# Use and Evaluation of the Critical-Depth Method for Estimating Peak Discharges in Mountain Streams

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**GSA Rocky Mountain and Cordilleran Section Meeting**

**Flagstaff, Arizona**

**May 17, 2018**

# Presentation Overview

- Introduction

- The Colorado September 2013 Rainstorm

- Resulting Widespread 2013 Flooding

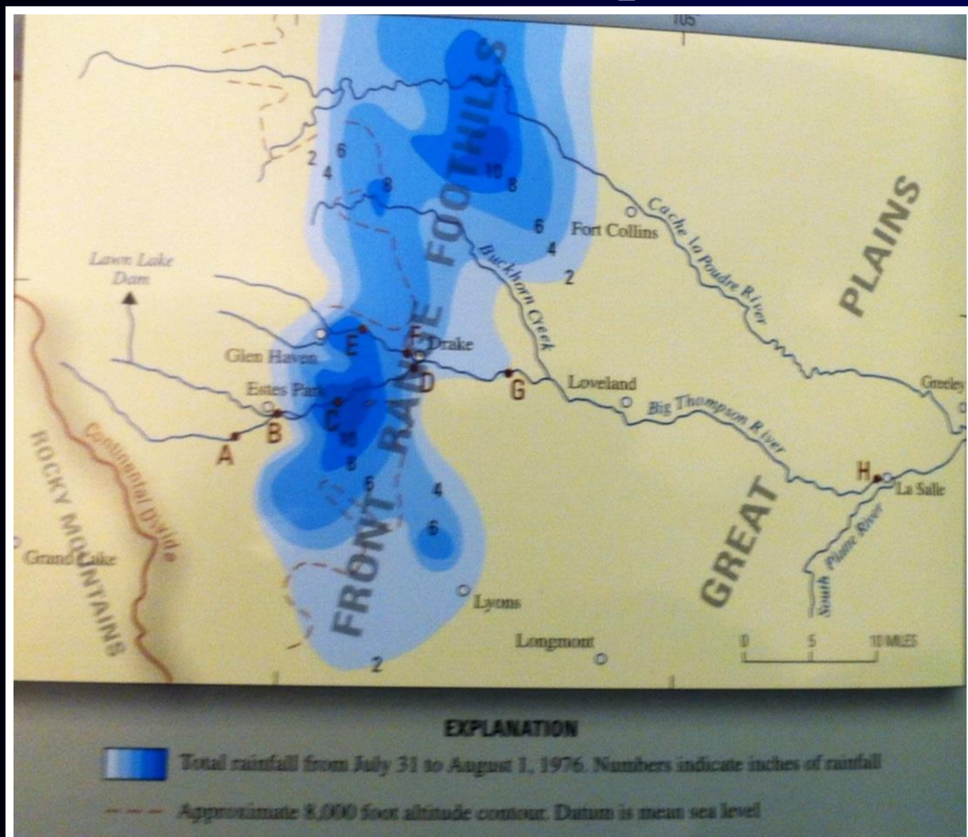
- 2013 Flood Documentation & Data Uses

- Comparison of  2013 Flood Results

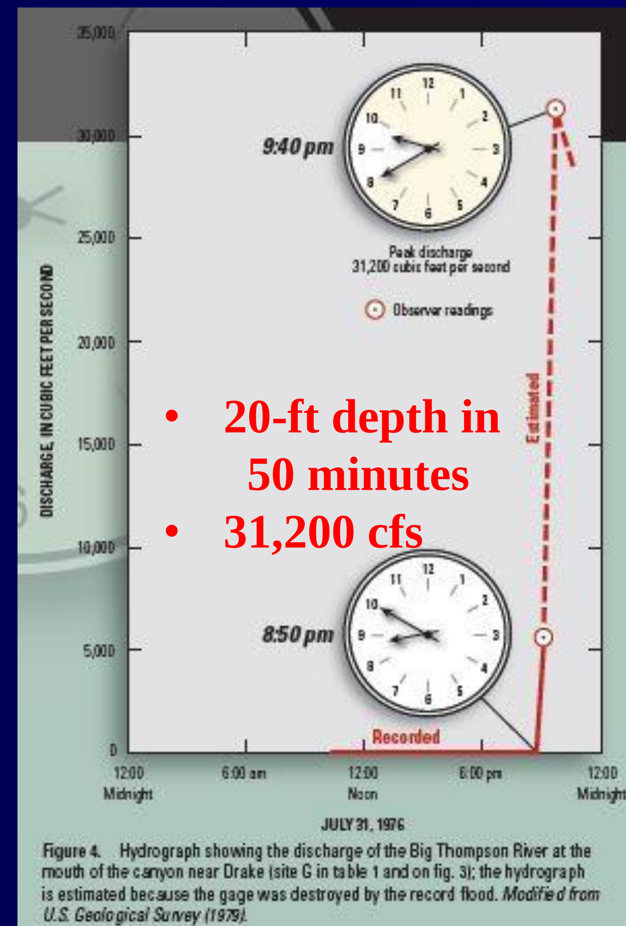
- Concluding Remarks

# 1976 Big Thompson Canyon Flood

## Rainfall Map




## Flash Flood Hydrograph




- 20-ft depth in 50 minutes
- 31,200 cfs

~7.5 inches in 1 hour; 12-14 inches in 4 hours

144 people killed; ~$35M damages (1977)

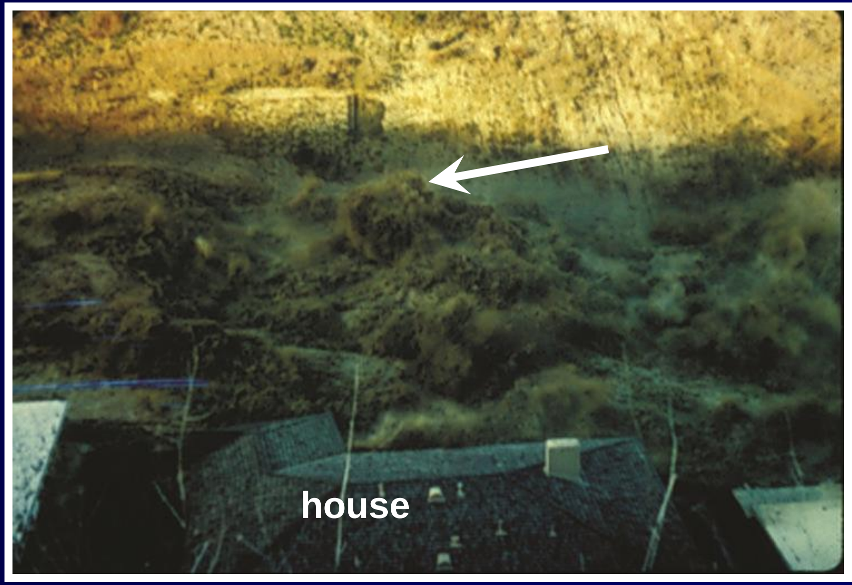
~$155M in 2018 (adjusted for inflation)

# Do All Floods Pose The Same Hazards?

**Low gradient river flood**

**Ohio River**

**Mountain flash flood**




**2 m to 5 m standing waves**

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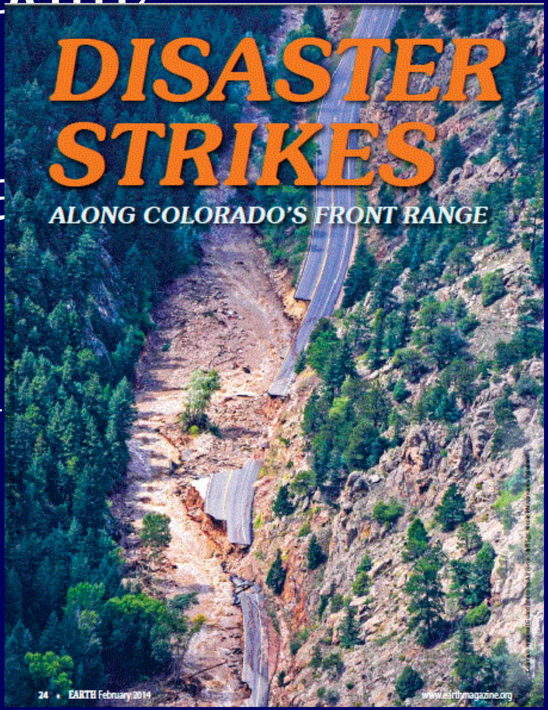
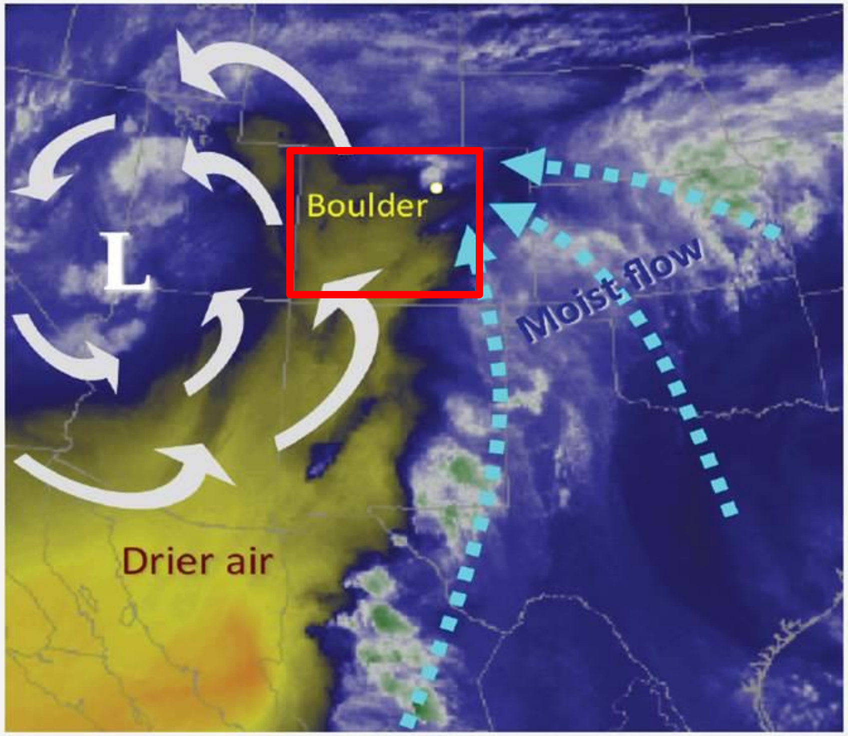


# Colorado September 2013 Storm

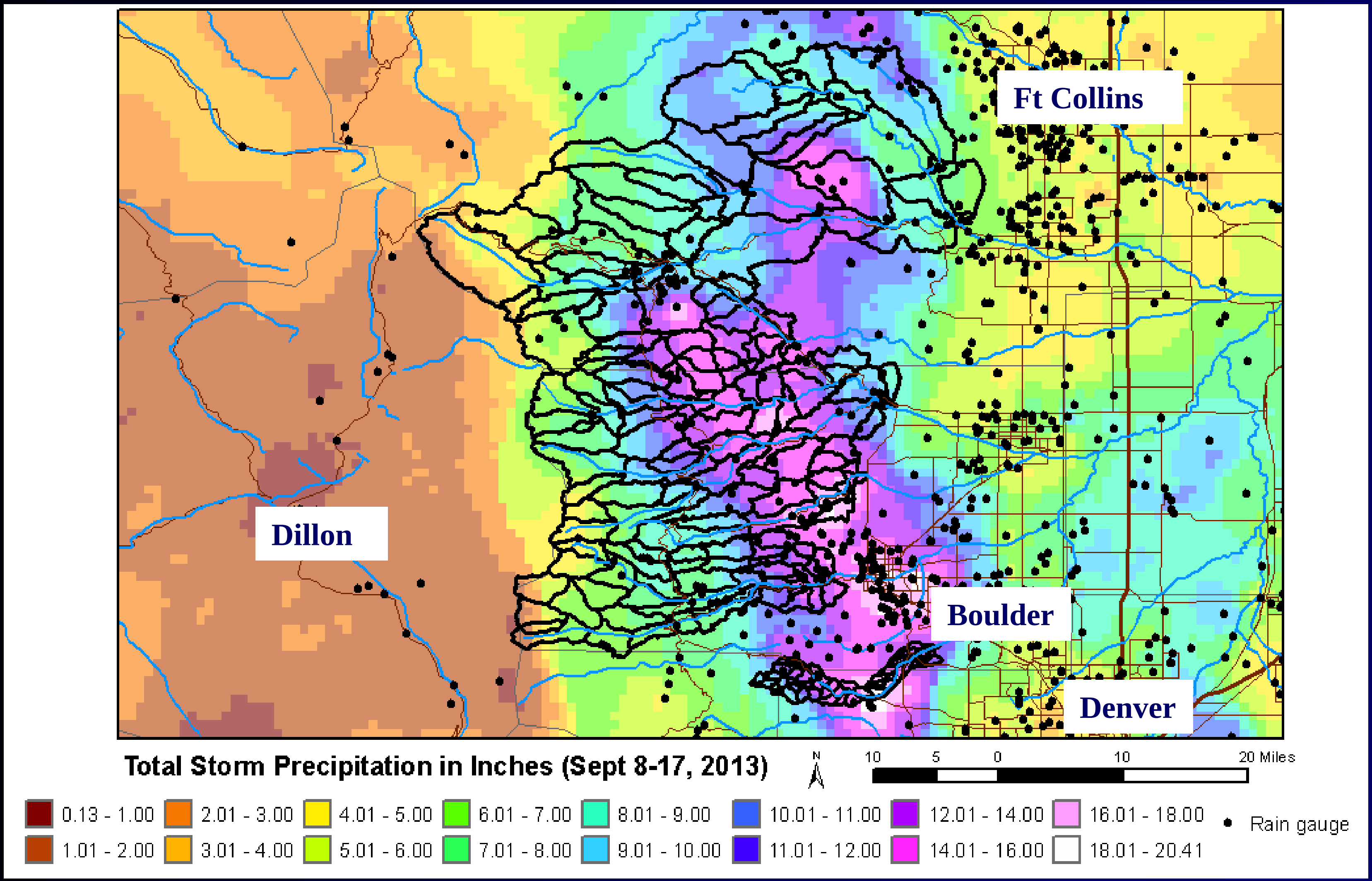
**"On the morning of the storm we did not expect significant rainfall and flooding. Then, the storm stalled for several days."**

**National Weather Service**
**Boulder, Colorado**



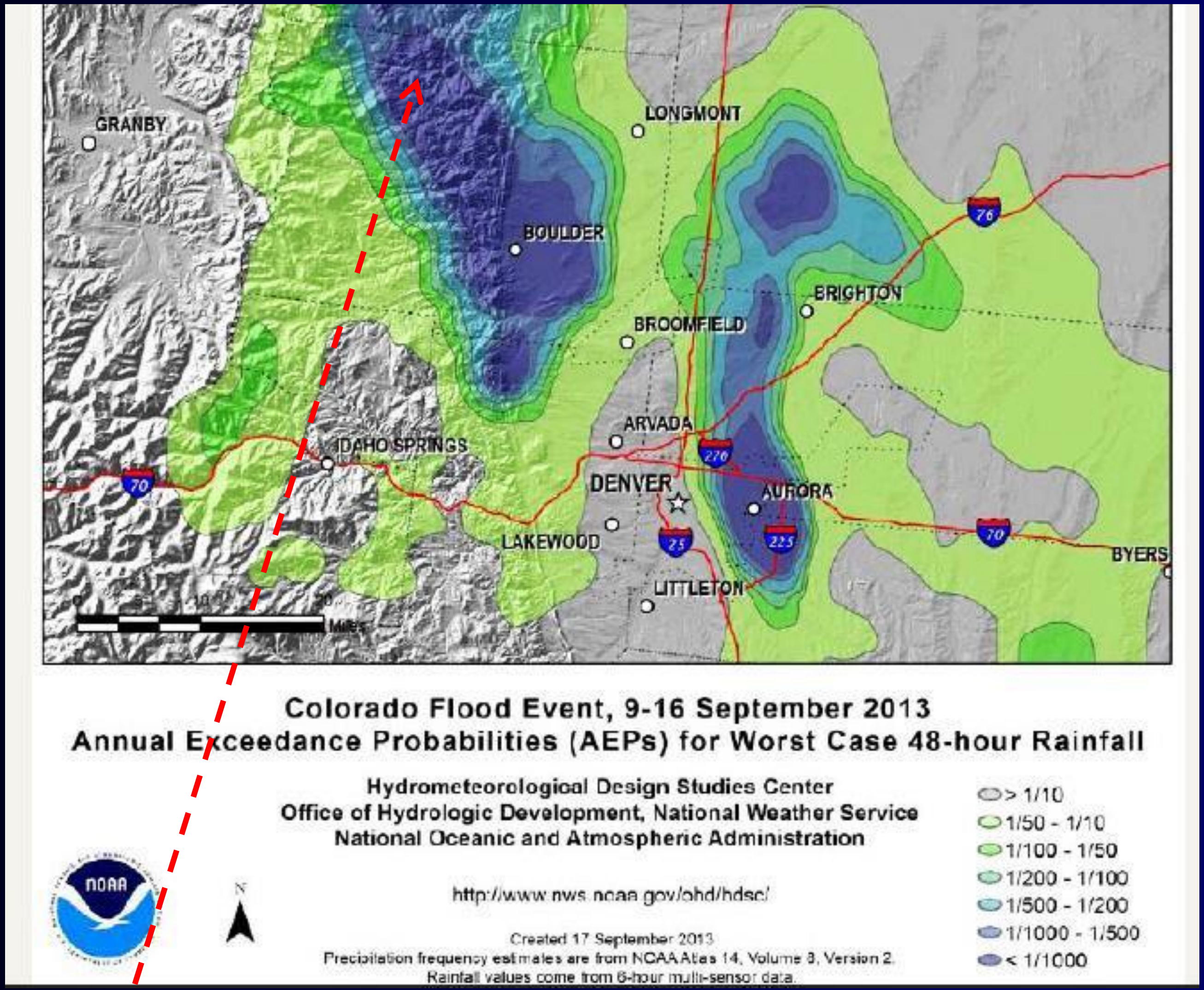

*Deep plumes of moisture (blue, white, and green) are drawn towards the Front Range from the Pacific and the Gulf of Mexico by the circulation around an upper-level low (L) over the Great Basin, at 11:15 pm MDT on September 11, 2013, during the peak rainfall intensity in Boulder. Drier air is shown in yellow. (Satellite image: CIMSS, University of Wisconsin)*

# Total Storm Rainfall



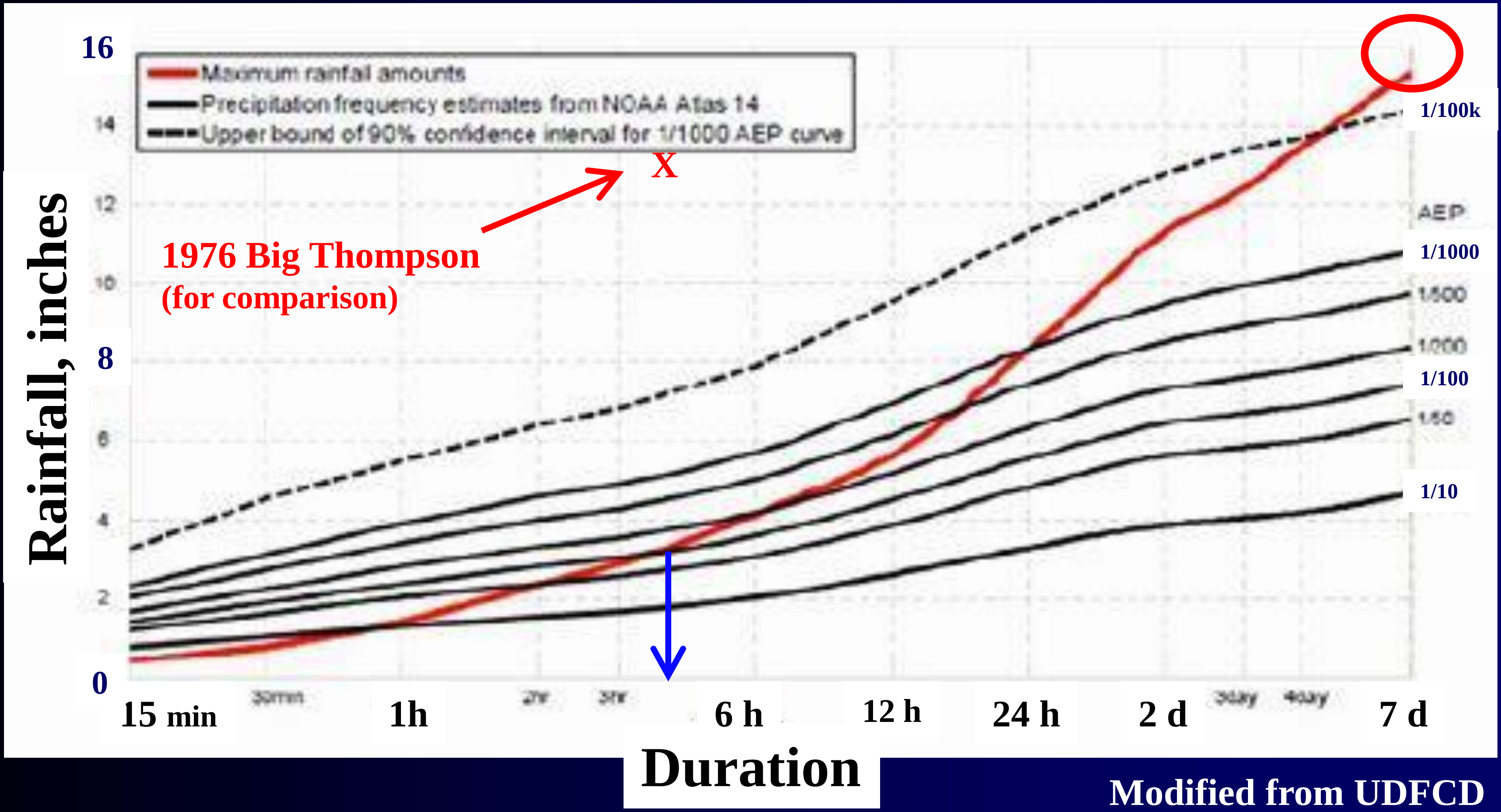

Up to 510 mm in 7 days

# NOAA-14 Rainfall Frequency Map




**At Big Elk Meadows, this was the 3nd 510 mm storm in 4 days in last 50 years!**

# NOAA Atlas 14
# Rainfall Frequency Duration Graph




Modified from UDFCD

2013 and 1976 exceeded NOAA's 100,000 yr recurrence interval !

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Voice of the Rocky Mountain Empire

THE DENVER POST

>1,000 missing

The Flood's Toll

**Four dead, thousands stranded or homeless**

South Platte River: 50 times more water than it normally has this time of year.

Jamestown: Military helicopters rescue nearly 300 people from isolated town.

# Sept 2013 Flood Damages





Source: UDFCD

# Sept 2013 Flood Damages


**NWS – cars are "Floating coffins"**

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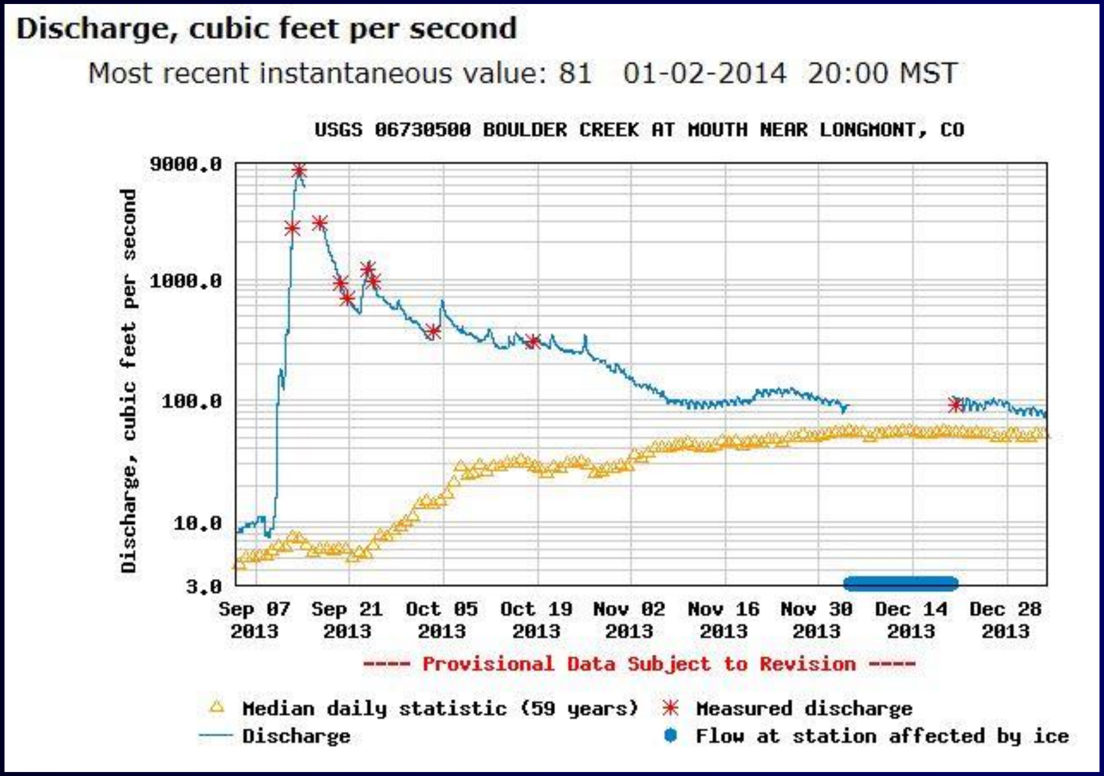
# 2013 Flood Documentation




- **USGS made direct discharge measurements for some gages during the flood (above)**
- **Most streamflow-gaging stations were inaccessible, damaged, or destroyed**
- **USGS made ~20 post-flood peak discharge estimates**
- **NRCS (Steve Yochum) made 15 post-flood peak discharge estimates**

# Rapid Flood Documentation

## Flood and Paleoflood Sciences, LLC


Funded by:

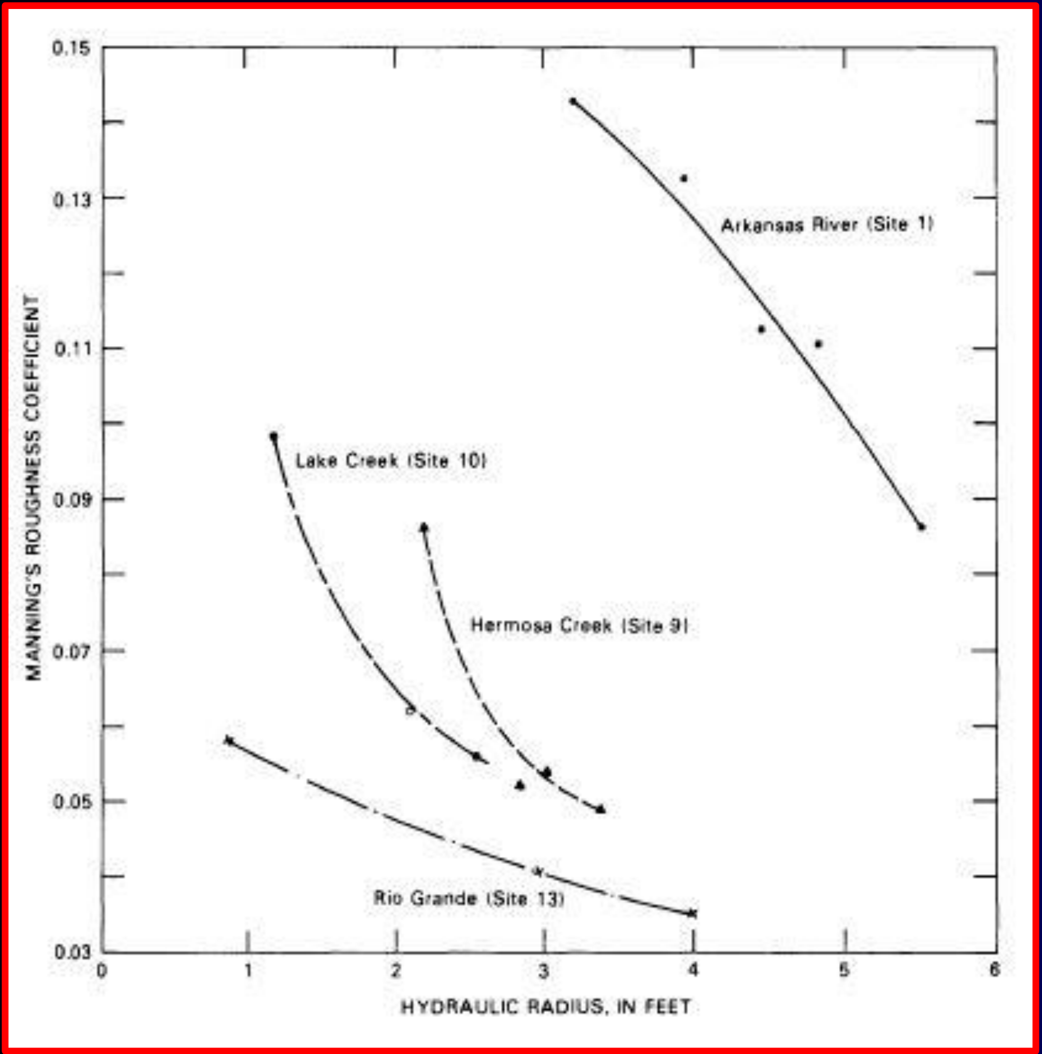
- Urban Drainage and Flood Control District

- Colorado Department of Transportation

**North Fk Big Thompson R at Drake gage**


**Because of the extraordinary nature of the storm/flood and damage to infrastructure, peak discharges were needed for many more streams**

# Validation of Manning's n-Values for Streams in Colorado




Manning's Equation

$$Q=1.49/n \times A\ R^{0.67}\ S^{0.5}$$

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**Can lead to questionable peak discharges in mountain rivers**

**Study results: Manning's n rapidly varies with flow depth**

**(Methods: Jarrett, 1985)**

# Selected equations to estimate channel roughness

$$\frac{n}{R^{1/6}} = \frac{0.0926}{a + 2.0 \log \frac{R}{d}},$$

$$n = 0.32 S^{0.38} R^{-0.16},$$

$$n = 3S - [(d_{84} - R + d_{84}^2) * 1.87S] - \left(9.13S * \frac{S}{R}\right) + \frac{(d_{84} - S)^{0.25}}{(26.2 - 4.68 * d_{84})}$$

$$\frac{1}{\sqrt{f}} = -0.355 \times S_f^{\;2} + S_f\left(1 - \log\left(\frac{R}{d_{84}}\right)\right) + 1.044 \times Ln\left(-0.519 \times S_f^{\;2} - Ln\left(\log\left(\frac{R}{d_{84}}\right)\right)\right) + S_f - \left(4.713 \times (9 + S_f)^2 \times \left(\log\left(\frac{R}{d_{84}}\right)\right)^2\right)$$

Equations are getting more complicated.

Yet, many people don’t even obtain particle size in rivers

# Critical-Depth Method for Estimating Peak Discharge

## 2013 Peak Discharge Sites

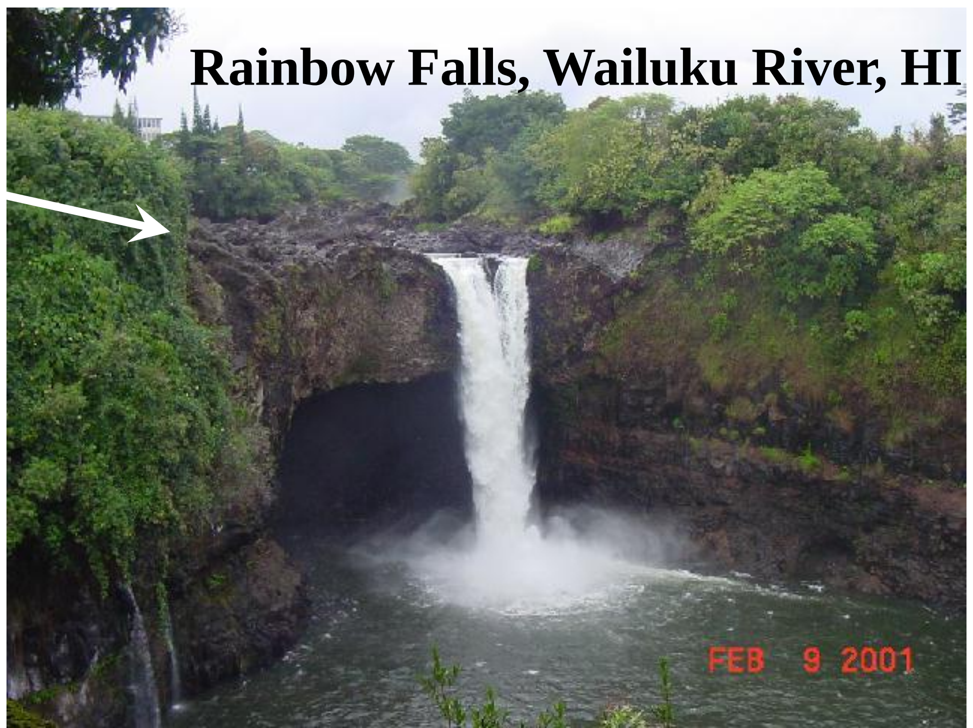
**Leyden Creek**

**Soda Creek**

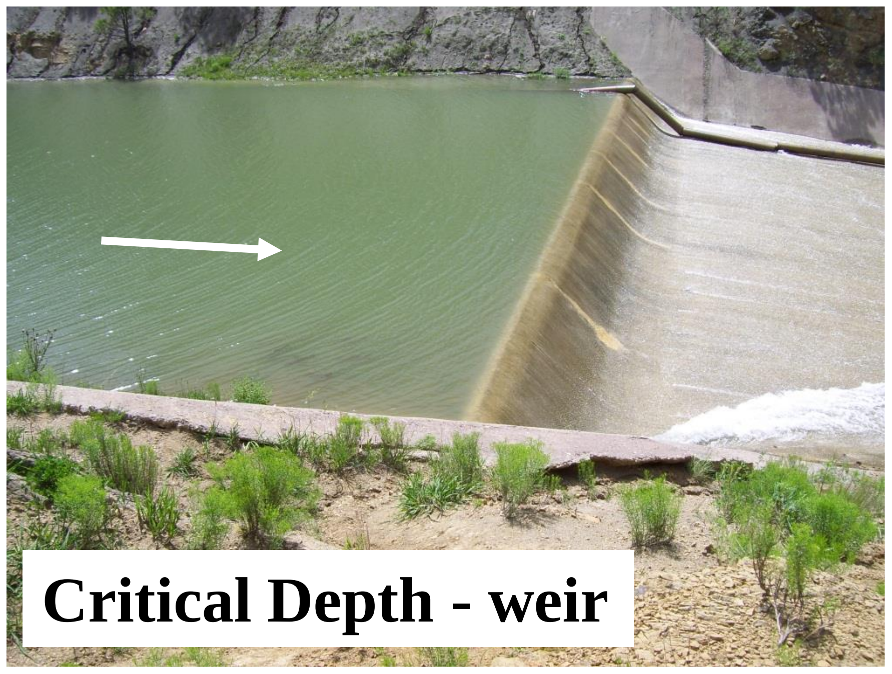
**For stream slopes ≥ 0.01 ft/ft = 0.01 m/m**

# Critical-Depth Sites For Discharge

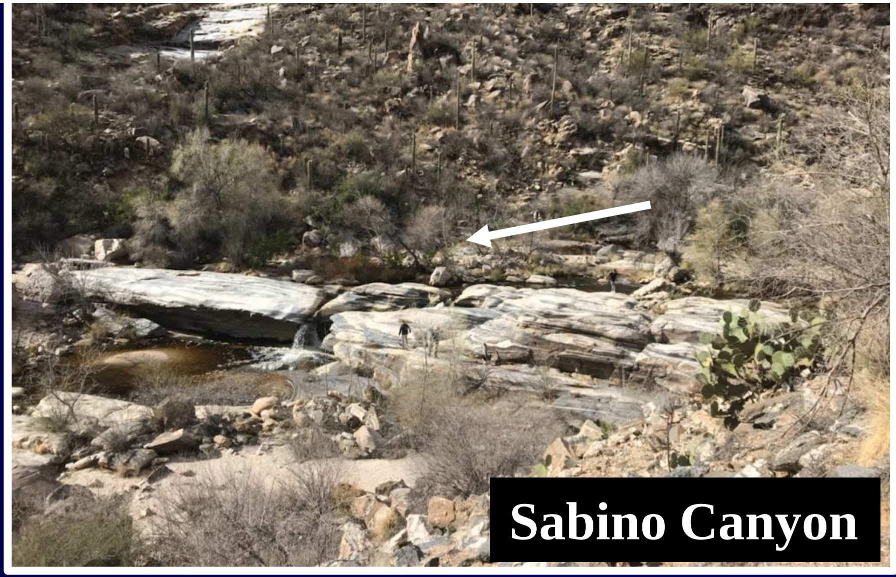
- Flow-over-road
- Weir/flumes
- Drops
- Waterfalls


Excellent controls for stage-discharge relationships

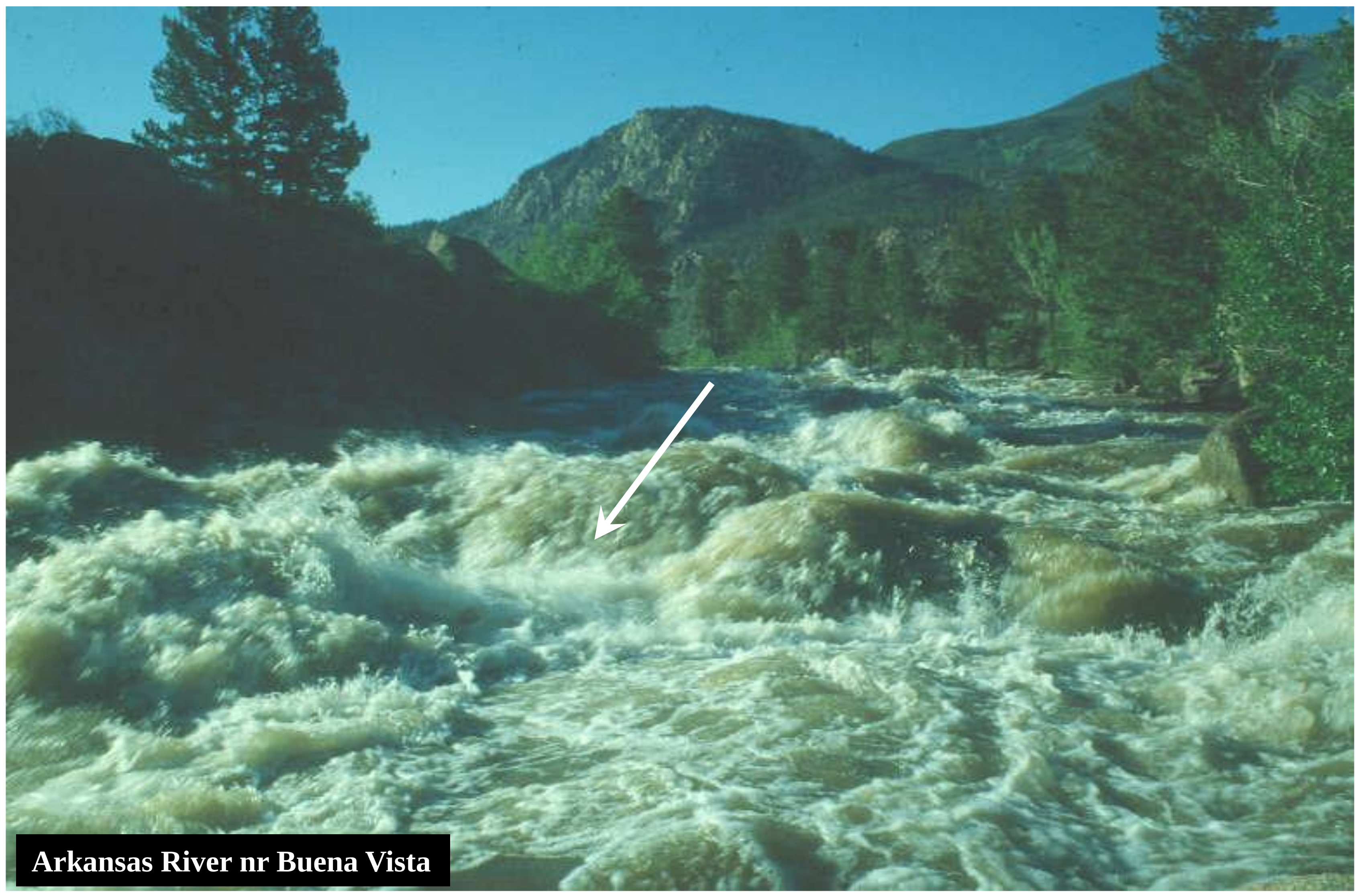



Critical depth - bedrock control



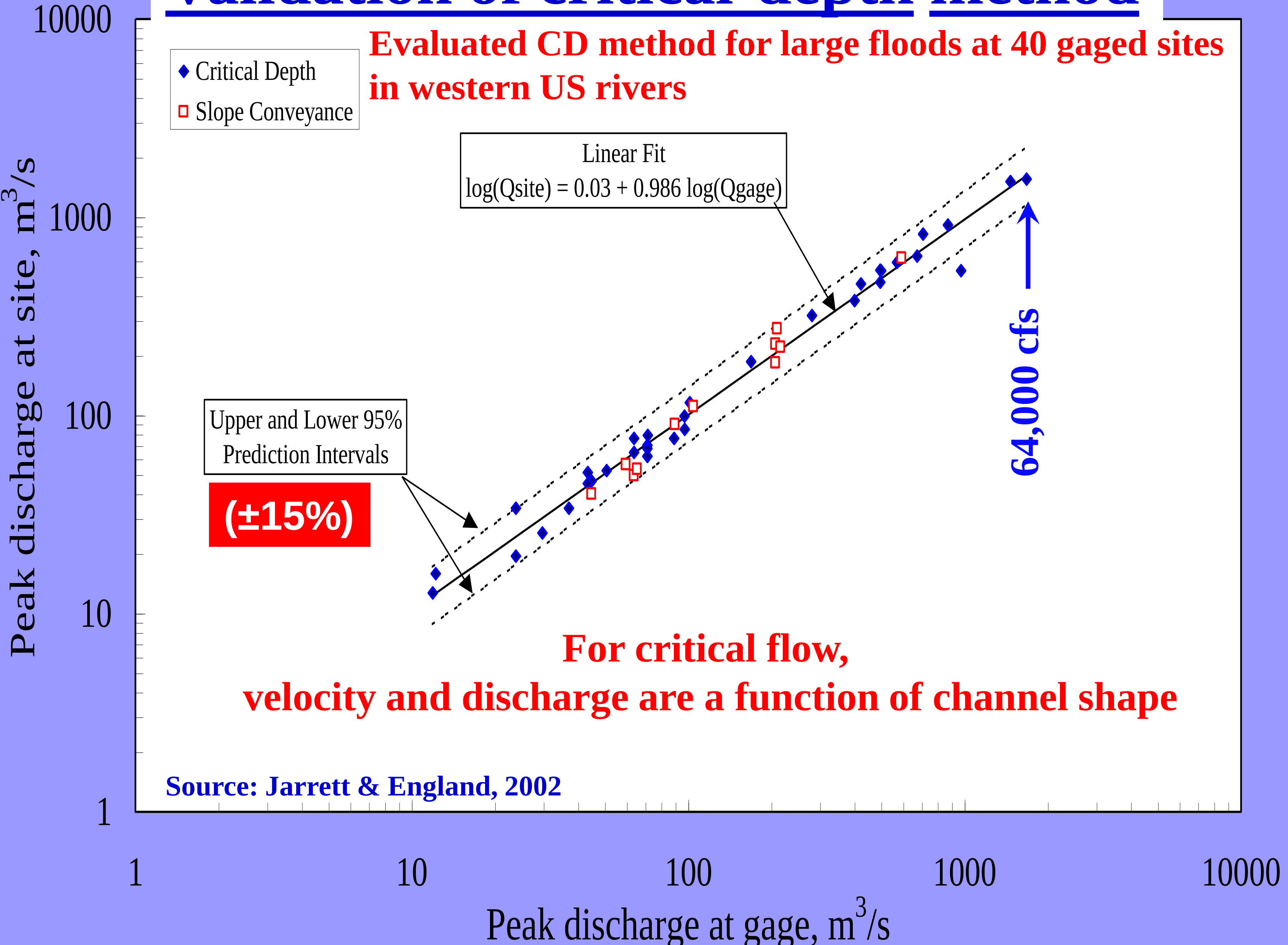

Critical Depth - Channel contraction (similar to a flume or bridge opening)

# Value of Using Critical-Depth Method

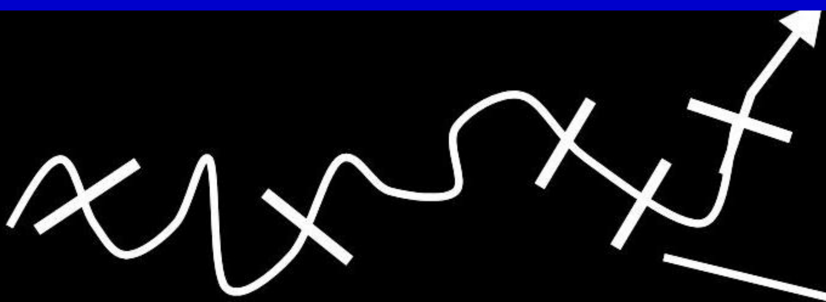



**Long reaches of near critical flow; Froude No. ~ 1 (Jarrett, 1984)**

# Validation of critical-depth method



# Lack of straight reaches mountain streams



— Cross sections

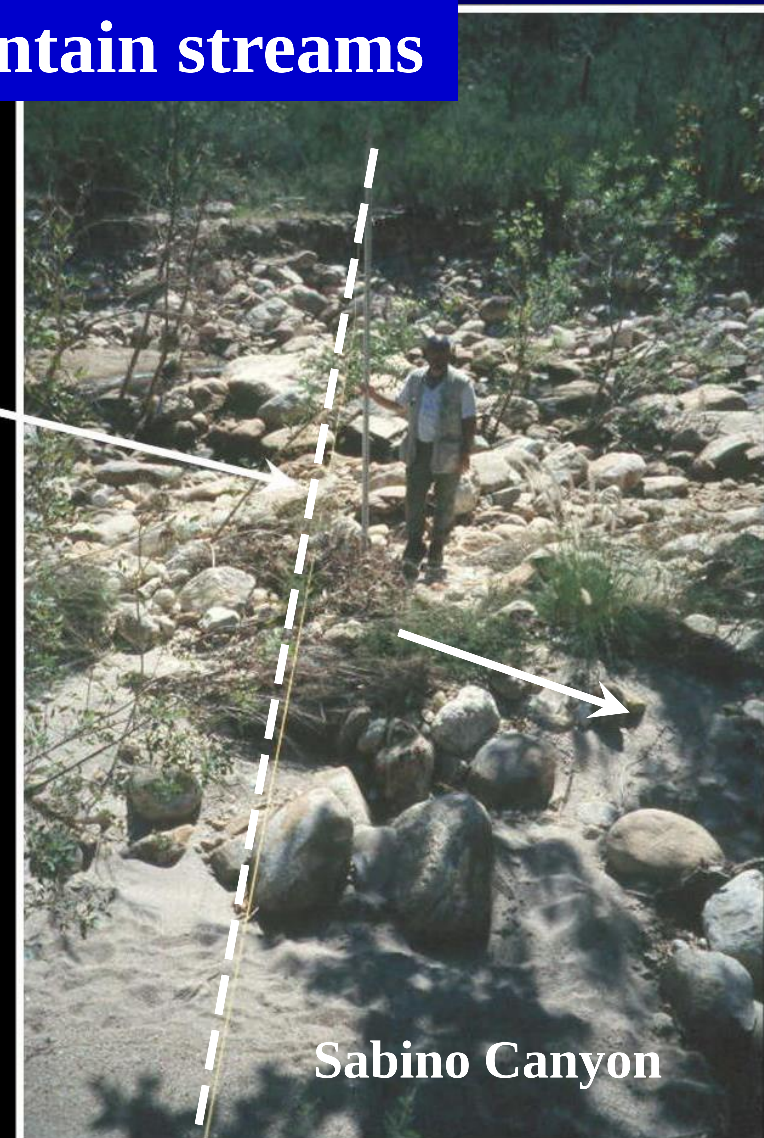
N = 2-3

~Straight, uniform sub-reaches

Subdivided XS as needed

$V_c = (g \times D)^{0.5}$ & $Q = V_c \times A$

Qp is average all XSs



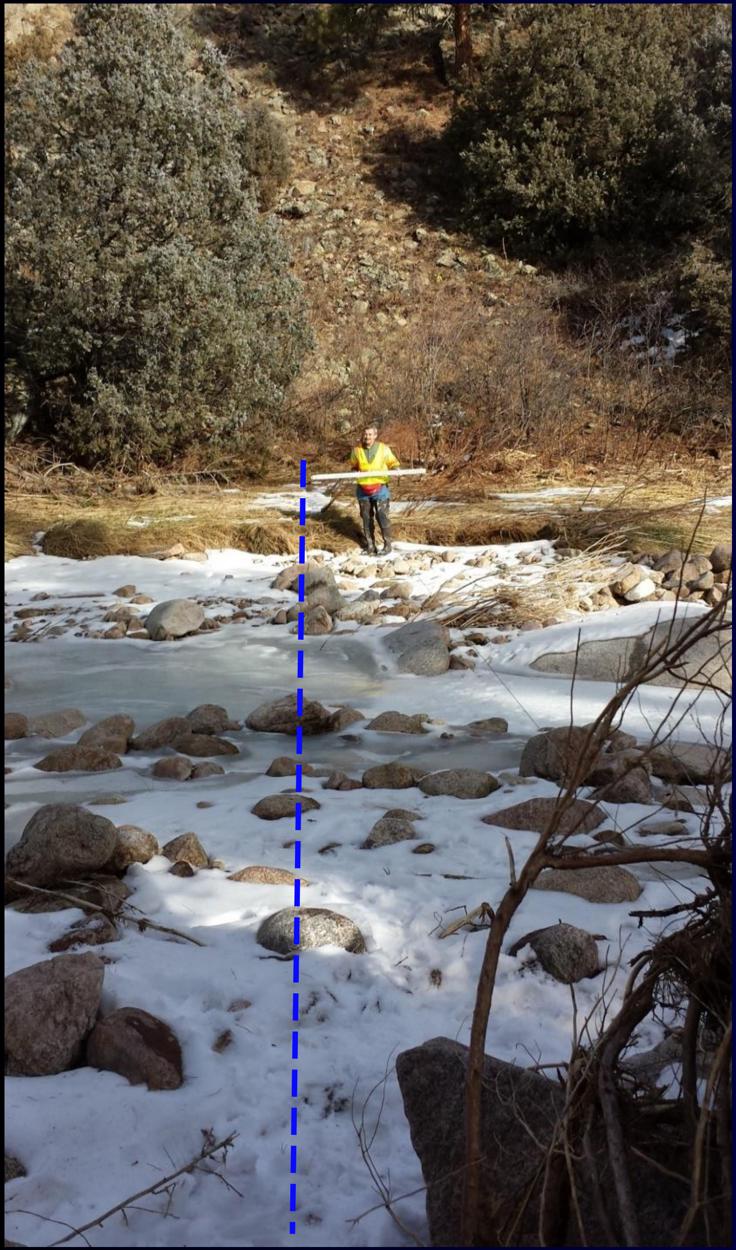

## Critical-Depth Method

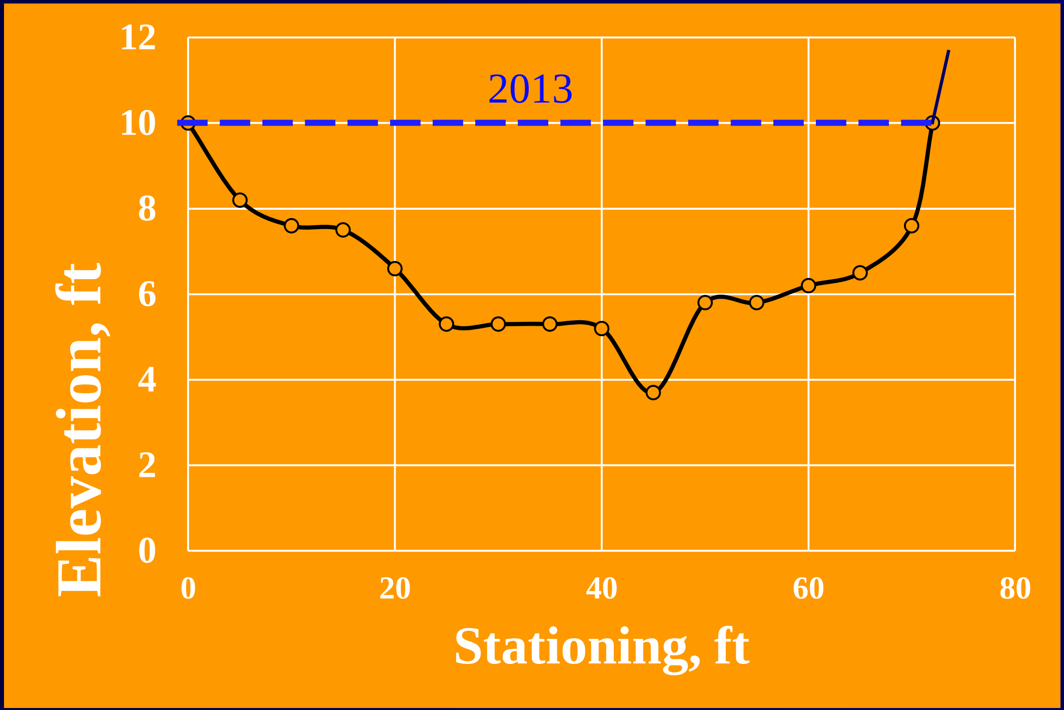
**Q is independent of n value; key is reach and cross section selection**

# Attributes of a Flood Reach for Peak Discharge Estimation

1. Stream slope greater than ~ 0.01 m/m
2. Relatively straight channel (~15 m)
3. Relatively uniform width
4. Reach is stable or
5. Minor channel change can be evaluated
6. Minimal obstructions (debris, boulders, trees)
7. Good high-water marks

# Little Thompson River (site 59B)





# Little Thompson River (site 59B)

## Critical-Depth Computation

Site (XS) 59B

| Sta, ft | Depth, ft blw HWM | |
|---|---|---|
| 0 | 0 | Exc HWM, fine debris on grass bank |
| 5 | 1.8 | edge of moderately dense brush |
| 10 | 2.4 | |
| 15 | 2.5 | |
| 20 | 3.4 | ave of top and bottom of 0.9 ft grass bank |
| 25 | 4.7 | |
| 30 | 4.7 | |
| 35 | 4.7 | less than 0.5 ft of pea gravel on pre-flood streambank brush |
| 40 | 4.8 | several large boulders on streambed at XS; did not move during flood |
| 45 | 6.3 | about 10-15 ft width of think ice |
| 50 | 4.2 | |
| 55 | 4.2 | S ~ 0.02 - 0.03 ft/ft |
| 60 | 3.8 | |
| 65 | 3.5 | cobble and boulders |
| 70 | 2.4 | |
| 72 | 0 | edge of large tree and thick tree mat |

D ave ~ 53.4/ 15 = <3.6 ft

**Qp = Qc = W x Dave x Vc; (Vc= sqrt (Dave x 32.2)= 10.7 ft/s)= (72 x 3.6 x 10.7) = 2,770 cfs**

**Qp Ave (XS A and B) = (2,600 + 2,770)/2 = 2,680 cfs (+/- ~15%)**

# CD-Method Flood Documentation

- 150 peak discharges for the 2013 flood
- Results provided the same or next day
- Average cost of $250/site vs $10,000/site using conventional methods

# Mountain streams ($S \geq 0.01$ m/m) comprise about 25 % of United States


**Thus, they are amenable for use of the critical-depth method**

# Uses of Flood Data

- 2013 peak discharges were an order-of-magnitude smaller than other CO floods
- Determine at-site flood frequency
- Used to calibrate/validate rainfall-runoff modeling to revise ungaged flood frequency
- Floodplain management
- Design of damaged/destroyed infrastructure
- River restoration

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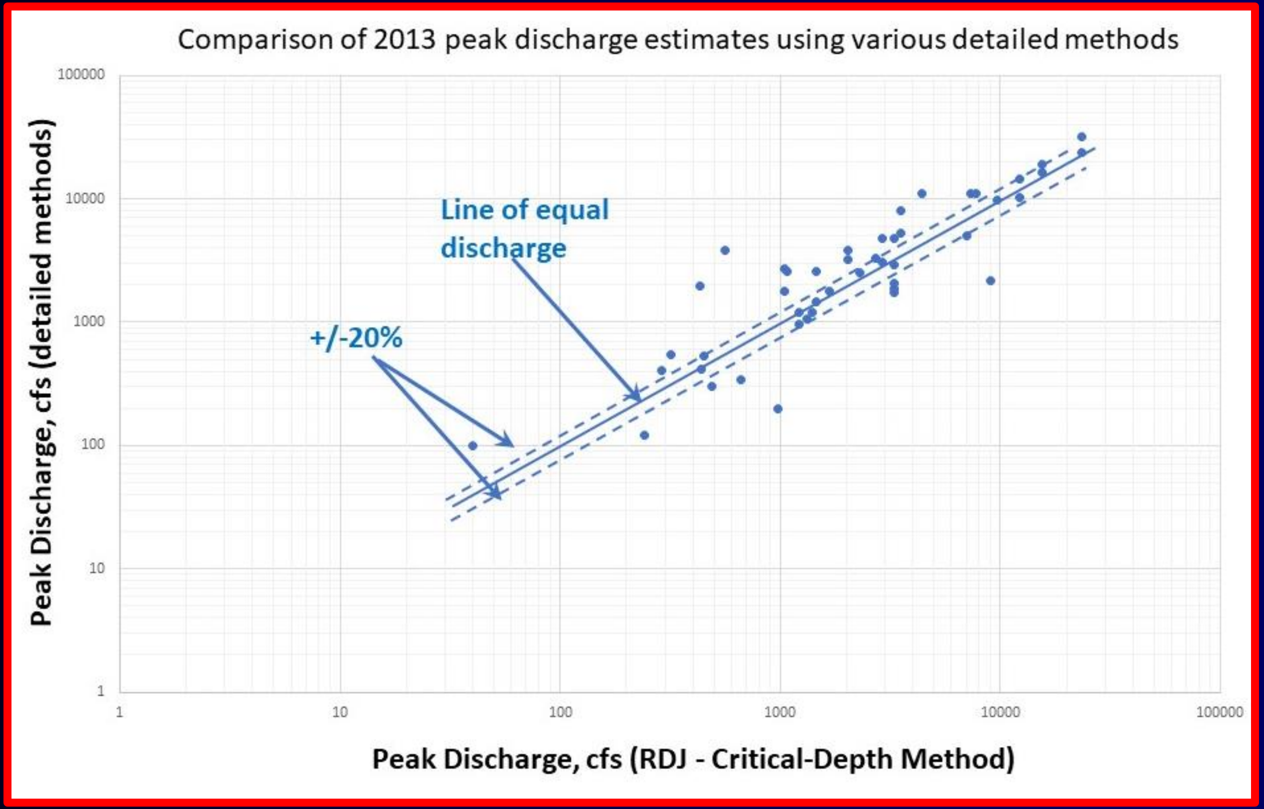
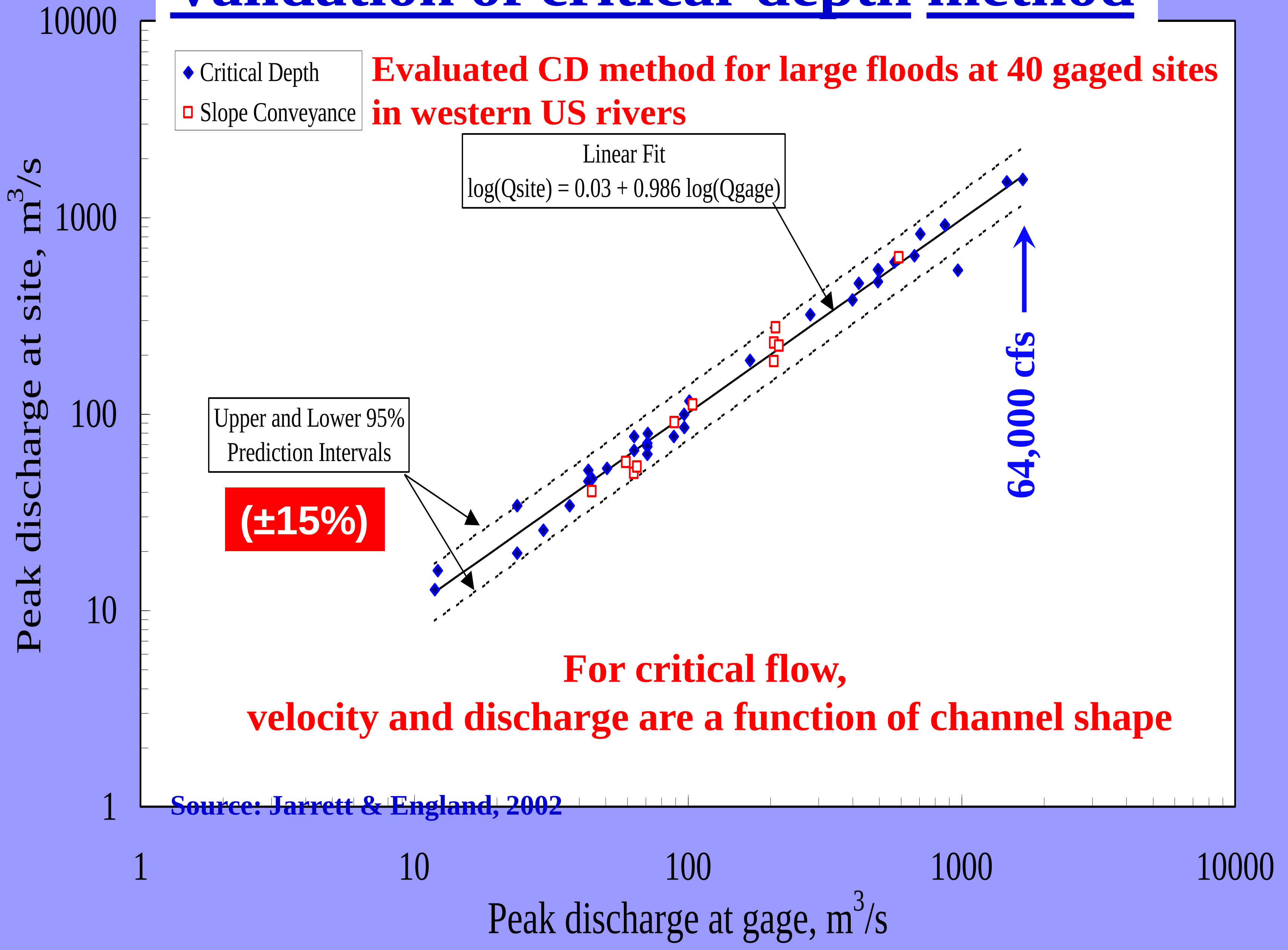
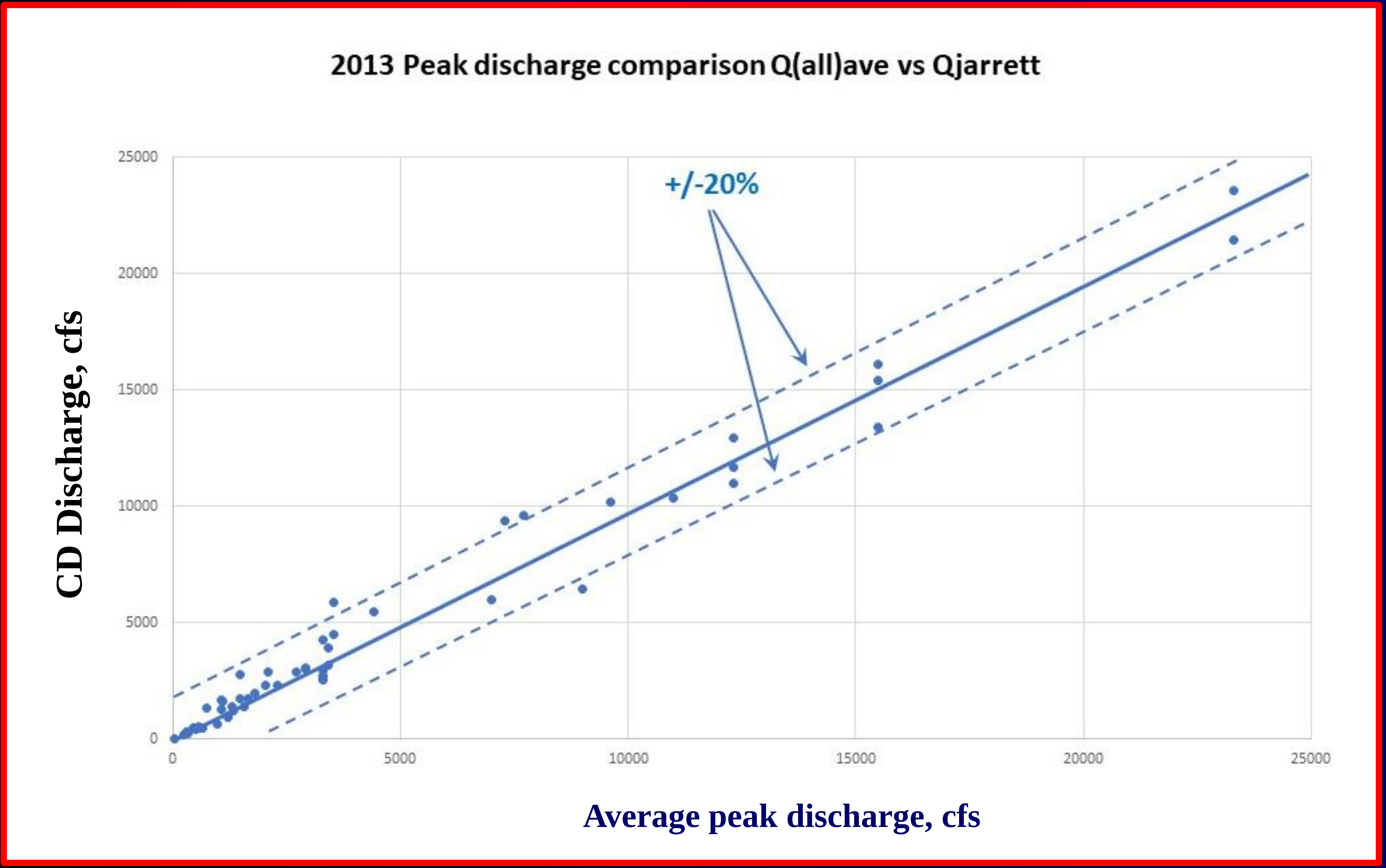
# Evaluation of Critical-Depth Method With Six Other 2013 Ivestigators

**We often don’t know the true 2013 discharges.**

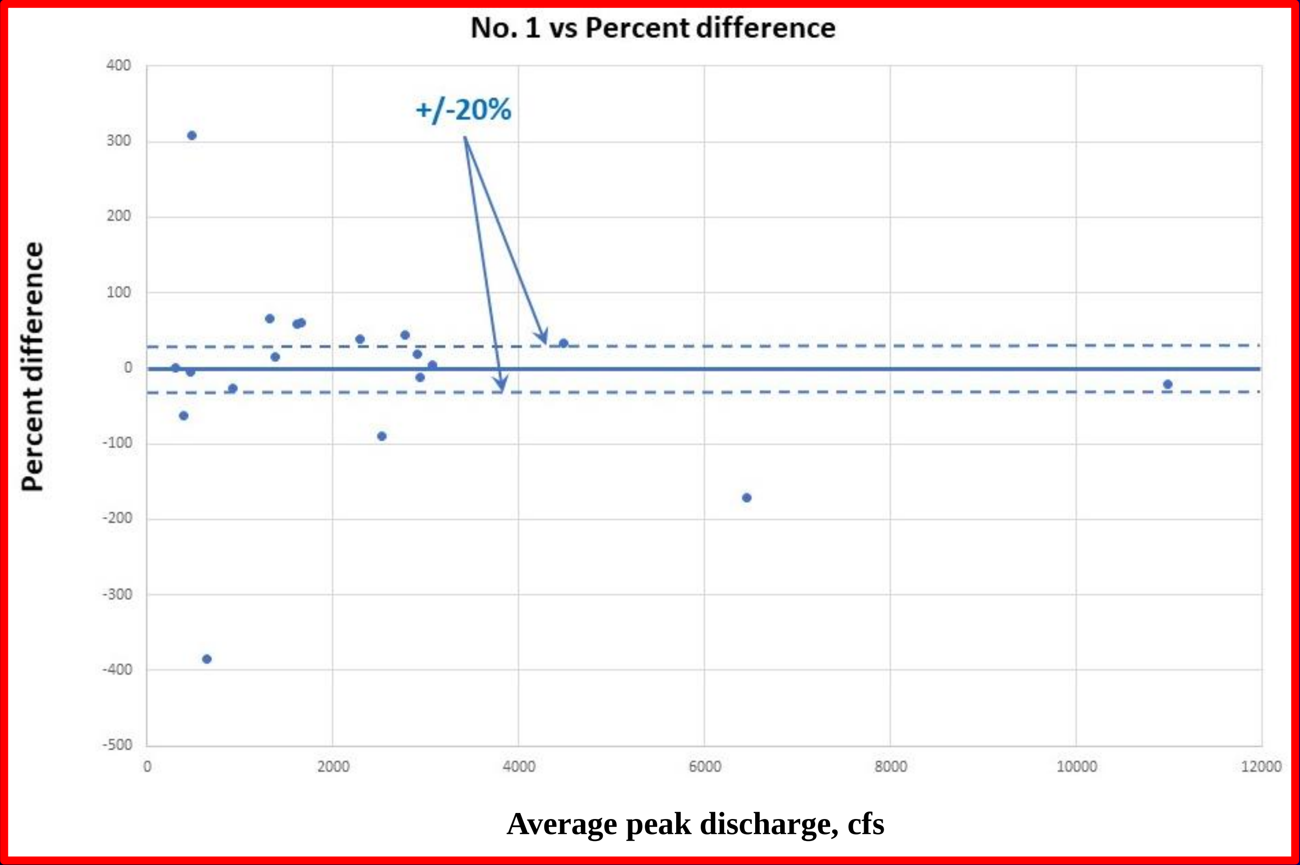


# Validation of critical-depth method



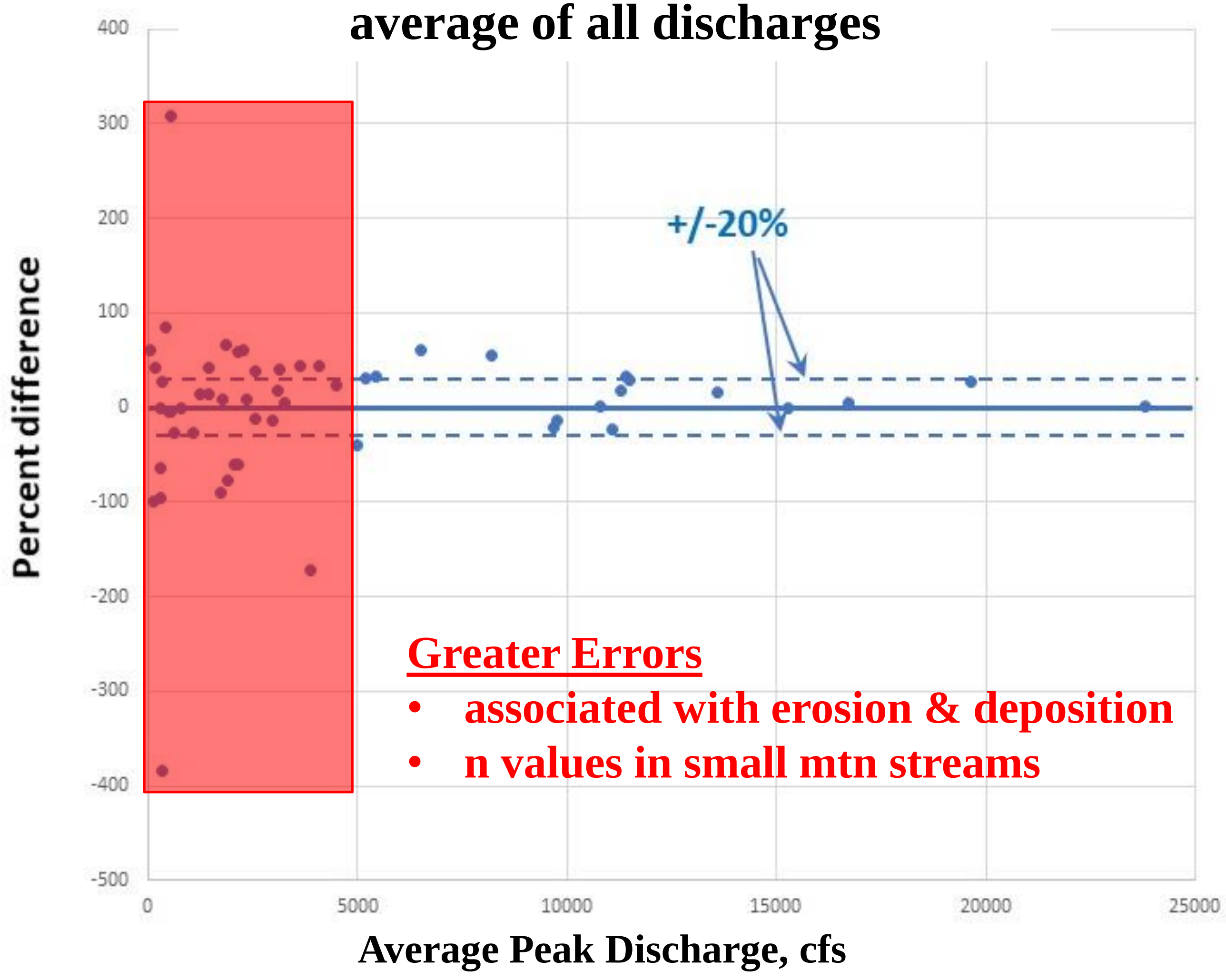

2013 Peak discharge comparison Q(all)ave vs Qjarrett
+/-20%
CD Discharge, cfs
Average peak discharge, cfs
25000
20000
15000
10000
5000
0
0
5000
10000
15000
20000
25000

# Evaluation of Flood Discharges By Flood Specialist No. 1




One team accounted for the majority of percent differences > 40%

# Comparison of all investigators vs the average of all discharges



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# Comparison of 1976 and 2013 Floods Big Thompson River (MOC)

**1976 Big Thompson Flood**

- ~7.5 inches of rain in 1 hour
  12-14 inches in 4 hours
- Peak = 31,200 cfs
- 144 people died
- $155 M in 2018 dollars

418 homes & businesses

**2013 Front Range Flood**

- ~1 inch of rain in 1 hour
  20 inches in 7 days
- Peak =15,500 cfs
- 9 people died
- $2 Billion in Damages
- 18,000 homes & businesses

# Lessons Learned

- Start fieldwork ASAP after flood
  - HWMs can be washed away by subsequent storms
  - There often are post-flood channel modifications
- Finding good reaches for conventional methods was difficult due to erosion and deposition
- Use Manning's n and equations with caution in mountain streams

# Conclusions

- **Sept 2013 rainstorm > 100,000 year event. Does NOAA Atlas 14 need to be revisited/revised?**
- **Flooding ~600-700 yr range in recurrence interval**
- **It could have been much worse with thunderstorm and flash flooding (time to peak less than an hour)**
- **Flood-chasing approach provides timely, cost-effective flood data ($250/site vs $10,000/site)**
- **Methods applicable in natural, burned, and urban higher gradient streams ($S \geq 1\%$) for a wide range of flows**

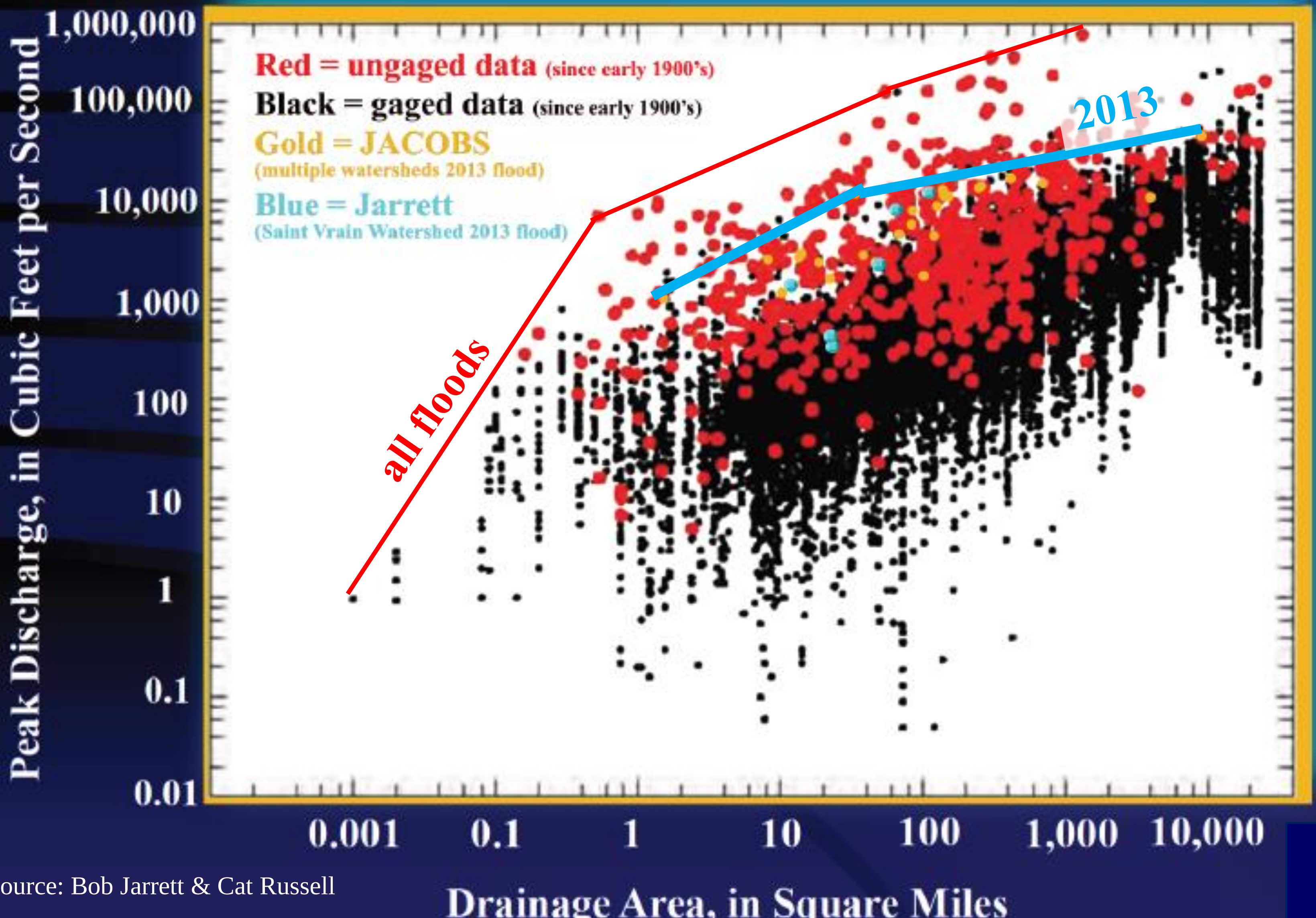
# "How Can This Happen?"

**Near-buried camper on large pickup-truck**

**Source: Dan Barber, OEM, Boulder**

# 2013 Floods in Perspective of Other Colorado Floods

## vs Saint Vrain Creek basin 2013 Floods




Source: Bob Jarrett & Cat Russell