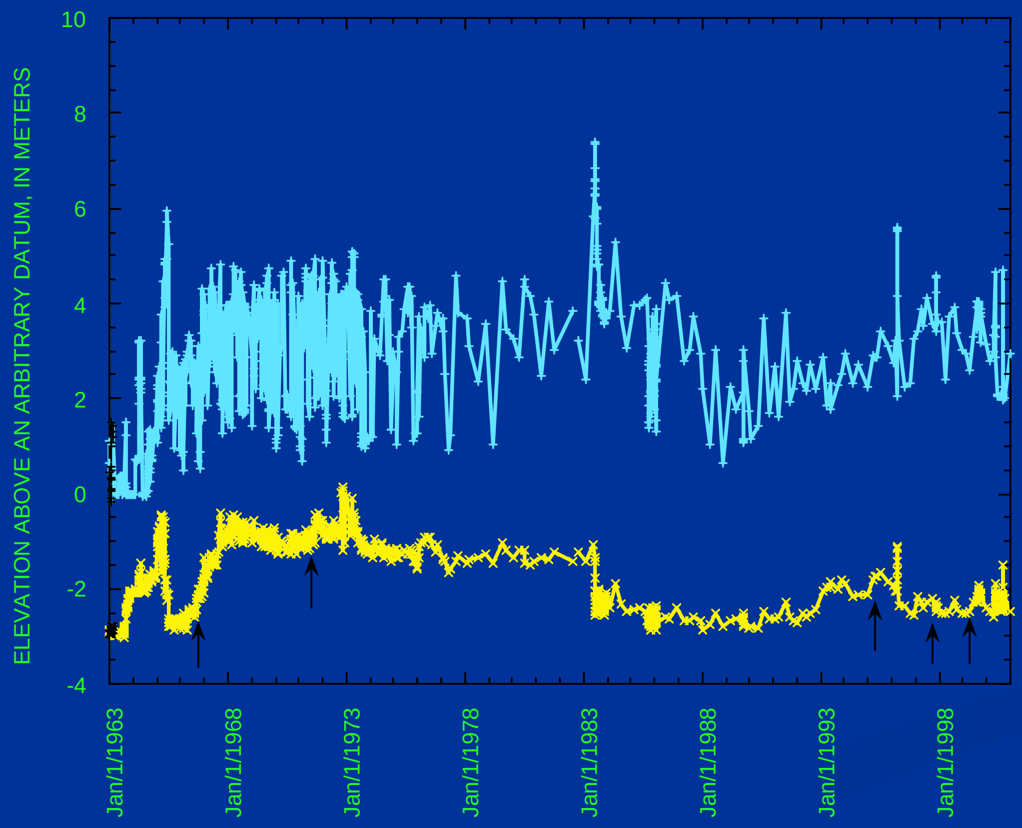
Due to long-term decrease in sediment delivery (Topping et al. 2000)

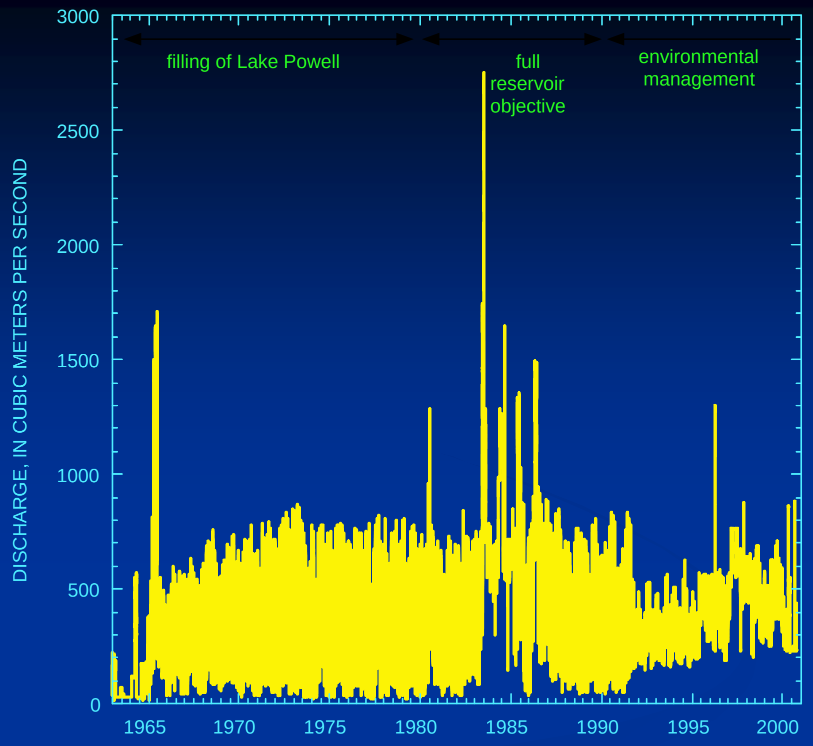
Seasonal sediment accumulation, in metric tons	Equivalent volume, in cubic meters[1]	Equivalent thickness, in meters, under three assumptions about the relative proportion of fine sediment stored in eddies and in the main channel and two assumptions about the proportion of the channel that can store 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)

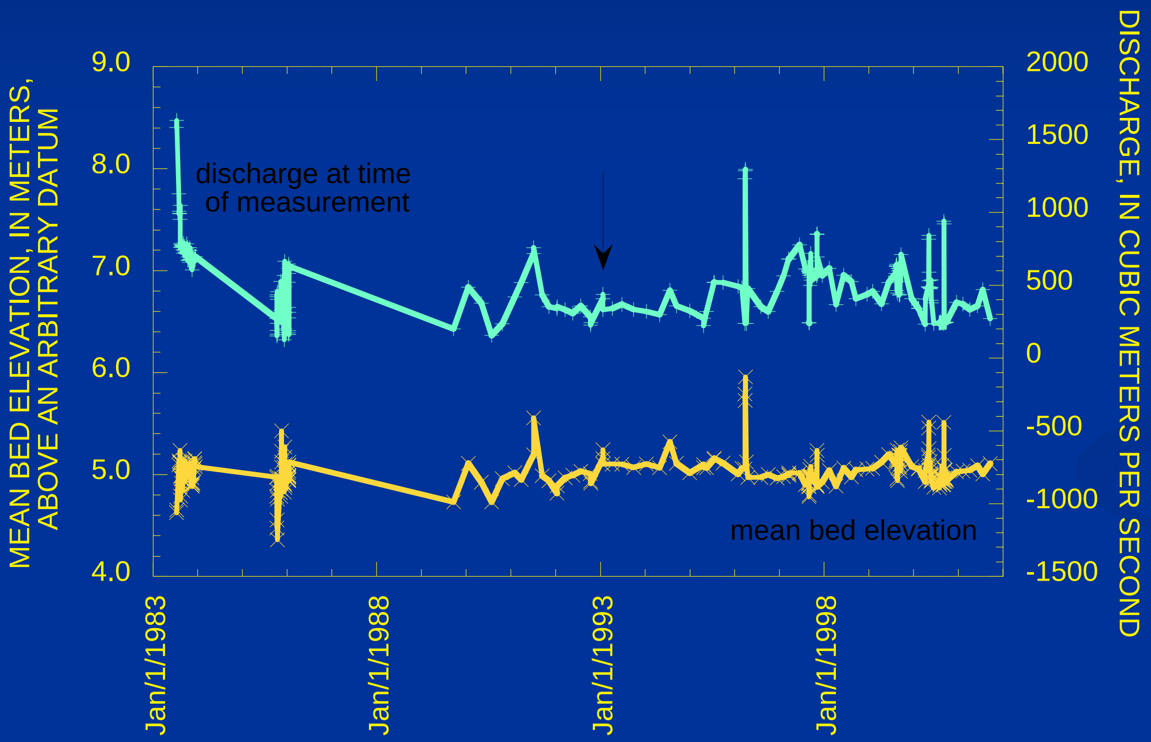
[1] assumes bulk specific weight of fine sediment is 1570 kg/m^3

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

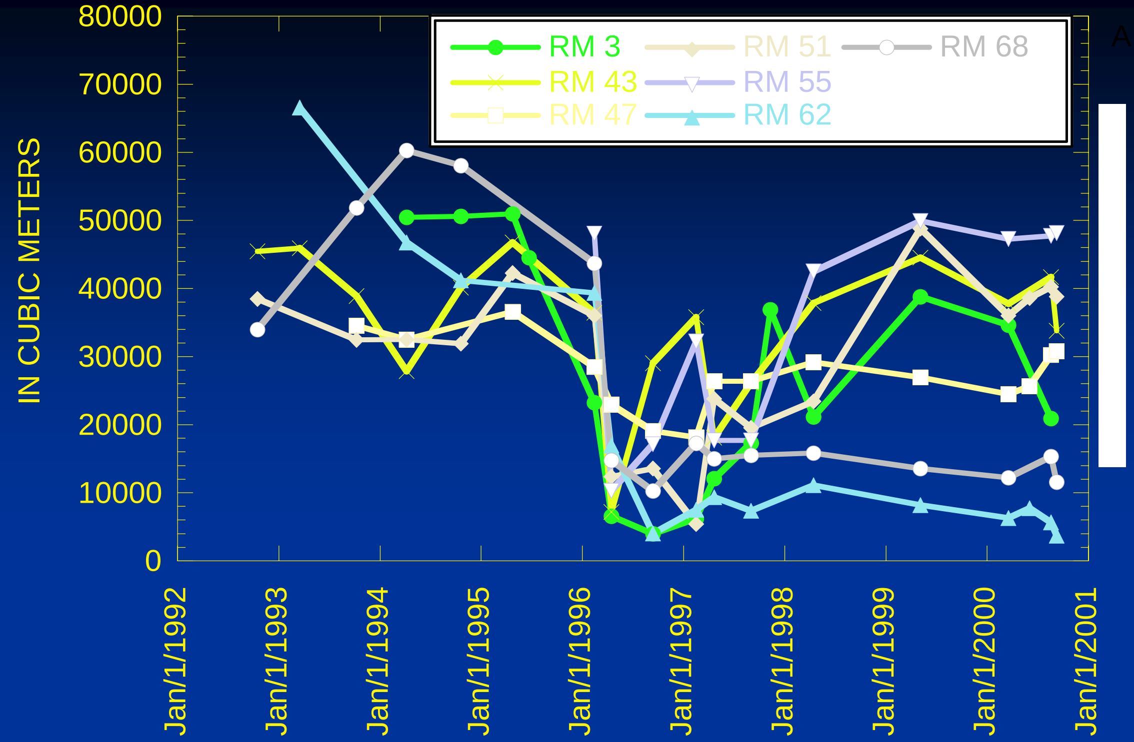
Location	Average change in bed elevation between 1950 and 2000, in meters	Average change in bed elevation between 1998 and 2000, in meters
RM 32.8A	0	
RM 32.8B	+0.1	
RM 39.5A	-0.9	
RM 39.5B	-1.0	0
RM 39.5C	-1.0	0
RM 39.5D	-0.4	+0.1


ELEVATION ABOVE AN ARBITRARY DATUM, IN METERS
10
8
6
4
2
0
-2
-4
Jan/1/1963
Jan/1/1968
Jan/1/1973
Jan/1/1978
Jan/1/1983
Jan/1/1988
Jan/1/1993
Jan/1/1998


filling of Lake Powell
full reservoir objective
environmental management
DISCHARGE, IN CUBIC METERS PER SECOND
3000
2500
2000
1500
1000
500
0
1965
1970
1975
1980
1985
1990
1995
2000

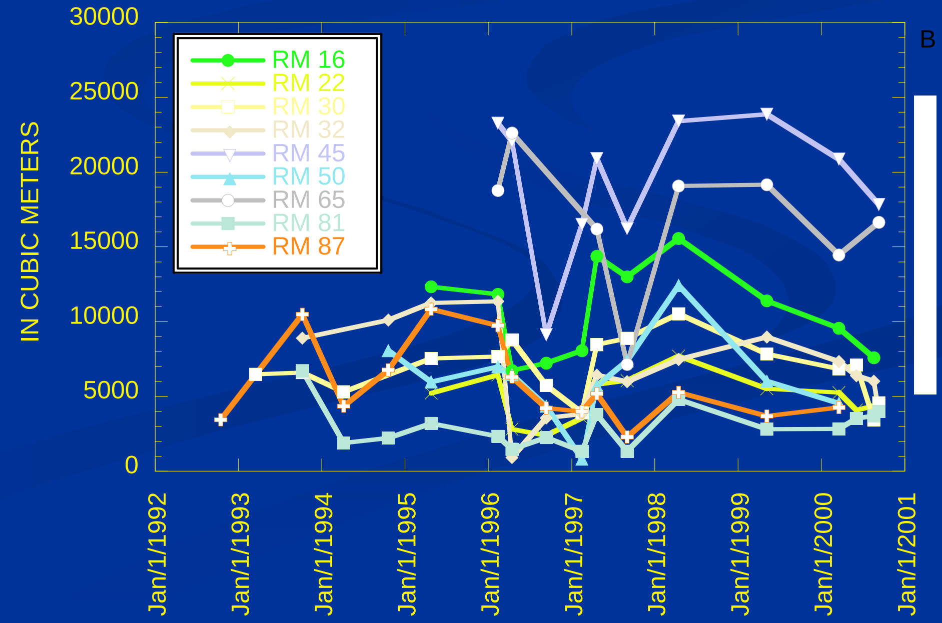


MEAN BED ELEVATION, IN METERS, ABOVE AN ARBITRARY DATUM
DISCHARGE, IN CUBIC METERS PER SECOND
9.0
8.0
7.0
6.0
5.0
4.0
2000
1500
1000
500
0
-500
-1000
-1500
discharge at time of measurement
mean bed elevation
Jan/1/1983
Jan/1/1988
Jan/1/1993
Jan/1/1998



Main channel pools offshore from eddies (NAU data)

No long-term aggradation



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

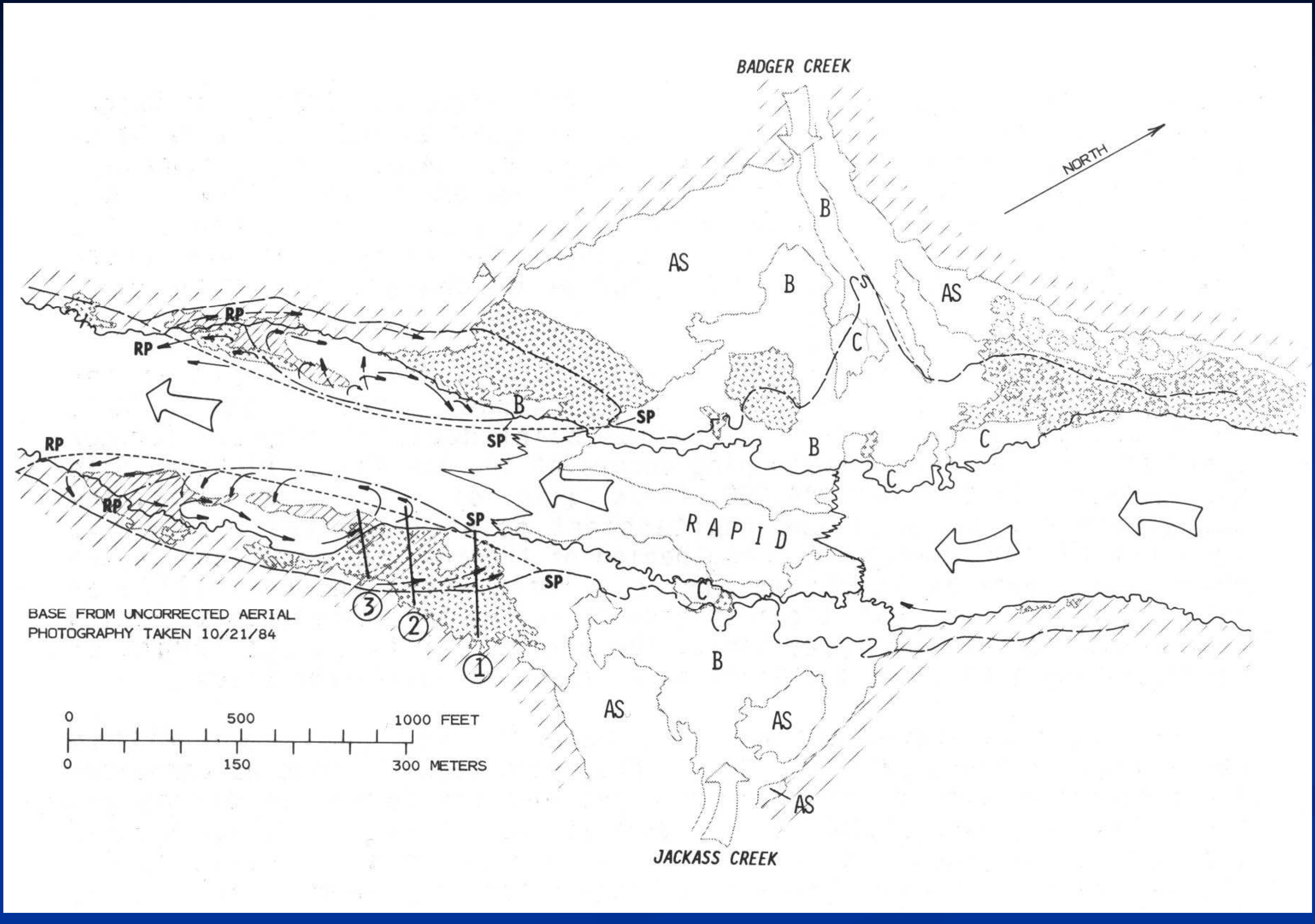
The Main Channel Bed

- Long-term slow loss of fine sediment in pre-dam period
- <30% of bed played significant role in seasonal accumulation
- Now, >90% of fine sediment is in eddies
- Multi-year accumulation only after local change in hydraulic controls

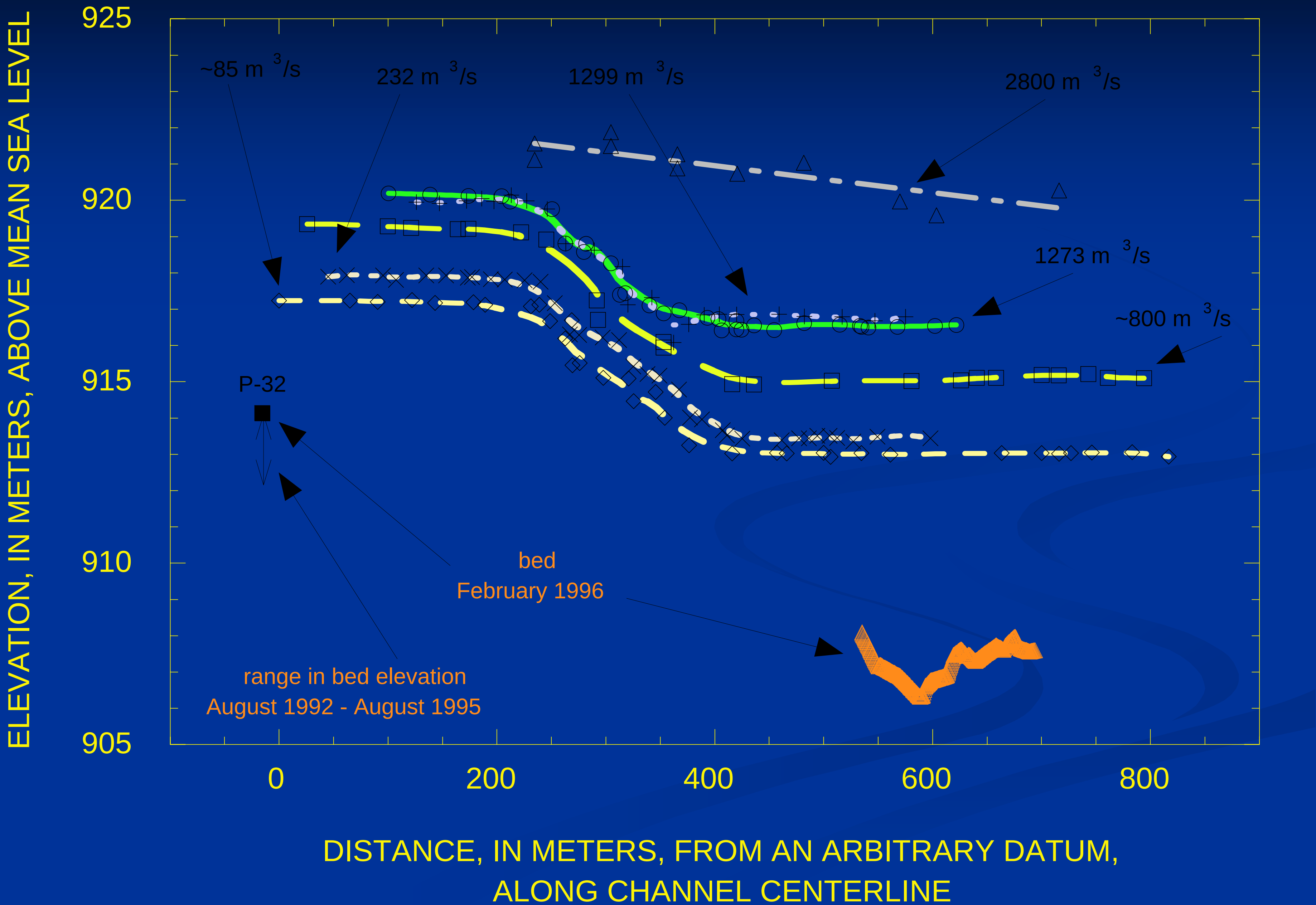
Now to the Eddies

History of Fine Sediment Storage at Specific Sites

The story of Badger Creek Rapids



BADGER CREEK
NORTH
AS
B
B
AS
C
RP
RP
B
SP
SP
C
B
RP
C
RP
SP
RAPID
SP
C
3
2
1
B
BASE FROM UNCORRECTED AERIAL
PHOTOGRAPHY TAKEN 10/21/84
0
500
1000 FEET
0
150
300 METERS
AS
AS
AS
JACKASS CREEK


925
920
915
910
905
ELEVATION, IN METERS, ABOVE MEAN SEA LEVEL
~85 m 3/s
232 m 3/s
1299 m 3/s
2800 m 3/s
1273 m 3/s
~800 m 3/s
P-32
bed
February 1996
range in bed elevation
August 1992 - August 1995
0
200
400
600
800
DISTANCE, IN METERS, FROM AN ARBITRARY DATUM,
ALONG CHANNEL CENTERLINE

1273 m^3/s

52-67 m^3/s

June 19, 1952

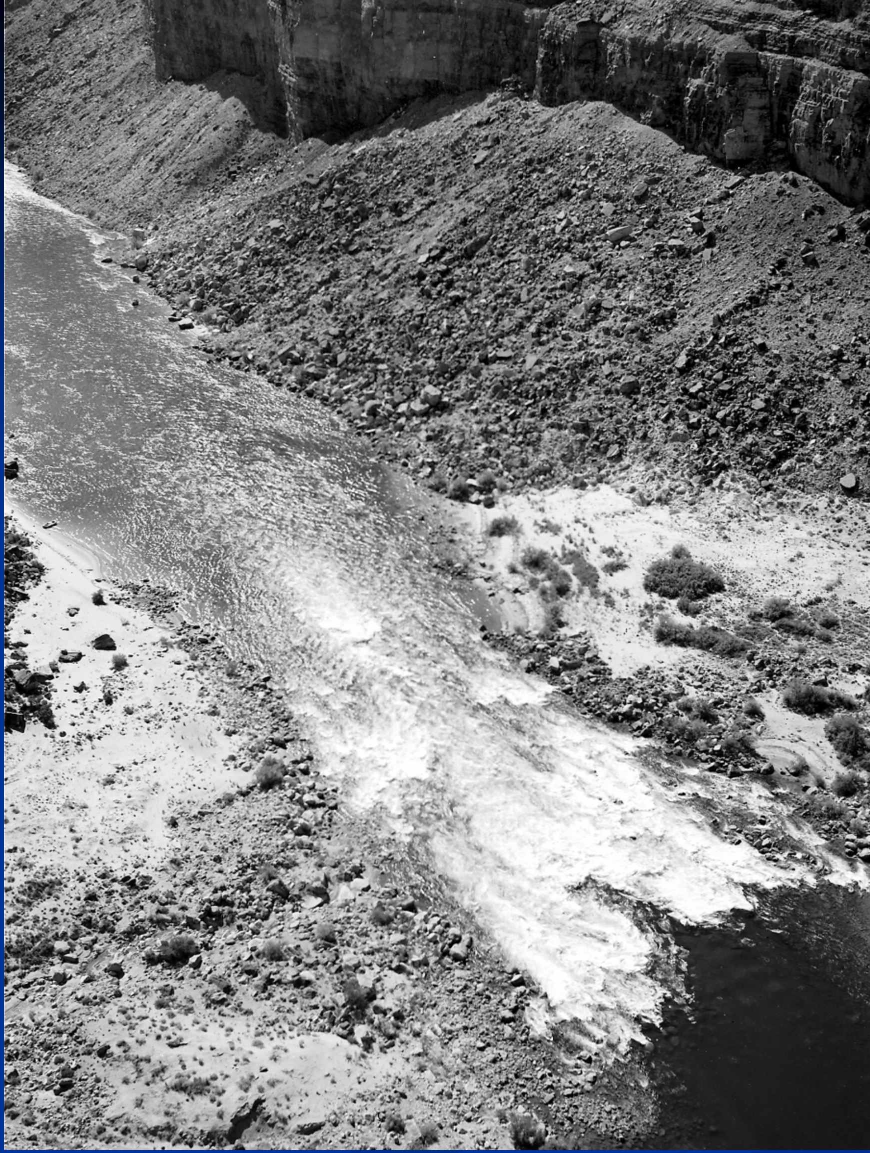
January 2, 1954

July 1956

August 1964

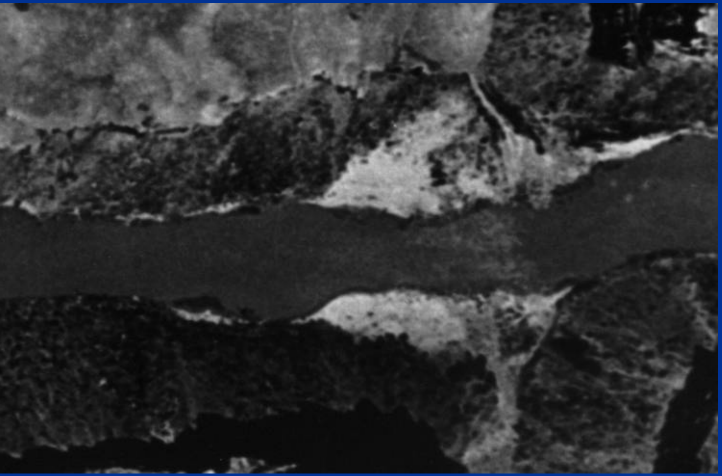
October 1968

August 21, 1972



October 4, 1991

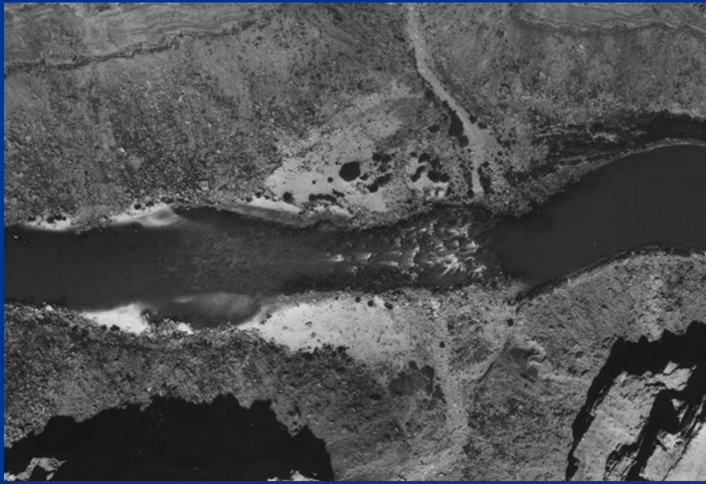
1935



1935

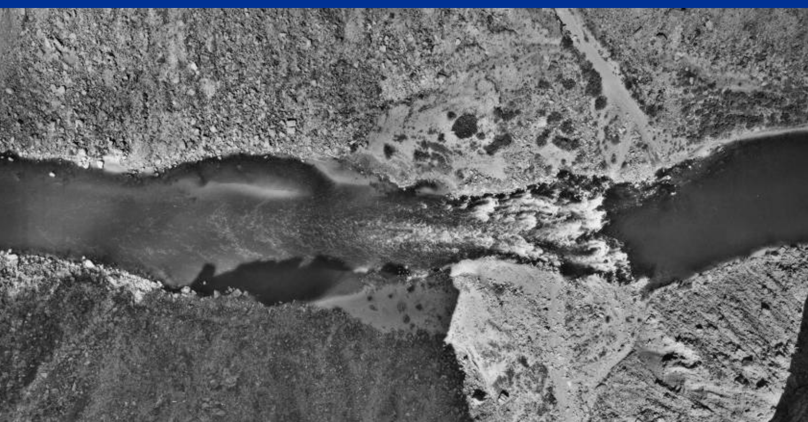
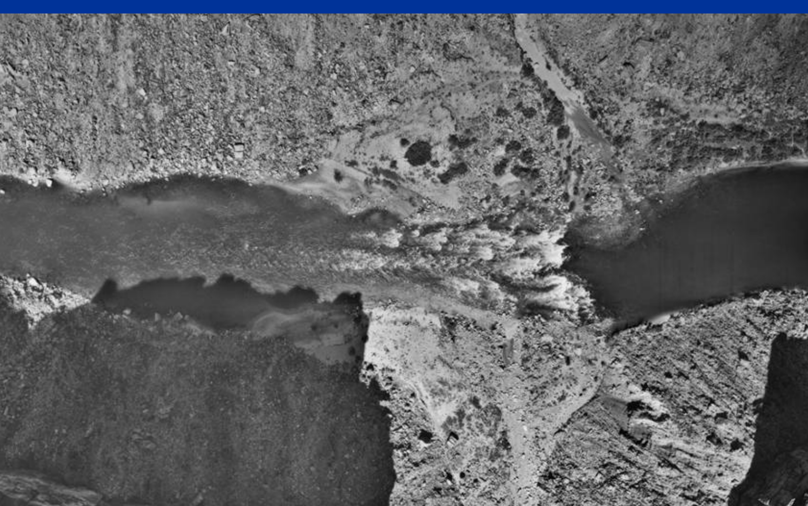
1952

1965



1973

1984

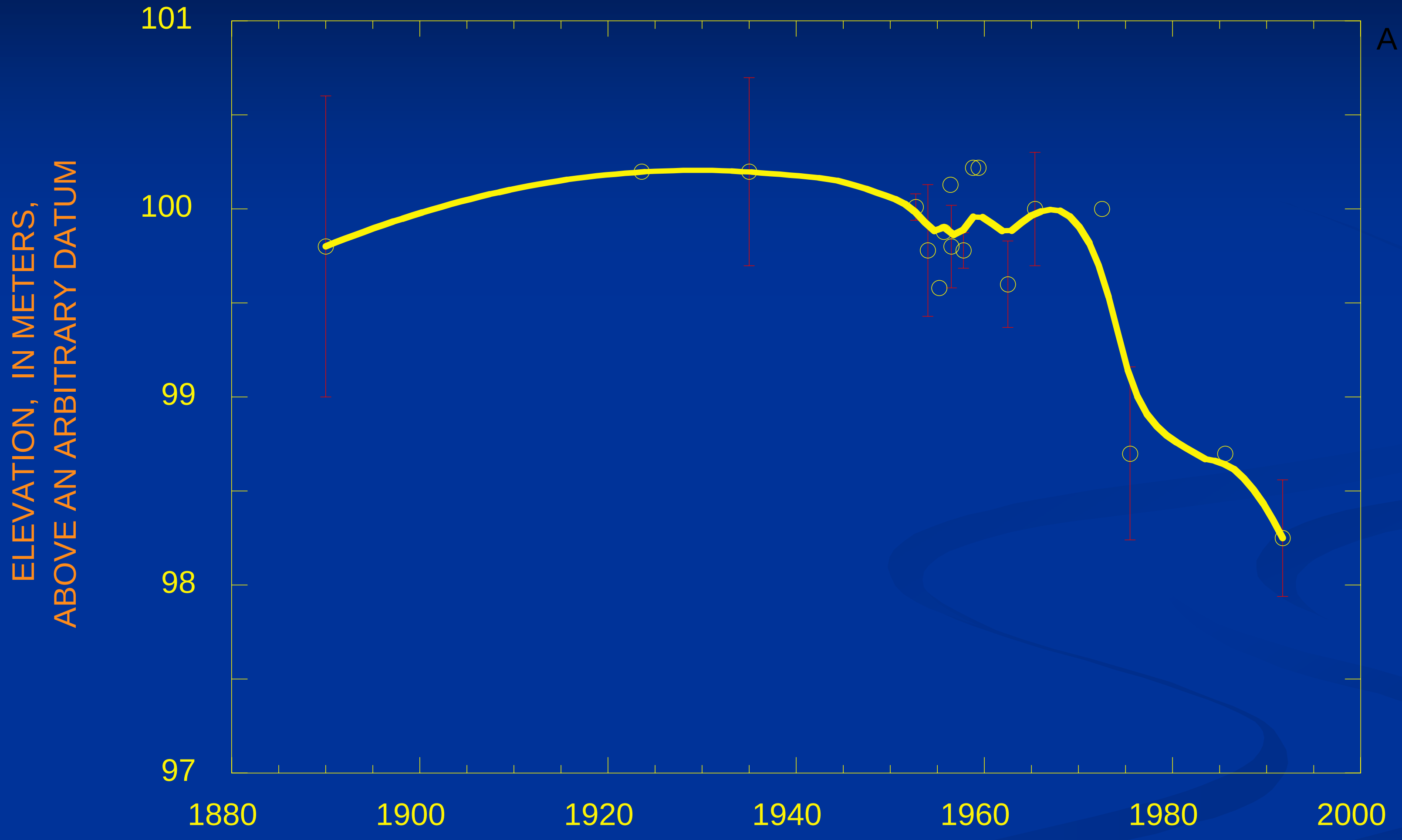





July 8, 1973

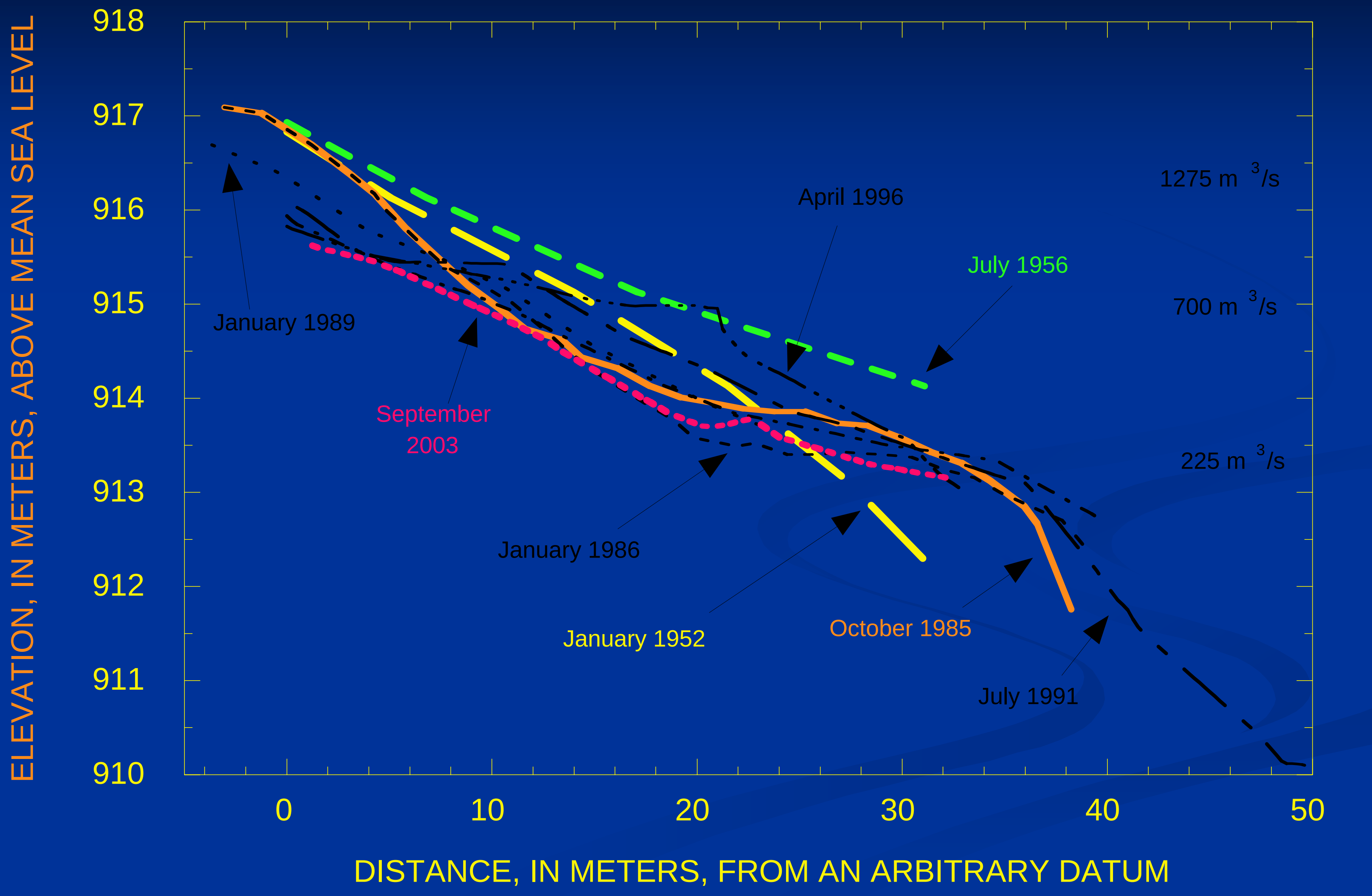
January 12, 1989

January 11, 1986

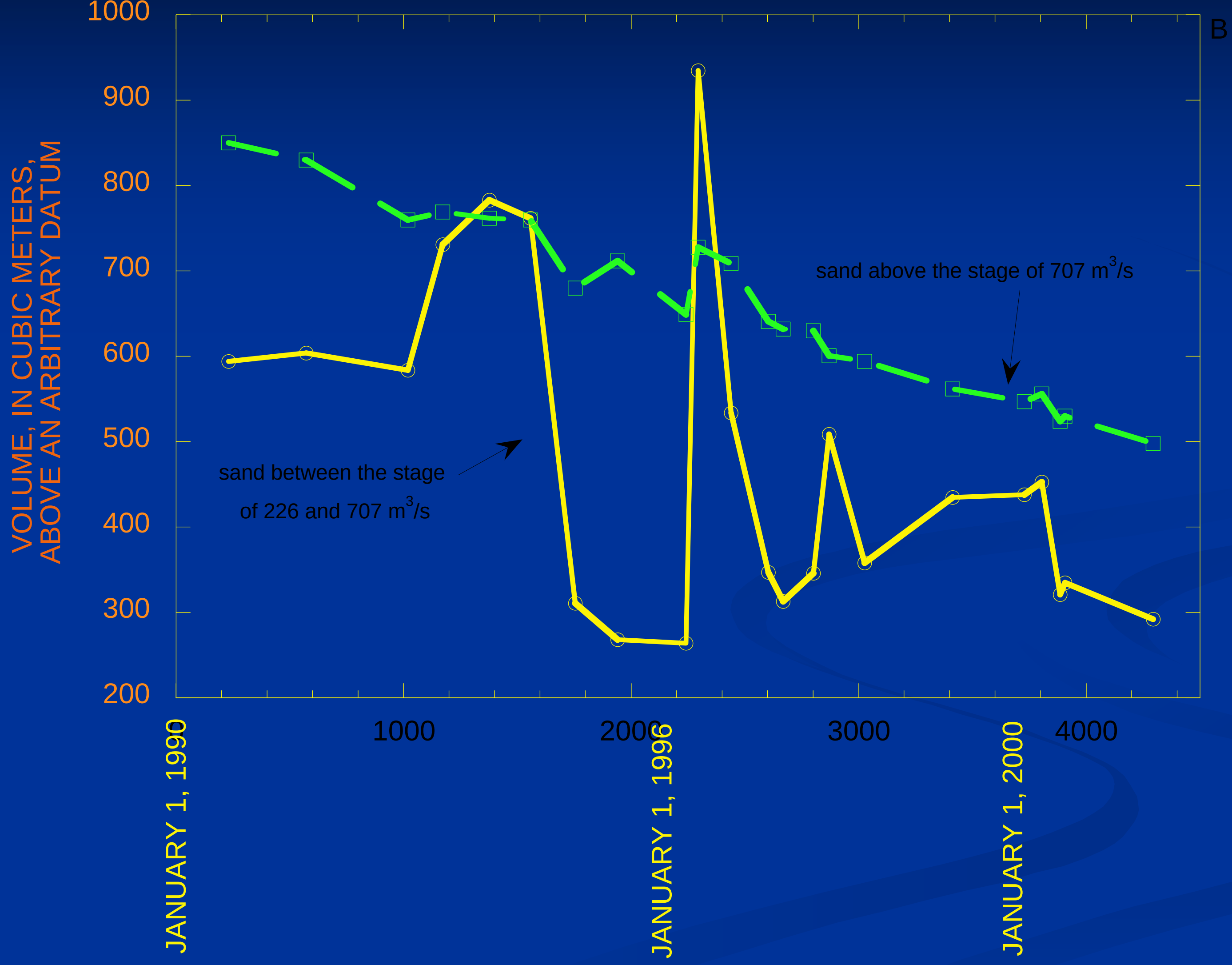
August 3, 1991



ELEVATION, IN METERS,
ABOVE AN ARBITRARY DATUM
101
100
99
98
97
1880
1900
1920
1940
1960
1980
2000
A

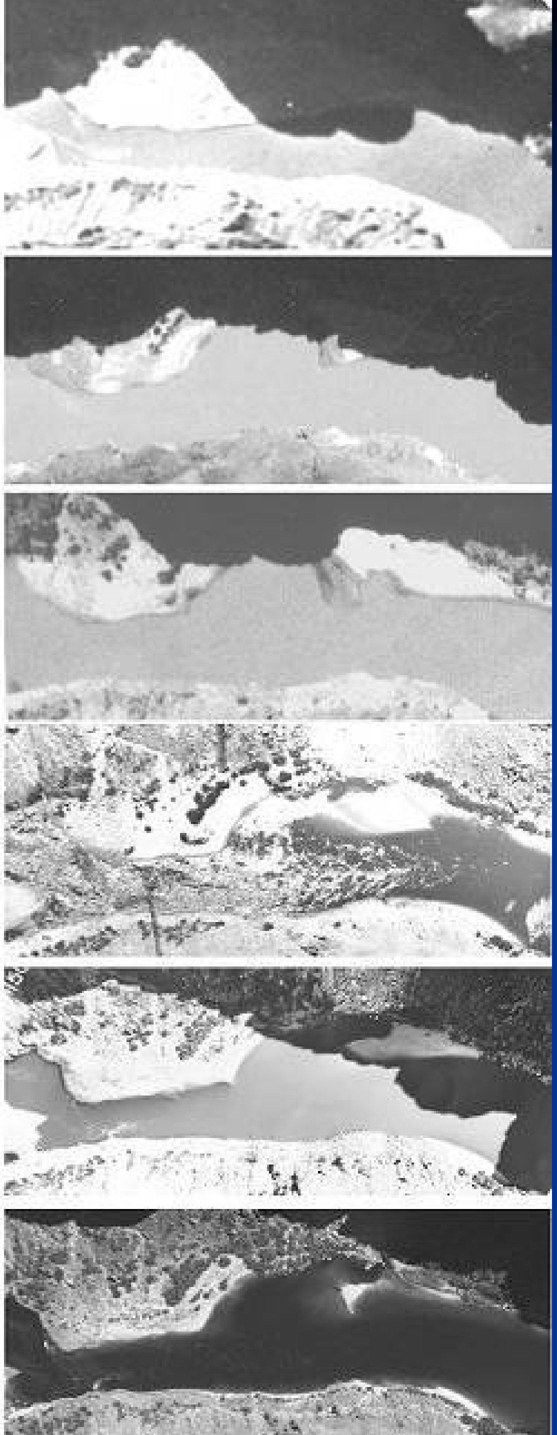


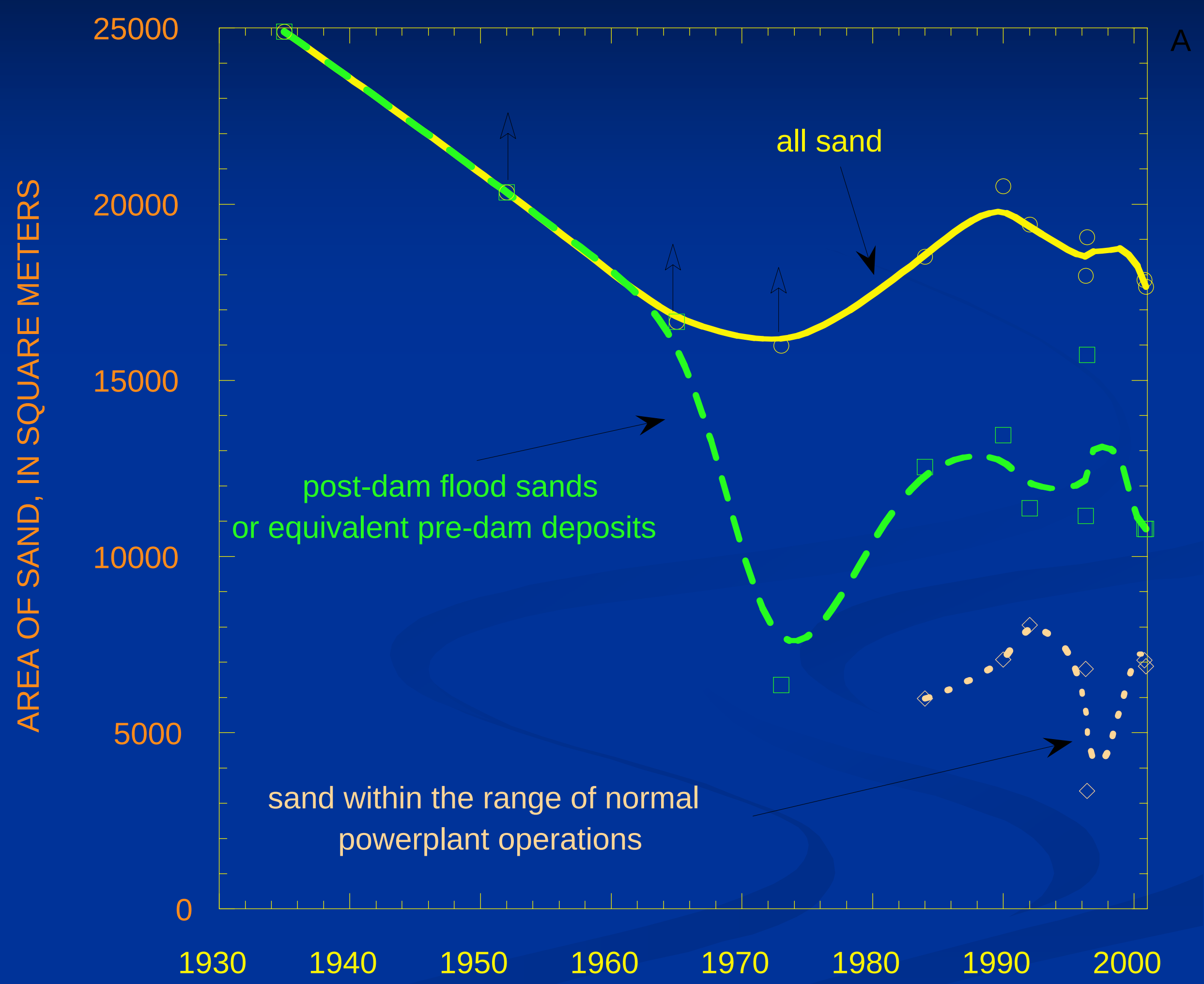
ELEVATION, IN METERS, ABOVE MEAN SEA LEVEL
918
917
916
915
914
913
912
911
910
0
10
20
30
40
50
DISTANCE, IN METERS, FROM AN ARBITRARY DATUM
1275 m ^{3}/s
700 m ^{3}/s
225 m ^{3}/s
April 1996
July 1956
January 1989
September 2003
January 1986
January 1952
October 1985
July 1991



VOLUME, IN CUBIC METERS, ABOVE AN ARBITRARY DATUM
1000
900
800
700
600
500
400
300
200
B
1000
2000
3000
4000
JANUARY 1, 1990
JANUARY 1, 1996
JANUARY 1, 2000
sand above the stage of 707 m3/s
sand between the stage of 226 and 707 m3/s

1935
1952
1956
1973
1984
, 2000



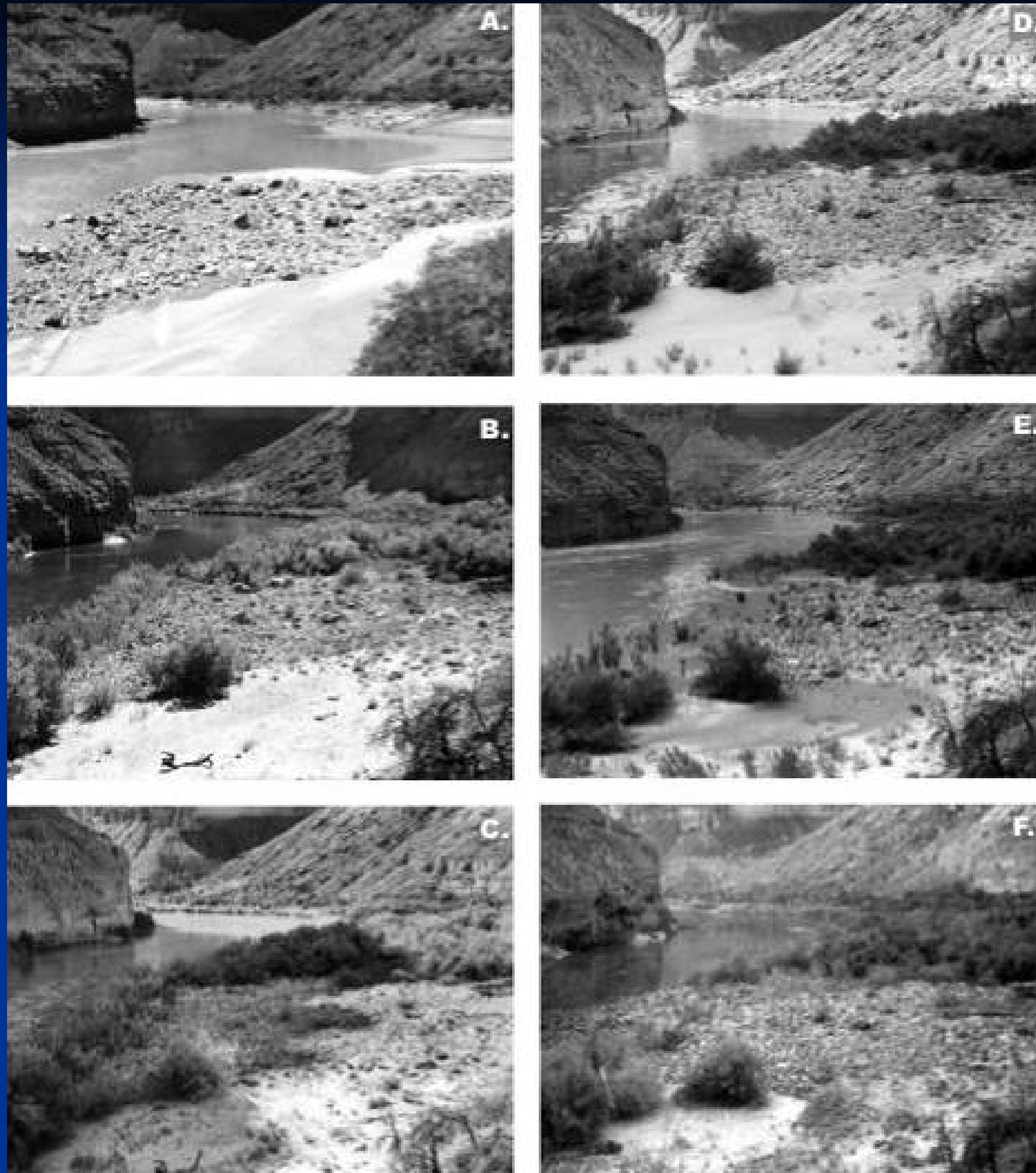


1897

1994

1923

1994



1923

1976

October 1982

October 1983

August 1984

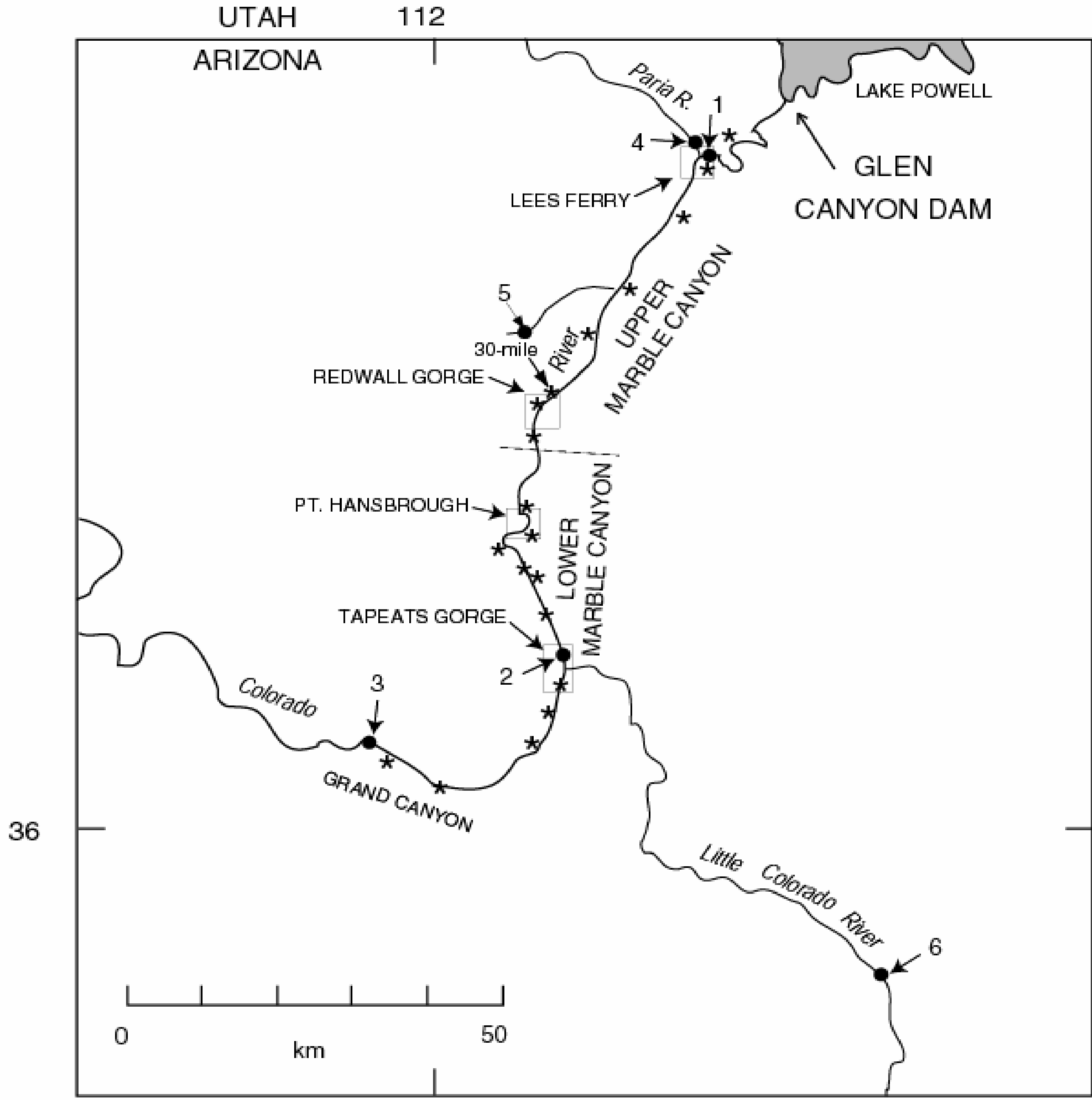
1990

Changes in the Area of Fine-Grained Alluvial Deposits Determined by Aerial Photograph Analysis

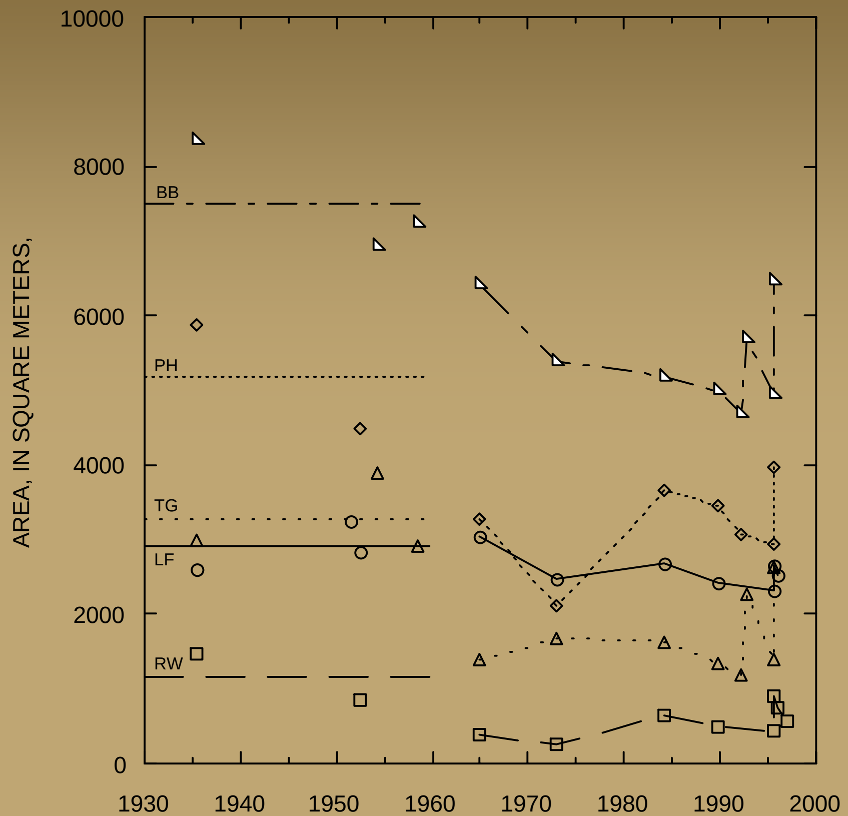
1,2,3,4,5,6 - gages

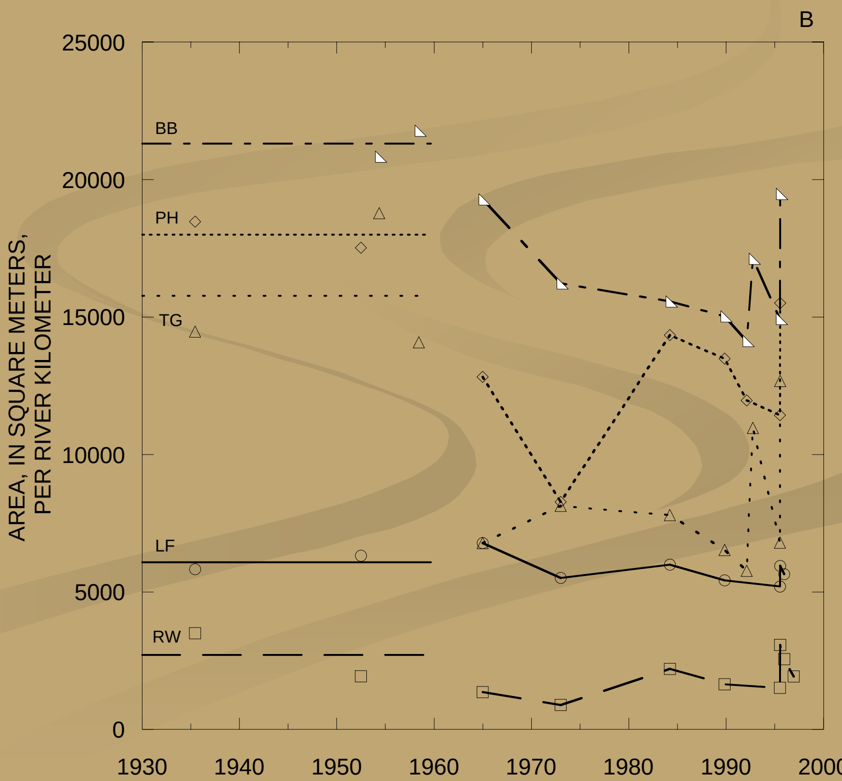
* - detailed survey sites

boxes - air photo analyses



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



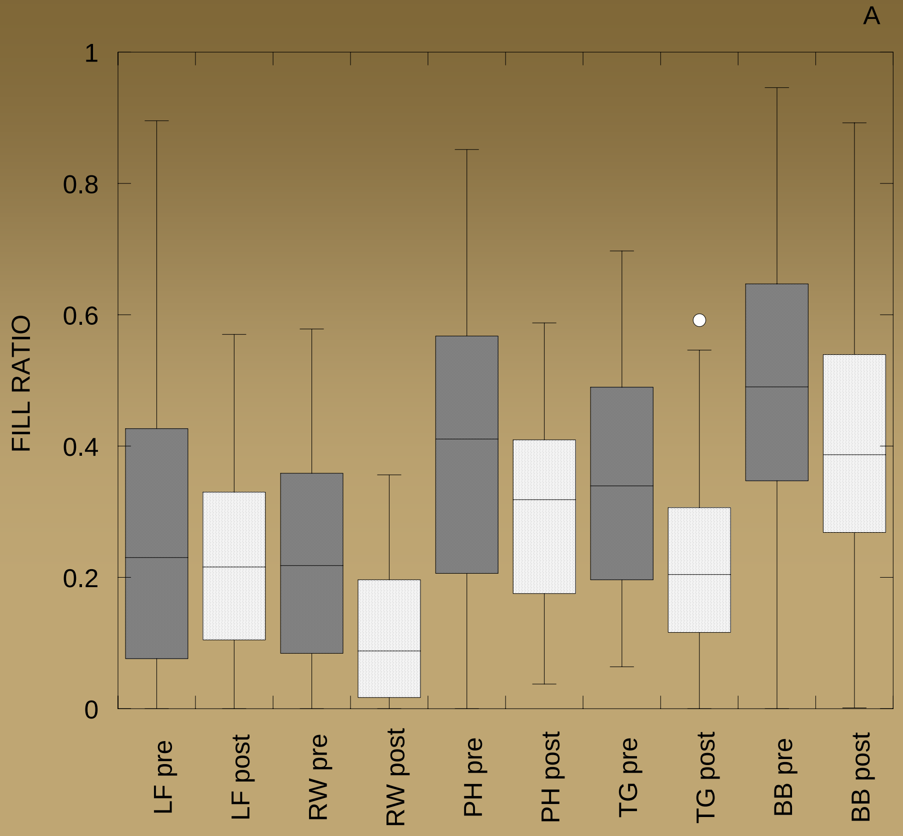


	EDZ inventory	mean	median
Lees Ferry			
All sand above water surface	-8%	-26%	-21%
Pre-dam and post-dam flood zone	-4%	-9%	-17%
Redwall Gorge			
All sand above water surface	+1%	-4%	+10%[1]
Pre-dam and post-dam flood zone	-1%	-47%	-55%
Point Hansborough			
All sand above water surface	-17%	-17%	+5%[1]
Pre-dam and post-dam flood zone	-20%	-25%	-17%
Tapeats Gorge			
All sand above water surface	-17%	-34%	-39%
Pre-dam and post-dam flood zone	-17%	-45%	-50%
Big Bend			
All sand above water surface	-12%	-17%	-4%
Pre-dam and post-dam flood zone	-14%	-23%	-38%

EDZ inventory = only consider EDZ where change > 1 SE of measurements

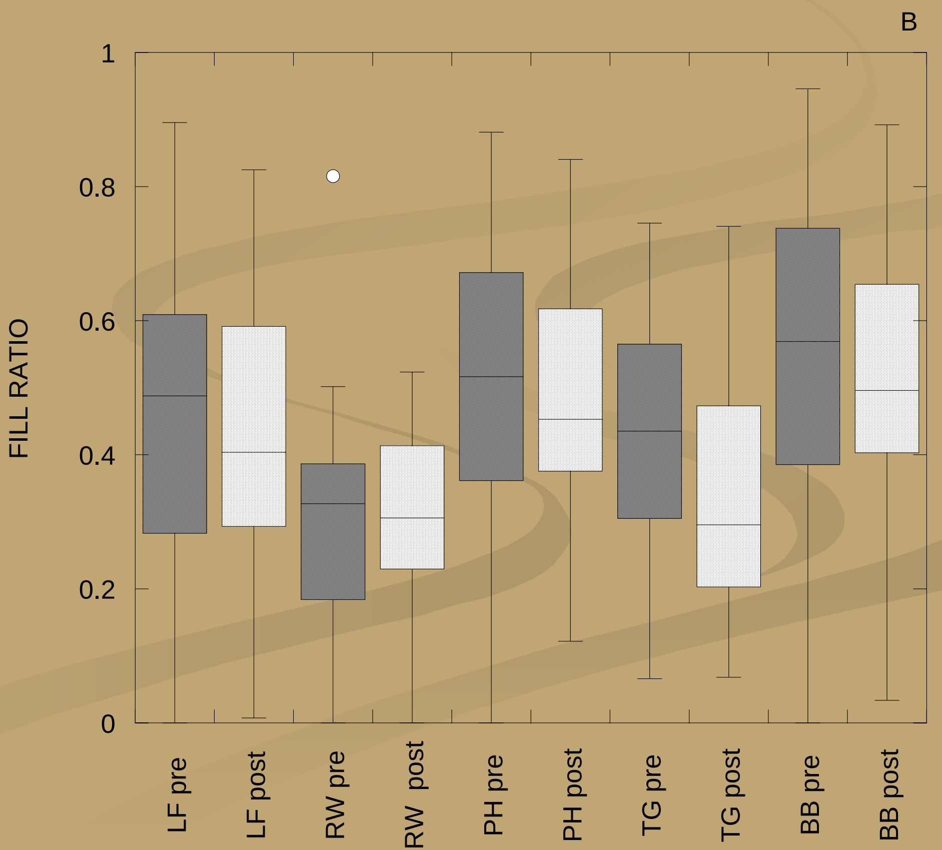
			All sand above water surface		Post-dam and pre-dam flood zone	
Location, in river mile (EDZ number)	Name of site	Eddy deposition zone area, in square meters	Decrease in area, in square meters	Increase in area, in square meters	Decrease in area, in square meters	Increase in area, in square meters
Lees Ferry						
1.1R (4)	Below Paria Riffle	67,000	22,100		7,700	
1.3L (5)		14,000	4,200			
2.4L (9)		7,000			500	
2.5L (10)	Above Cathedral Wash (NAU)	11,800	500		600	
2.8R (12)	Cathedral Wash	8,800	600			
4.1L (19)	Four Mile Wash	14,400	800			
5.9R (30)	Six Mile Wash	14,900	1,500			
6.0L (31)	Six Mile Wash	10,500	800			
6.6R (32)		13,800				300
7.0L (33)		20,900	1,600			
7.5L (34)		6,900		2,300		1,200
8.1R (36)	Badger	15,200	2,300		2,200	
8.1L (37)	Jackass (NAU)	16,900	1,300		500	
Redwall Gorge						
29.8R (2)		8,200			200	
30.7R (8)	Fence Fault (NAU)	11,500		100		
33.6R (34)		5,000			300	
34.2L (47)		6,800		300		100
34.6R (53)		1,700	100			

Point Hansborough						
43.3L (9)	Anasazi Bridge (NAU)	25,300	7,000		7,000	
43.5L (10)		34,000	8,500		4,600	
43.8L (14)		16,000				2,400
44.0L (16)	President Harding	23,500	6,300		1,400	
44.4L (21)	Eminence Break (NAU)	34,400	2,200		7,400	
44.8L (27)		28,300	1,000		2,500	
45.1L (31)		29,400	1,800		5,900	
46.8R (55)		7,400	100			
47.0R (58)	Triple Alcoves	43,300	6,000[1]			6,000[1]
47.5R (63)	Saddle Canyon	45,000	9,800		14,700	
48.5L (74)		14,500	700			
48.6L (77)		17,400		900		
48.6R (78)		14,600	700		2,000	
48.8R (79)		14,700	300		1,200	
Tapeats Gorge						
60.2L (2)	Below Sixtymile Rapid	23,900	6,900		5,800	
60.4L (3)		13,600	4,500		3,000	
60.6R (5)		7,500	0		100	
60.6L (6)		4,500			100	
60.8L (7)		19,600	4,400		3,100	
61.3L (11)		10,600	1,200		1,200	
62.3L (25)		11,600	2,200		2,000	
62.4R (26)		9,100	100		1,000	
62.6R (28)		14,800			100	
62.9R (29)	Crash Canyon (NAU)	20,100	3,600		600	
63.5L (34)		33,200	3,500		3,200	
63.8R (38)		8,500	600			
64.0L (39)		15,200	700		800	
64.2L (40)		17,900	200			
64.3L (43)		33,300	500		1,400	
64.6L (45)		18,800	2,500		1,600	
64.7R (46)		8,300	100		800	



Sand in the post-dam flood zone

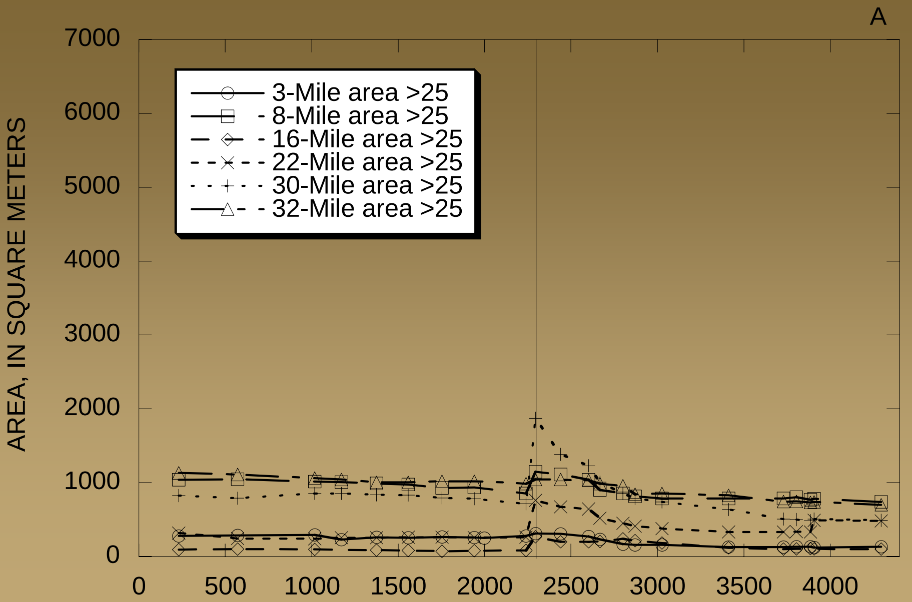
All emergent sand

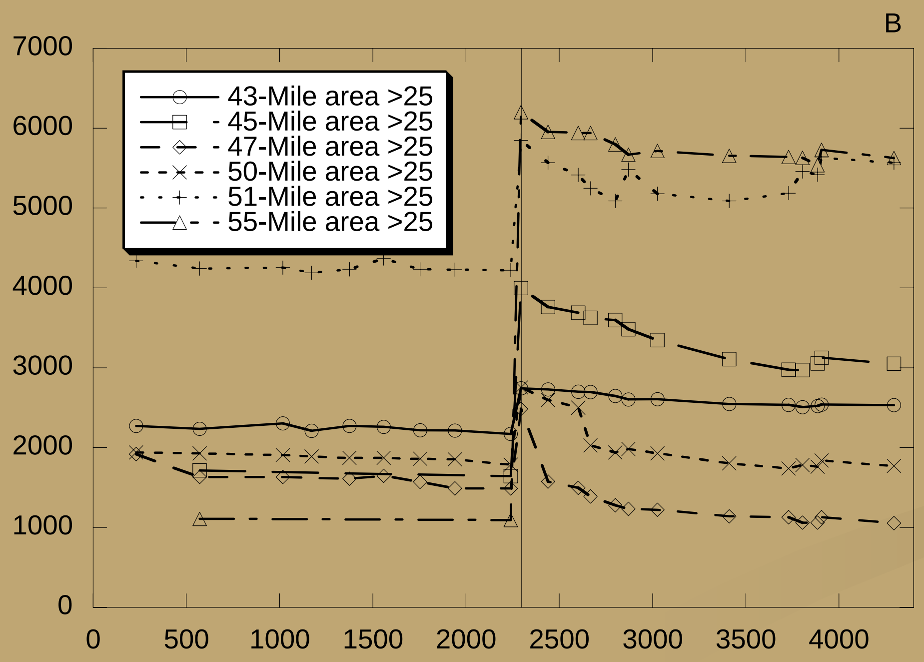


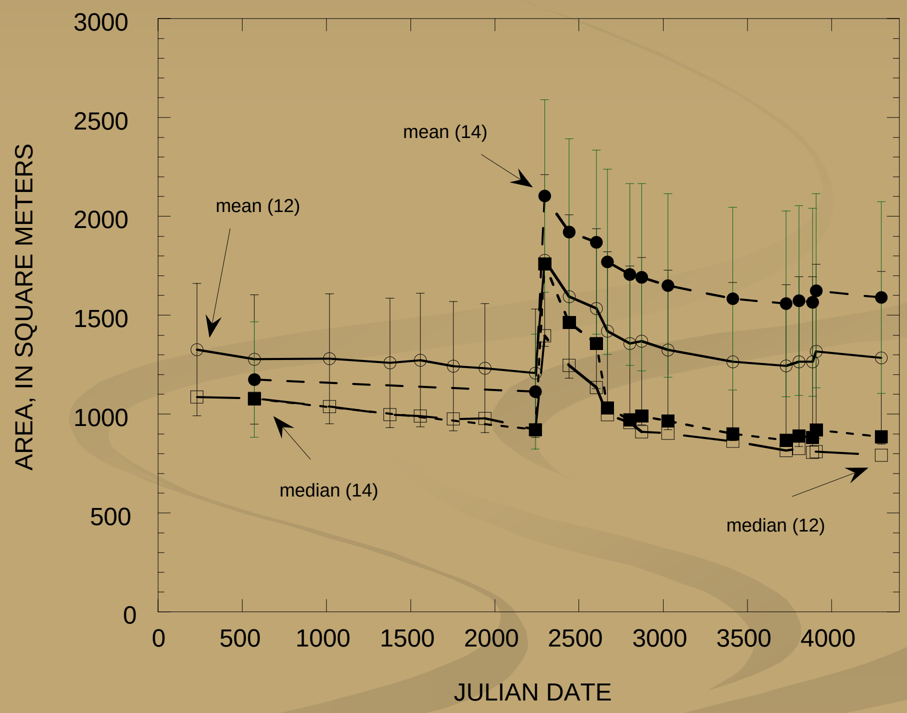
Now to the last decade

- The NAU data set

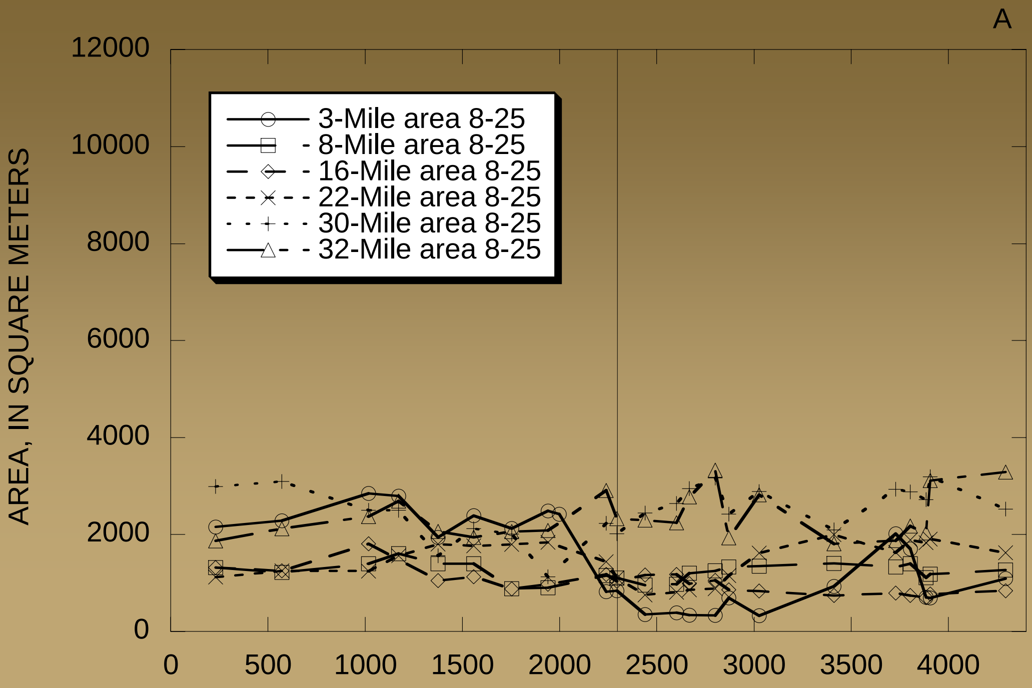
Post-dam flood zone

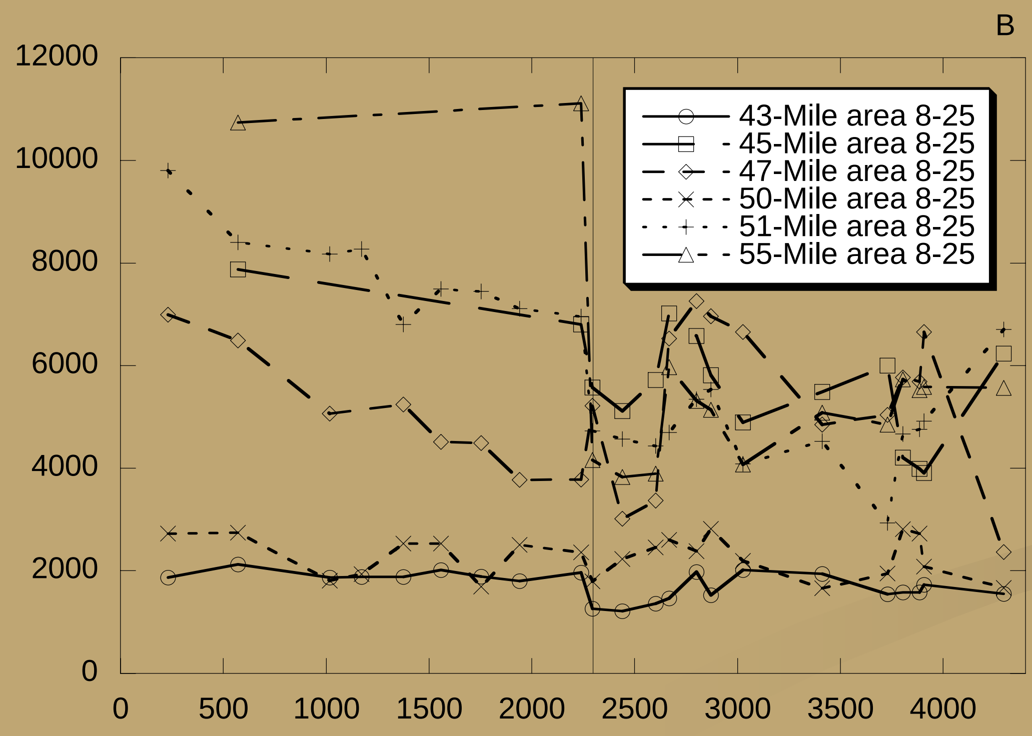


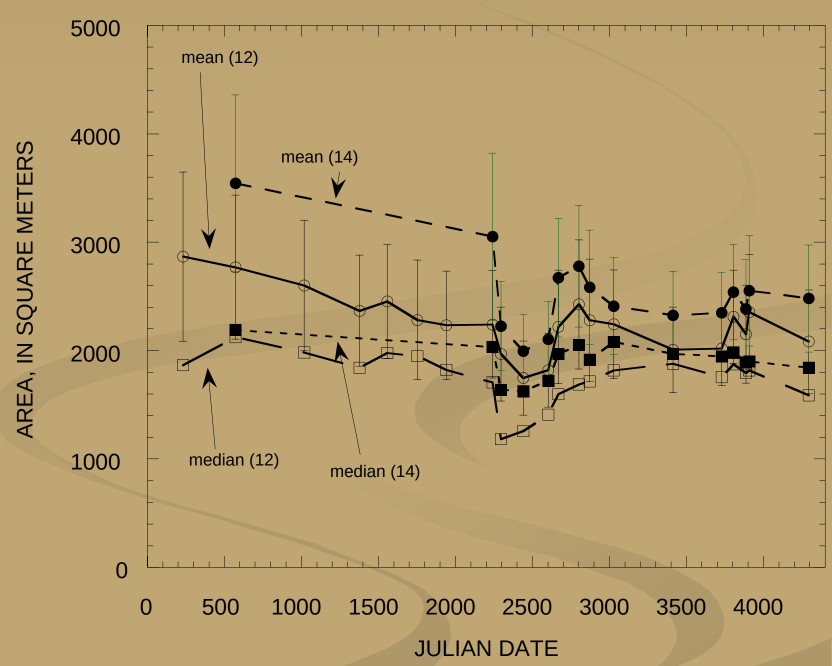


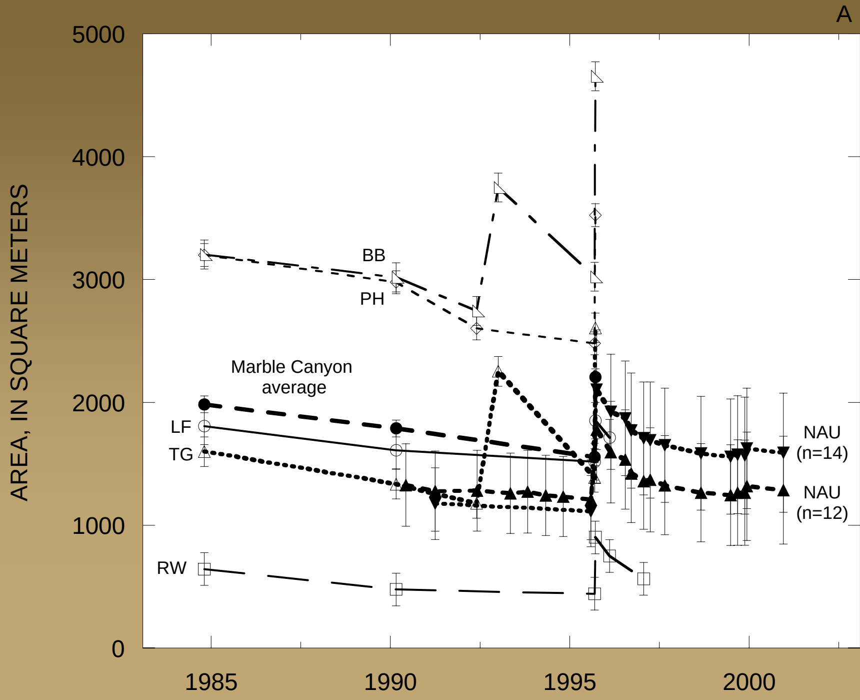


Fluctuating flow zone



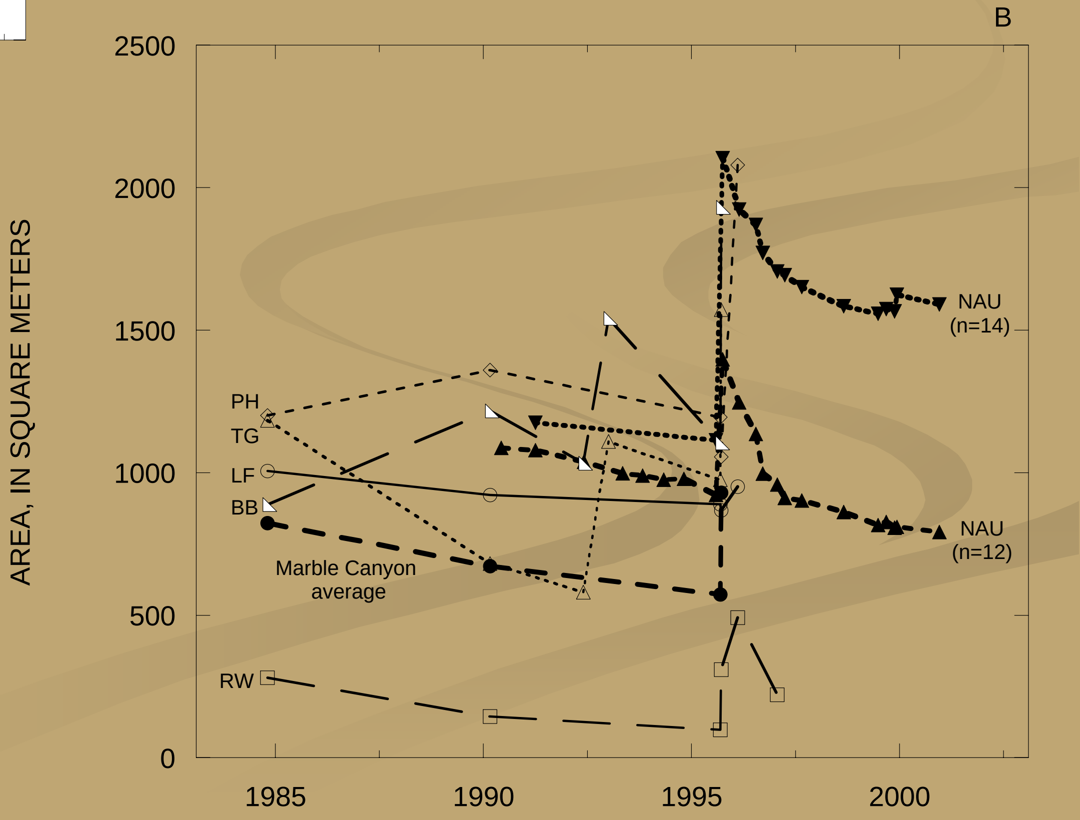






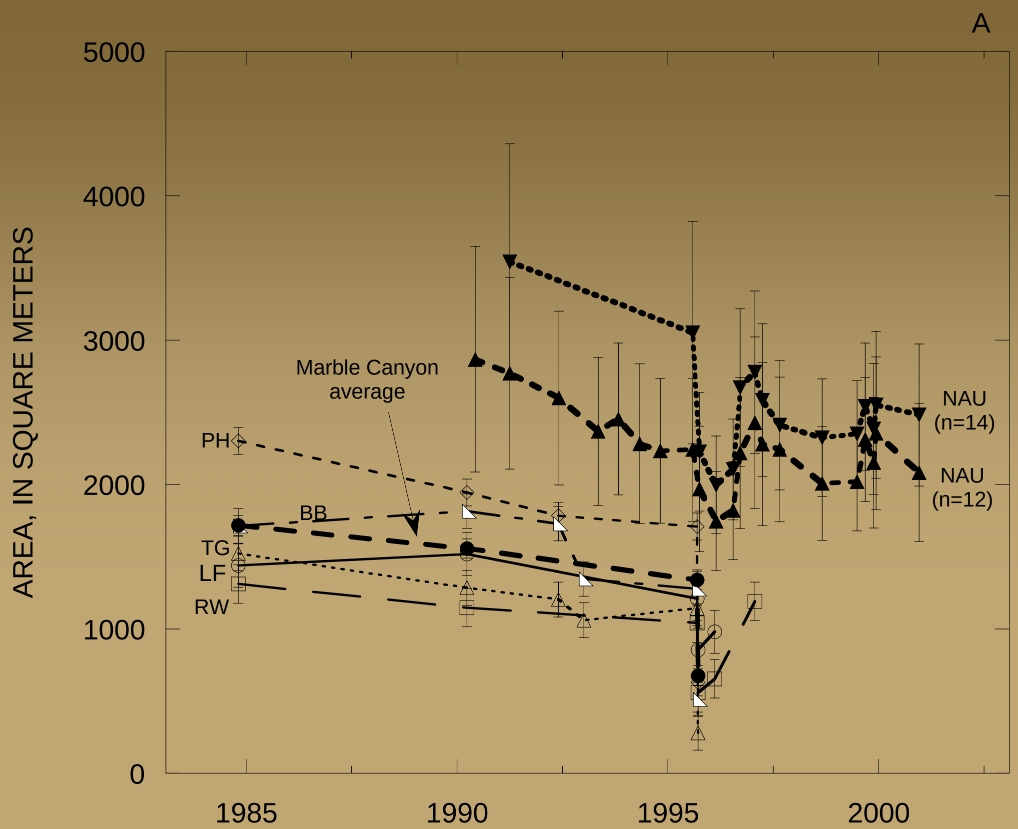
A
5000
4000
3000
2000
1000
0
AREA, IN SQUARE METERS
BB
PH
Marble Canyon
average
LF
TG
RW
NAU
(n=14)
NAU
(n=12)
1985
1990
1995
2000

mean

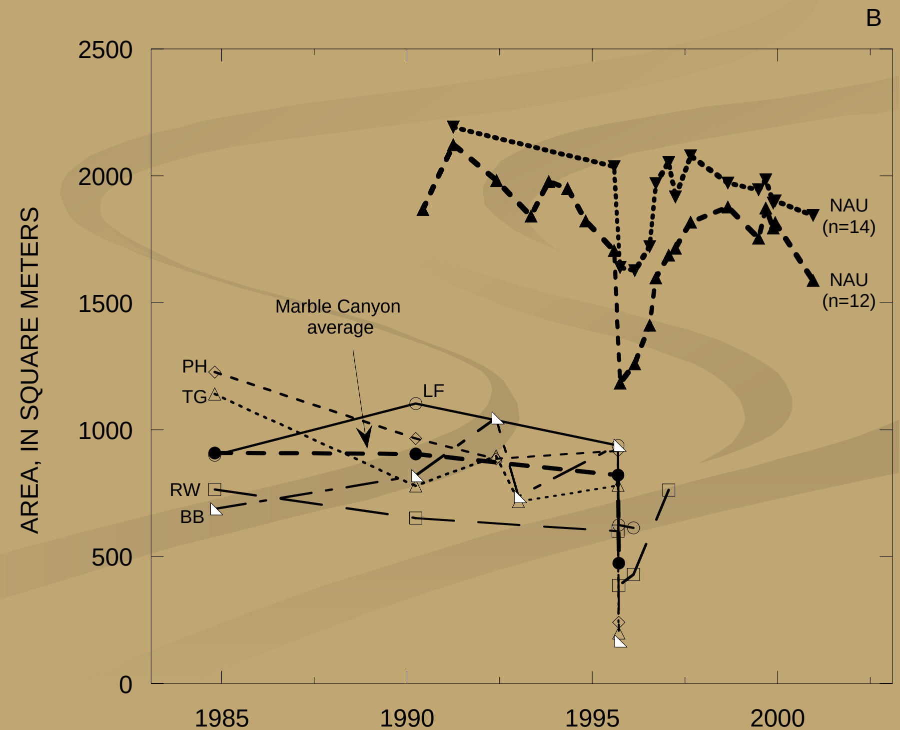


B
2500
2000
1500
1000
500
0
AREA, IN SQUARE METERS
PH
TG
LF
BB
Marble Canyon
average
RW
NAU
(n=14)
NAU
(n=12)
1985
1990
1995
2000

median


A
5000
4000
3000
2000
1000
0
1985
1990
1995
2000
AREA, IN SQUARE METERS
Marble Canyon
average
PH
BB
TG
LF
RW
NAU
(n=14)
NAU
(n=12)

mean


B
2500
2000
1500
1000
500
0
1985
1990
1995
2000
AREA, IN SQUARE METERS
Marble Canyon
average
PH
TG
LF
RW
BB
NAU
(n=14)
NAU
(n=12)

median

So …

- 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
- Sand is less since 1984
- Sand is less than 1990
- Sand is less at low elevation as well as at high elevation