Geomorphology of the Colorado River in Grand Canyon —what have we learned and what do we need to know?

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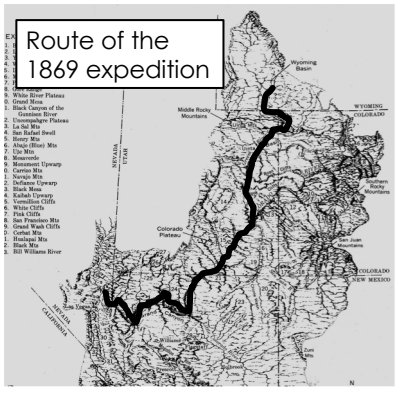
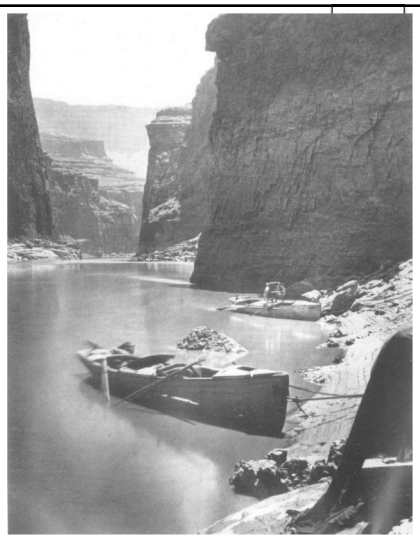
Utah State University

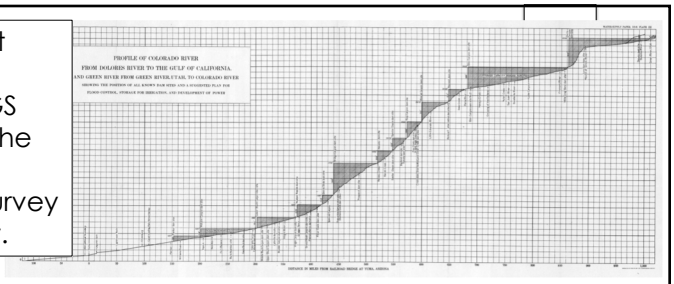
The photo record of the Powell expeditions (1869 and 1871) provides a basis for evaluating landscape change.





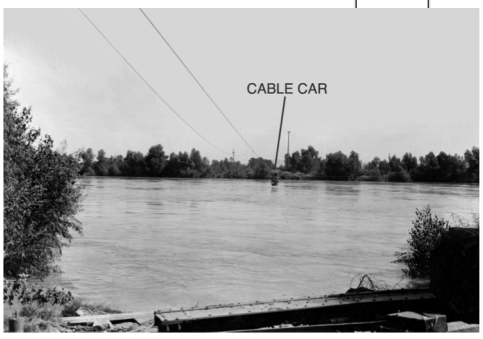
Marble Canyon, 1872

Dam sites throughout Grand Canyon were identified by the USGS (LaRue 1916, 1925). The Birdseye (1924) longitudinal profile survey is still analyzed today.



B. ALTERNATIVE DAM SITE IN MARBLE GORGE AT VASEYS PARADISE, 32.2 MILES BELOW PARIA RIVER

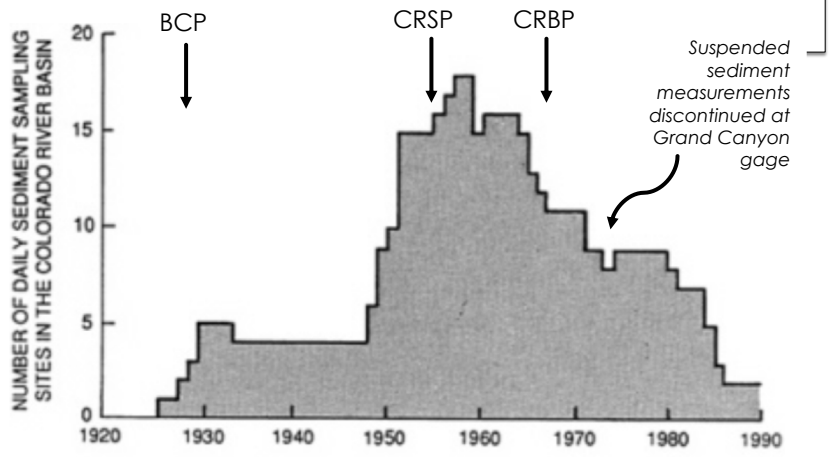
Stream gaging provided data for the negotiation of the Colorado River Compact, bi-national treaty negotiation and compliance, and to plan river and water development.



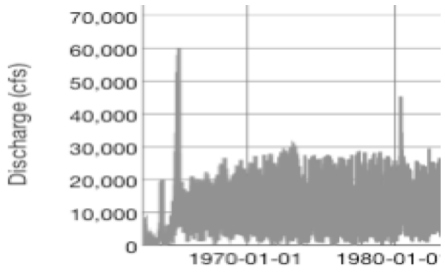
Yuma, June 1921

Lees Ferry, September 1923

Andrews, 1990



Suspended sediment transport was measured at many gages in order to estimate the rate of sedimentation in proposed reservoirs.



- Rapids
  - Controls on location
  - Effects of flood control
- Ecosystem effects of flood control and hydropeaking
  - Beach erosion
  - Vegetation encroachment
- Fine-grain sediment budget
- Bed degradation (magnitude, rate)

1969 – Leopold, *The Rapids and the Pools – Grand Canyon*

1974 – Dolan et al, *Man's Impact on the Colorado River in Grand Canyon*

1976– Laursen et al, *On Sediment Transport through the Grand Canyon*
1976 – Pemberton, *Channel Changes in the Colorado River …*

1977 – Cooley et al, *Effects of the Catastrophic Flood of December 1966, North Rim Area …*

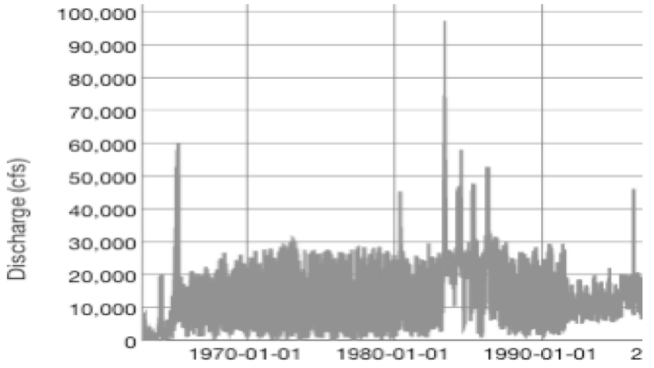
1978 -- Dolan et al, *Structural Control of the Rapids and Pools of the Colorado River …*

1979 – Graf, *Rapids in Canyon Rivers*
1979 – Valentine and Dolan, *Footstep-Induced sediment displacement in the Grand Canyon*

1980 – Graf, *The Effect of Dam Closure on Downstream Rapids*
1980 -- Turner and Karpiscak, *Recent Vegetation Changes along the Colorado River …*

1981 – Howard and Dolan, *Geomorphology of the Colorado River in the Grand Canyon*

River science: 1960s – 1970s



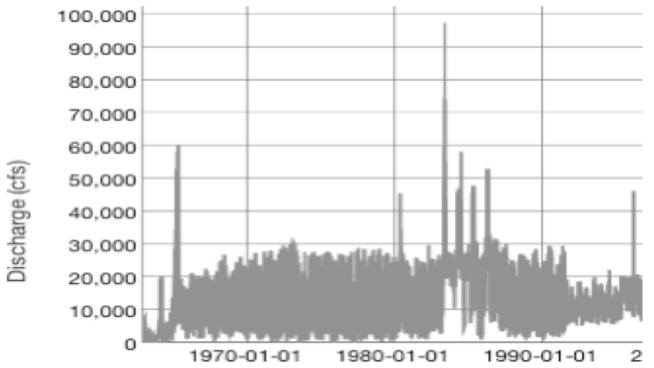
NPS
USBR

GCES I

River science: 1980s

- Mainstem sediment transport measurement and modeling
- Bed sediment measurement
- Sand bars (formation, determinants of size, effects of hydropeaking); monitoring initiated
- Debris flows, rapids, reworking by floods
- Riparian vegetation change

1985 – Beus et al, *Topographic Changes in Fluvial Terrace Deposits Used as Campsites …*
1985- Kieffer, *The 1983 Hydraulic Jump in Crystal Rapid*
1987 – Stephens and Shoemaker, *In the Footsteps of John Wesley Powell …*
1988 – Webb et al, *Monument Creek Debris Flow …*
1990 – Andrews, *The Colorado River – a Perspective from Lees Ferry*
1990 – Rubin et al, *Origin, Structure, and Evolution of a Reattachment Bar …*
1990 – Schmidt, *Recirculating Flow and Sedimentation …*
1990 – Schmidt and Graf, *Aggradation and degradation of alluvial sand deposits …*



NPS
USBR

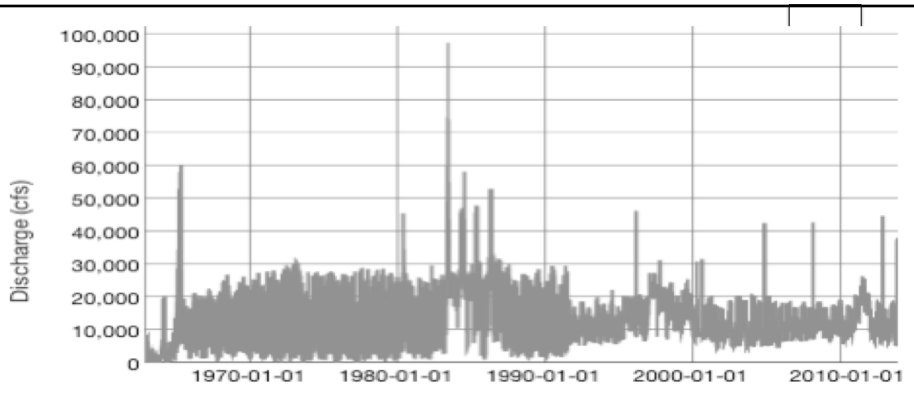
GCES I

GCES II

1991 – Carothers and Brown, *The Colorado River in Grand Canyon …*
1991 – Marzolf, *Colorado River Ecology and Dam Management*
1996 – Webb, *Grand Canyon, A Century of Change …*

- Sand bars
  - Erosion processes (waves, seepage, episodic mass failures
  - Campsite change
  - Hydraulics and flume modeling
  - Sand thickness and distribution
- Surficial geology
- Debris flows
  - Frequency
  - Distribution)
- Mainstem
  - Sand mass balance
  - Hydropower wave propagation

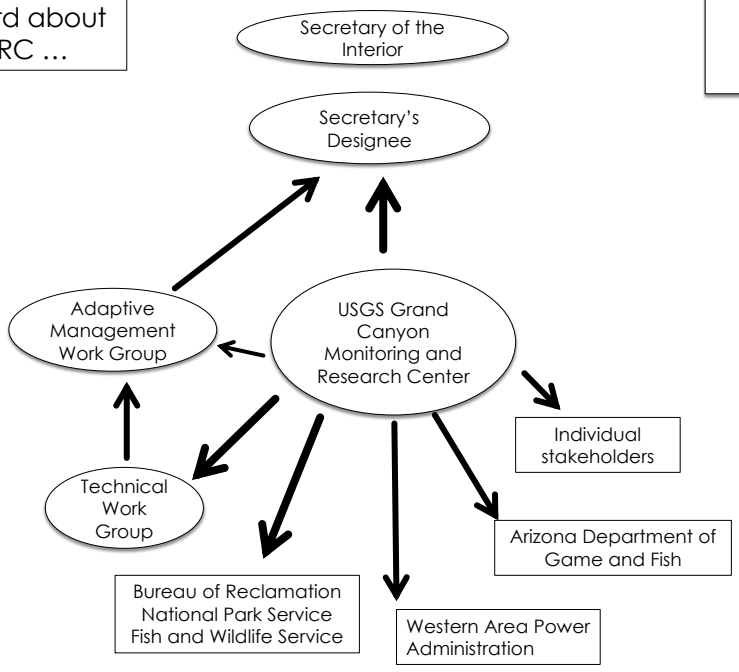
River science: early 1990s

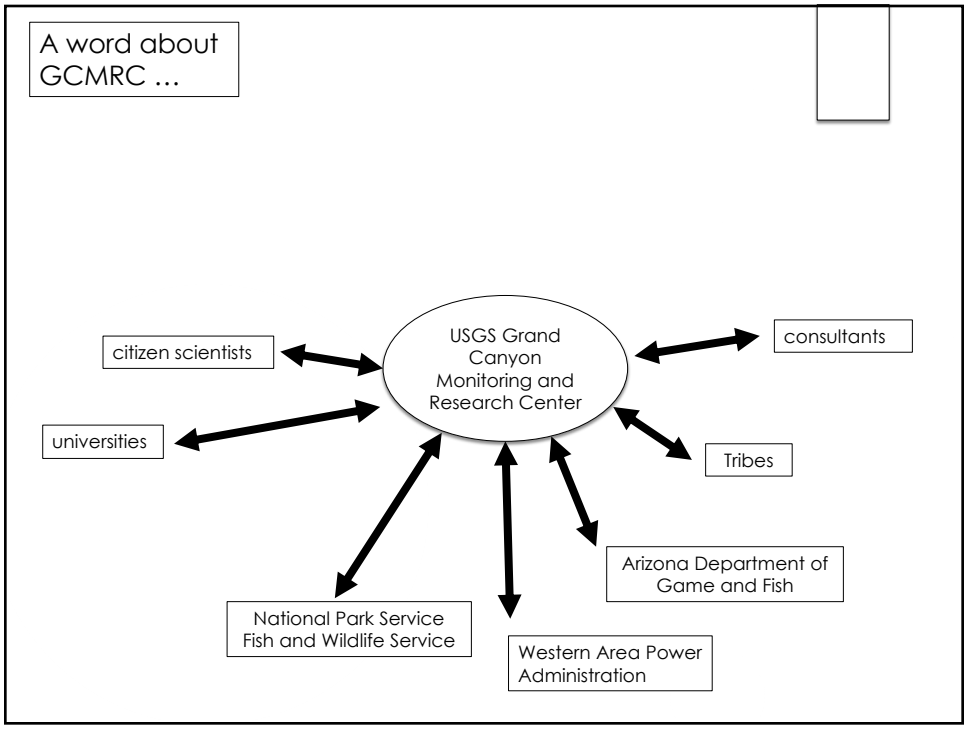


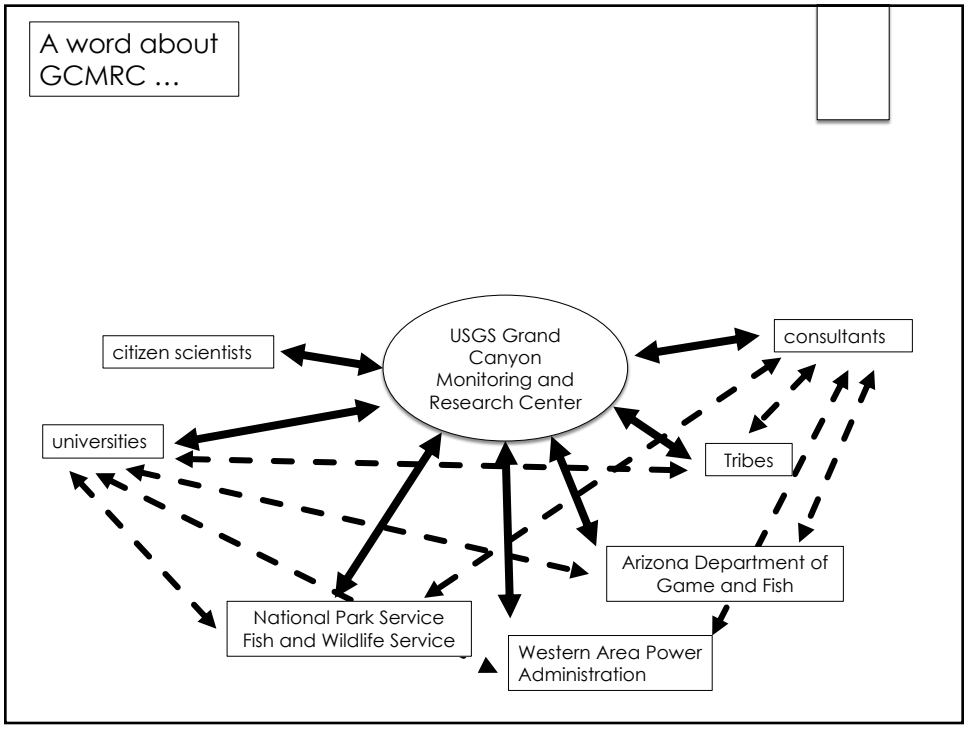
River science: late 1990s

- Mainstem sediment transport
  - Hysteresis and supply limitation (measured and historical re-evaluation); clarify sand budget
  - Controls on suspended sediment concentration
- Recirculating flow and sand bars
  - Observation, monitoring, modeling, and prediction
- Debris flows

A word about GCMRC …




A word about GCMRC …
USGS Grand Canyon Monitoring and Research Center
citizen scientists
universities
consultants
Tribes
Arizona Department of Game and Fish
National Park Service
Fish and Wildlife Service
Western Area Power Administration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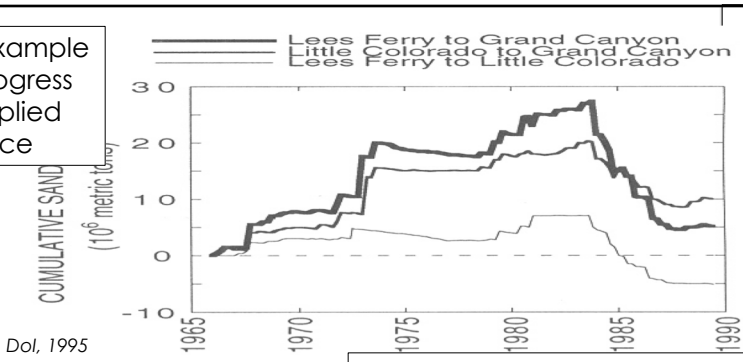
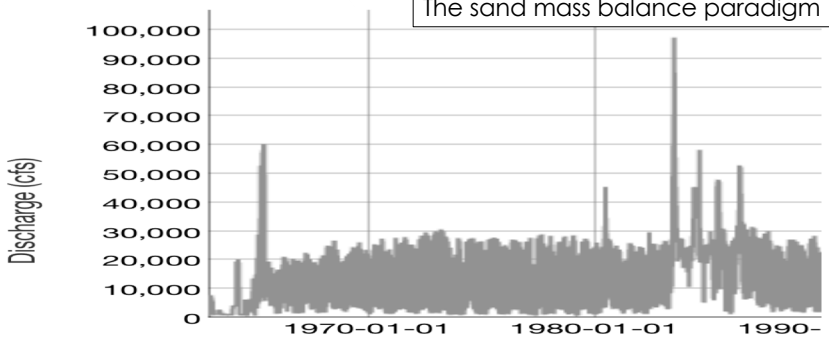
An example of progress in applied science



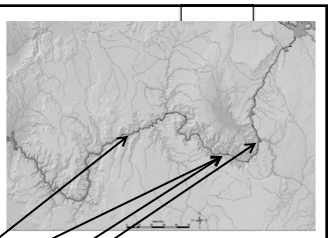
Dol, 1995

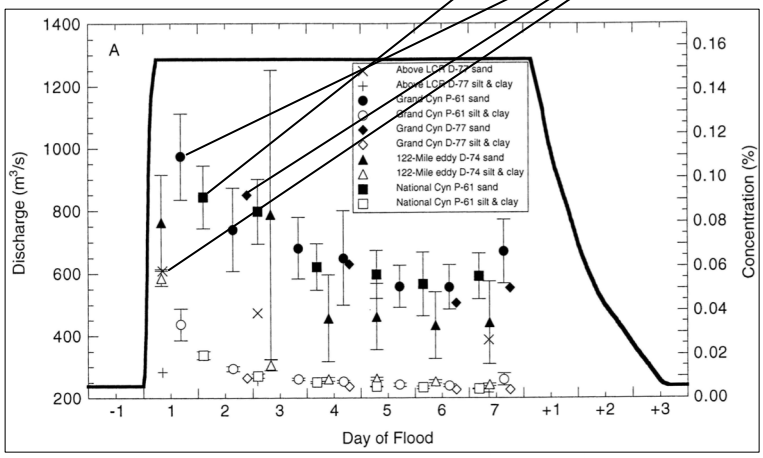
The sand mass balance paradigm (1995)



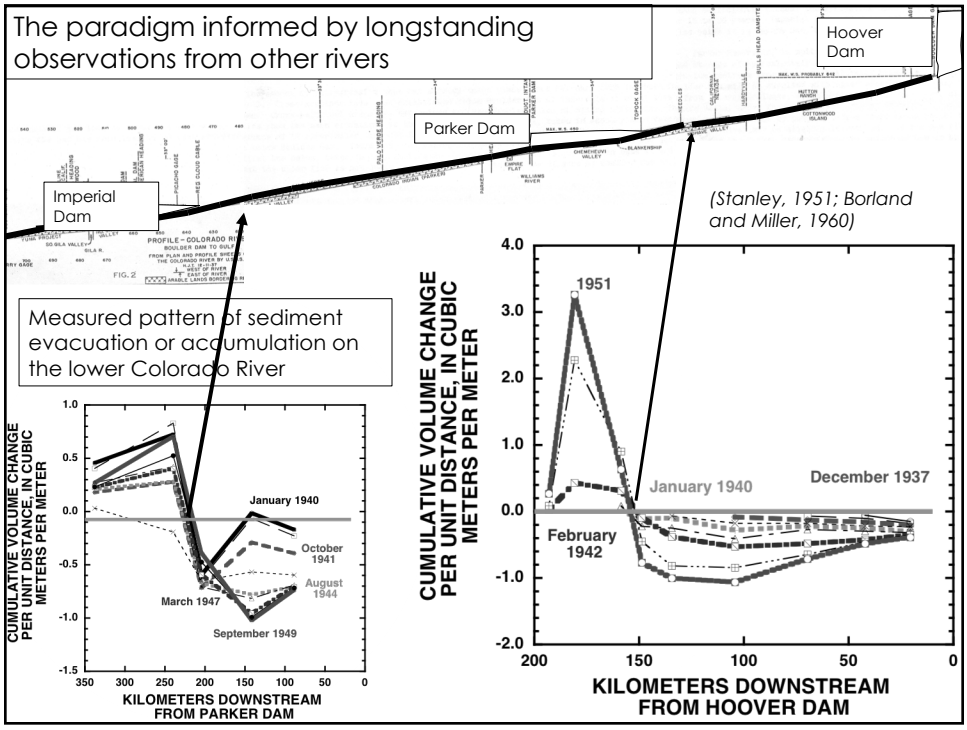
The paradigm questioned

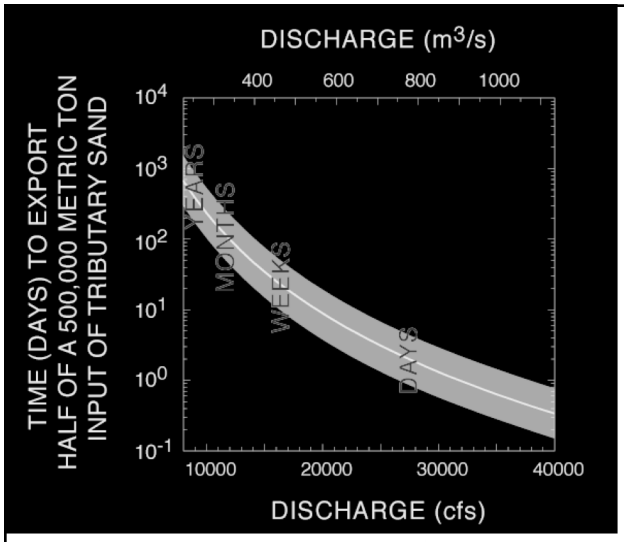
In 1996, suspended fine sediment concentration decreased greatly during 7 days of steady discharge (Topping et al., 1999)

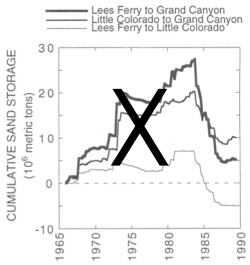




The paradigm informed by longstanding observations from other rivers

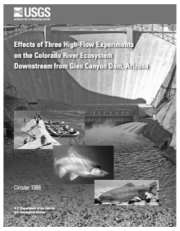






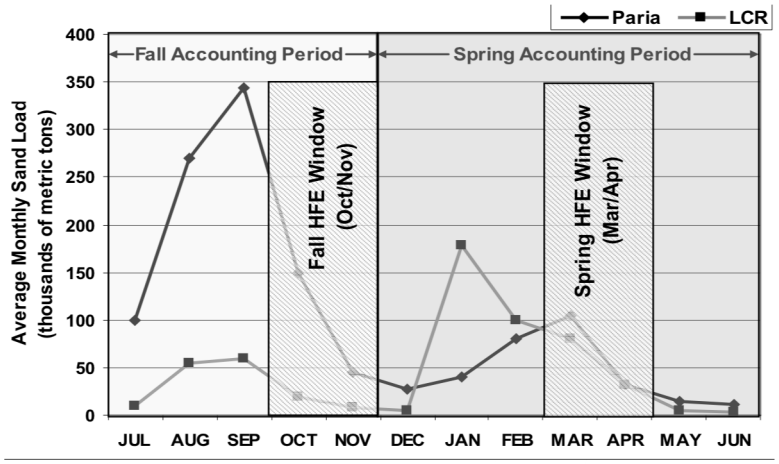
Calculated time to export 0.5 million mt of tributary sand past Grand Canyon gage. Upper limit is based on average suspended sand concentration for post-dam period; lower limit is based average suspended sand concentration for sediment enriched conditions; middle curve is based on concentrations that decrease with time from high transport values to mean conditions.

A new paradigm

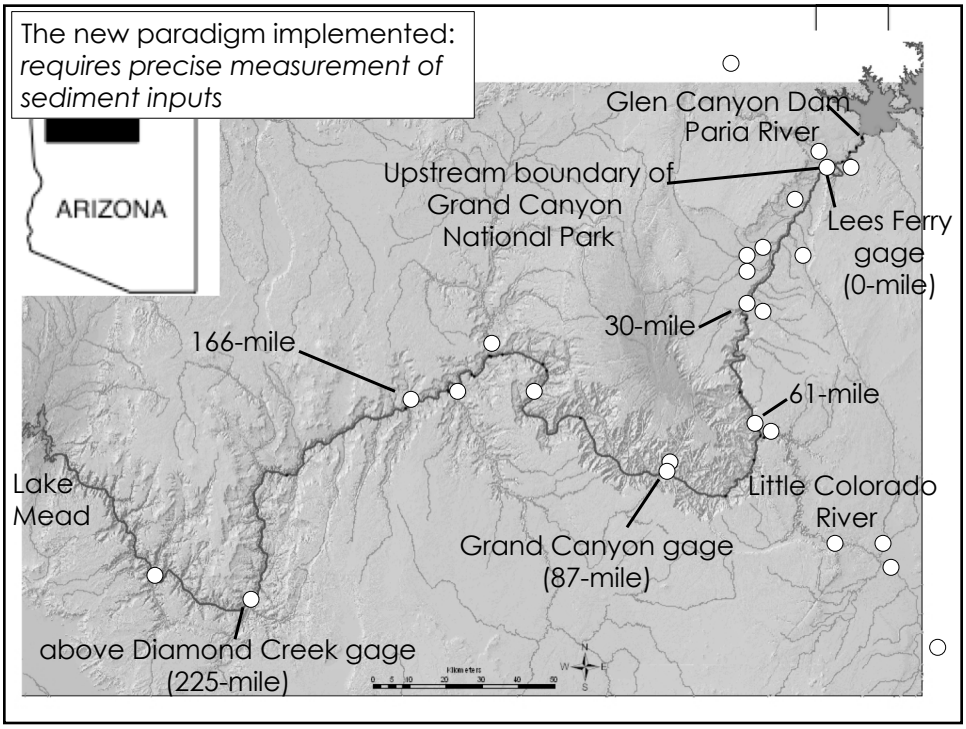


The new paradigm implemented

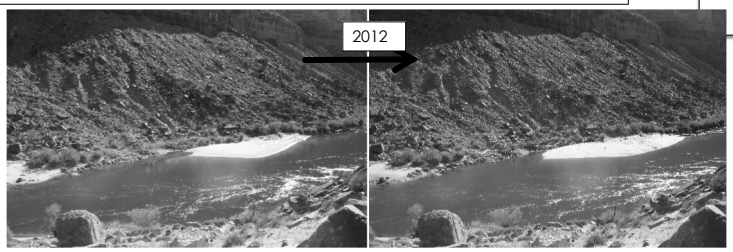
The HFE Protocol defines two seasons of accumulation and two seasons when controlled floods (called High Flow Experiments – HFEs) can occur.



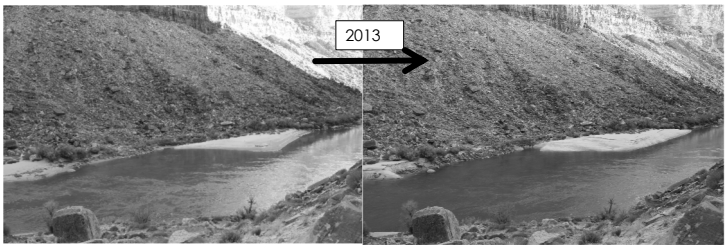
The new paradigm implemented: *requires precise measurement of sediment inputs*

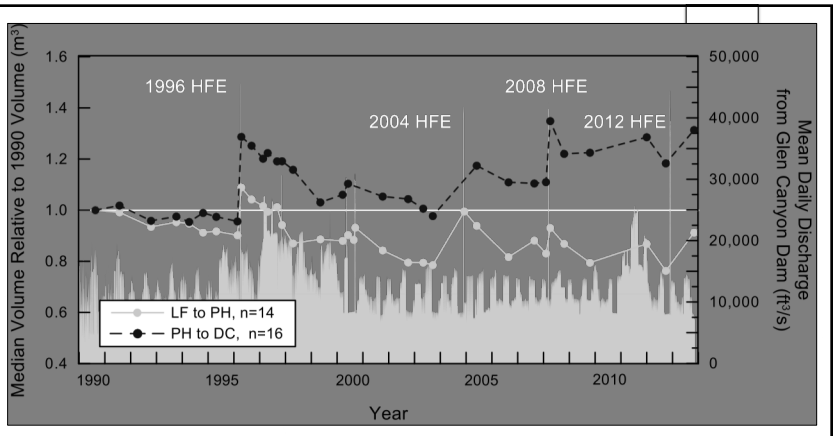


Does implementation of the new paradigm result in larger sandbars?



The same eddy sand bar in two floods

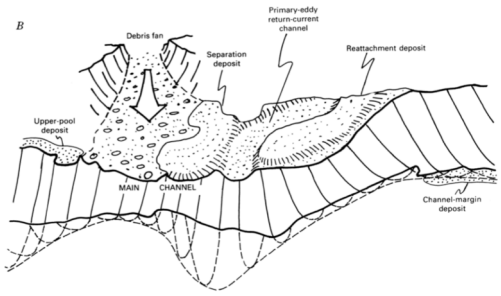




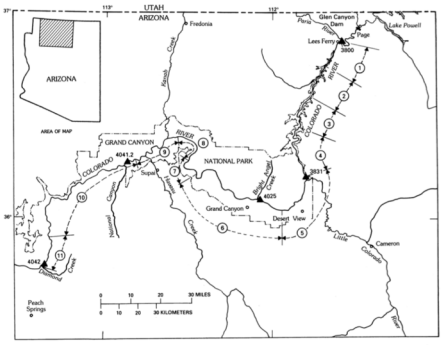
Hazel et al, "The NAU Time Series"

Force a longstanding scientific question to be revisited -- What averaging scheme should be used to generalize site measurements about sandbars to the entire river corridor?

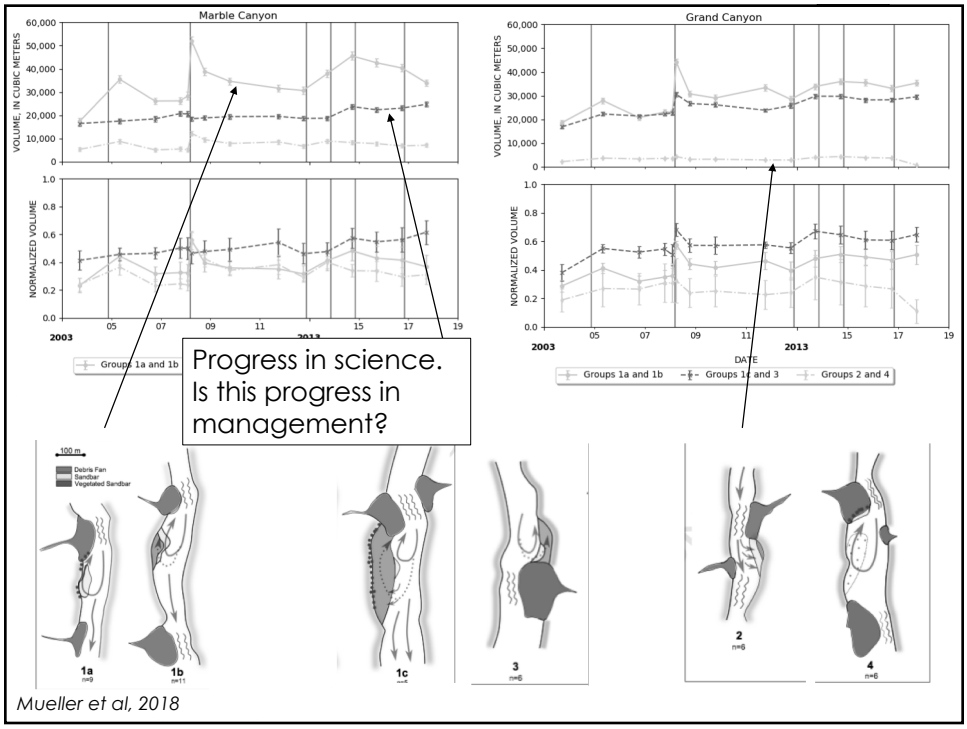
Detailed field surveys at a few sites need to be averaged to represent average response for entire Grand Canyon.



- How to generalize sandbars
  - Types within a fan-eddy complex
  - Large-scale location



Schmidt and Graf, 1990



Mueller et al, 2018

- Questions that have been resolved; monitoring now implements management
  - Fine sediment transport
  - Stream flow
  - Sand bars (what precision is needed to inform management?)
- Questions that endure
  - Is there enough sand to maintain sandbars in perpetuity?
  - What is the magnitude of sand mass balance deficit? Are there segments in equilibrium?
  - What is the average response of eddy bars to floods (how extrapolate site measurements?)
  - Do long-term changes in channel bed topography matter to sand bars?
  - 2-D and 3-D hydraulic modeling (tractable? to what degree is it needed?)
- New questions
  - Does downslope colonization of riparian vegetation significantly affect sandbar topography and stability?
  - Is upslope redistribution of fine sediment to hillslopes significantly affected by sandbar size and distribution?
- Questions that are no longer a focus of active investigation
  - How do sandbars form?
  - What are the erosional effects of waves, footsteps, camping, and hydropeaking?
  - Does silt and clay significantly increase sandbar stability?
  - Significance of hillslope erosion processes at upslope archaeological sites
  - What flows significantly rework debris flow deposits?

Existence of dam

Reservoir operations

Change rules concerning which reservoirs store water; change allocation agreements

Restore sediment supply by sediment by-pass

Change flood control rules

Eliminate fragmentation caused by dams

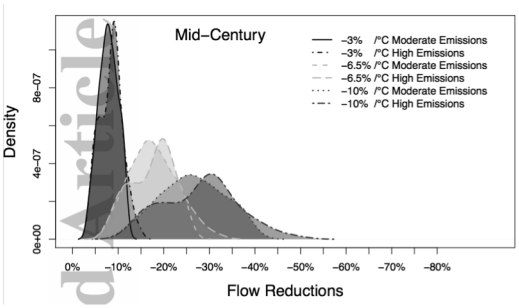
Flow regime changes
- Controlled floods
- Change seasonality of flows

Temperature regime changes
- Increase summer water temperature
- Decrease decrease winter water temperatures

Reduce or eliminate hydropeaking

Applied river science to date has led to adjustments in dam management focused on changing reservoir operations, but …

… the climate is changing

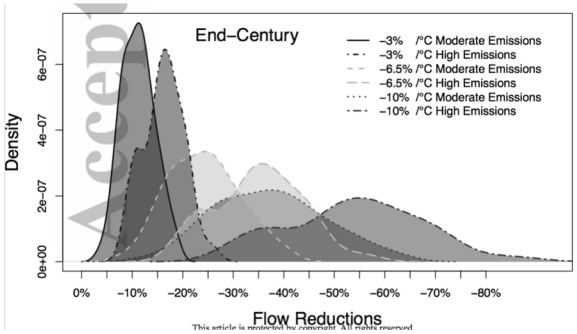


-17% reduction in runoff in 2050 based on moderate emissions scenario and mid-range estimate of flow sensitivity to temperature increase

(12.6 million af)

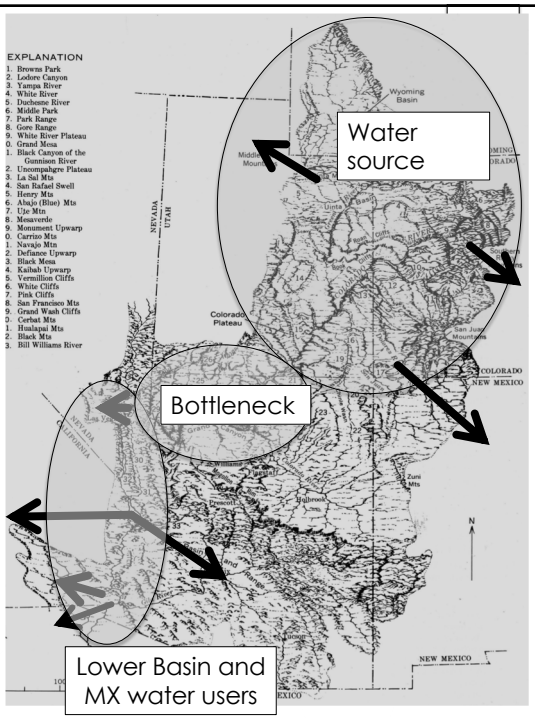
-25 to -35%% reduction in runoff in 2100 based on moderate emissions scenario and mid-range estimate of flow sensitivity to temperature increase

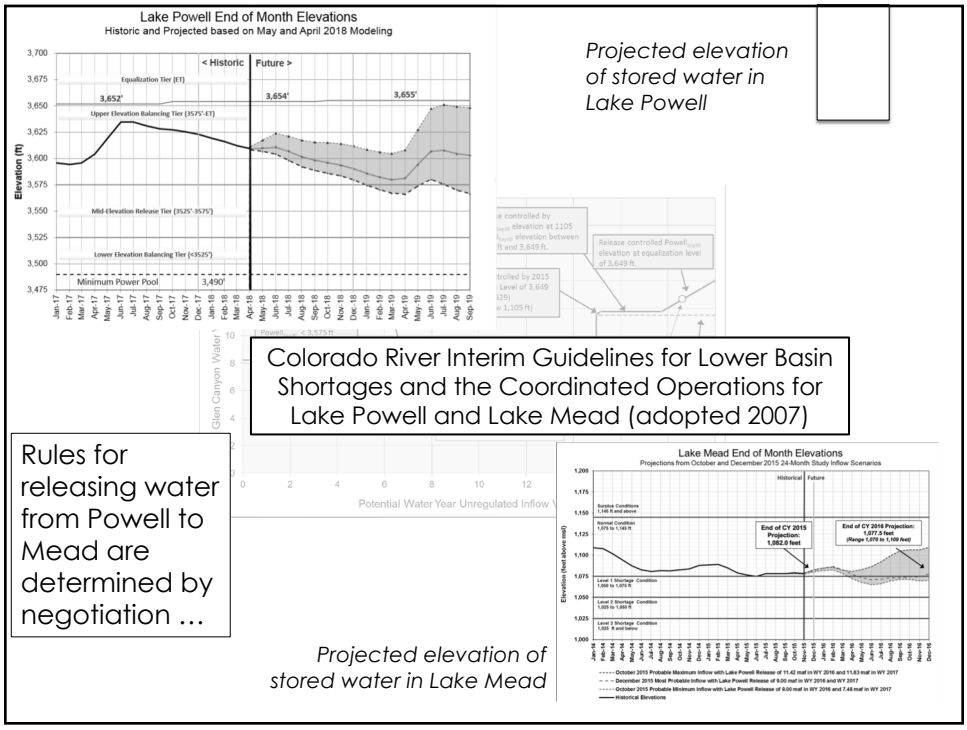
(9.8 to 11.3 million af)

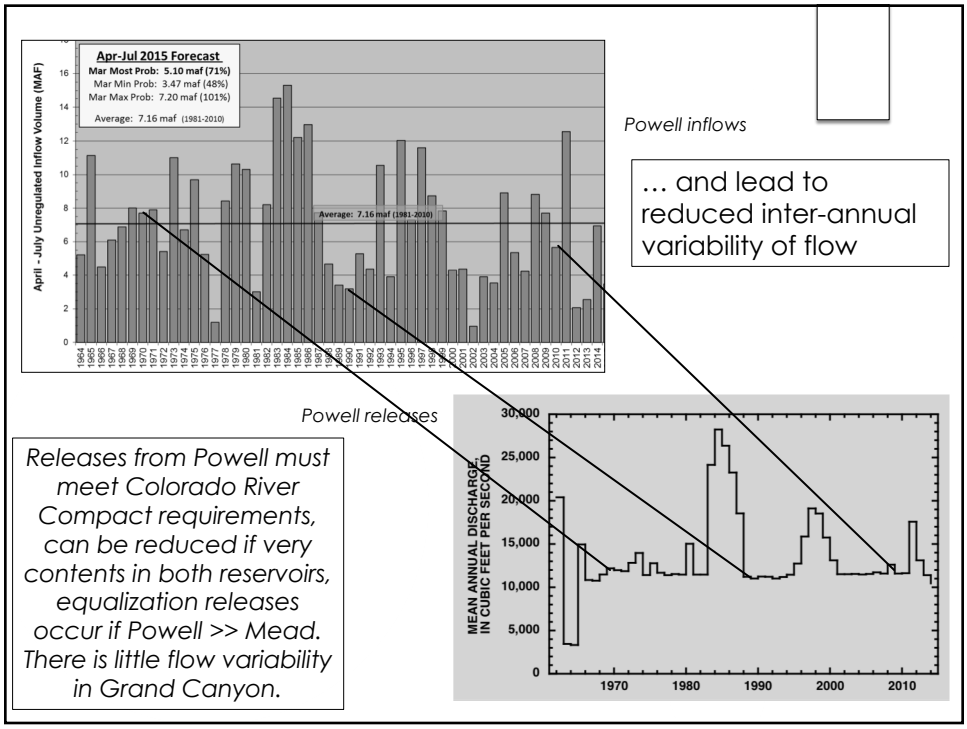


(Udall and Overpeck, 2017)

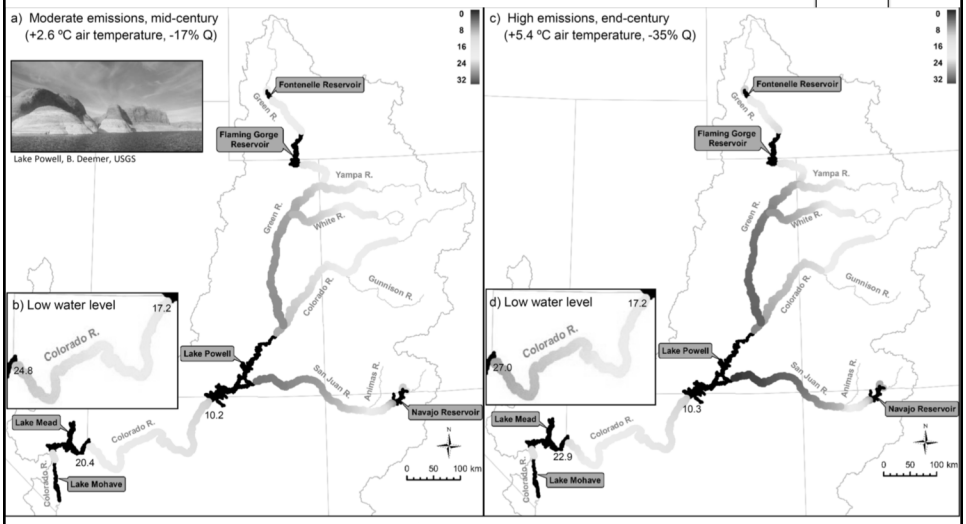
All water that enters Lake Powell passes through the southern Colorado Plateau and is released from Lake Mead to Lower Basin users




Lake Powell End of Month Elevations
Historic and Projected based on May and April 2018 Modeling
< Historic
Future >
Equalization Tier (ET)
3,652'
3,654'
3,655'
Upper Elevation Balancing Tier (3575'-ET)
Mid-Elevation Release Tier (3525'-3575')
Lower Elevation Balancing Tier (<3525')
Minimum Power Pool
3,490'
Elevation (ft)
Projected elevation of stored water in Lake Powell
Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead (adopted 2007)
Rules for releasing water from Powell to Mead are determined by negotiation …
Lake Mead End of Month Elevations
Projections from October and December 2015 24-Month Study Inflow Scenarios
End of CY 2015 Projection: 1,082.0 feet
End of CY 2016 Projection: 1,077.5 feet
Projected elevation of stored water in Lake Mead


Apr-Jul 2015 Forecast
Mar Most Prob: 5.10 maf (71%)
Mar Min Prob: 3.47 maf (48%)
Mar Max Prob: 7.20 maf (101%)
Average: 7.16 maf (1981-2010)
April - July Unregulated Inflow Volume (MAF)
Powell inflows
… and lead to reduced inter-annual variability of flow
Powell releases
MEAN ANNUAL DISCHARGE IN CUBIC FEET PER SECOND
Releases from Powell must meet Colorado River Compact requirements, can be reduced if very contents in both reservoirs, equalization releases occur if Powell >> Mead. There is little flow variability in Grand Canyon.

Dibble et al., in prep.



Water supply decisions have a large potential impact on options considered for river rehabilitation. For example, river temperature regimes in the future will be determined by storage volumes in reservoirs,

Conclusions

- *River science has shifted from studies to support the development of dams and diversions throughout the watershed to the environmental management of segments downstream from specific dams.*
- *Questions asked of/by scientists have shifted and changed during the past decades.*
- *Some questions have been resolved, some discarded, and new questions asked. Other questions endure. Progress in science does not necessarily mean progress in management.*
- *Impending reduction of watershed runoff will lead to new questions not previously asked. These questions will inevitably be at a watershed scale.*