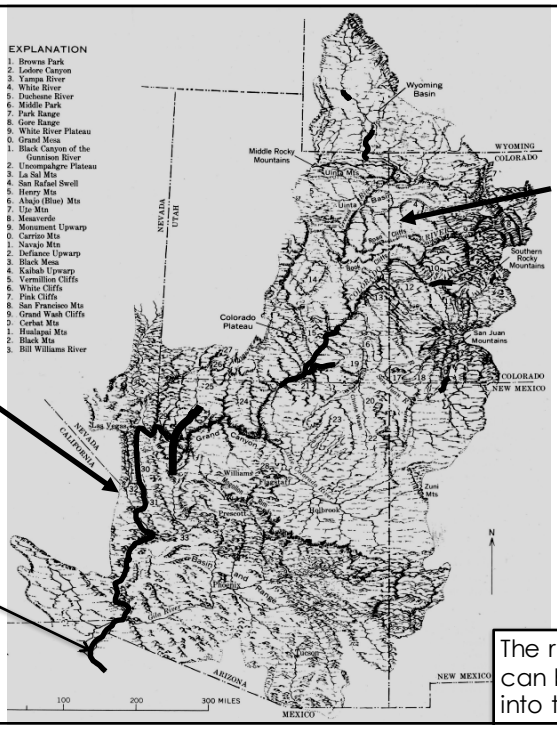
The Transformed River:

~50% of river length is now reservoirs; elsewhere levees and channelization; 2-3 m of bed incision in parts; large reductions in stream flow

The Delta

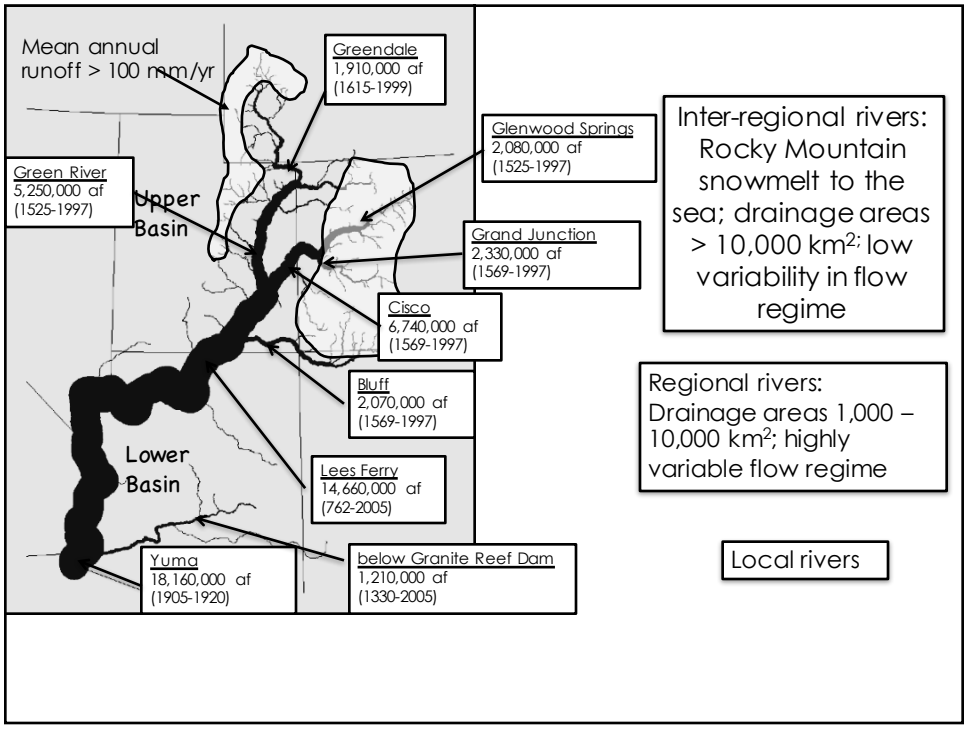
Mostly confined in levees; little water



The Upper River:

Long segments of river remain; no levees or channelization; near dams there is evidence of sediment evacuation, but there is evidence of sediment accumulation elsewhere

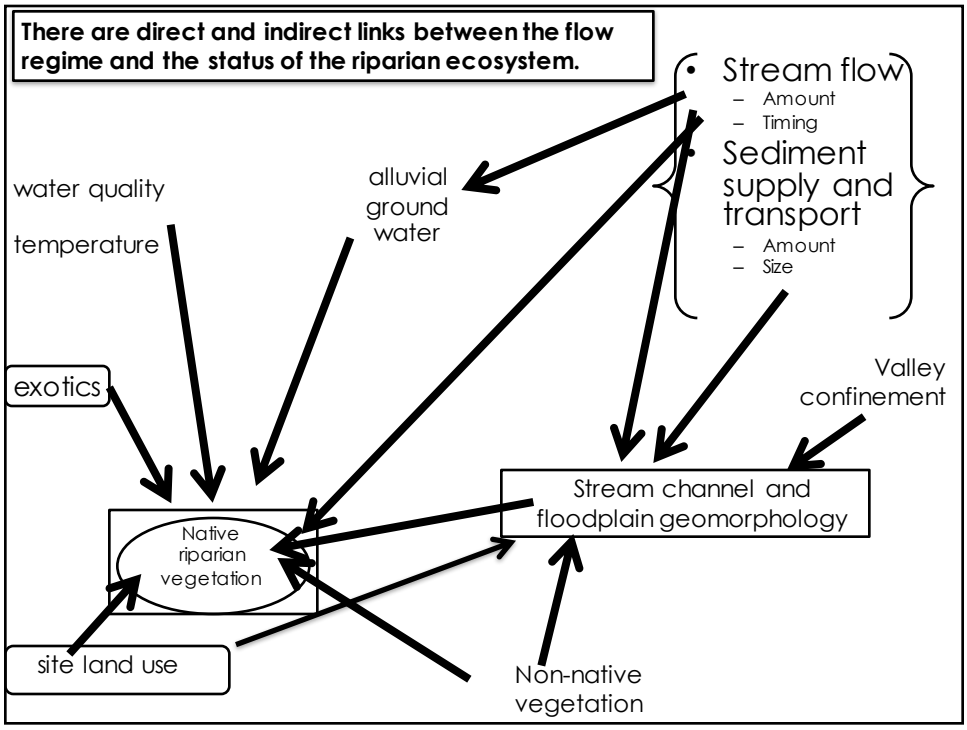
The river network can be divided into three parts



Inter-regional rivers: Rocky Mountain snowmelt to the sea; drainage areas > 10,000 km^2; low variability in flow regime

Regional rivers: Drainage areas 1,000 – 10,000 km^2; highly variable flow regime

Local rivers



Spatial scales and spatial categories relevant to considering interactions between flow regimes / sediment transport / geomorphology and riparian vegetation

Bed material
- Boulder/cobble bed
- Gravel bed
- Sand bed

Scale of the river *(Graf, 1987)*
- inter-regional rivers
- regional rivers
- local streams

Geomorphic organization *(Ikeda, 1989)*
- multi-thread channels
- confined free meanders
- restricted meanders
- fixed meanders
- debris fan-affected canyons
- deltas

Perturbations caused by water development *(Schmidt and Wilcock, 2008)*
- mass balance perturbation
- bed incision
- width changes

Different categories have different distinctive geomorphic processes and different challenges to restoration.

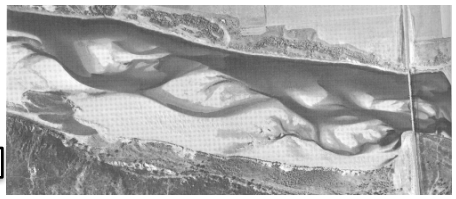
Boulder/cobble bed

Different bed material creates different channel/floodplain processes and interactions

Does the bed material move?

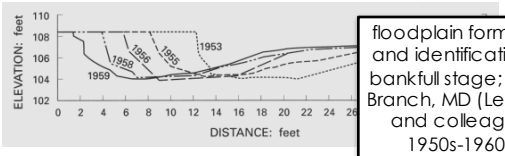
Gravel-bedl

Does all the gravel entering the reach move through?

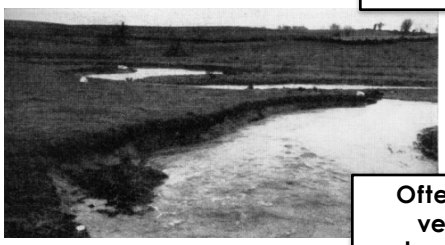


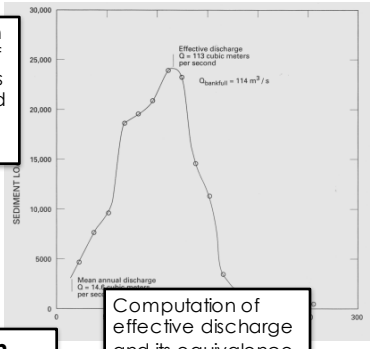
Sand bed

Does all the fine sediment entering the reach move through?



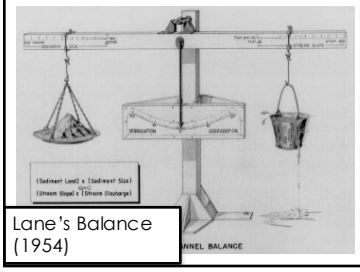
floodplain formation and identification of bankfull stage; Watts Branch, MD (Leopold and colleagues 1950s-1960s)



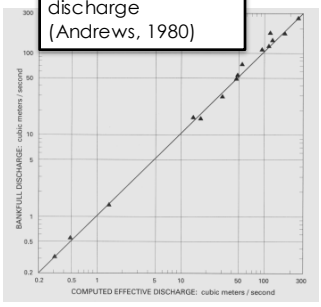


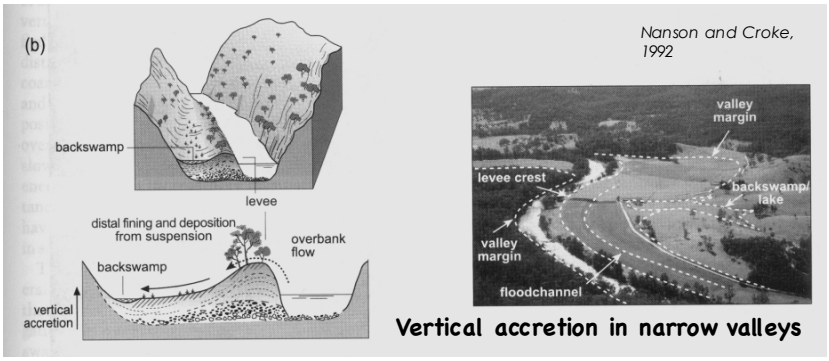
Computation of effective discharge and its equivalence with bankfull discharge (Andrews, 1980)

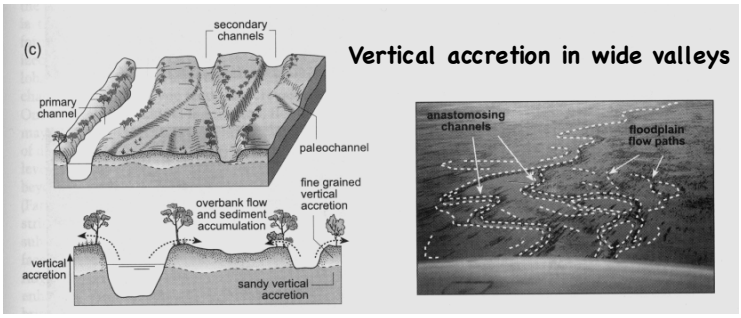
Often, riparian vegetation restoration is linked to the paradigm of equilibrium and the lateral accretion model of floodplain formation. These channels typically have low suspended-sediment loads.



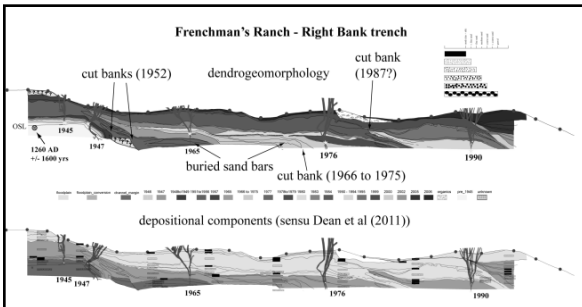
Lane's Balance (1954)

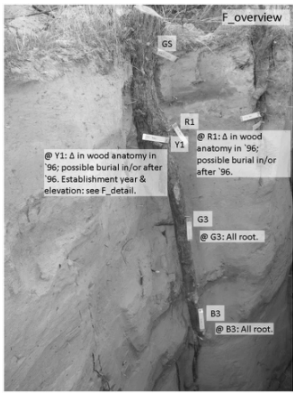


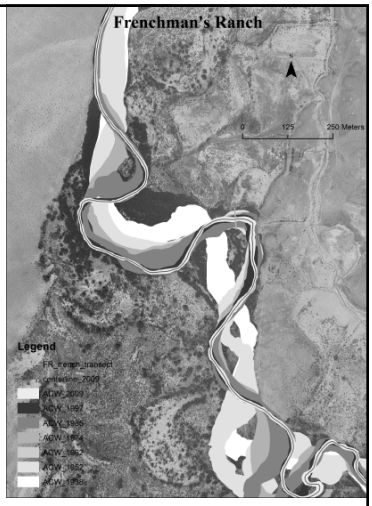




But floodplains form in different ways. Vertical accretion dominates where suspended sediment transport is high.

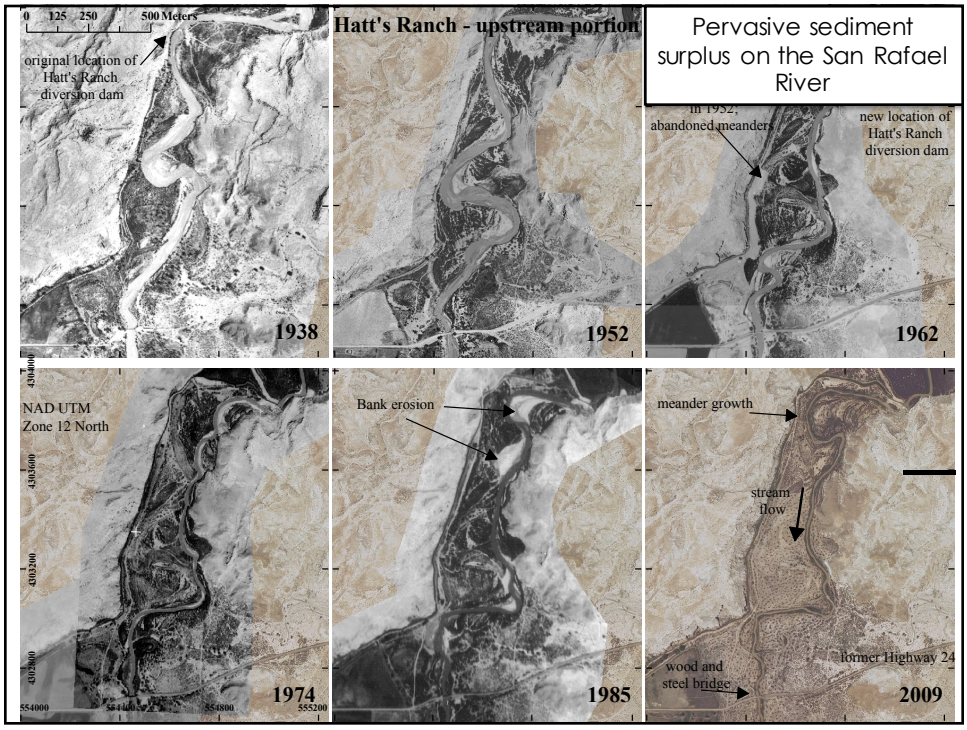






Channel narrowing by vertical accretion and inset floodplain formation on the San Rafael River

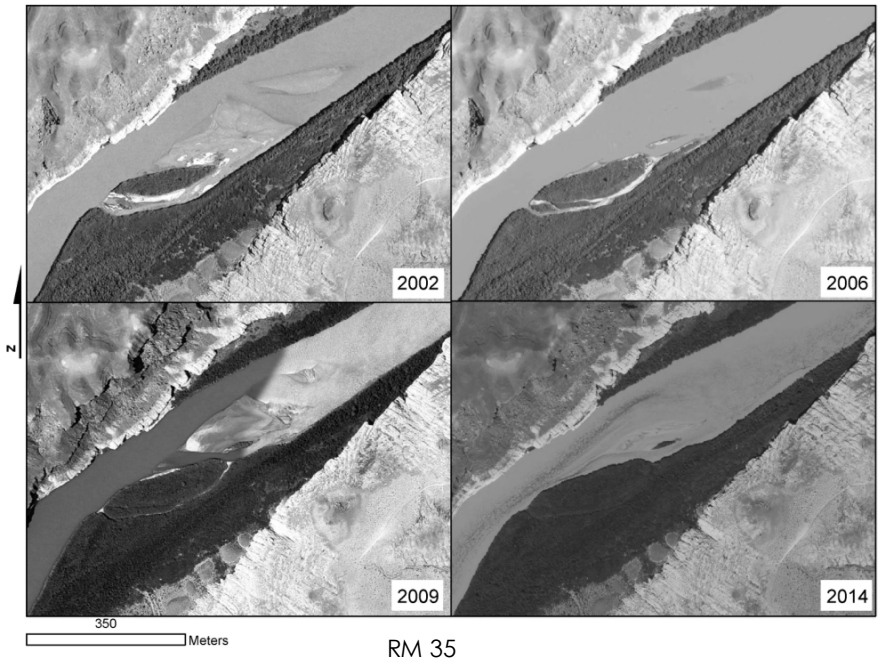
Fortney, 2015



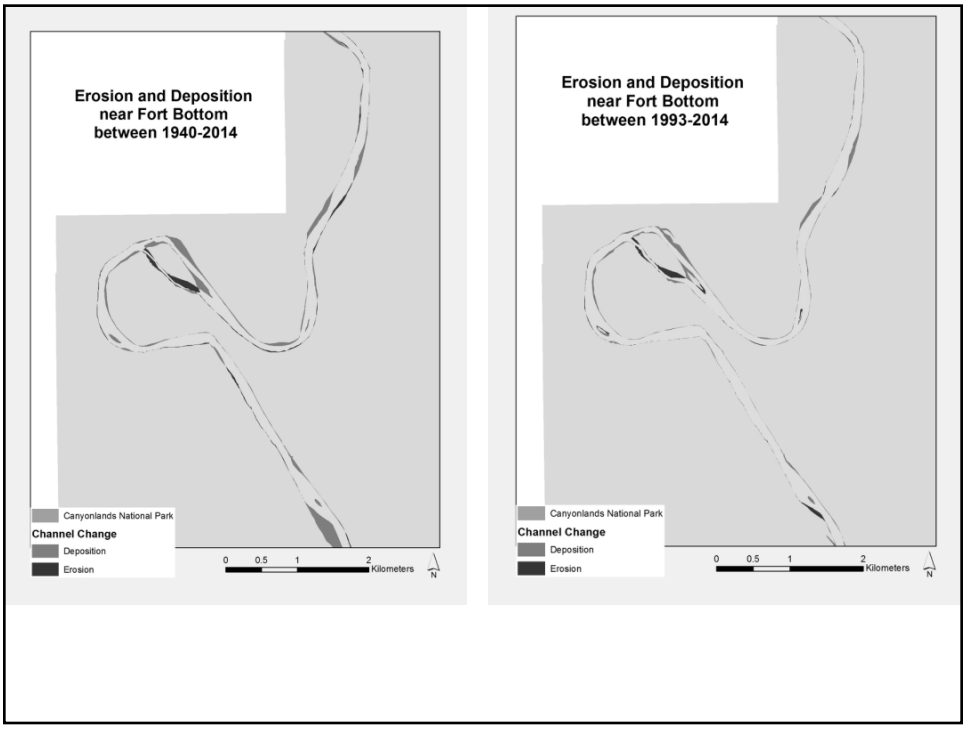
1

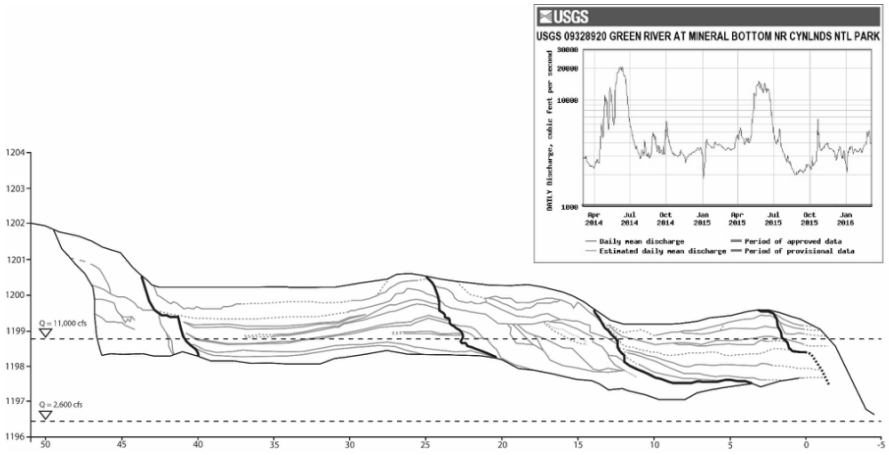
Bonita Bend

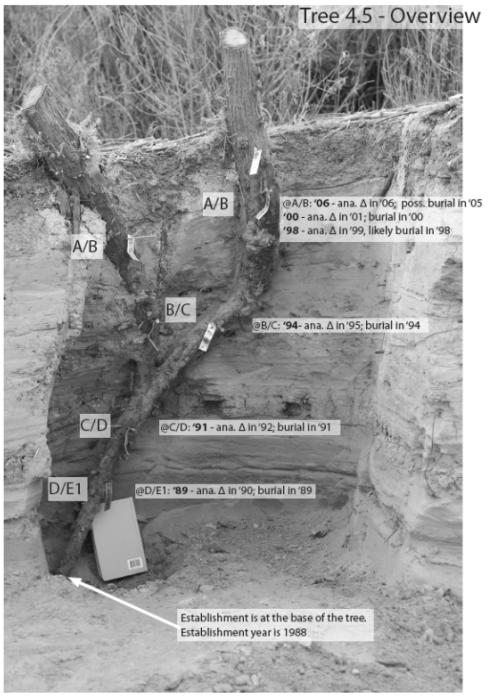
Photos courtesy of R. Webb

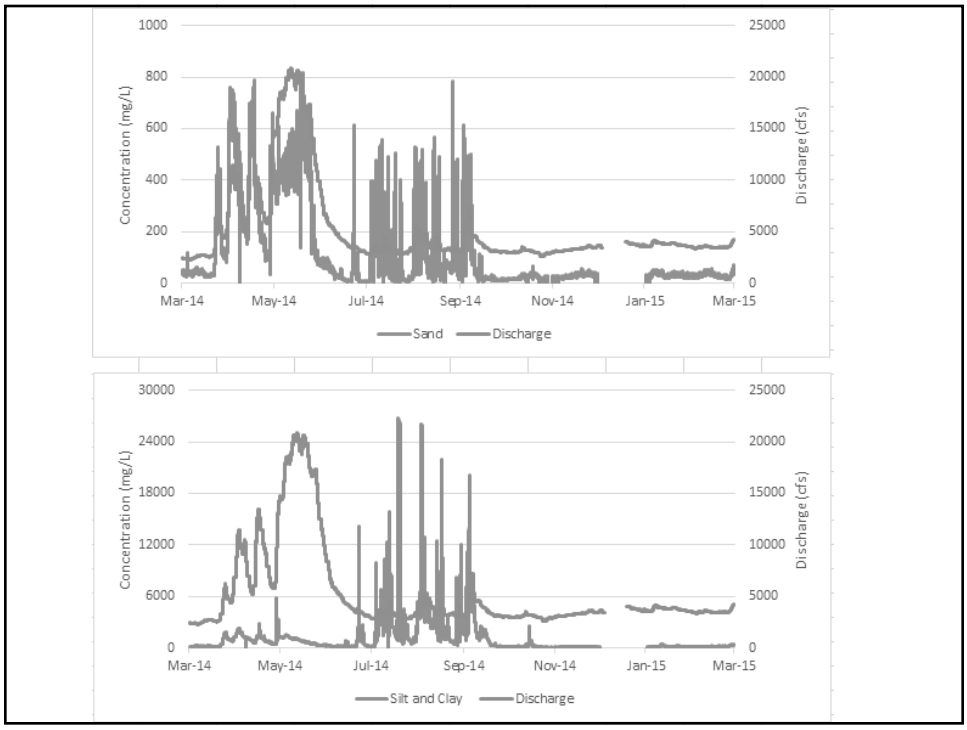

2002
2006
2009
2014
N
350
Meters

RM 35

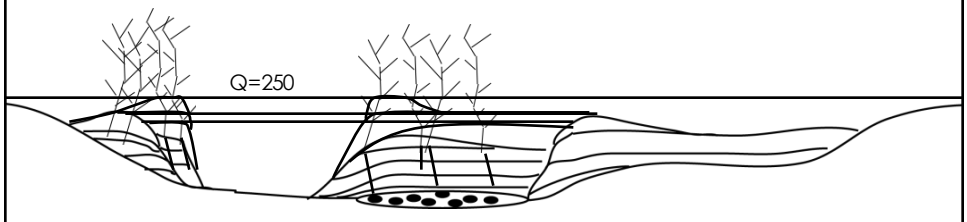

Erosion and Deposition
near Fort Bottom
between 1940-2014
Canyonlands National Park
Channel Change
Deposition
Erosion
0 0.5 1 2
Kilometers
N
Erosion and Deposition
near Fort Bottom
between 1993-2014
Canyonlands National Park
Channel Change
Deposition
Erosion
0 0.5 1 2
Kilometers
N


USGS
USGS 09328920 GREEN RIVER AT MINERAL BOTTOM NR CYNLNDS NTL PARK
DAILY Discharge, cubic feet per second
30000
20000
10000
1000
Apr 2014
Jul 2014
Oct 2014
Jan 2015
Apr 2015
Jul 2015
Oct 2015
Jan 2016
Daily mean discharge
Estimated daily mean discharge
Period of approved data
Period of provisional data
1204
1203
1202
1201
1200
1199
1198
1197
1196
Q = 11,000 cfs
Q = 2,600 cfs
50
45
40
35
30
25
20
15
10
5
0
-5


Tree 4.5 - Overview
A/B
@A/B: '06 - ana. Δ in '06; poss. burial in '05
'00 - ana. Δ in '01; burial in '00
'98 - ana. Δ in '99, likely burial in '98
A/B
B/C
@B/C: '94- ana. Δ in '95; burial in '94
C/D
@C/D: '91 - ana. Δ in '92; burial in '91
D/E1
@D/E1: '89 - ana. Δ in '90; burial in '89
Establishment is at the base of the tree.
Establishment year is 1988

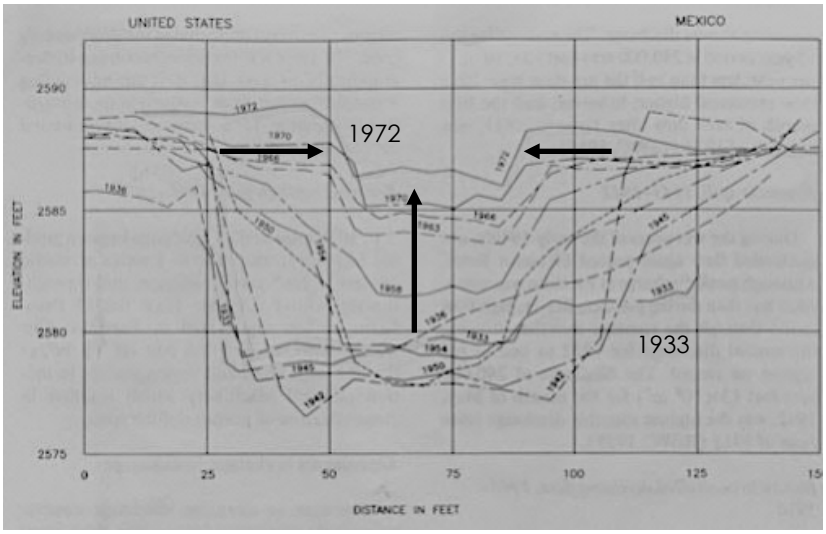


Positive feedback model of lateral floodplain accretion caused by decreasing channel capacity caused by invasion of riparian vegetation and sedimentation within the channel maintains the rate of deposition of sediment on the floodplain even when flows decrease



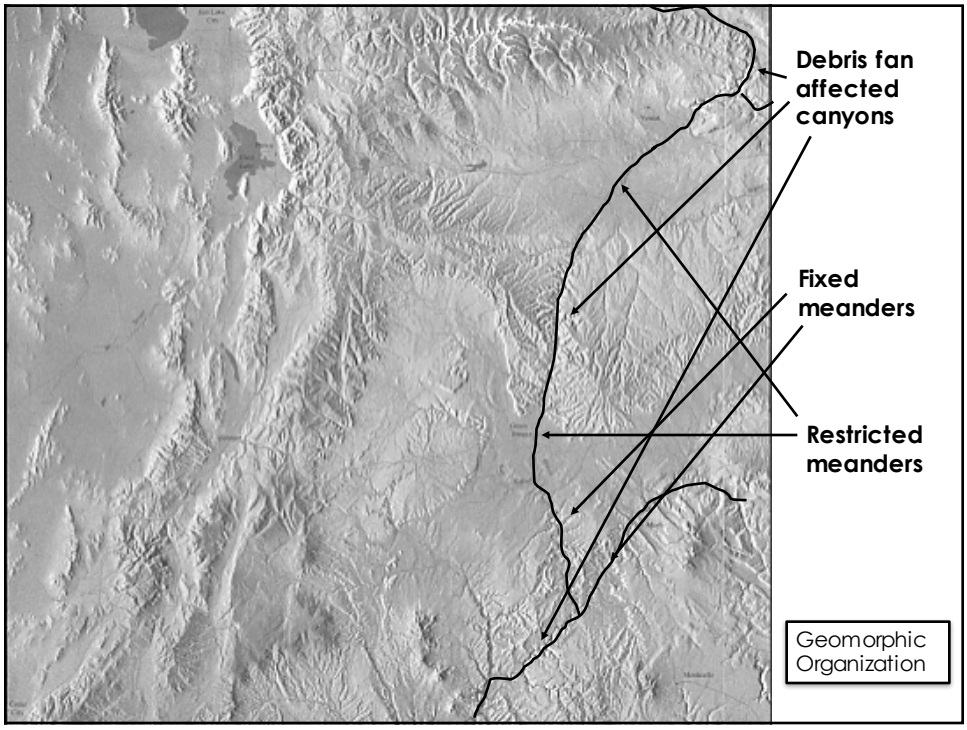
- Channel narrowing resulted in increases in stage
- Overbank deposition resulted in additional vertical floodplain accretion
- Dense vegetation increases sedimentation

Dean and Schmidt, 2011



Sediment surplus: Rio Grande/Rio Bravo upstream from the Rio Cochos, near Presidio, TX

Everitt (1993)

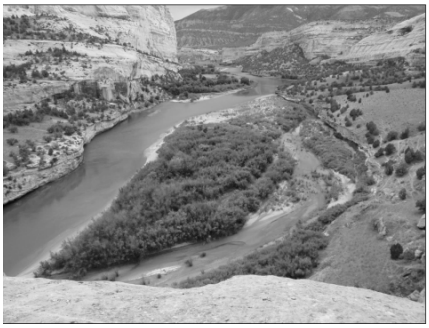


Multi-thread reaches

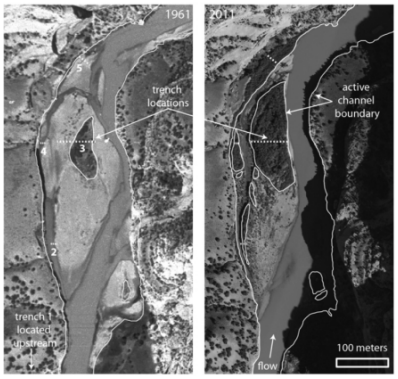
Loss of secondary channels in multi-thread reaches due to reduction in flood peaks – Green River near Green River, UT

1938 1993

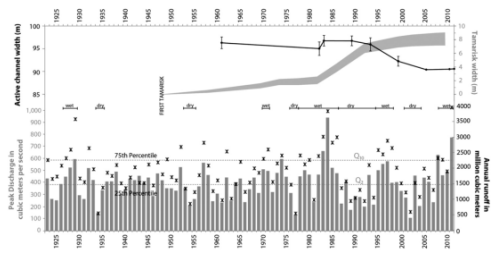
Allred and Schmidt, 1999



Multi-thread reaches

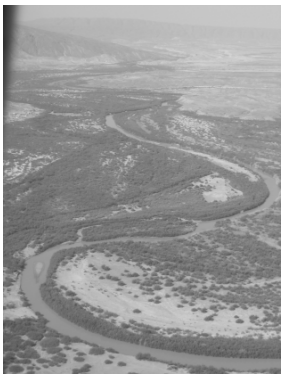


Manners et al. (2014)



Subtle changes in the flow regime have caused channel narrowing and habitat loss on the Yampa River due to vegetation invasion during drought years

Manners et al., 2014



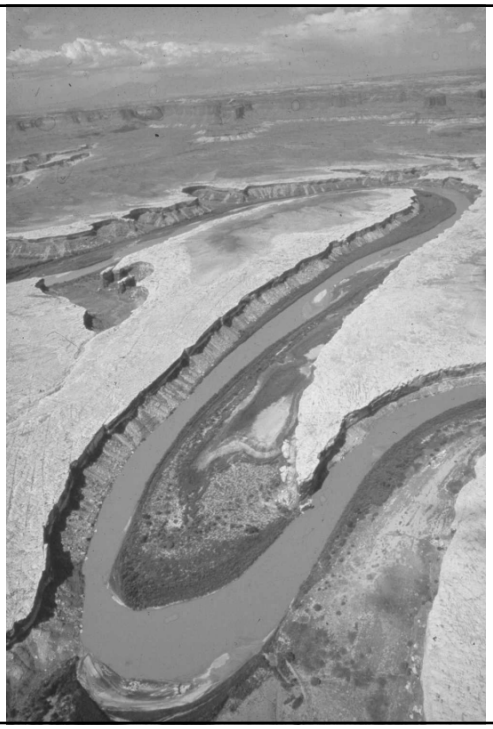
Confined free meanders

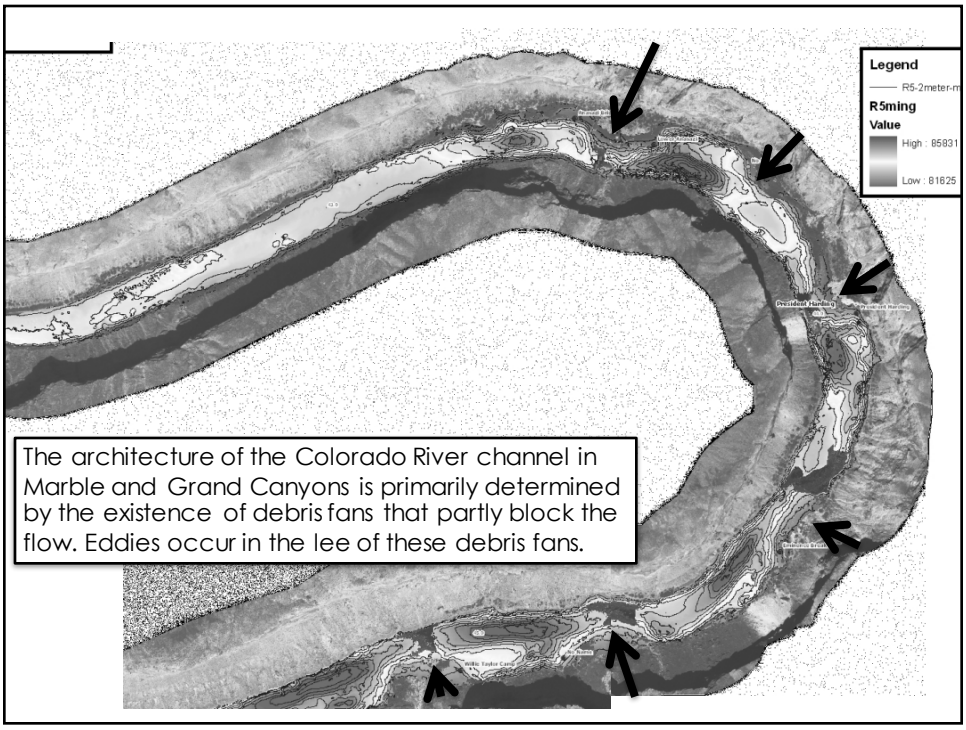
Rio Grande, Big Bend

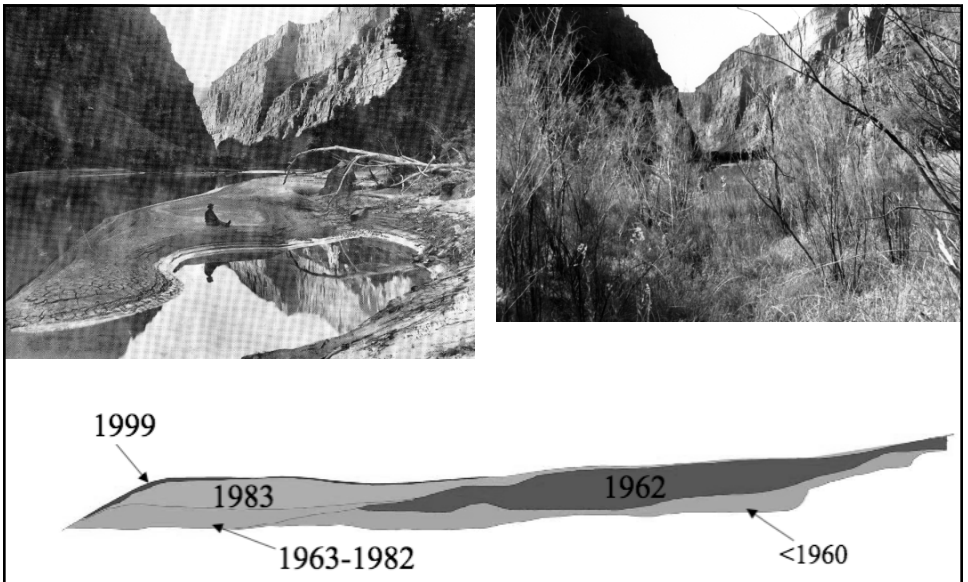
Restricted meanders

Green River, Uinta Basin

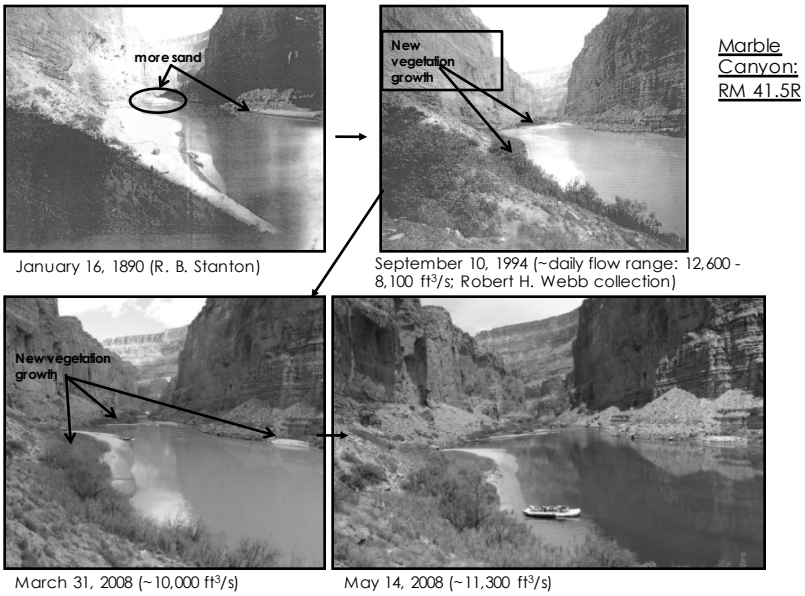
Fixed meanders




Legend
R5ming
Value
High : 85931
Low : 81625
The architecture of the Colorado River channel in Marble and Grand Canyons is primarily determined by the existence of debris fans that partly block the flow. Eddies occur in the lee of these debris fans.


1999
1983
1962
1963-1982
<1960
Eddy bars can convert to floodplain features with large reductions in flood regime

Glen Canyon Dam Adaptive Management Program and Grand Canyon National Park have concerns …



Marble Canyon: RM 41.5R

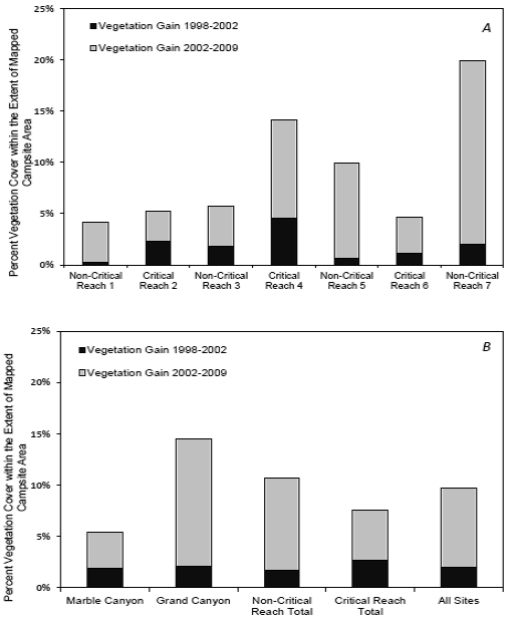
January 16, 1890 (R. B. Stanton)

September 10, 1994 (~daily flow range: 12,600 - 8,100 ft³/s; Robert H. Webb collection)

March 31, 2008 (~10,000 ft³/s)

May 14, 2008 (~11,300 ft³/s)

Courtesy of B. Ralston



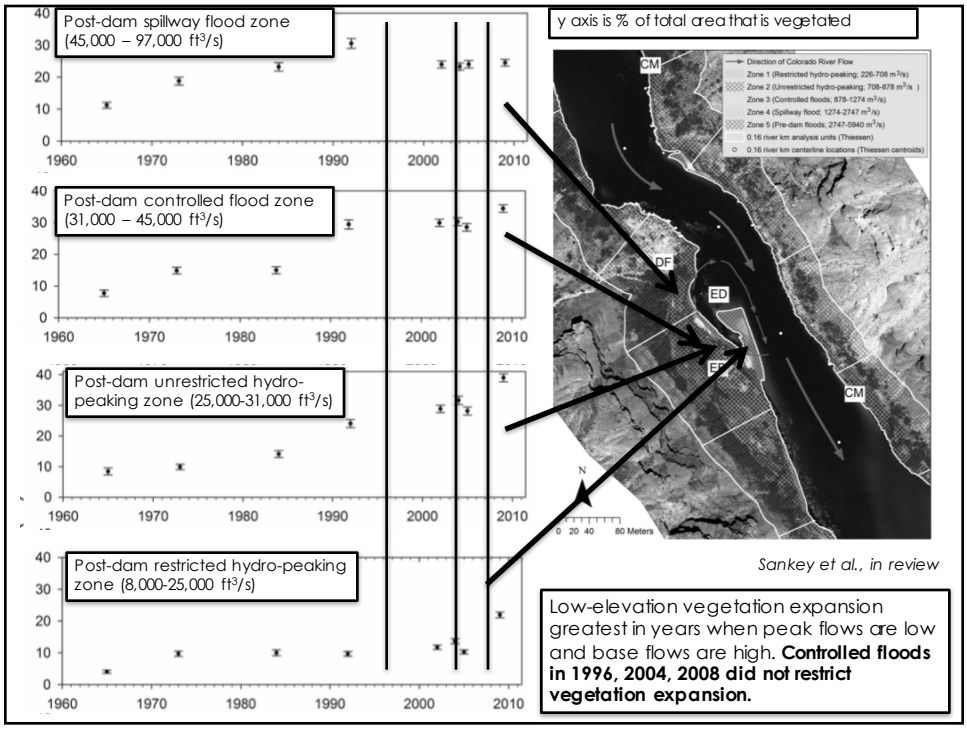
Riparian vegetation area at campsites continues to expand.

Increase in riparian vegetation at surveyed campsites

2% increase in vegetation area 1998-2002

8% increase in vegetation area 2002-2009

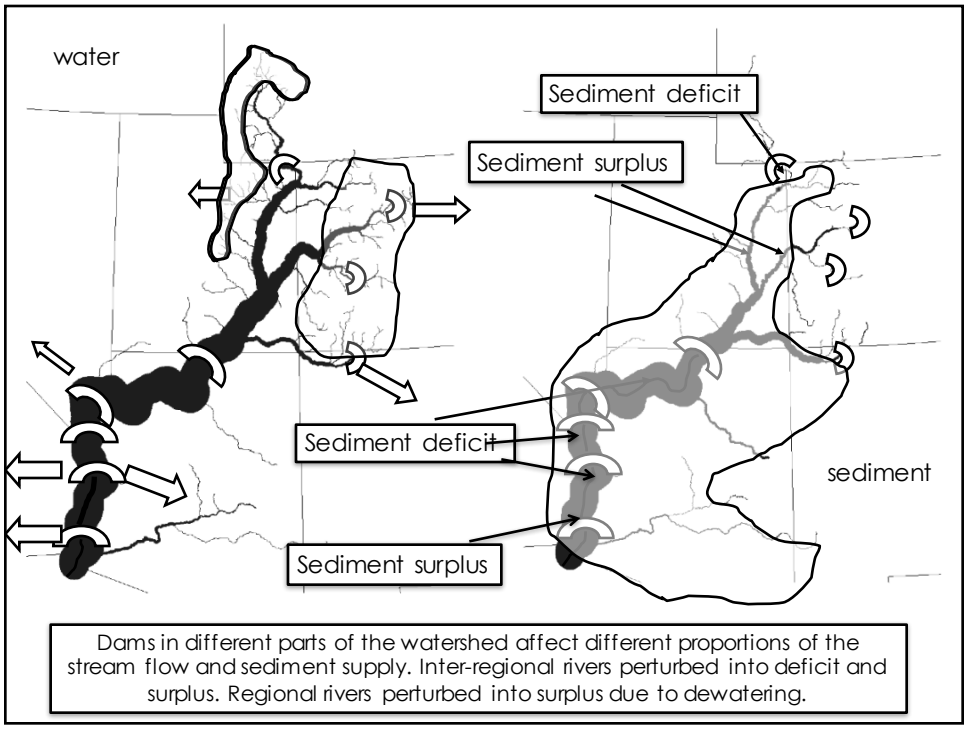
Hadley, 2014



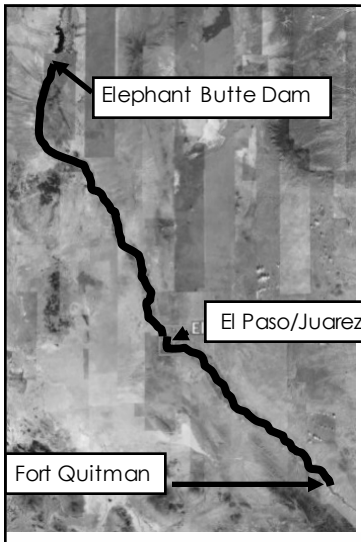
Three Metrics of Channel Change

- Perturbation of the predam sediment mass balance
  - Assessing shifts towards deficit or surplus
- Likelihood of post-dam bed incision
- Potential for changes in width based on proportional change in annual floods

Schmidt and Wilcock, 2008



Dams in different parts of the watershed affect different proportions of the stream flow and sediment supply. Inter-regional rivers perturbed into deficit and surplus. Regional rivers perturbed into surplus due to dewatering.

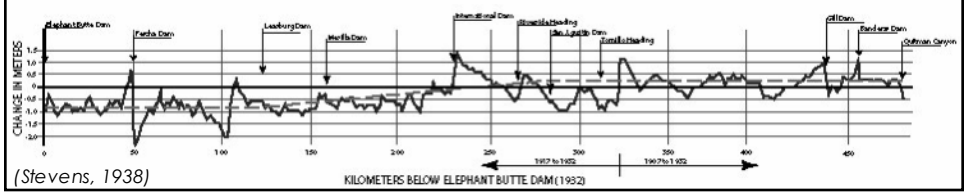


sediment deficit may, or may not, lead to bed incision

sediment surplus may, or may not, lead to bed aggradation

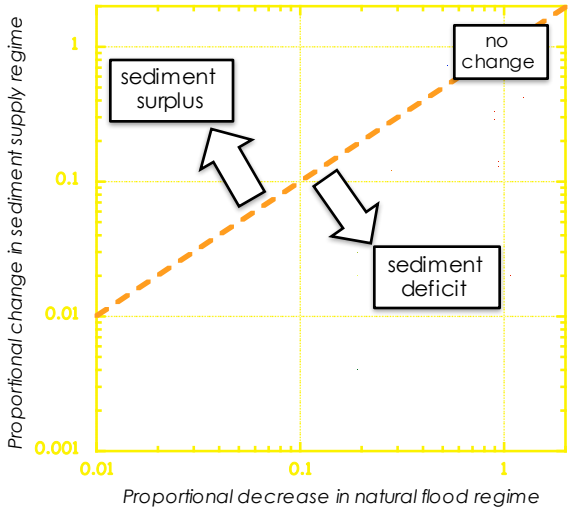
Downstream from Elephant Butte Dam, the Rio Grande **incised its bed** as much as 1 m within 225 km downstream from the dam between ~1917 and ~1933. Downstream from El Paso/Juarez, the bed **aggraded** about 0.25 m.

(Stevens, 1938)



(Stevens, 1938)

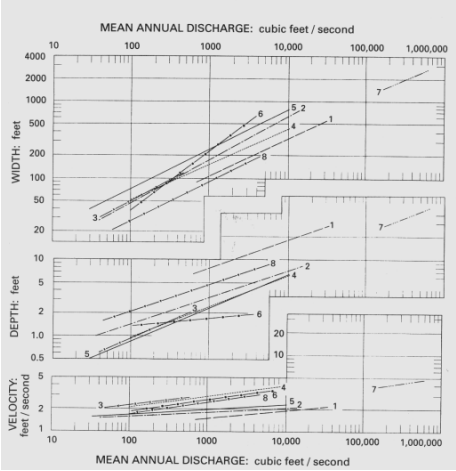
Large dams typically trap all of the incoming sediment supply. **Diversions** have the potential to remove large amounts of water but not necessarily deplete the sediment supply.



Schmidt and Wilcock, 2008

Channels immediately downstream from dams are typically perturbed into **deficit**. Channels immediately downstream from diversions (where there are no dams) are typically perturbed into **surplus**. Far downstream from dams and diversions, the perturbations can reverse.

Predicting width changes

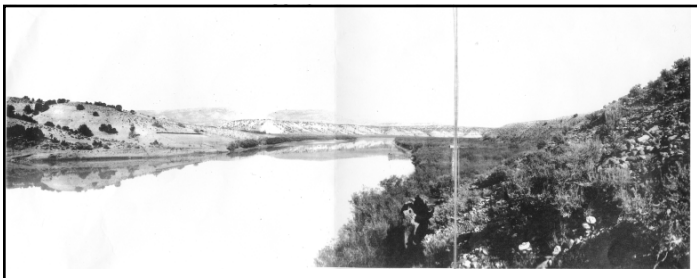


Leopold and Maddock (1953) argued that there is a commonality in the slope of downstream hydraulic geometry relations for many of the world's watersheds.

- $b = 0.5$ $\mathbf{B} = aQ^b$
- $f = 0.4$ $\mathbf{h} = cQ^f$
- $m = 0.1$ $\mathbf{U} = kQ^m$

- **Thus, streams get wider downstream in relation to their depth**

The downstream hydraulic geometry predicts that channels will narrow when the index discharge decreases.

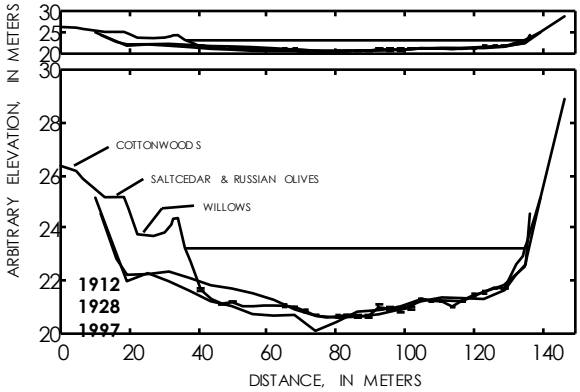


Green River in Browns Park; no bed incision; large flood reduction; 20-30% narrowing

Narrowing under deficit conditions and no bed incision

(Grams and Schmidt, 2005)

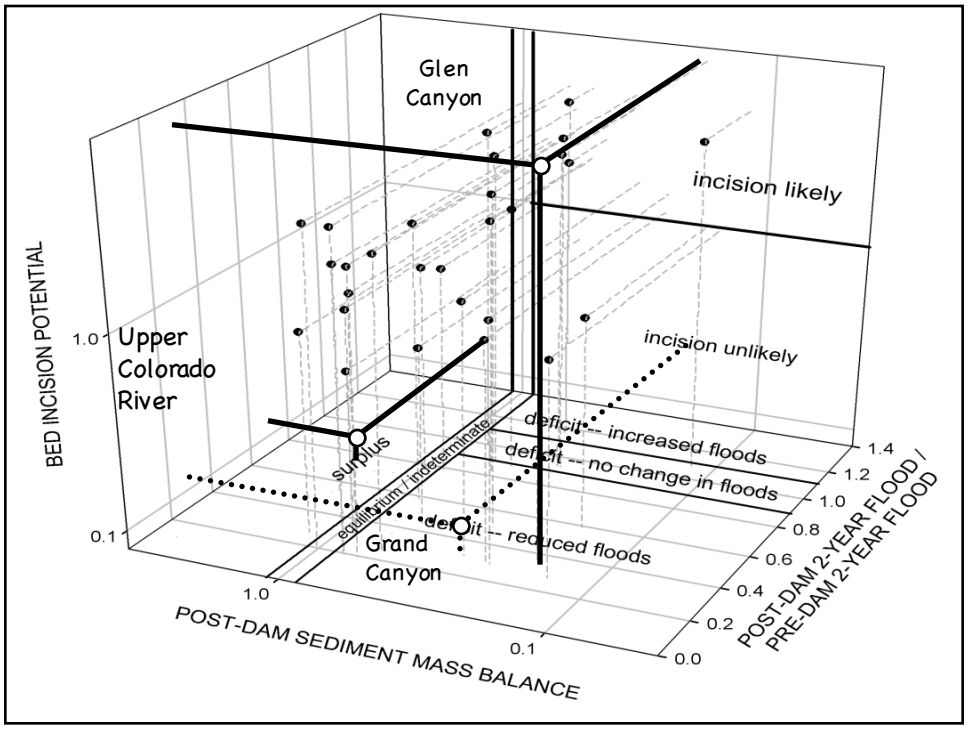
Green River, near Green River, UT



15% narrowing

Narrowing where flood magnitude reduced and mass balance remains in equilibrium

(Allred and Schmidt, 1999)



Remove tamarisk

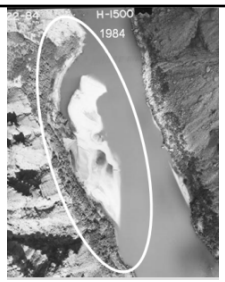
Implementing environmental flows may be impossible in decoupled systems. Physical intervention is being pursued. But interventions may be overwhelmed by fine sediment supply where surplus exists.

Add gravel

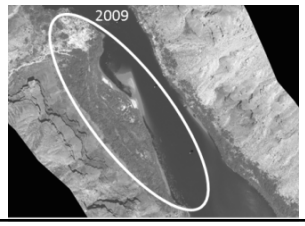
Facilitate beaver colonization

The desired end state of the active channel and floodplain differs among rivers and depends on stakeholder preferences and management objectives.

In Grand Canyon, we seek a novel ecosystem … **plant native vegetation where we want it, eradicate non-native vegetation elsewhere, ponder what to do with expanding native vegetation in undesired places.**

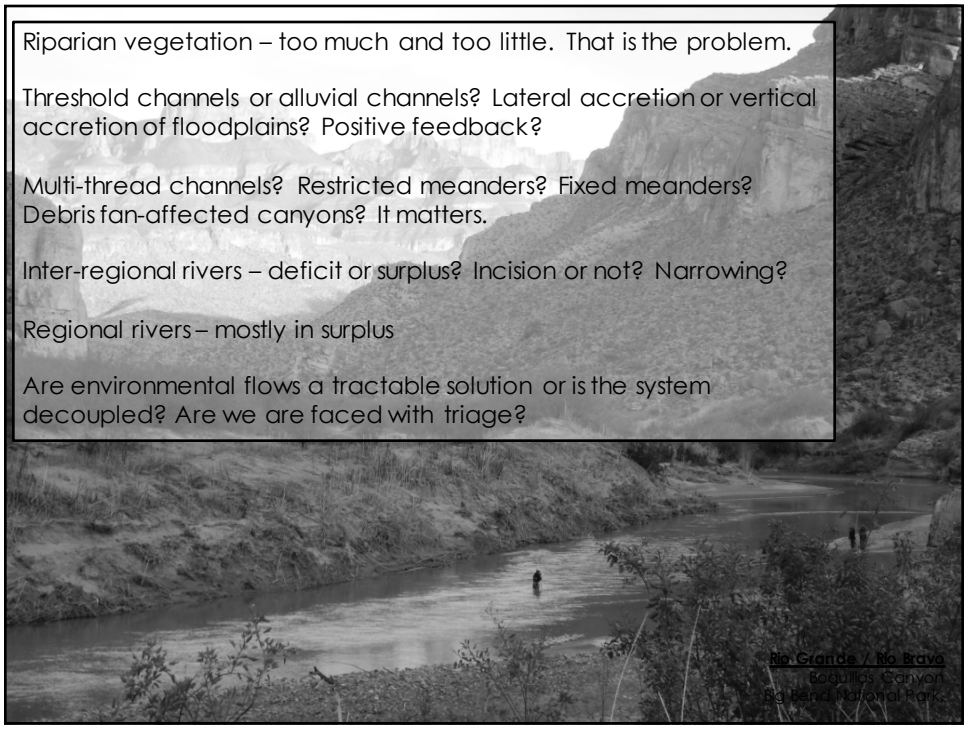


1984



2009

Restoring native vegetation or removing unwanted riparian vegetation? Either way … geomorphic processes and context matters.


Riparian vegetation – too much and too little. That is the problem.
Threshold channels or alluvial channels? Lateral accretion or vertical accretion of floodplains? Positive feedback?
Multi-thread channels? Restricted meanders? Fixed meanders? Debris fan-affected canyons? It matters.
Inter-regional rivers – deficit or surplus? Incision or not? Narrowing?
Regional rivers – mostly in surplus
Are environmental flows a tractable solution or is the system decoupled? Are we are faced with triage?
Rio Grande / Río Bravo
Boquillas Canyon
Big Bend National Park