DEBRIS FLOWS IN GRAND CANYON: MODELING CHANGES IN THE LONGITUDINAL PROFILE OF THE COLORADO RIVER

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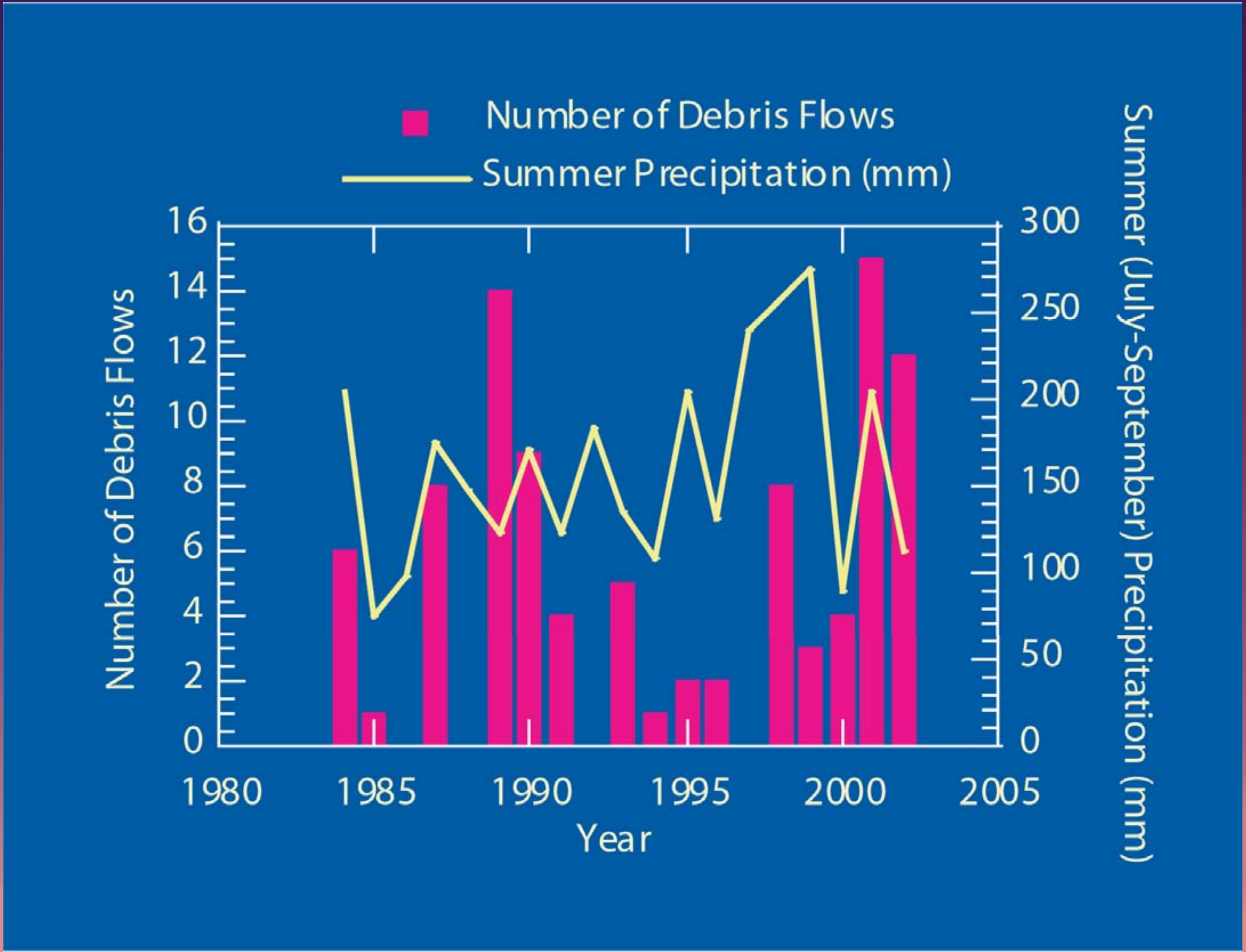
USGS Survey Expedition, 1923

MODELING DEBRIS-FLOW SEDIMENT YIELD

Based on substantial data on debris flows, we developed a stochastic model with 3 components:

1. Debris-flow frequency component
2. Sediment-yield component
3. Boulder-delivery and reworking component

Observed Debris Flows, 1984-2002



Ref: Griffiths et al. (2004)

Repeat Photography and Debris Flows

- Matched 1,365 photos showing debris-flow evidence.
- Earliest photo: 1871. Most useful group: 1890.
- 113 debris flows at 160 tributaries (1890-1983).
- Extrapolation: 5.0 debris flows per year (1890-1983).

1890

1990

Ref: Webb (1996), Webb et al. (1999a)

Debris Flow Frequency

- From 1890-1983, the reconstructed frequency of debris flows is 5.0 events/yr.
- From 1984-2003, a total of 101 debris flows were observed in Grand Canyon (5.1/yr).
- From 1984-2003, 11 increased the severity of existing rapids, 8 changed existing riffles into rapids, and 3 created new riffles.

Ref: Griffiths et al. (2004)

Debris-Flow Frequency (Logistic Regression)

- Photography records at least one debris flow in 84 of 160 tributaries (57%) from 1890 through 1990.
- We analyze debris-flow occurrence as “yes/no” categorical data with 22 geologic and morphologic variables.
- We calculate debris-flow probabilities with 5-7 significant variables (e.g., drainage area, lithology, aspect).
- We convert logistic probabilities to a lognormal frequency factor.

Ref: Webb et al. (2000), Griffiths et al. (2004)

Frequency Model Development

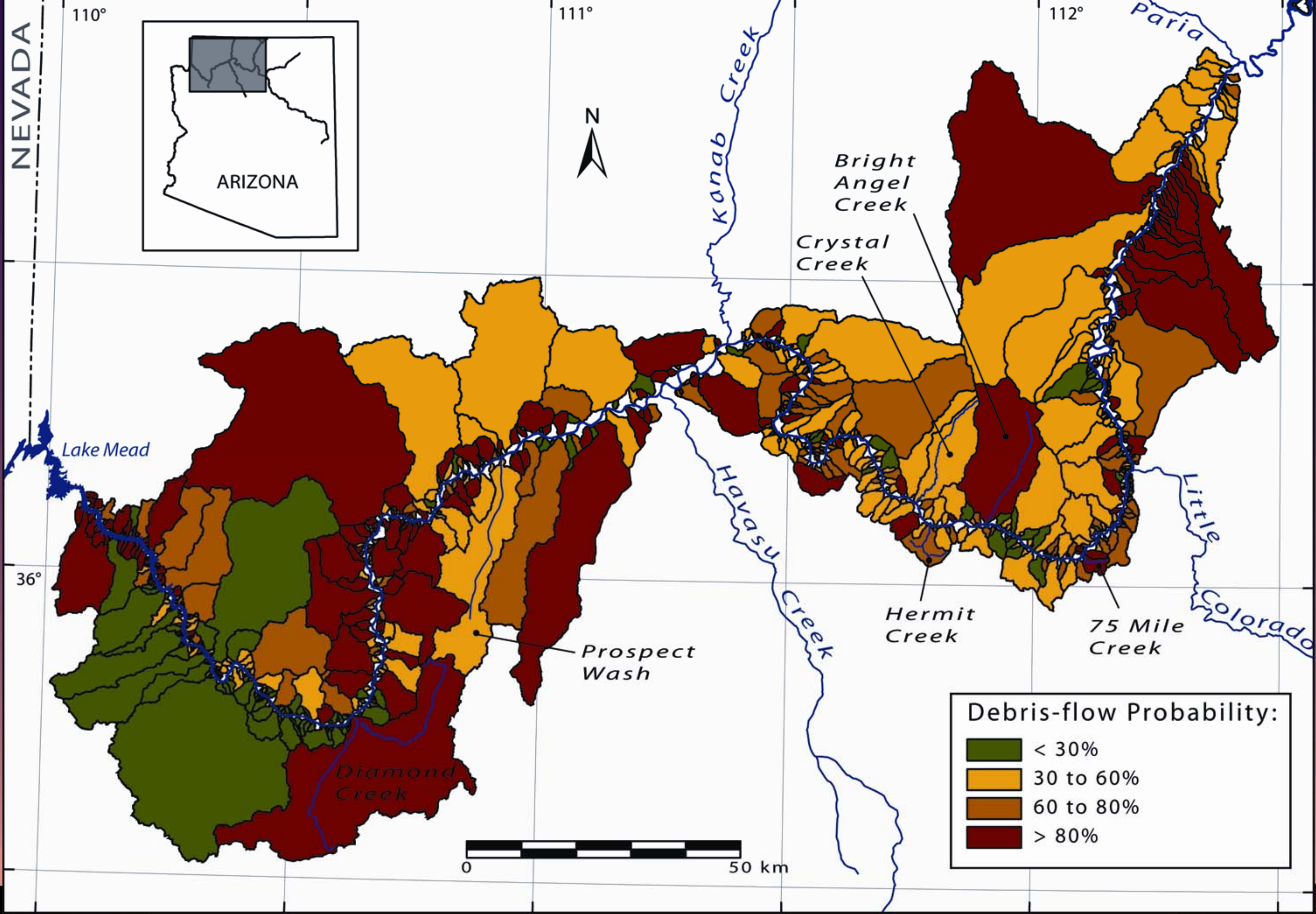
- Logistic probability is a cumulative density function.
- Assume the logistic probability, $\pi(x)$, is equivalent to a cumulative binomial density function.
- For large n, cumulative binomial density function can be approximated with a lognormal distribution [*i.e.*, $P(\ln(x)) = \pi(x)$].

Therefore, we used the “frequency factor” approach:

$$F = e^{(\mu + K[\pi(x)] \,.\, \sigma)}$$

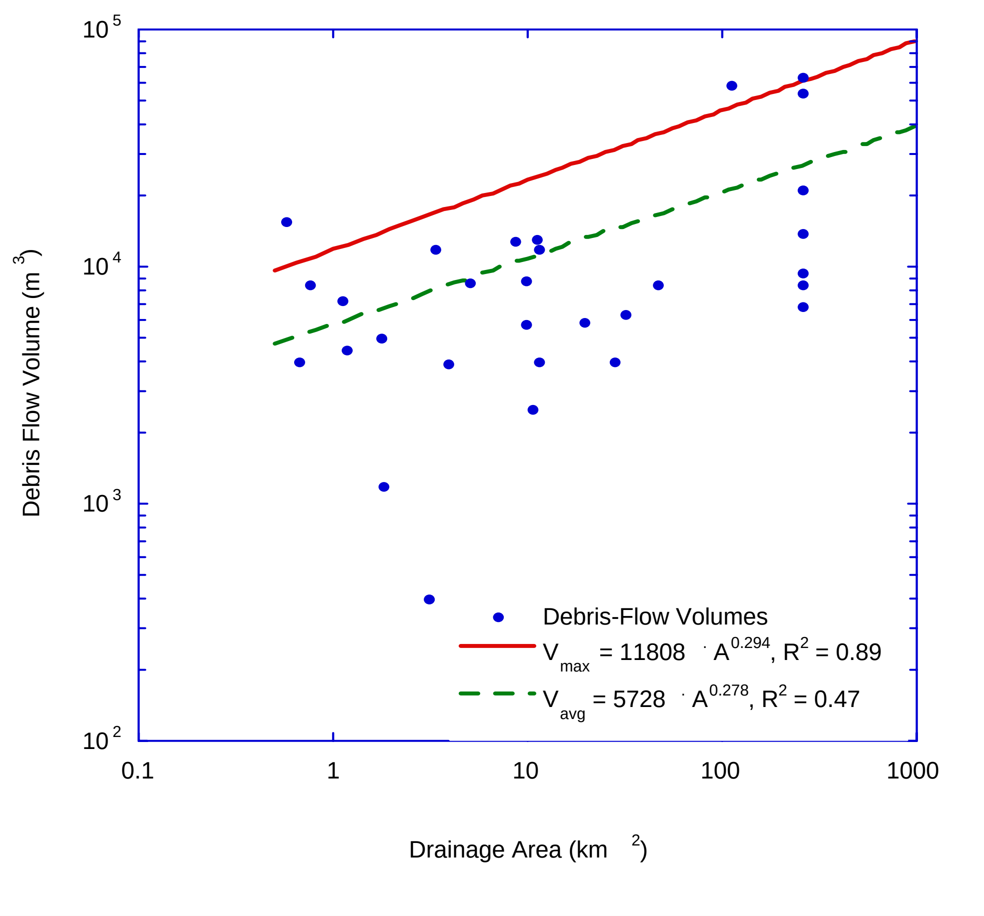
where F = expected value of number of debris flows per century, K = standard normal deviate, and μ and σ are mean and standard deviation of a lognormal distribution.

Ref: Webb et al. (2000)



Ref: Griffiths et al. (2004)

Debris-Flow Sediment Yield



$$Q_{sdf} = 0.17 \cdot F[\pi(x)] \cdot a \cdot A^{b}$$

where

Q_{sdf} = sediment yield per decade
$F[\pi(x)]$ = the DF frequency factor
a, b = empirical coefficients
0.17 is a conversion factor.

Ref: Webb et al. (2000)

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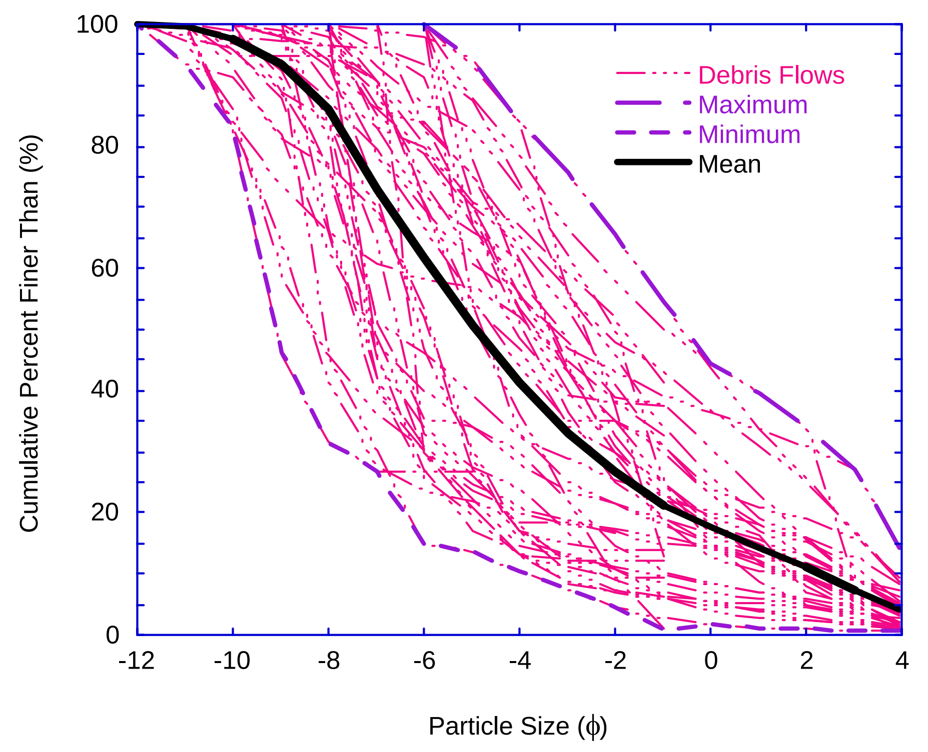
Modeling Coarse Sediment Inputs

- Debris-flow sediments, on average, are 14% boulders, 65% gravel and cobbles, and 18% sand.
- Model predicts sediment inputs into the river based on long-term averages.
- This model could be used to predict (with a river-reworking component) where gravel would accumulate in Grand Canyon.



Ref: Melis (1997), Webb et al.(2000)

Boulder-Delivery Model

- Model form is:

$$Q_b = \Sigma\,(0.769 \cdot E\{PS_b\} \cdot F[\pi(x)] \cdot V\,(A)),$$

where Q_b = boulder delivery (m^3/ka), $E\{PS_b\}$ = 0.138, $F[\pi(x)]$ = frequency factor from logistic regression, $V\,(A)$ = expected debris-flow volume, and the summation occurs over a thousand years.

- Deposition area in river, A_d, is:

$$A_d = W_u \cdot L_r + A_{df}\,,$$

where W_u = width of unconstricted river, L_r = length of rapid, and A_{df} = area of modern debris fan (all measured at 227 m^3/s).

- Bed rise (m/ka), $H = Q_b / A_d$.

Ref: Melis (1997), Webb et al. (2000)

Largest Rapids Versus Predicted Bed Rise

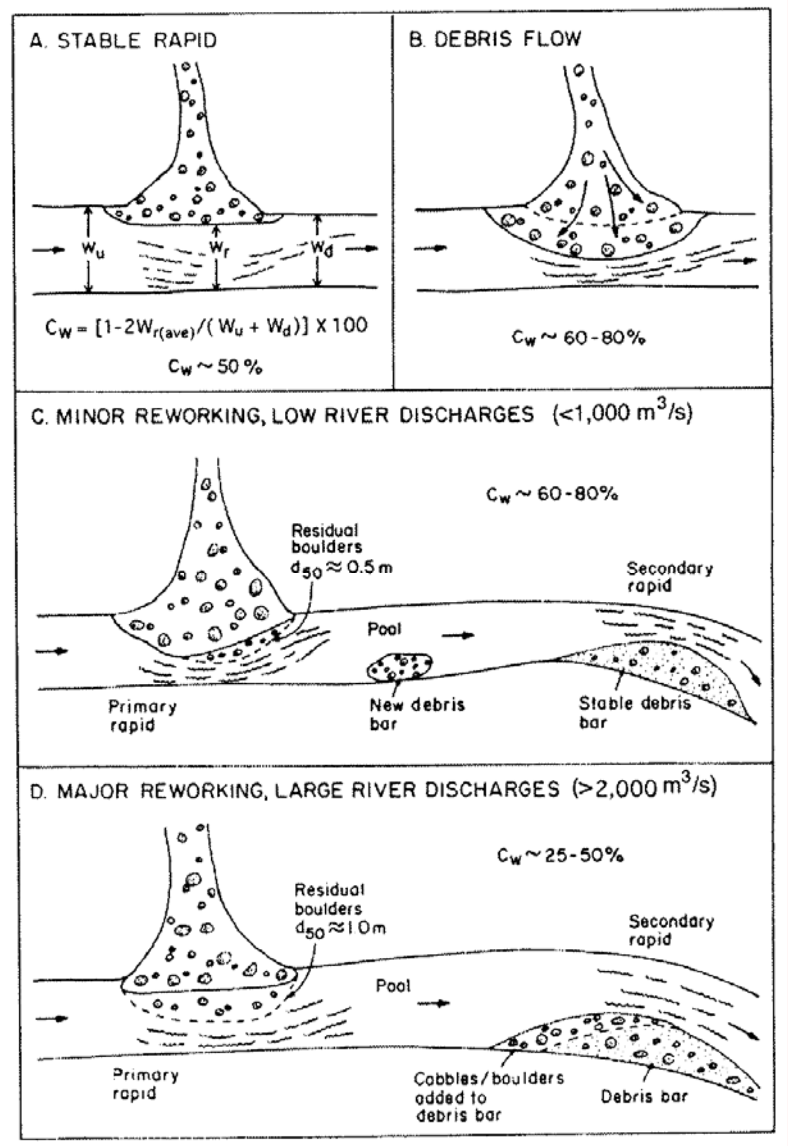
- Realistic: Lava Falls has 4.3 m drop, is predicted to have a 2.75 m drop.
- Questionable: Bright Angel Creek Rapid has a 5.9 m drop, is predicted to have a 12.5 m drop.
- Unrealistic: South Canyon has a 1.2 m drop, is predicted to have a 13.0 m drop.

Ref: Webb et al. (2000, 2004)

Assumptions And Limitations Of Boulder Delivery Model

- Boulder content can be modeled as an space invariant expected value (13.8% of debris flow by volume)
- Cobbles and finer particles are all removed from rapids
- Boulders are not washed downstream (no reworking), and no dissolution or corrasion occurs
- Drops created in model do not influence one another (no “drowning out” of rapids upstream of a debris flow)
- The 227 m^3/s deposition area does not represent the true area of deposition available for debris flows except in constricted reaches

River Reworking

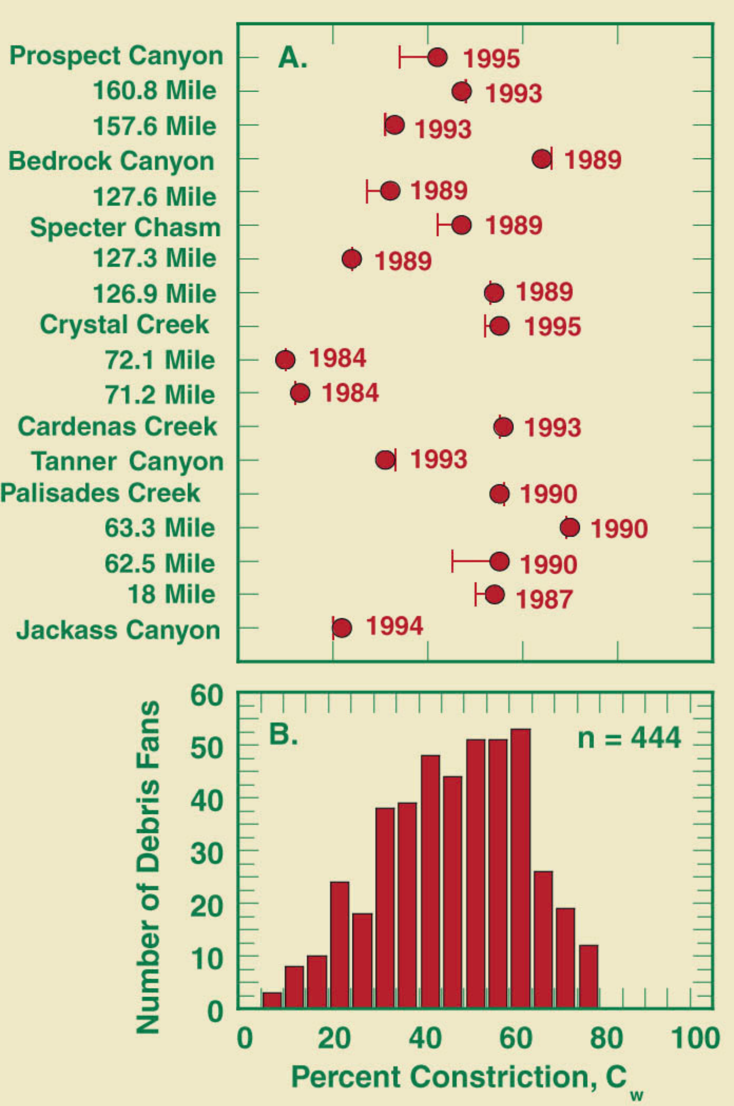


- Glen Canyon Dam completed in 1963.
- Pre-dam floods (to 8,500 m^3/s) removed all particles <1-2 m (b-axis diameter).
- Post-dam floods (< 2,720 m^3/s) move smaller particles up to 1.5 m in diameter.
- Particles now end up in the pool instead of the secondary rapid.

Ref: Melis (1997), Webb et al. (1999a, 1999b, 2000)

Reworking of Aggraded Debris Fans (the 1996 Flood)

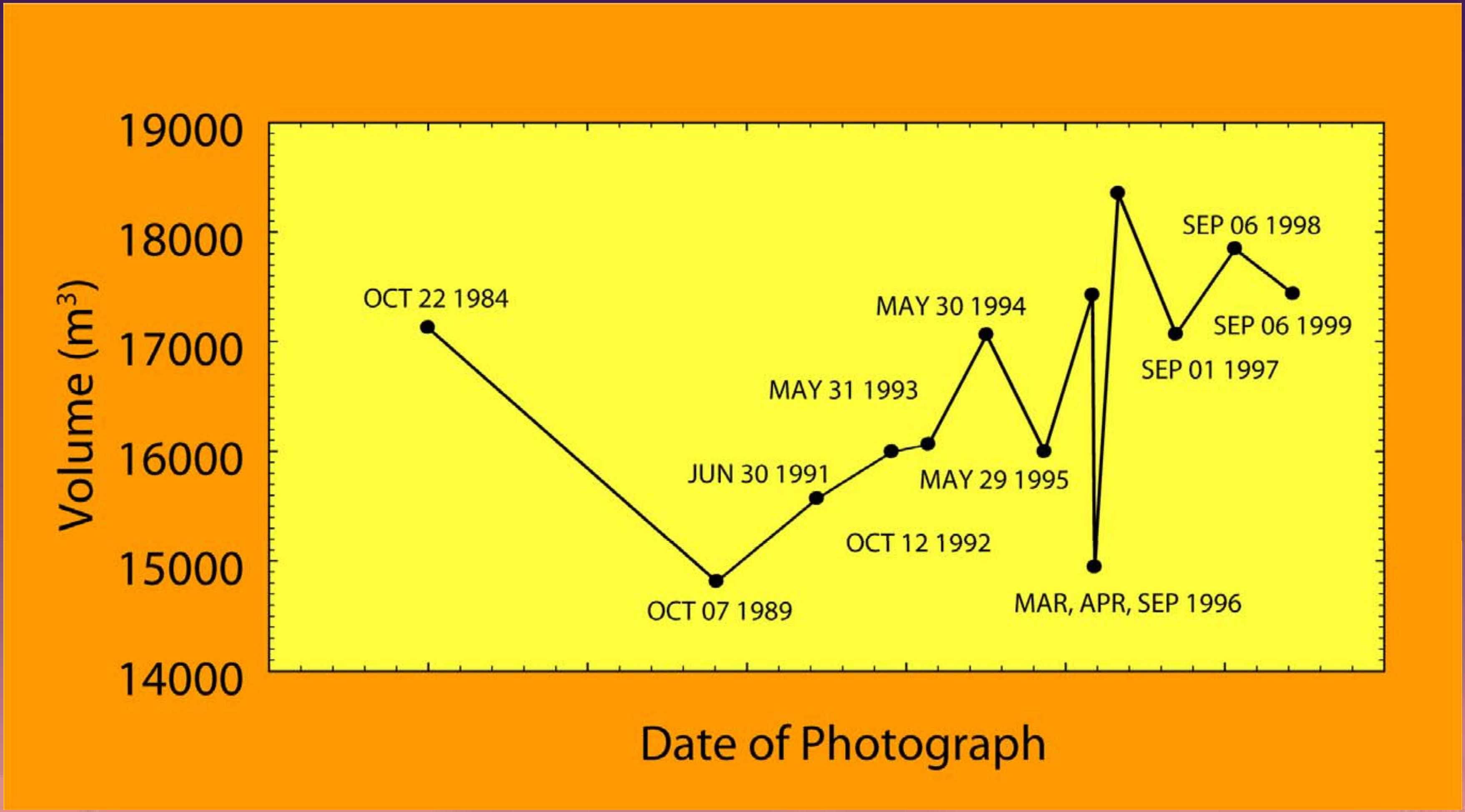
Lava Falls Rapid. A. March 25, 1996. B. April 6, 1996. The rapid widened by about 20 m by reworking of 1995 debris-flow deposits.



Ref: Webb et al. (1999b), Pizzuto et al. (1999)

Reworking of Debris Fan at Granite Rapid

Photogrammetric analysis using ERDAS



Ref: Yanites (in preparation)

Geomorphic Change Detection in Grand Canyon: Comparison of 1923 Survey and 2000 Lidar Data

1923 Birdseye Expedition

2000 Lidar Overflight

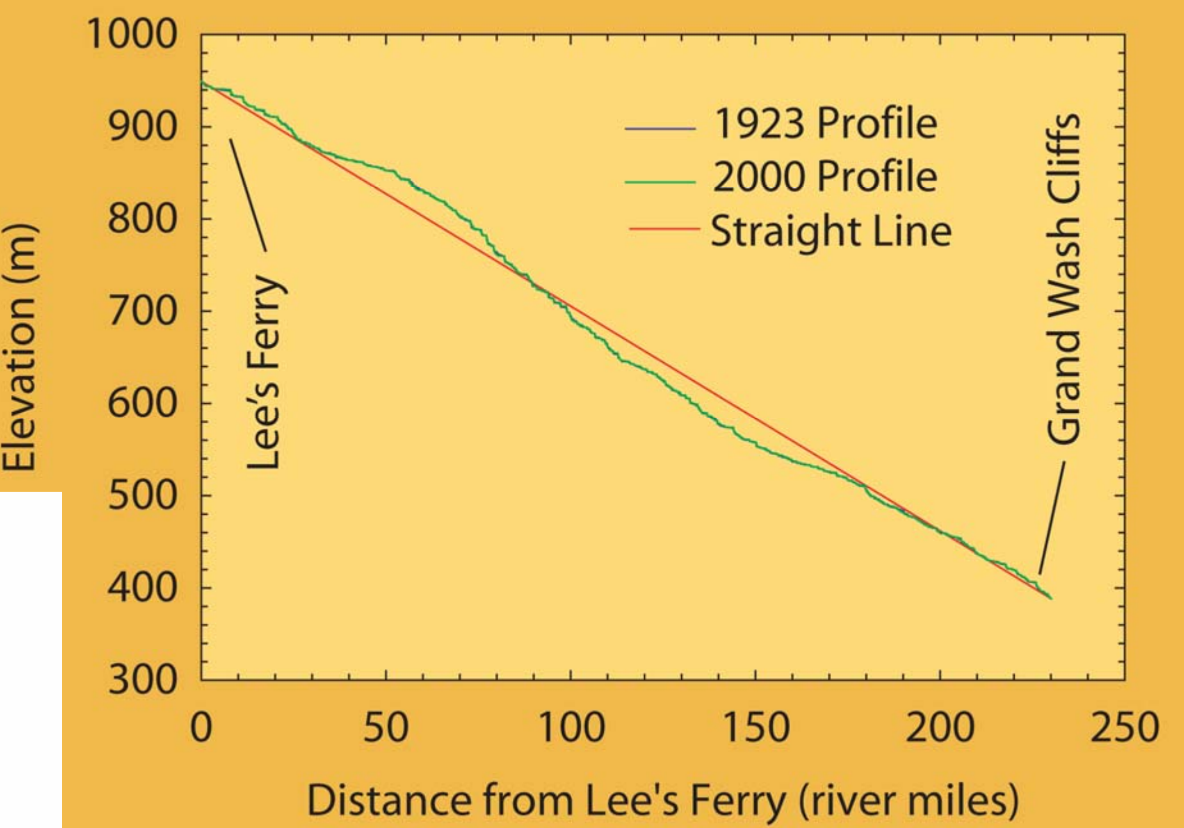
The water-surface profile in Grand Canyon has been measured twice:

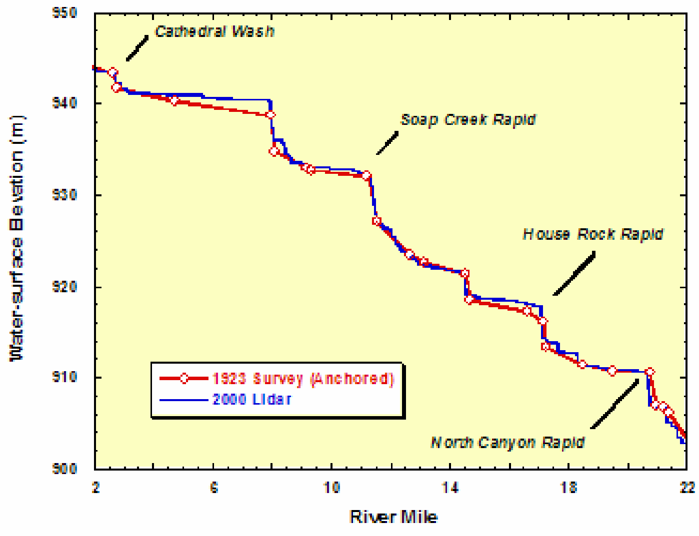
1. Directly surveyed by the USGS expedition in 1923.
2. Extracted from Lidar data collected in 2000.

Ref: Magirl et al. (in press)

Grand Canyon Longitudinal Profile

The profiles measured in 1923 and 2000 do not show differences at the scale of the full length of the canyon.

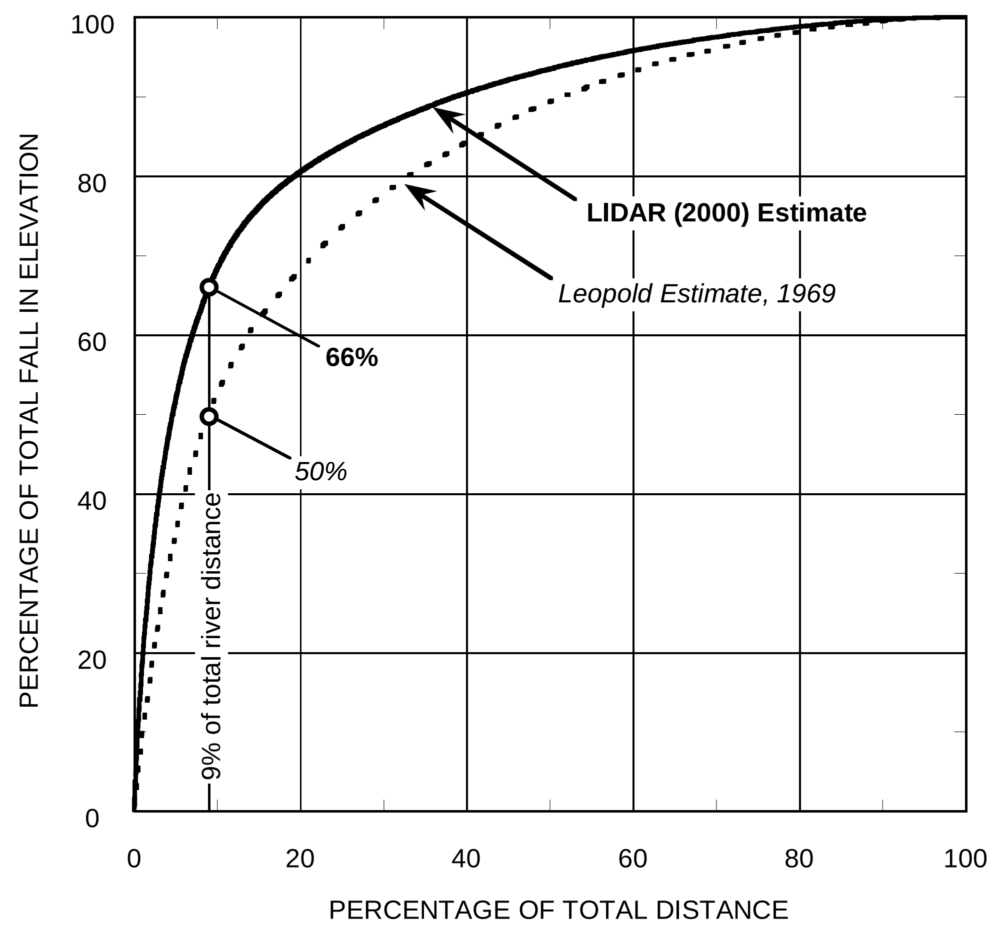




Refs: Magirl et al. (in press), Hanks and Webb (submitted)

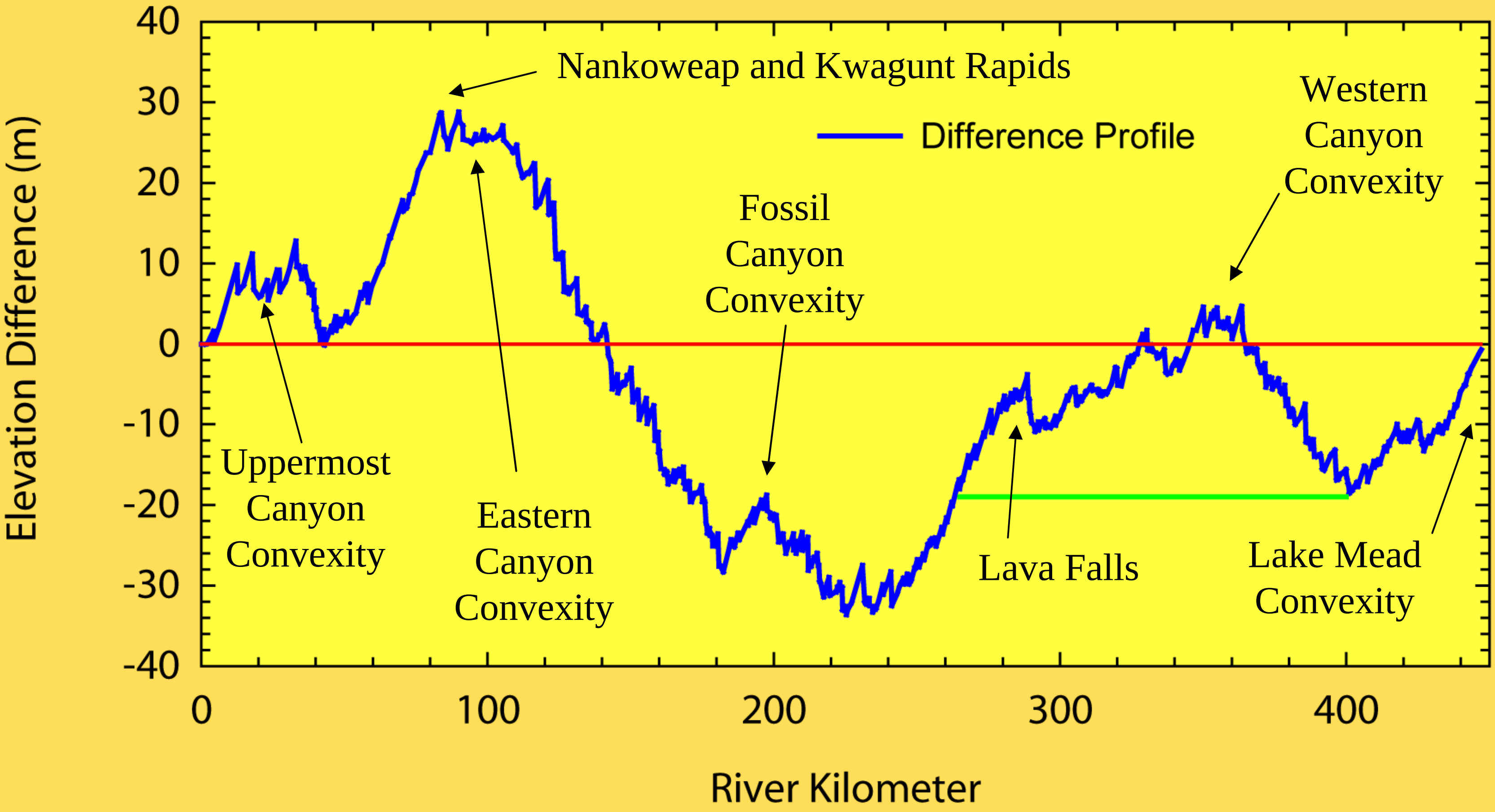
Interpretation of Profile Change

- Leopold (1969) found that 50% of total decrease in elevation takes place in only 9% of the total river distance (1923 profile).
- 2000 Lidar data indicates that 66% of drop occurs in 9% of distance.



Ref: Magirl et al. (in press)

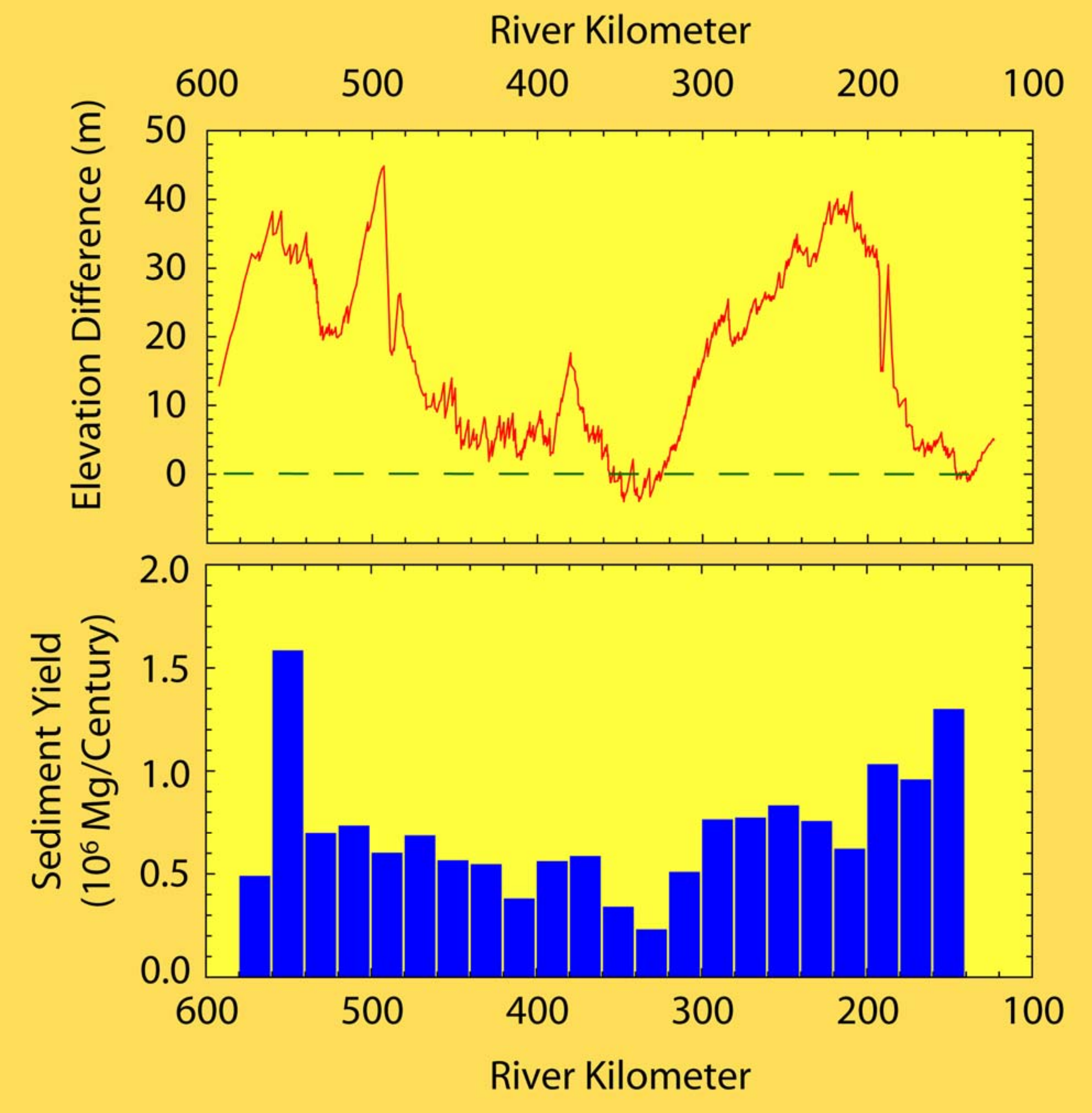
Difference Profile Reveals Convexities



Ref: Hanks and Webb (submitted)

Profile Difference and Debris-Flow Sediment Yield

Ref: Webb et al.
(unpublished data)

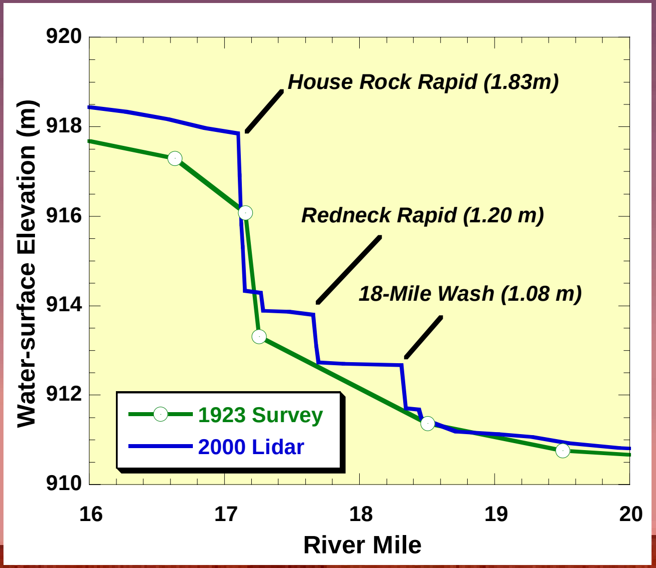


Largest Rise at Head of a Rapid

House Rock Rapid, mile 16.8

1923

1991

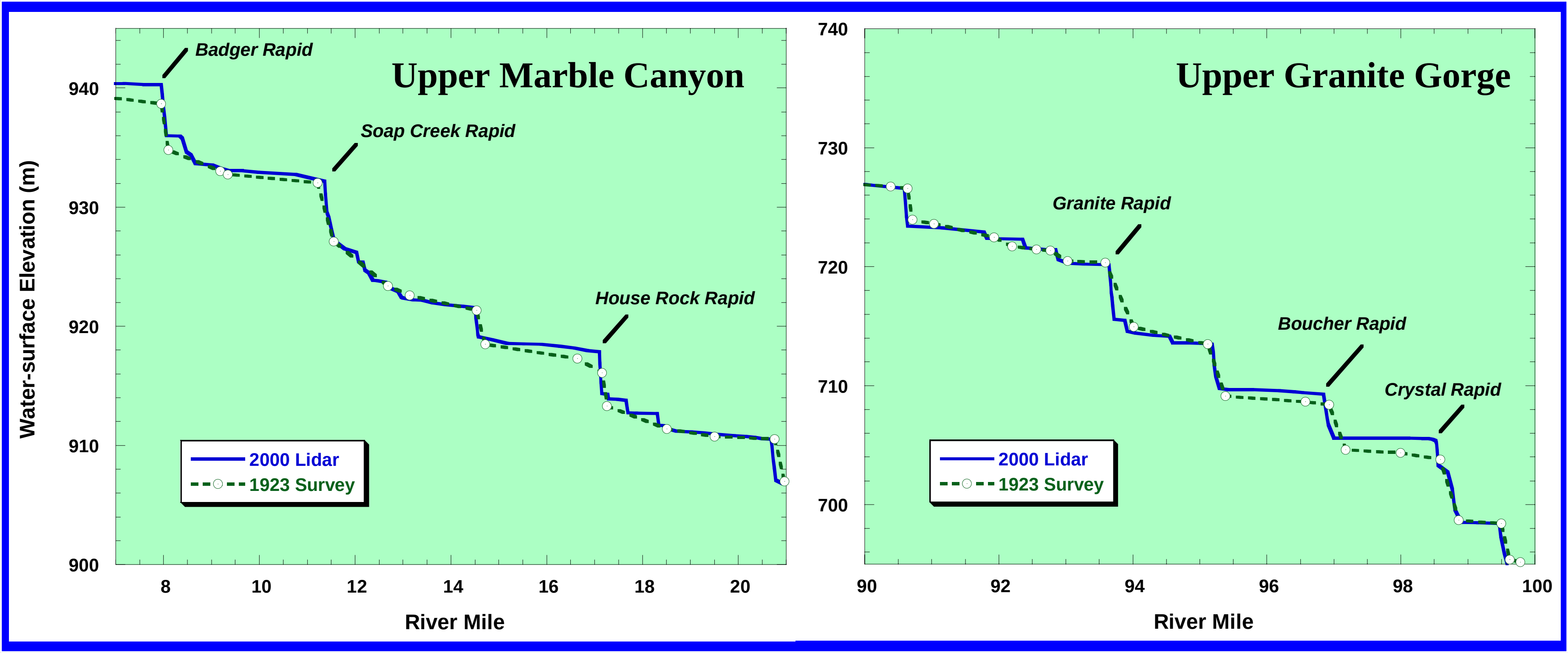


Net Rise: 1.83 m.

Ref: Magirl et al. (in press)

Change in Longitudinal Profile Over 77 Years

- The average change in rapids was +0.26 m, indicating net aggradation between 1923 and 2000.
- The river now has an enhanced pool-rapid morphology.



Ref: Magirl et al. (in press)

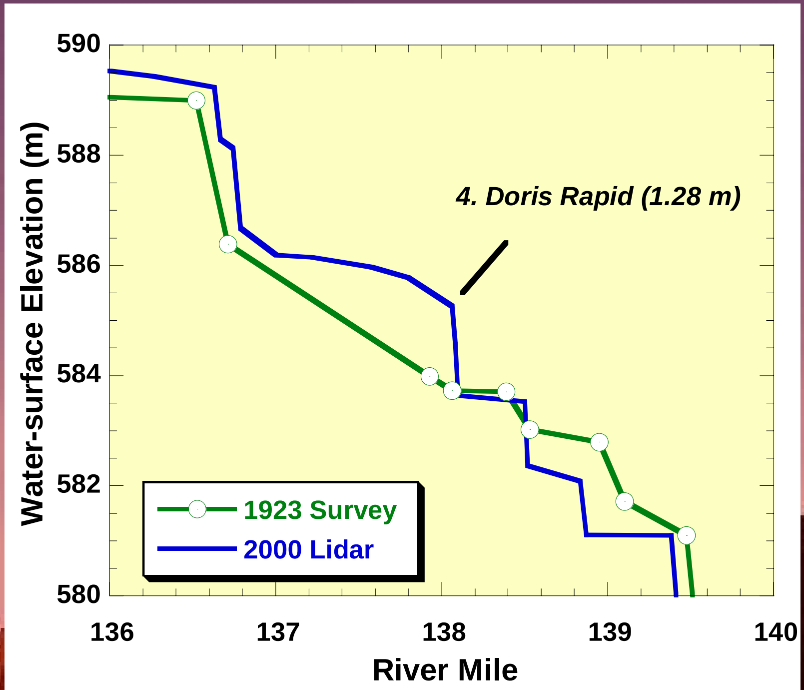
Detection of Previously Unknown Debris Flows

The riddle of Doris Rapid (mile 137.7):

- 1890: Stanton reports a 8-10 foot drop
- 1923: Birdseye measures a 1 foot drop
- 1940: Doris Nevills swims an enlarged rapid
- 2000: LIDAR measures a 5 foot drop

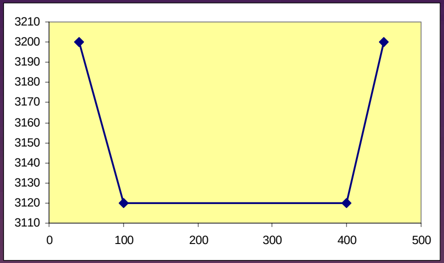
Possible Explanation:

1. Debris flow occurs between 1884-1890
2. The 220,000 ft^3/s flood in 1921 reworks the first deposit
3. A second debris flow occurs between 1923-1940



1-D Hydraulic Modeling

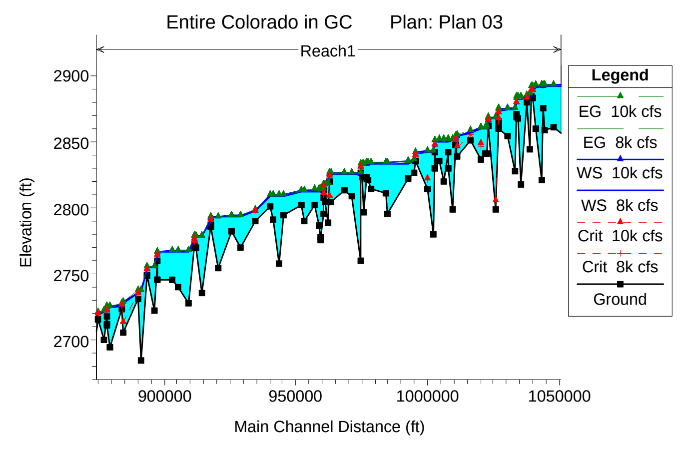
Randle and Pemberton (1987) STARS Model



- Based on 1923 and some 1984 data
- Limited to 30,000 ft^3/s peak discharge
- Most cross sections were idealized as trapezoids

Converted into HEC-RAS working model (2002)

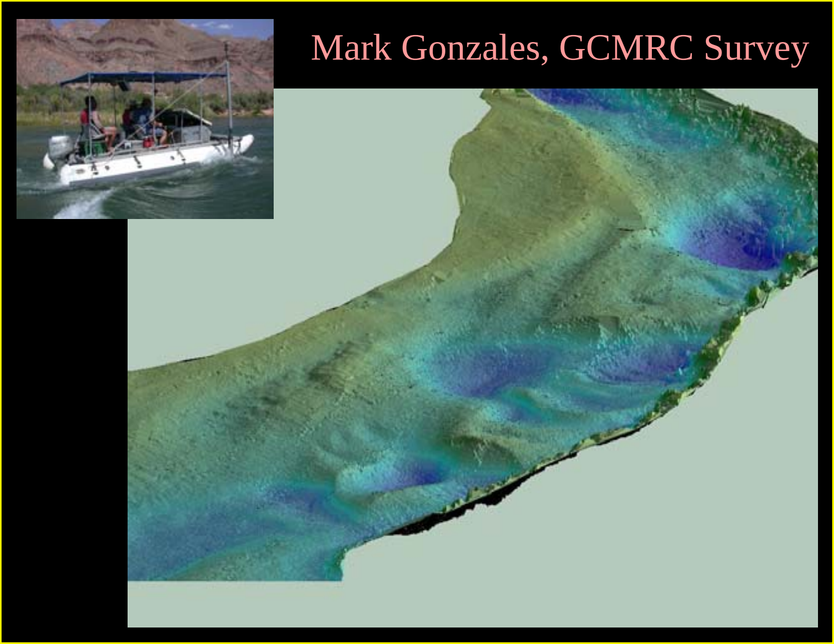
- Entire river length modeled
- Uses STARS cross sections (still based on 1923/1984 data)
- Ultimate goal is modeling of gravel and coarse particle transport for conceptual modeling



Ref: Magirl (in preparation)

Improved Hydraulic Model using GCMRC Data

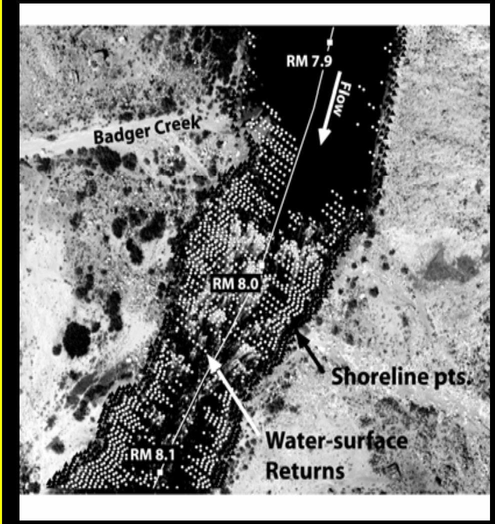
2002 Bathymetry

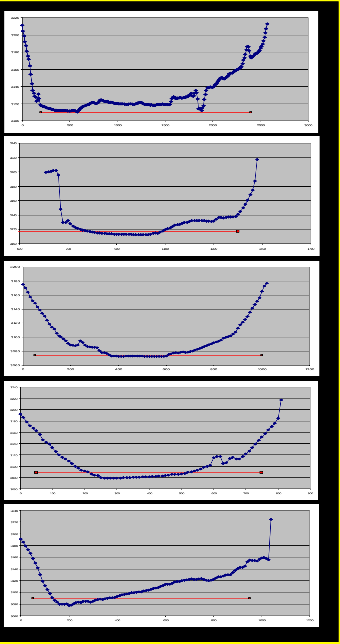


Mark Gonzales, GCMRC Survey

2002 LIDAR Topography

Mike Breedlove, GCMRC GIS





State-of-the-Art 1-D Hydraulics

GSTARS

- Gravel transport
- Fish spawning
- Sand storage

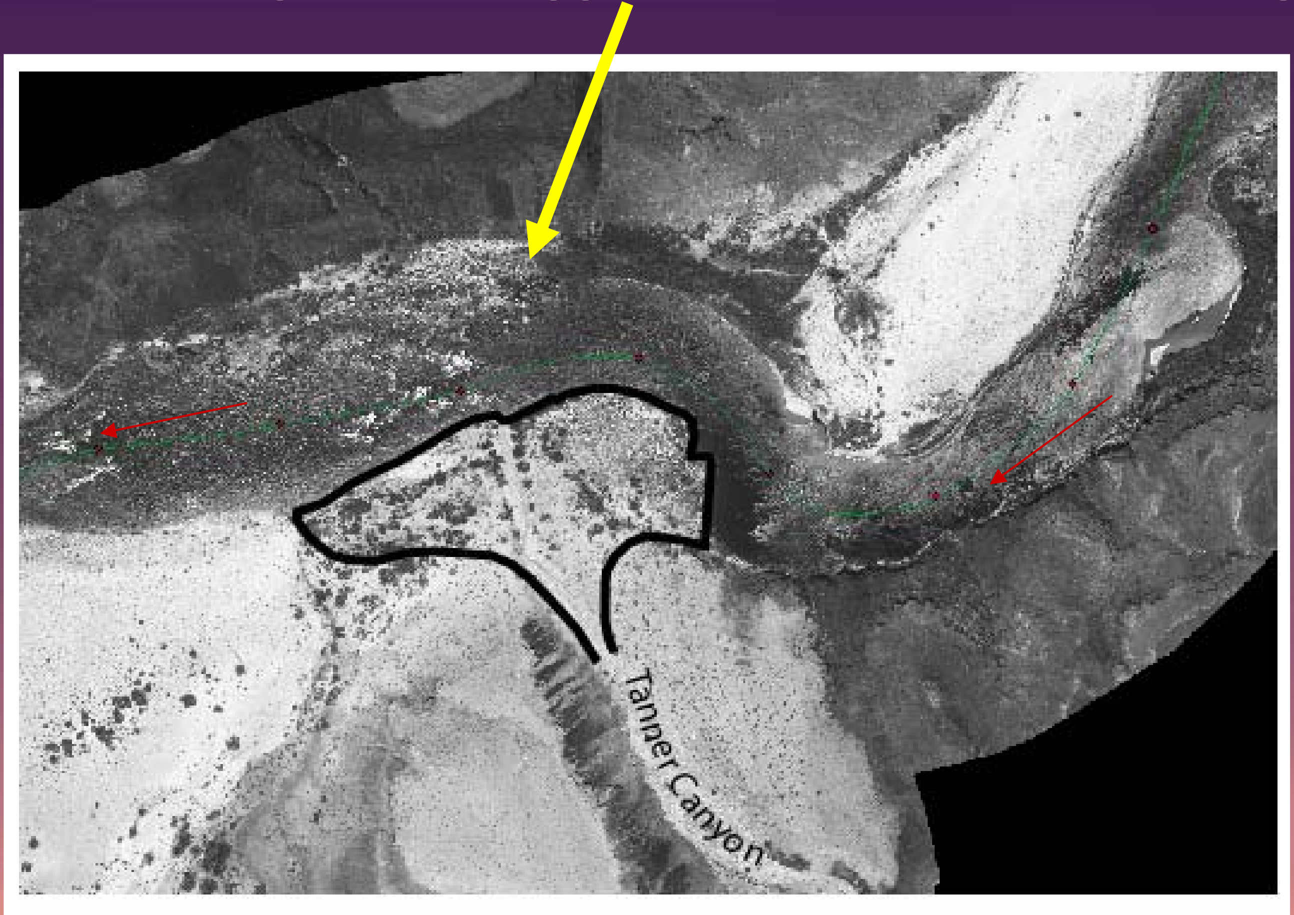
HEC-RAS

- Inundation to PMF level
- Debris fan reworking
- Combine w/ DF model

Ref: Magirl (in preparation)

Debris-Flow Effects at Tanner Rapid (RM 69.0)

Kaibab boulders on right side suggest late Holocene damming of river



Aerial Photo 2002

Ref: Magirl et al. (in preparation)

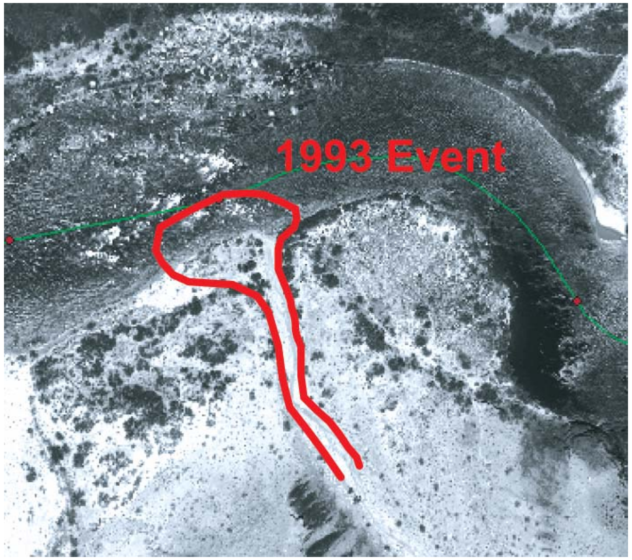
Tanner Rapid Geomorphic History

River response:

+1.0 m rise

The Debris Flow of 1993

- Induced by fire-hose effect from intense thunderstorm 8/22/93
- 7,500 m^3 of material deposited in or near the river
- Constricted the river by 30% (30 m)



Ref: Melis et al. (1994)

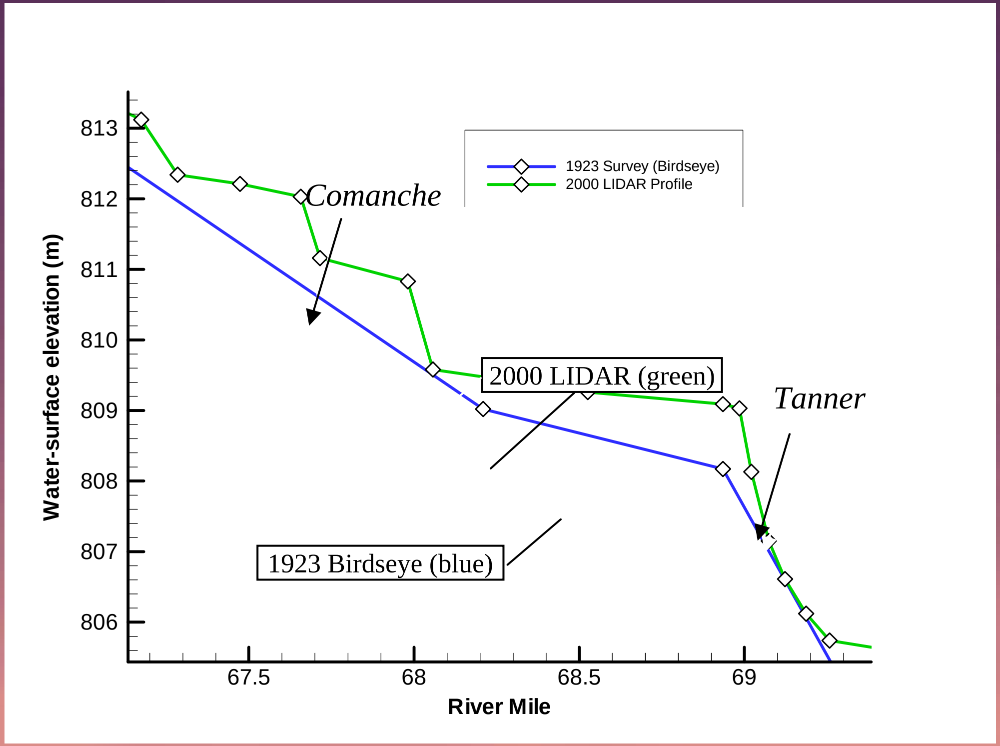
Tanner Rapid

	River response
Debris flow 1993	**+1.0 m**
Flood of 1996	**-0.27 m**

Ref: Webb et al. (1999)

Tanner Rapid Geomorphic History

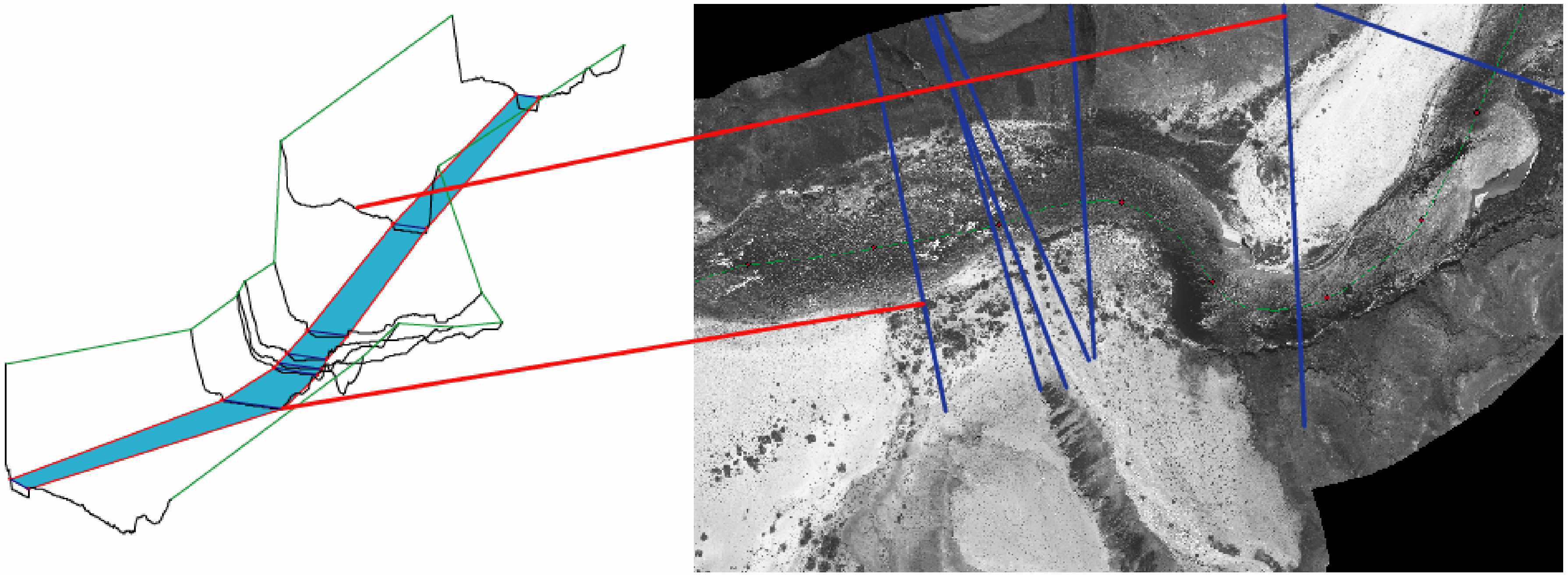
	River response
The Debris Flow 1993	**+1.0 m**
Flood of 1996	**-0.27 m**
Net change, 1923 to 2000	**+0.9 ± 0.7 m**



Ref: Magirl et al. (in press)

HEC-RAS 1-D Hydraulic Model

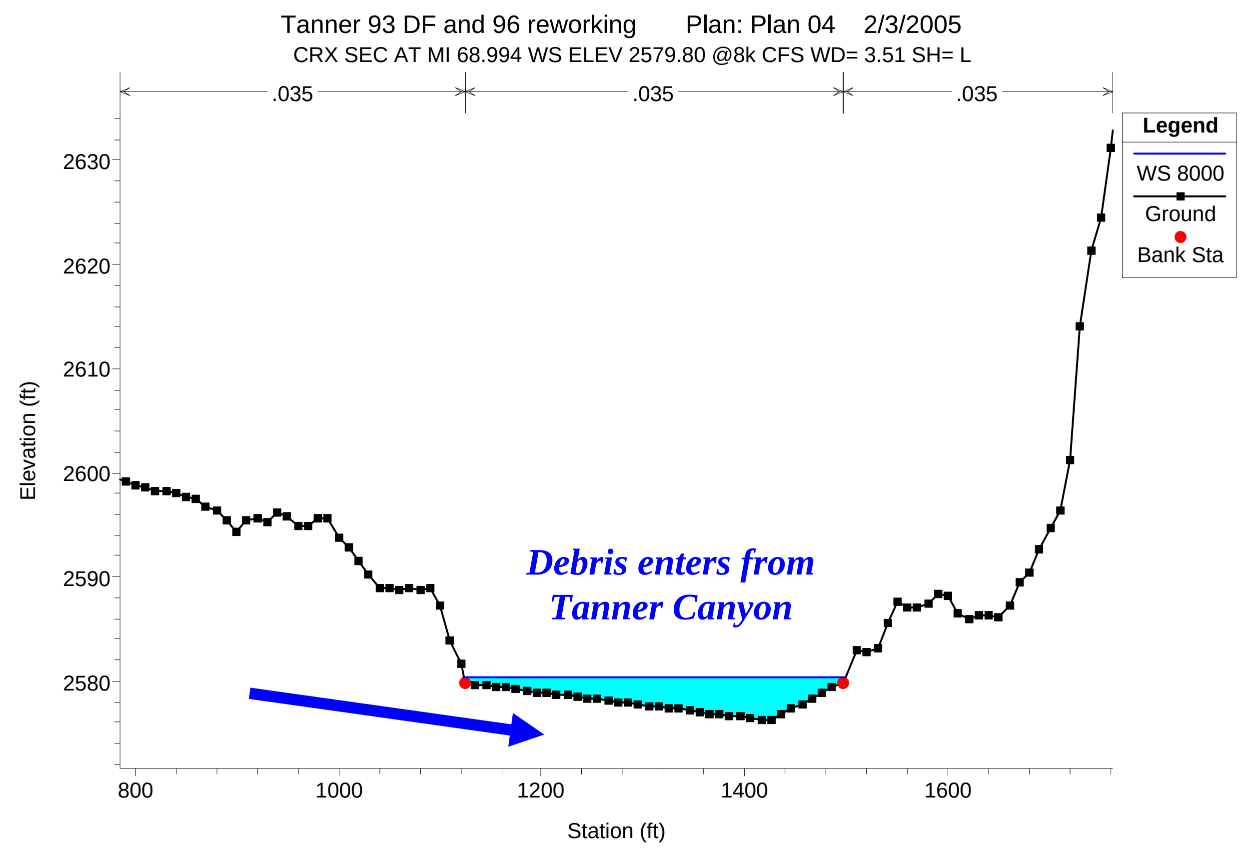
- Topography from ISTARS Imagery
- Inferred bathymetry calibrated to match known 8k cfs water surface
- Critical flow at Tanner Rapid set WSE of upper pool



Ref: Magirl (in preparation)

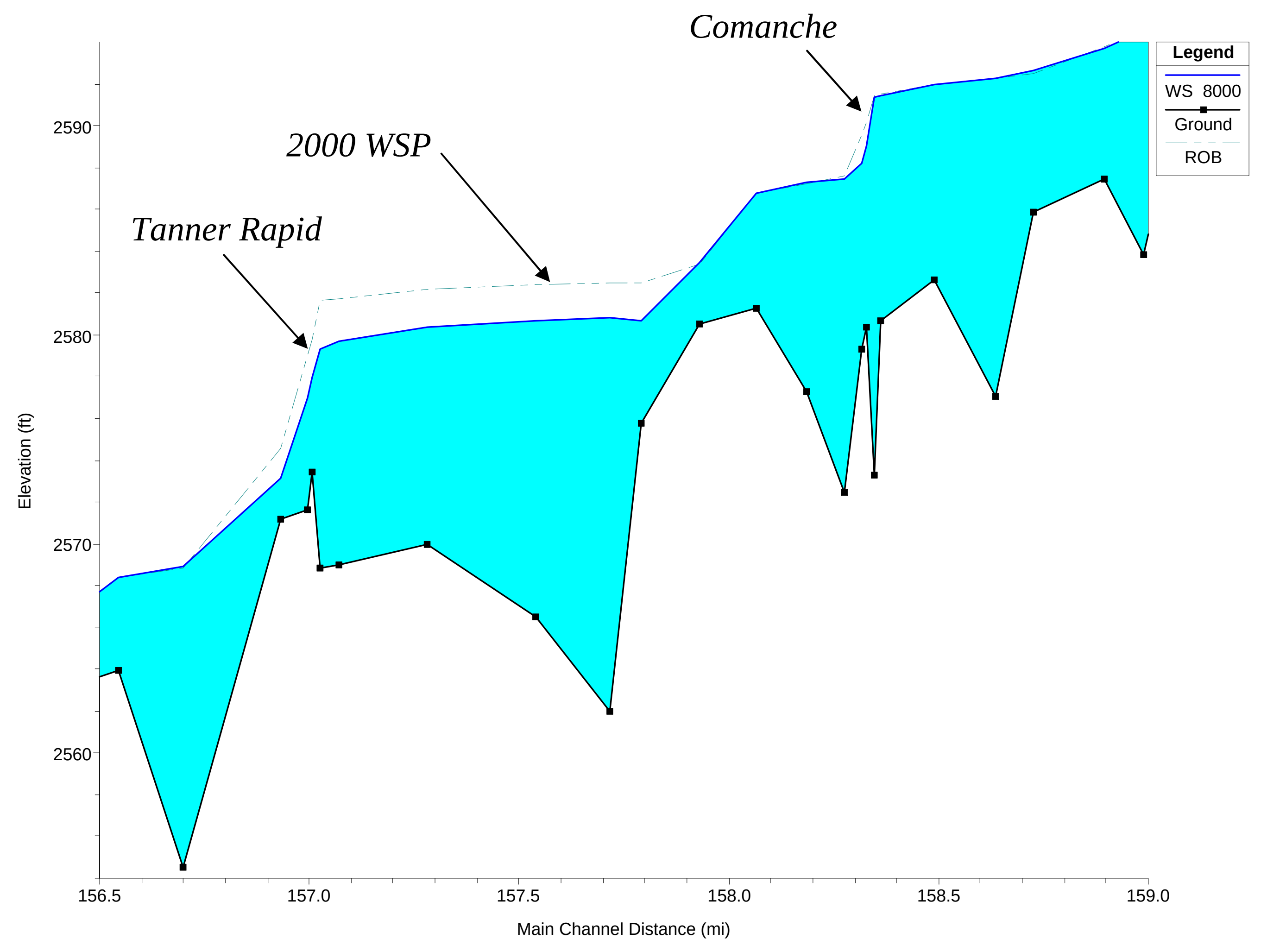
Tanner Rapid

- Bathymetry at the rapid modeled as a V-shaped wedge of alluvium
- Debris enters channel from river left
- Wedge of material adjusted up or down to match observed effect in upper pool



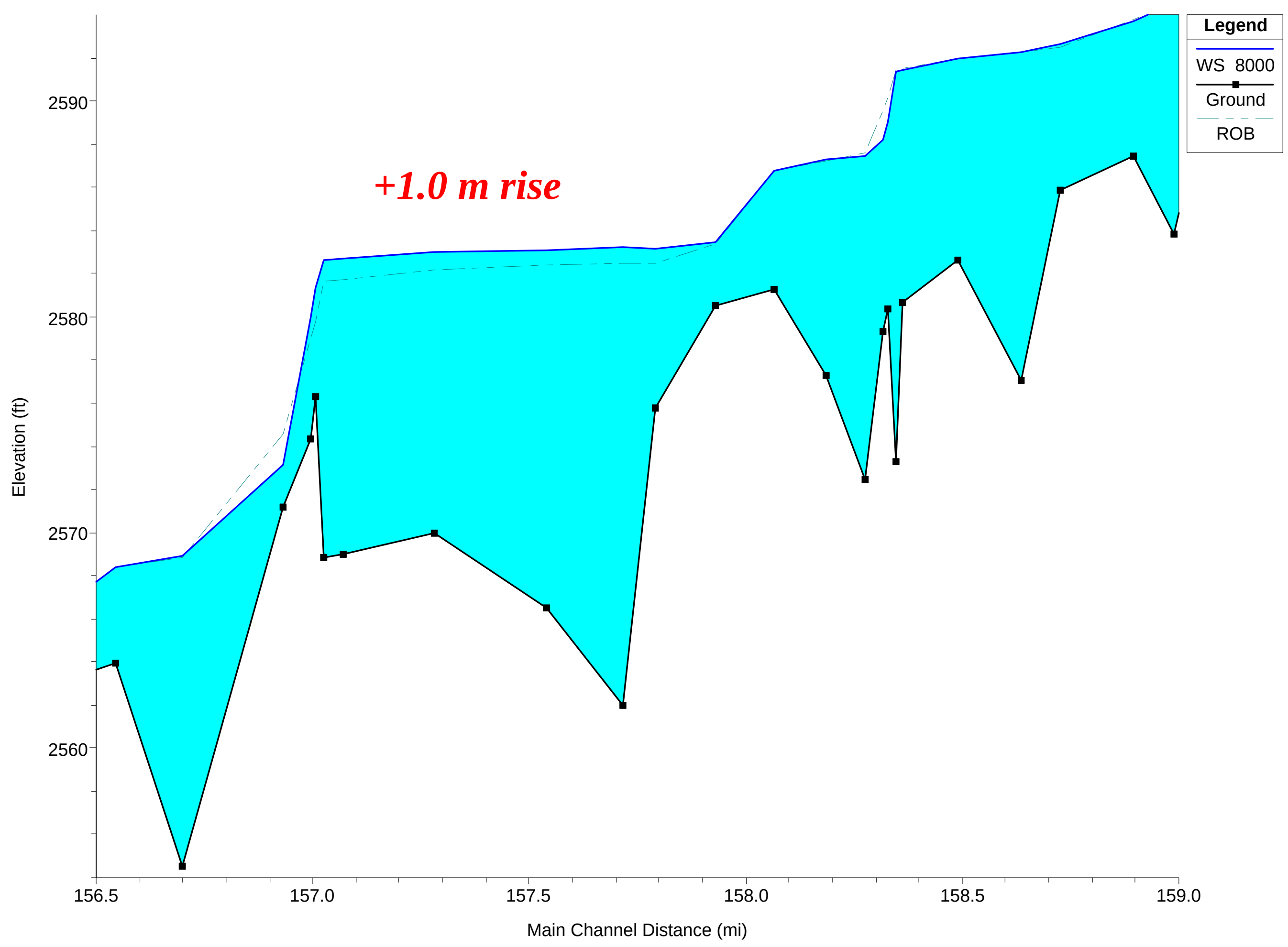
Ref: Magirl (in preparation)

Simulation of 1923 Water-Surface Profile



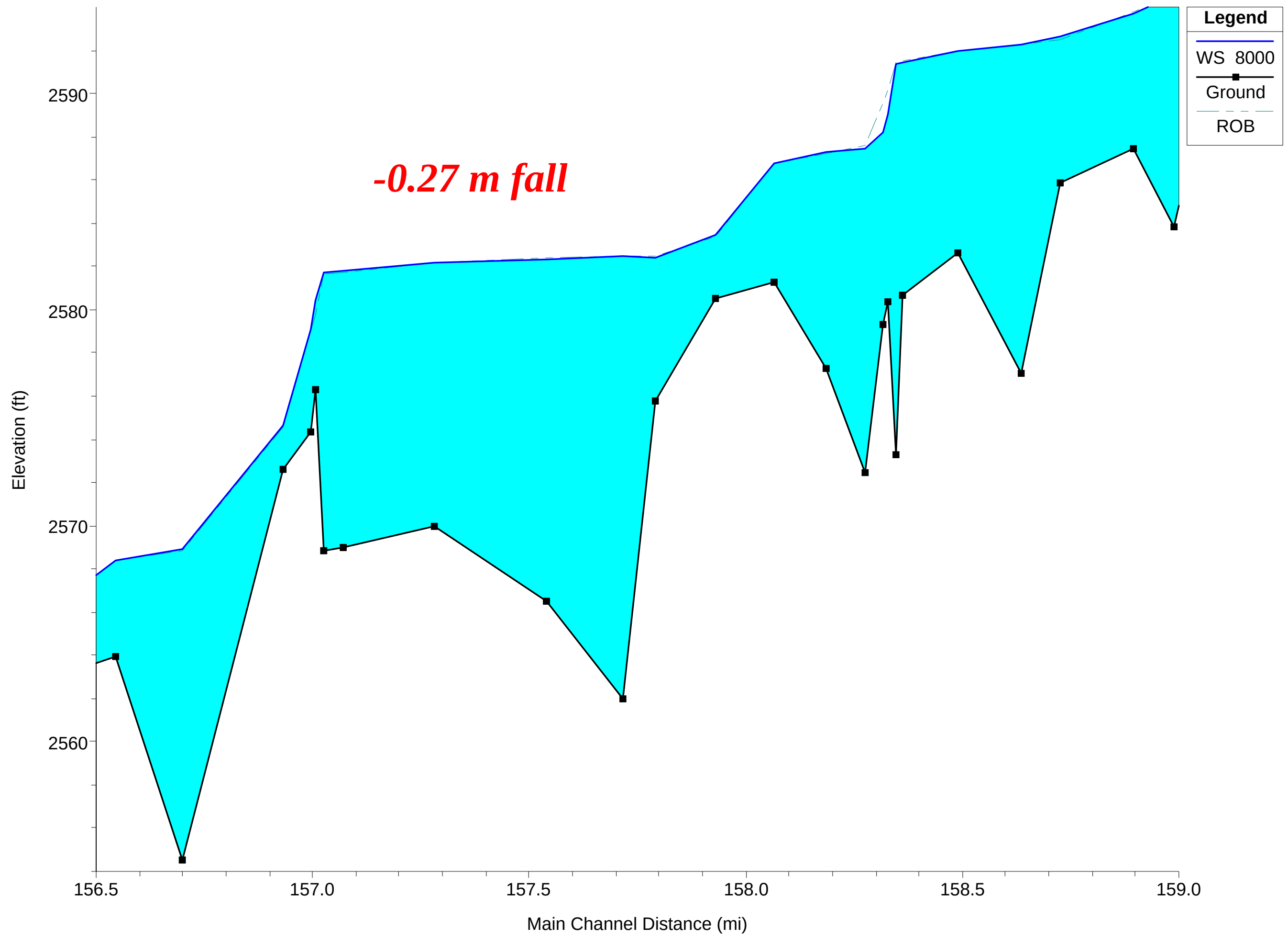
Ref: Magirl (in preparation)

1993 Post Debris Flow



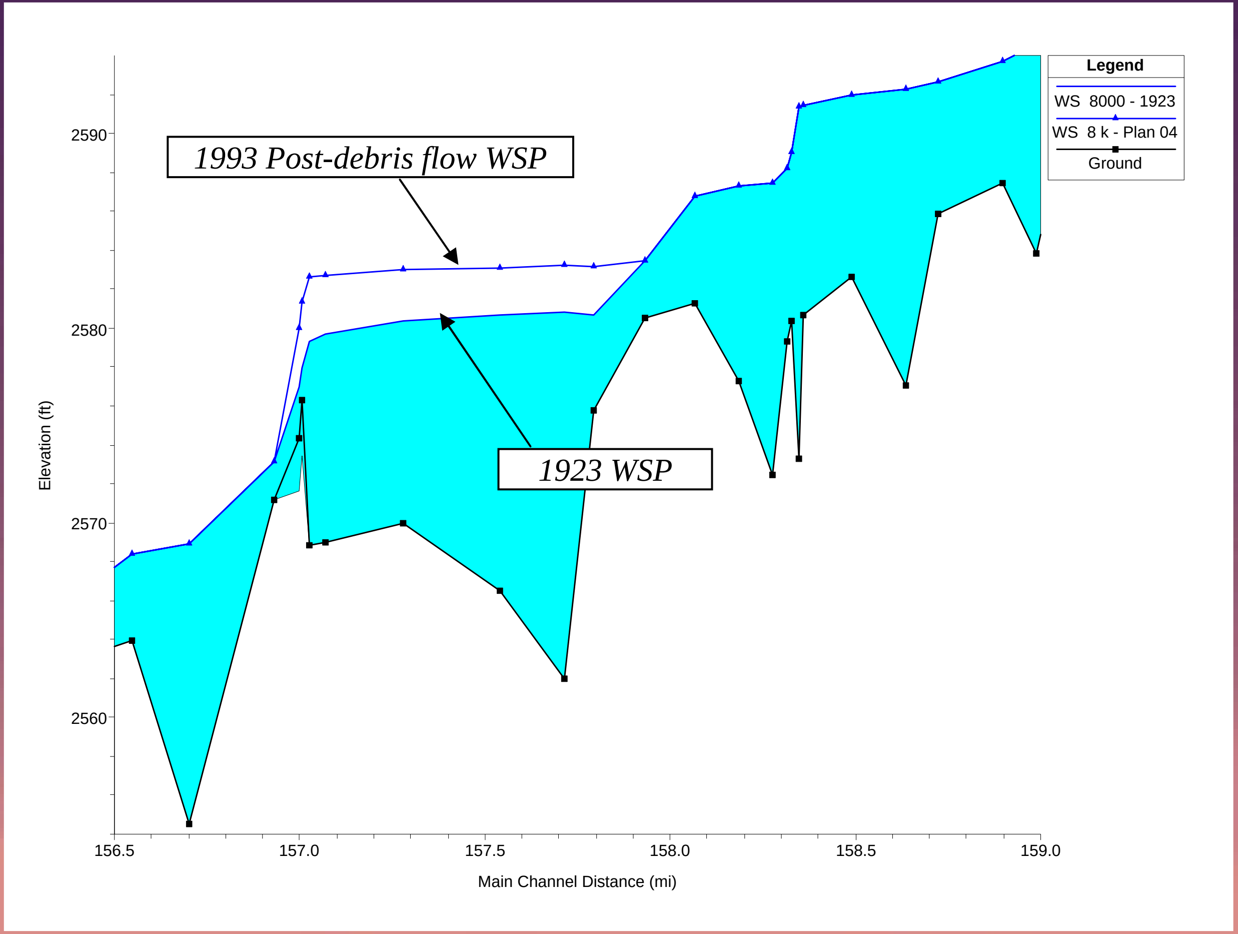
Ref: Magirl (in preparation)

1996 Flood Reworks to Current Profile



Modeled Debris Flow Impact to River

- Pooled backwater that extended one river mile upstream
- Created higher and steeper rapid
- Slowed current in upper pool leading to sand storage



Ref: Magirl (in preparation)

Conclusions

- Howard and Dolan (1981) predicted that the longitudinal profile through Grand Canyon is becoming an enhanced pool-drop profile as a result of operations of Glen Canyon Dam. Owing to minimal data from about 1963, this is difficult to demonstrate conclusively.
- Modeling of sediment transport by episodic events such as debris flows is beginning to explain some small- and large-scale features of the river corridor.