Paleoflood Research to Improve Flood Science

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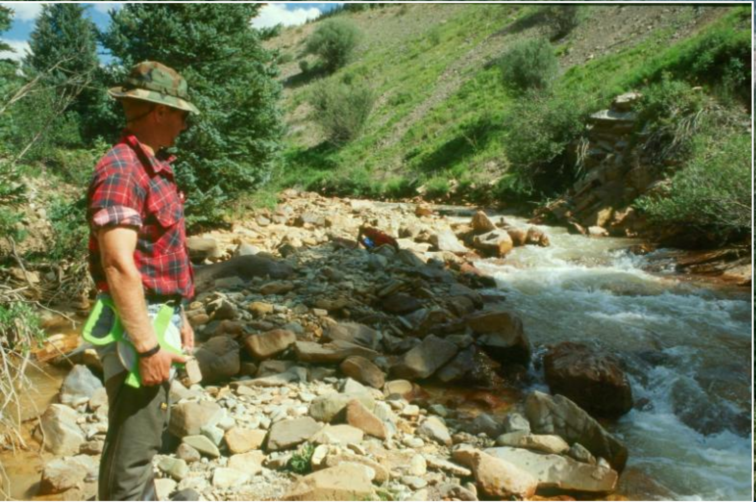
Jon Pruess, USGS, photos



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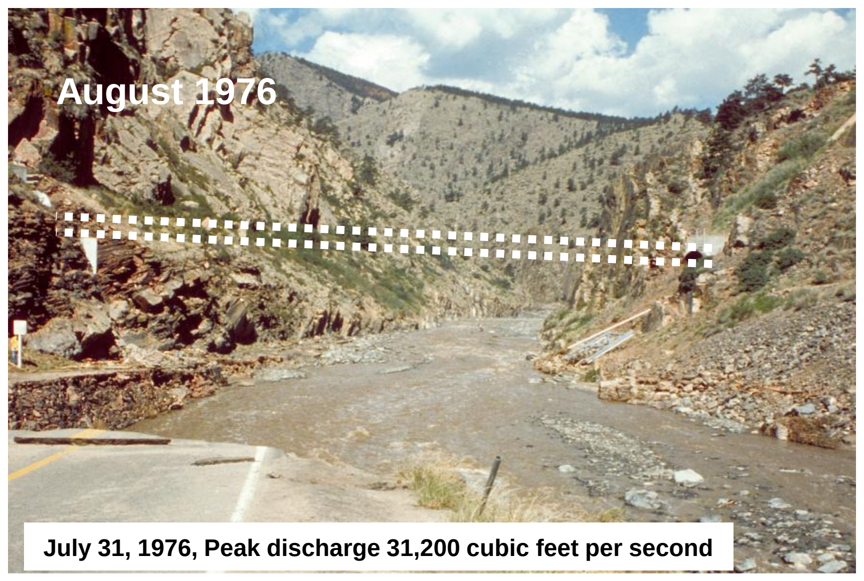
Animas River below Silverton, CO

Paleoflood Research to Improve Flood Science

- Introduction
- Overview of Paleoflood Hydrology
- Recent Paleoflood Research Topics
- Two applications
    - Dam Safety
    - Climate Change & Maximum Flooding
- Concluding Remarks



Big Thompson River at Mouth of Canyon

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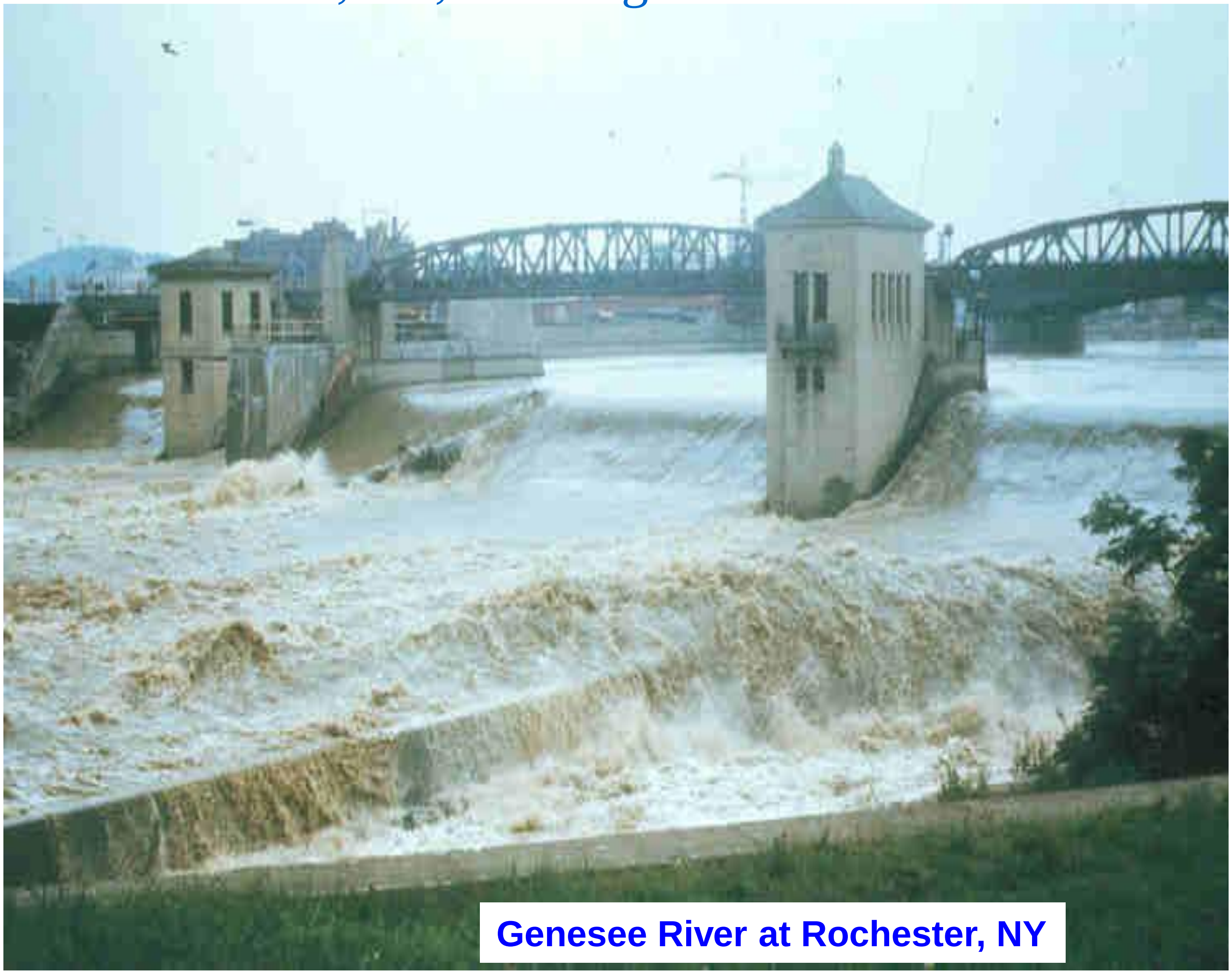
June 1972 Agnes Flood - most flood damage in US history until the 1993 Mississippi River Flood



Genesee River at Rochester, NY

Bob Jarrett's first job, Agnes Flood Studies, Corps of Engineers, NY 1971-1974

1976 Big Thompson Flood

1982 Lawn Lake dam failure flood

Dozens of 100-year or larger floods

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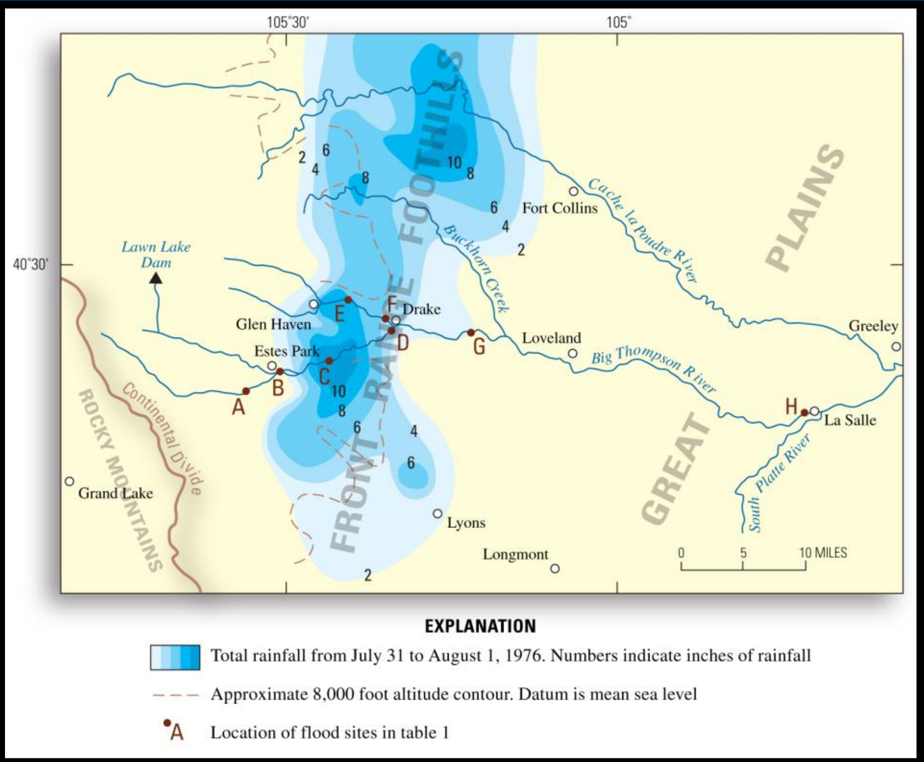
Importance of USGS Flood Science

- Operate national stream-gage network and conduct research
- Understand and help predict the magnitude and frequency of floods
- Help assess the effects of climate variability (change) on flooding
- To save lives, minimize property damages, and reduce flood risks

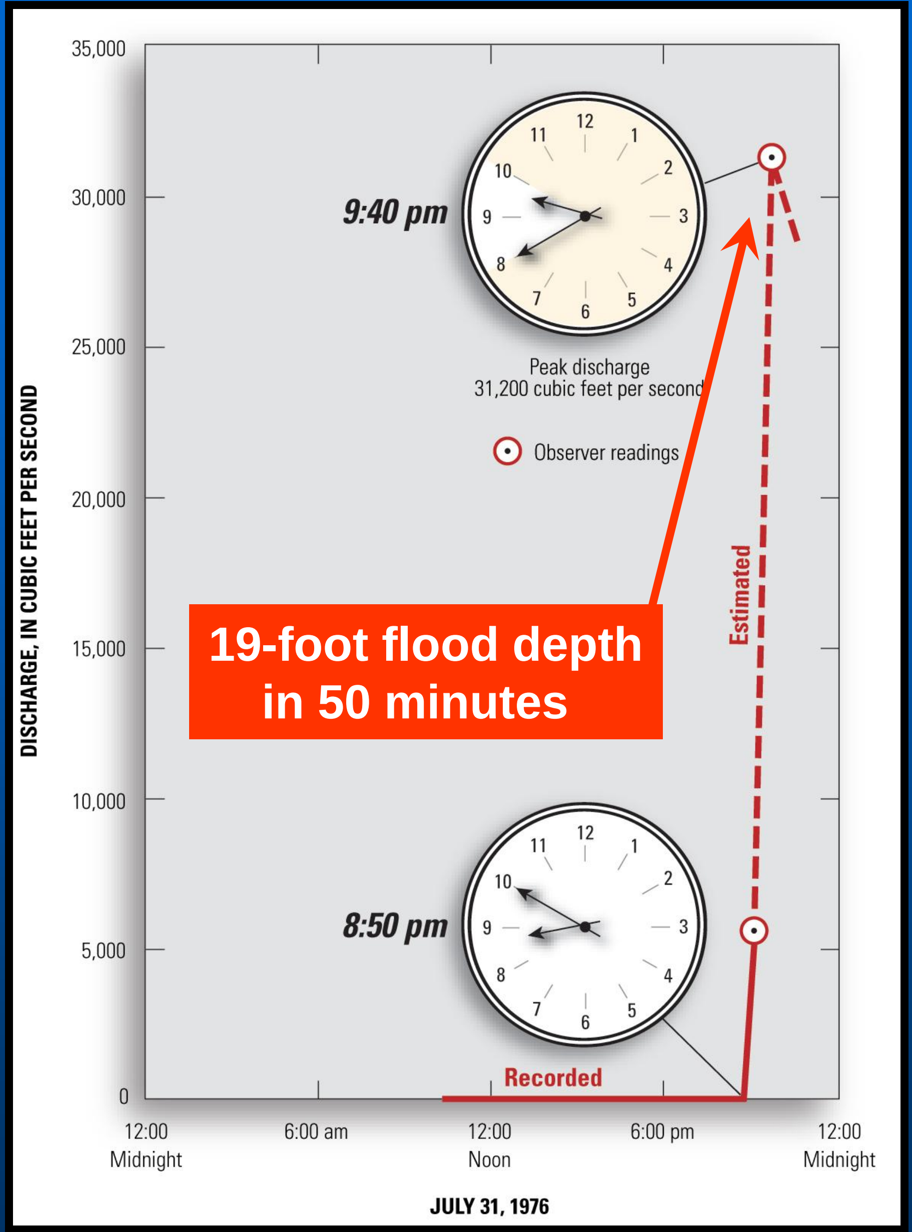
Map showing measured and estimated total July 31, 1976, rainfall, Colorado



7.5 inches of rainfall in an hour

12 inches in 4 to 6 hours

145 killed; $35M damages



Hydrograph, Big Thompson River at mouth of canyon stream-flow gage

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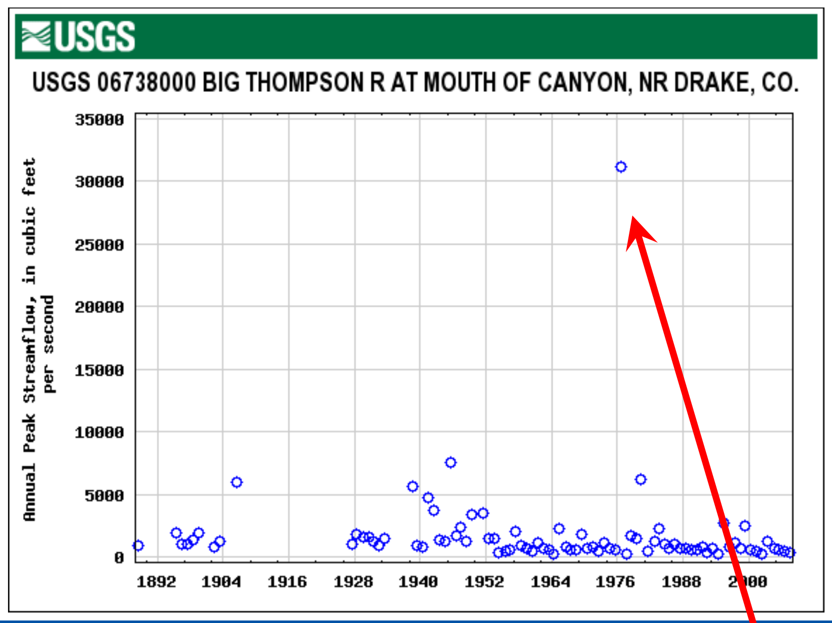
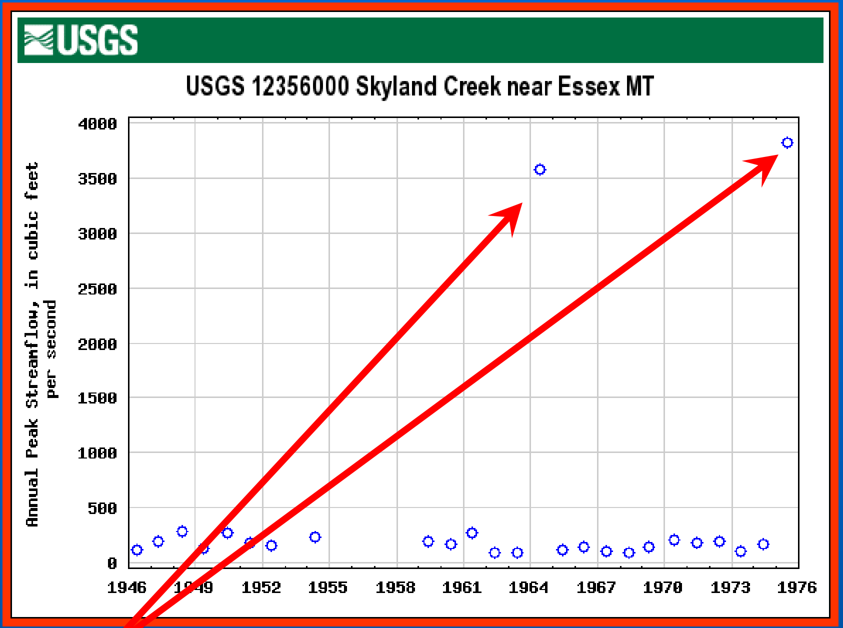
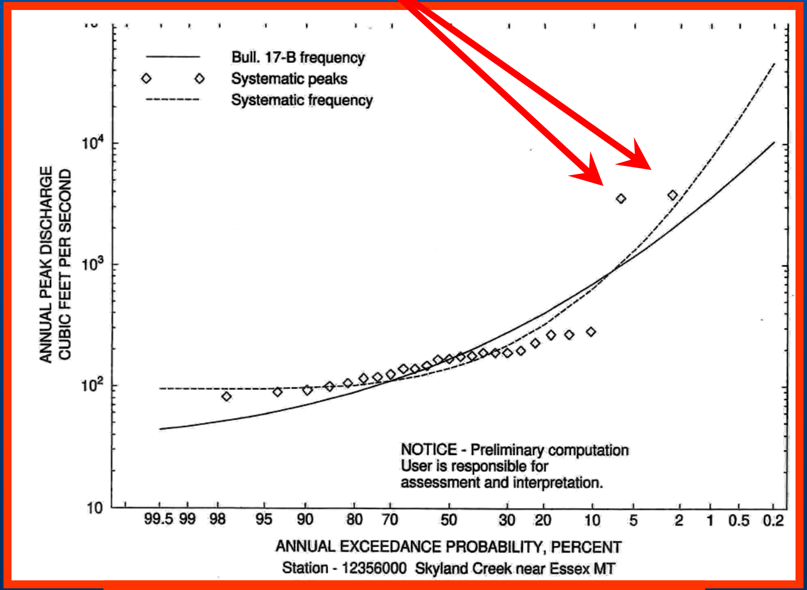




high outliers



Skyland Creek near Essex, Montana

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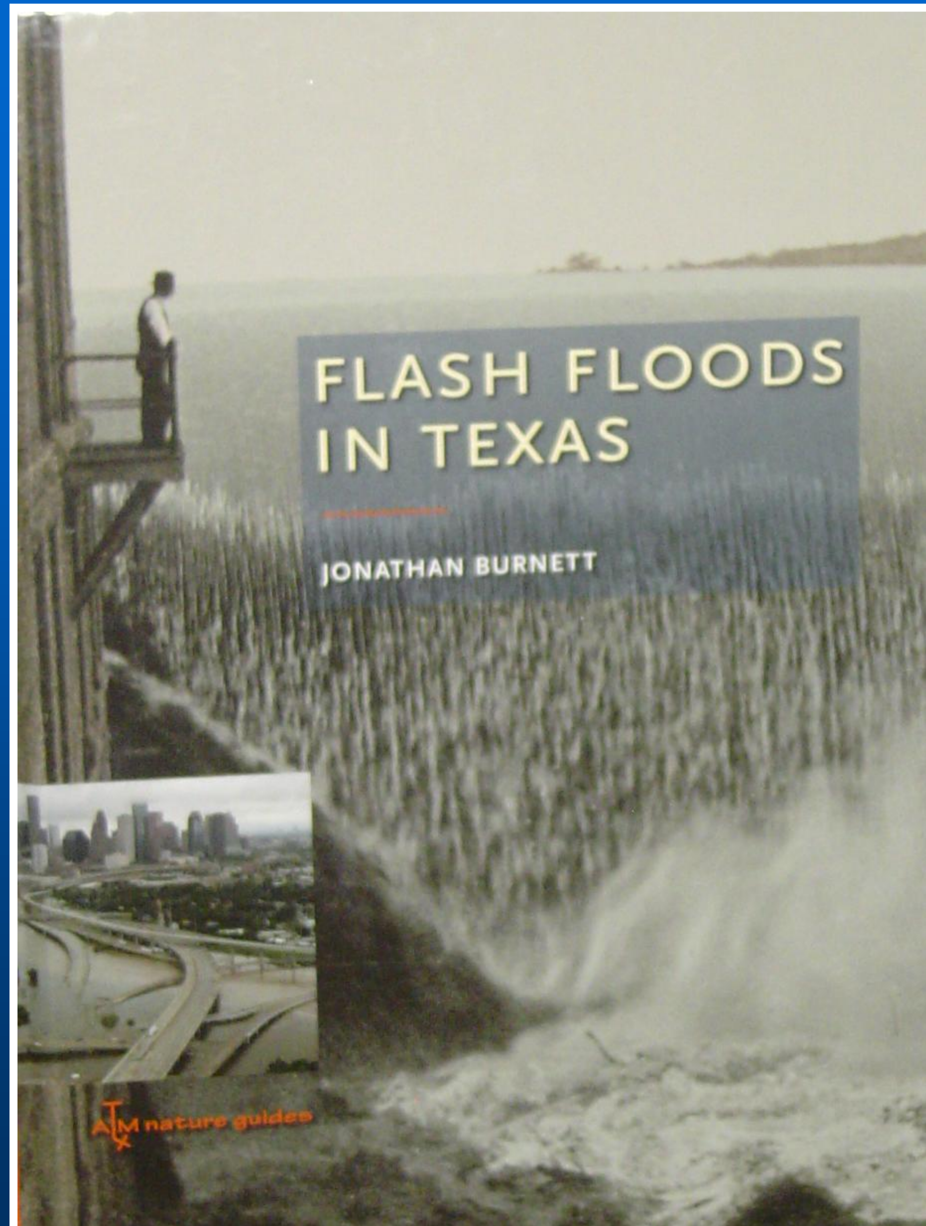

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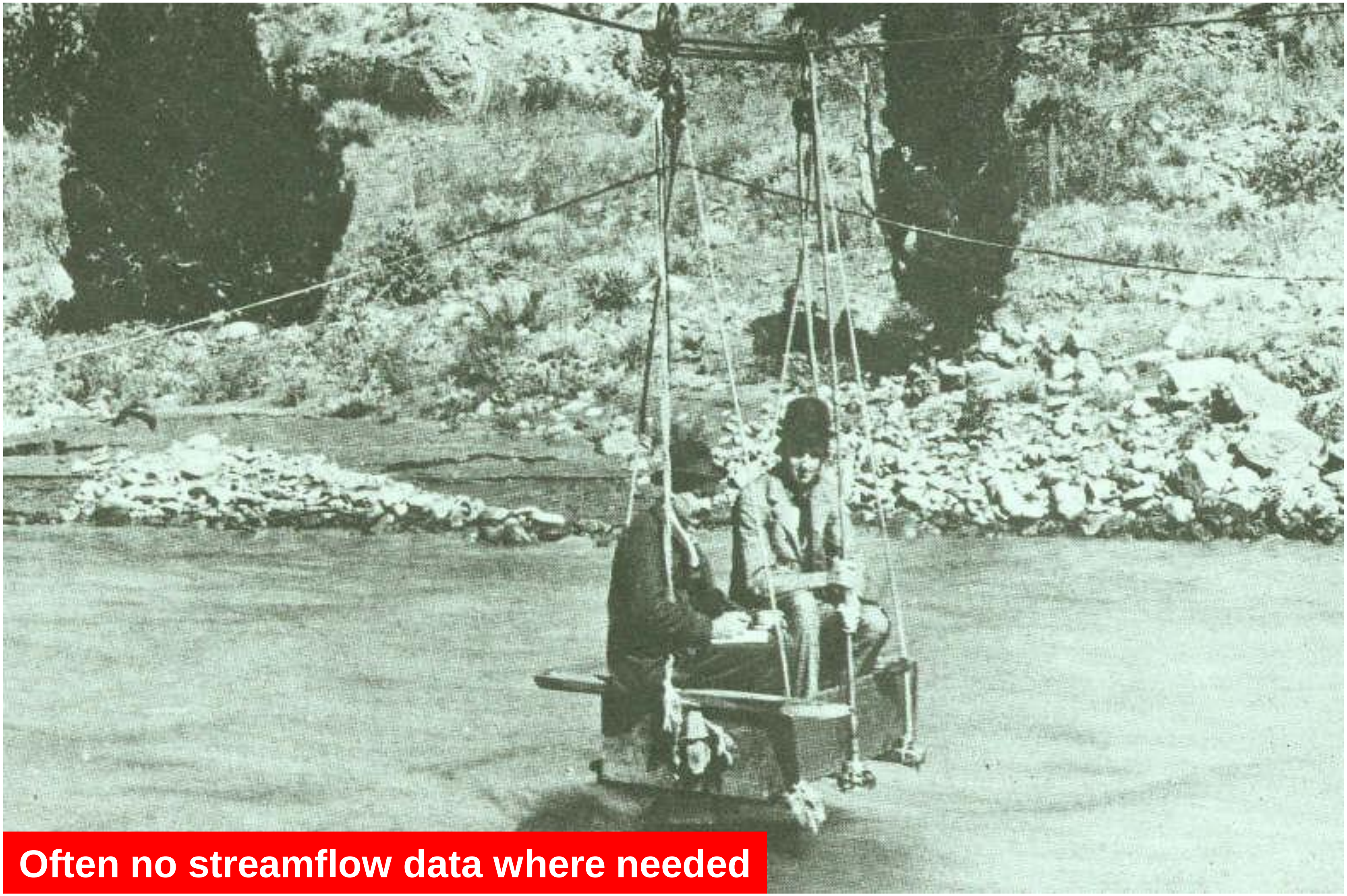
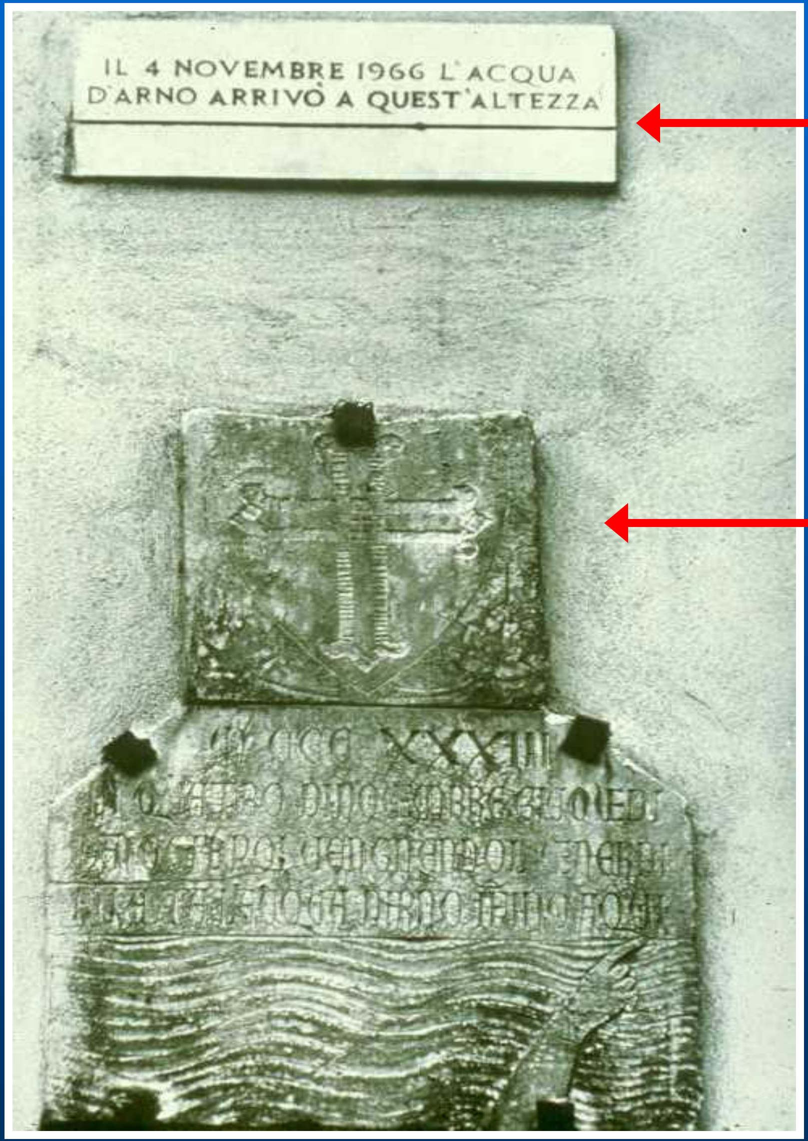
Estimation of flood (& paleoflood) discharge



Often no streamflow data where needed

Arkansas River, CO, ca 1900; USGS photo library

D’Arno River, Italy



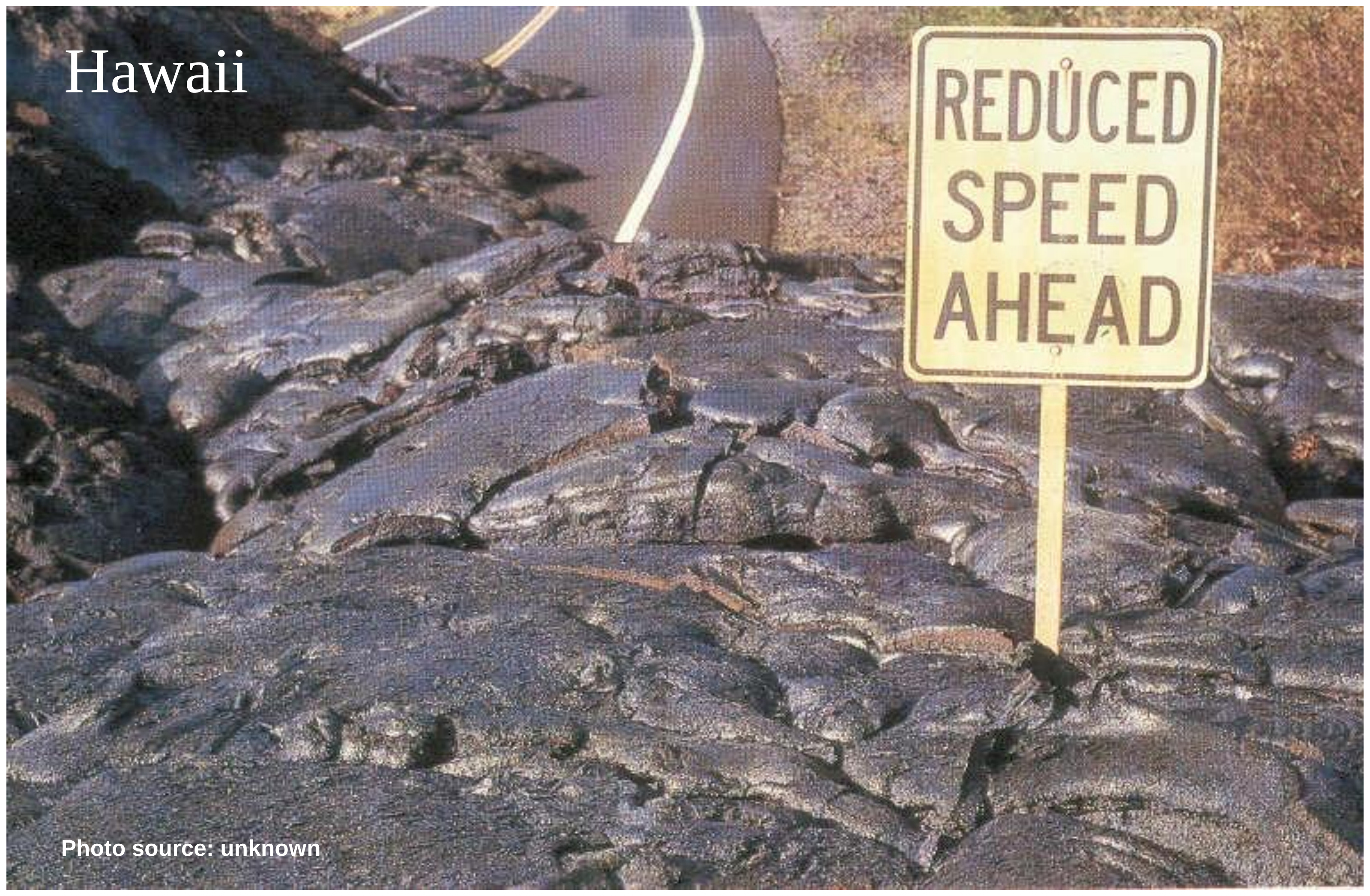
1966 flood

1333 flood

Photo by
J.R. Wallis
IBM research

Renewed emphasis needed on locating/documenting historical floods

Man made and environmental warning signs



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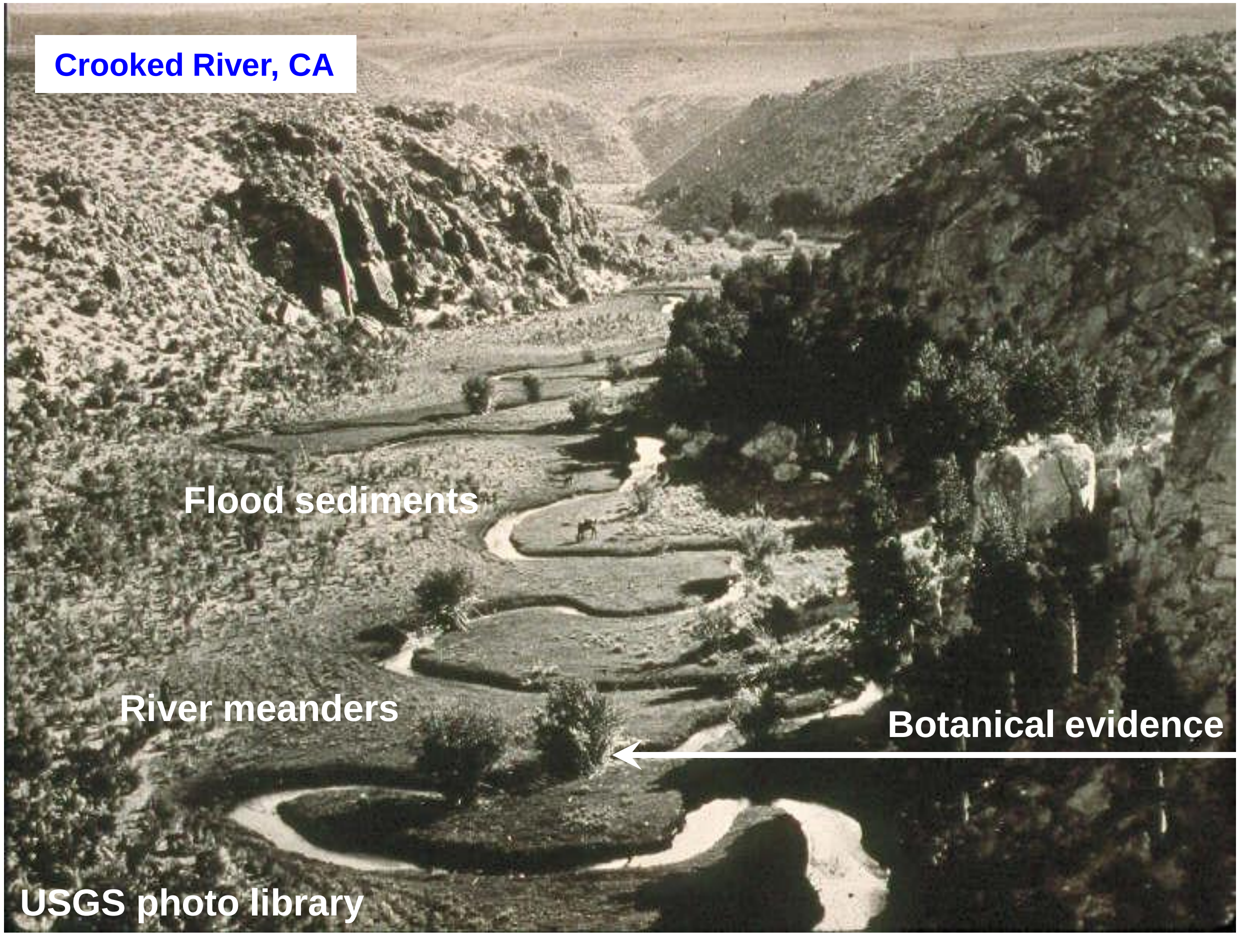
Environmental signs include paleoflood data

Paleoflood Hydrology

Study of environmental signatures of past floods to help better understand present and future flood hazards, and the effects of future climate variability



1976 flood scar
Big Thompson River
at Drake

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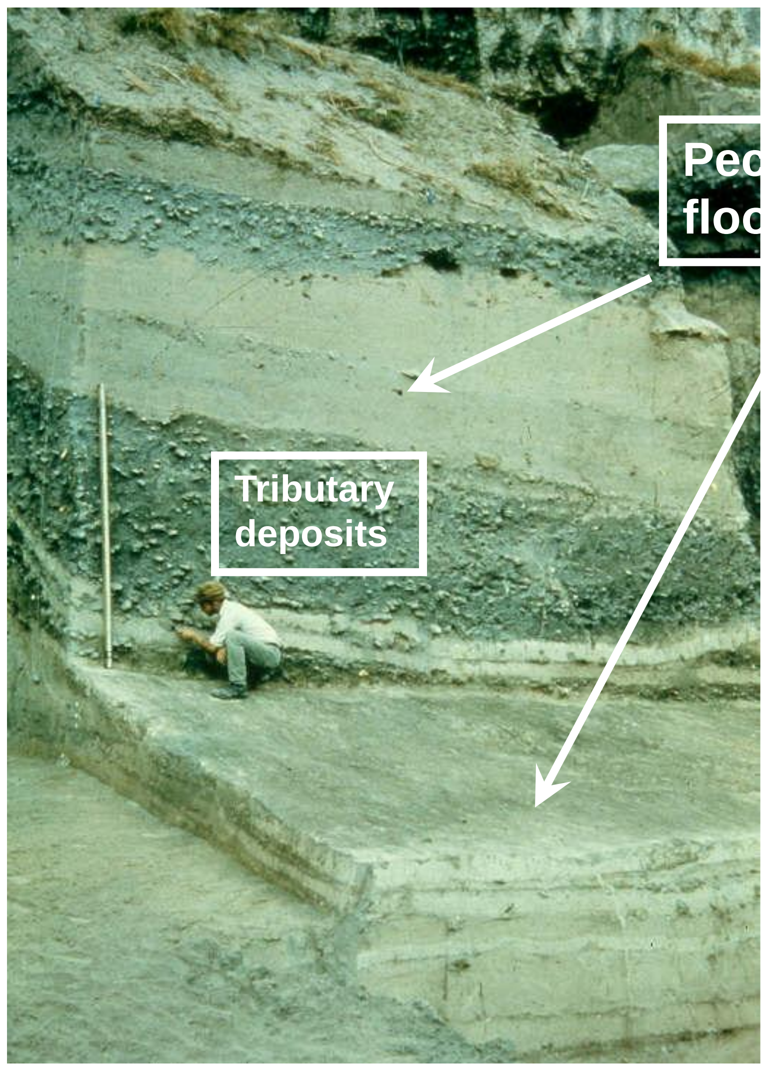
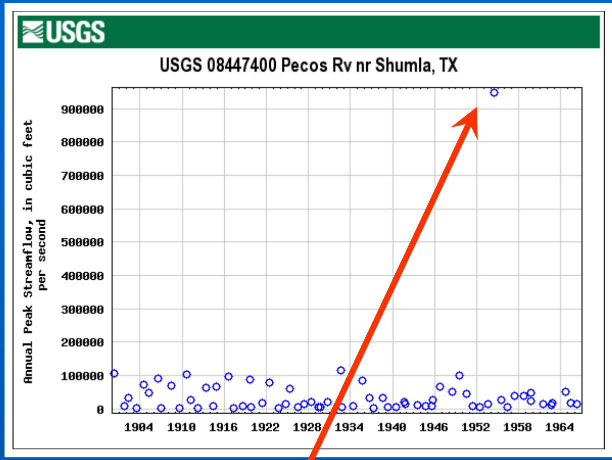
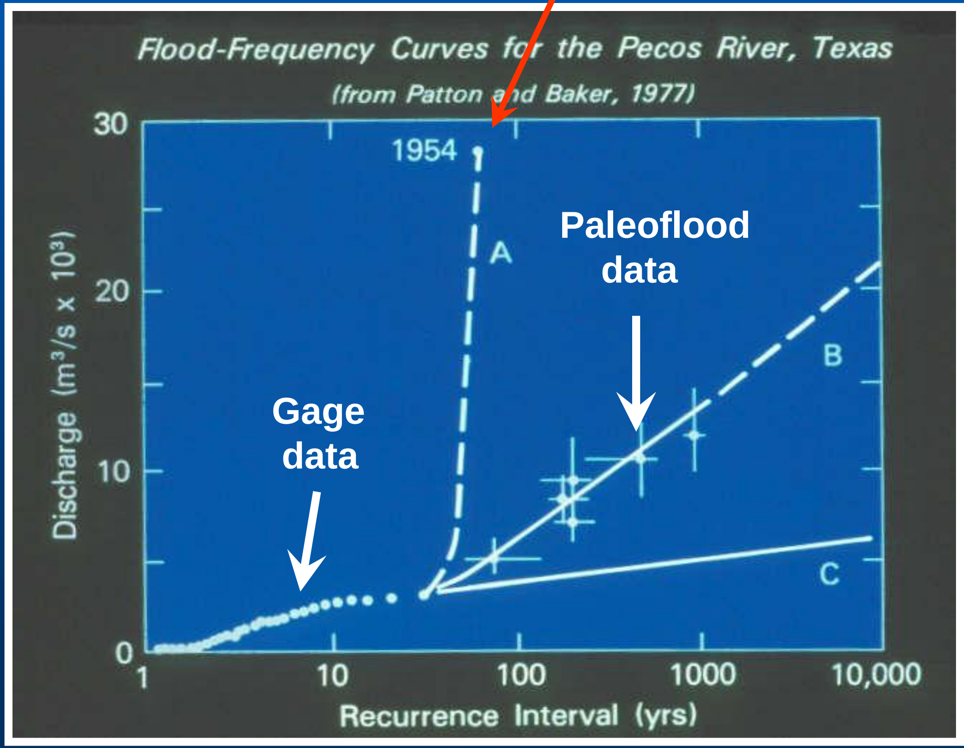
Paleoflood data extend short-term streamflow-gaging station records







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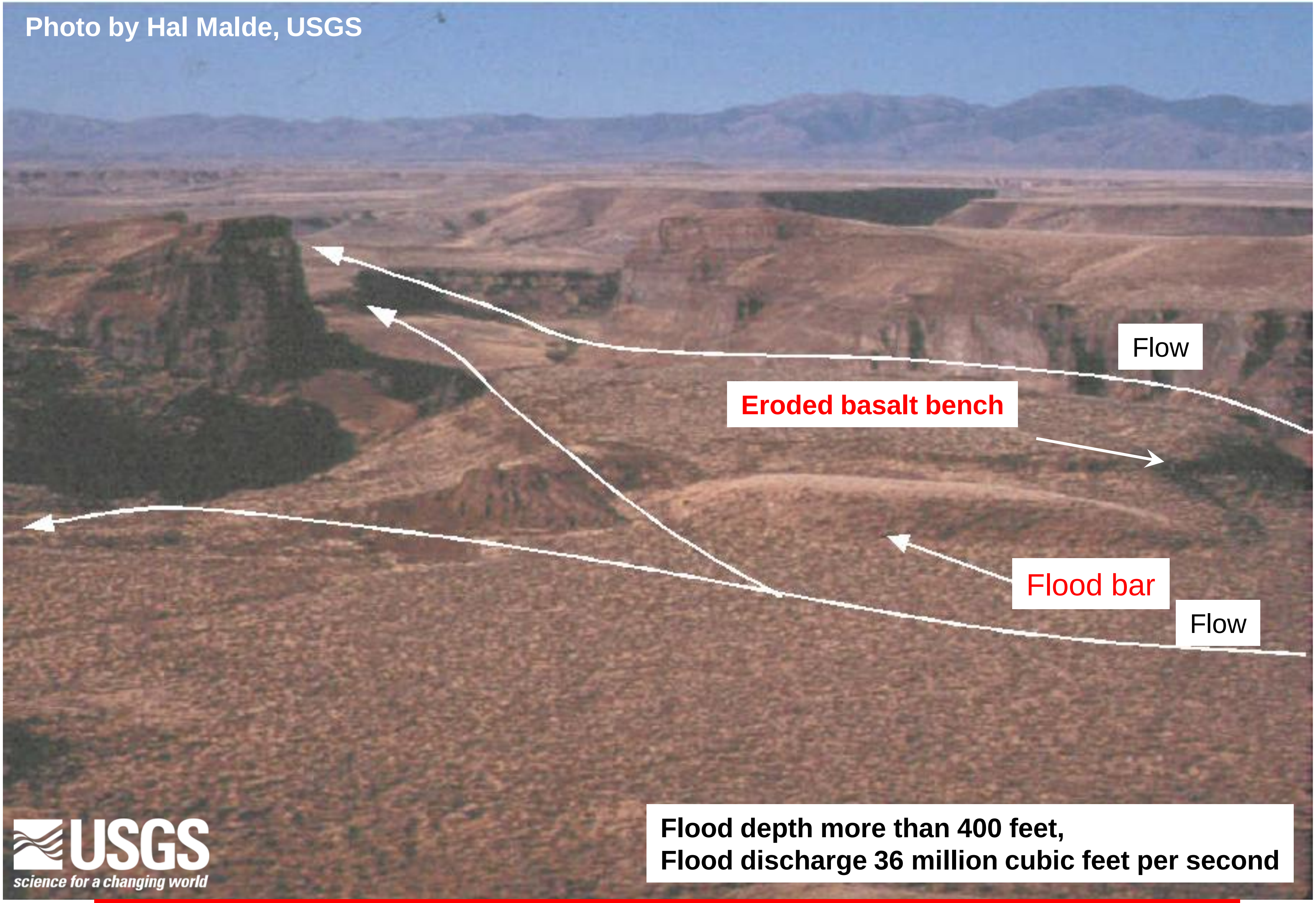
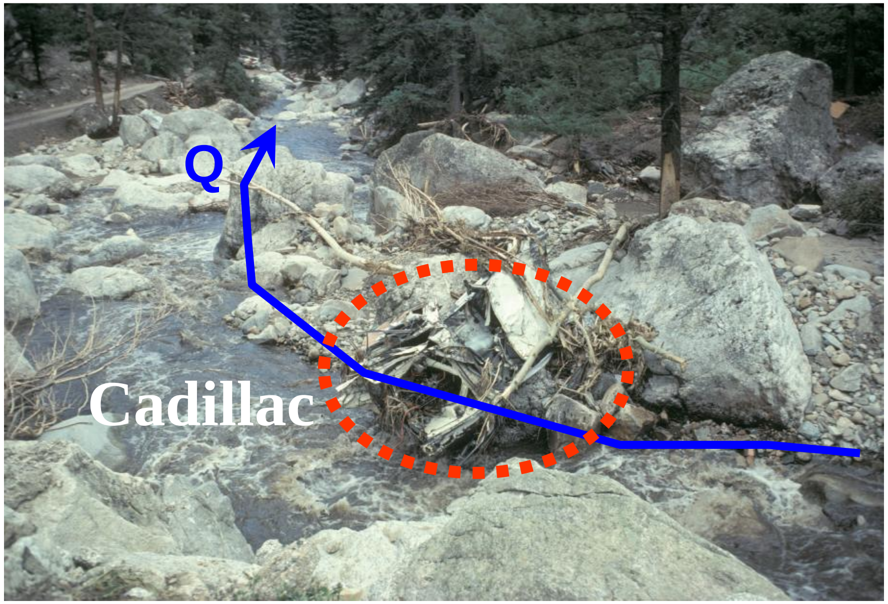
Bonneville Glacial Lake Outburst Flood ~15,000 years ago (Snake River, ID)



Note: preservation of paleostage indicators for 10’s of thousands of years

Paleoflood Research to Improve Flood Science

- Introduction
- Overview of paleoflood hydrology
- Recent paleoflood research topics
- Two Applications
- Concluding remarks



1976 Big Thompson Flood damage

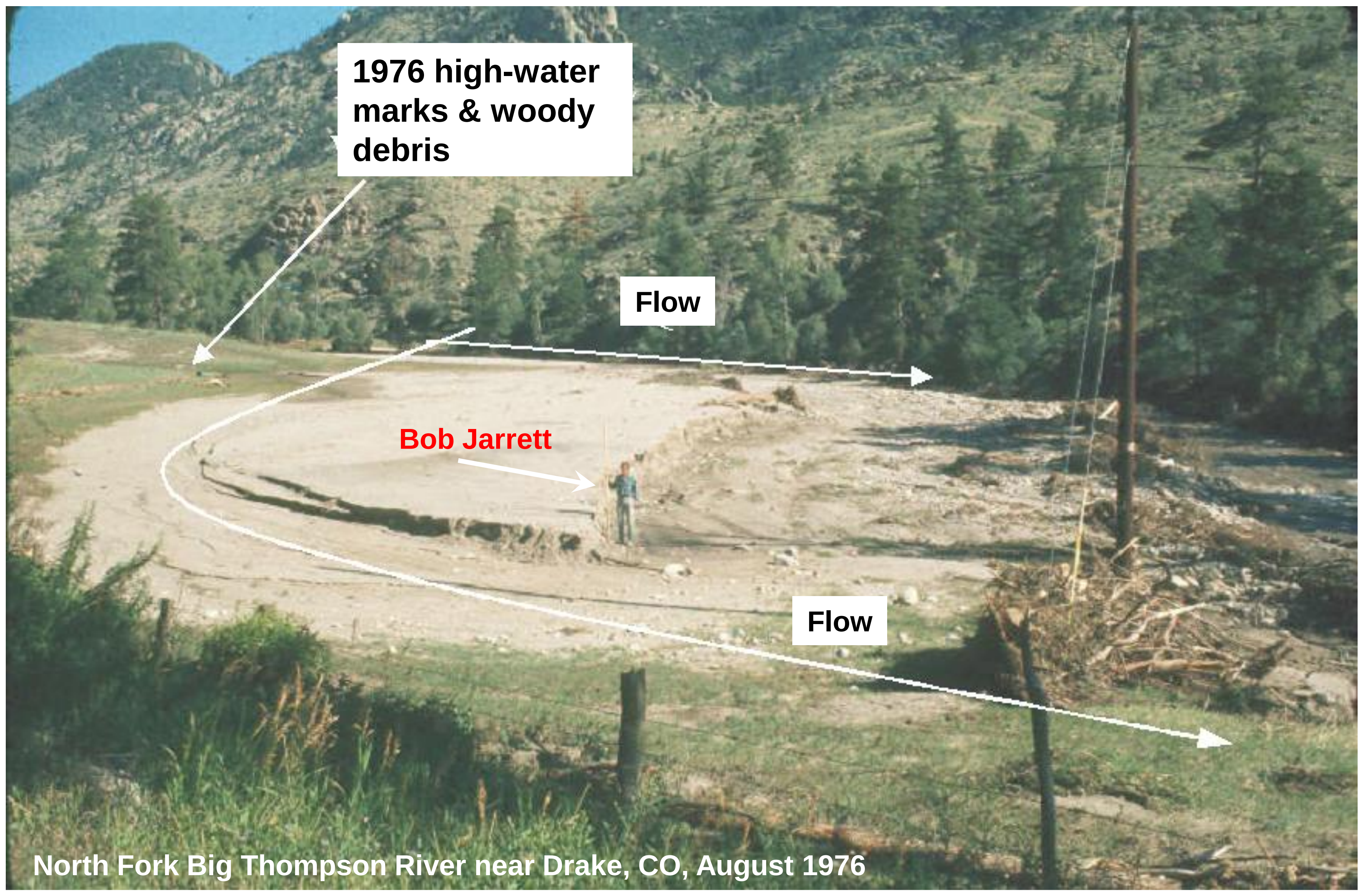


Photo by Jerry McCain, USGS

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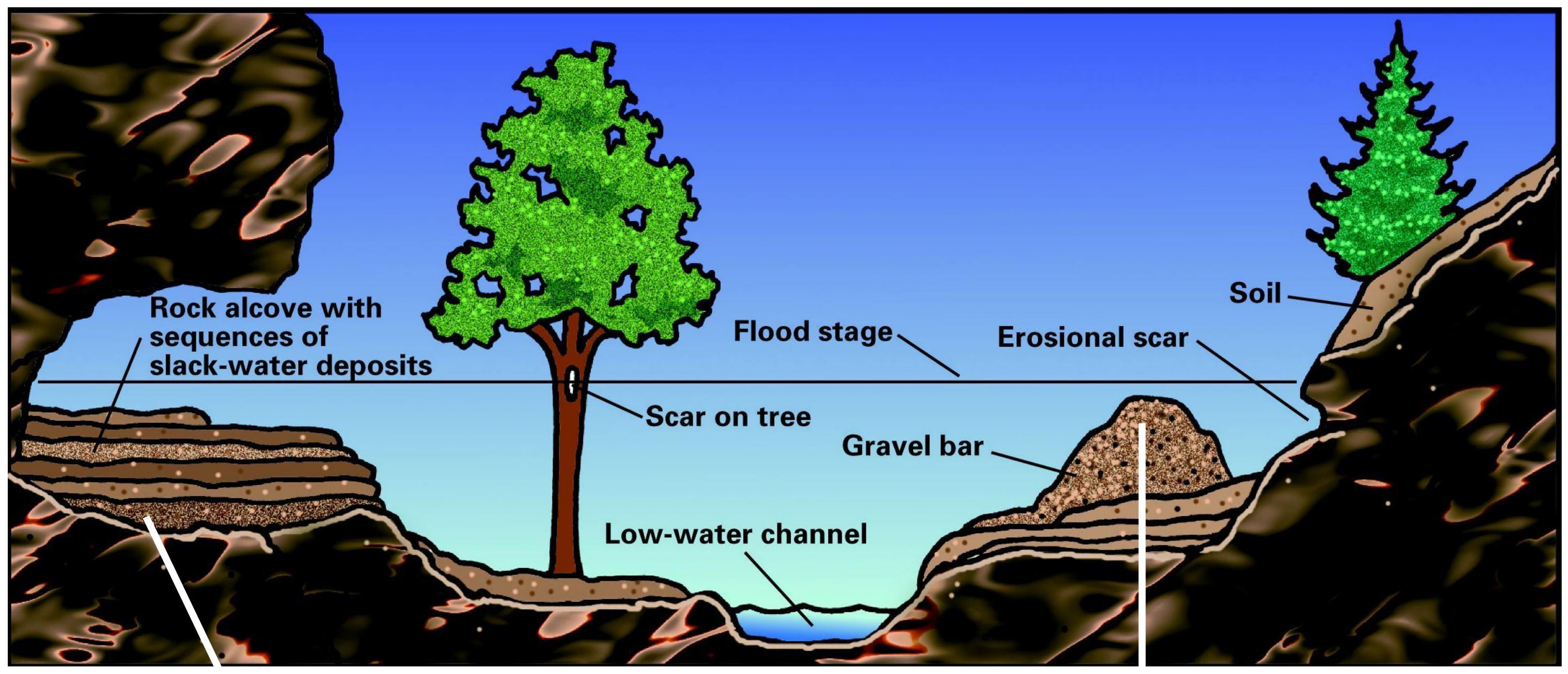
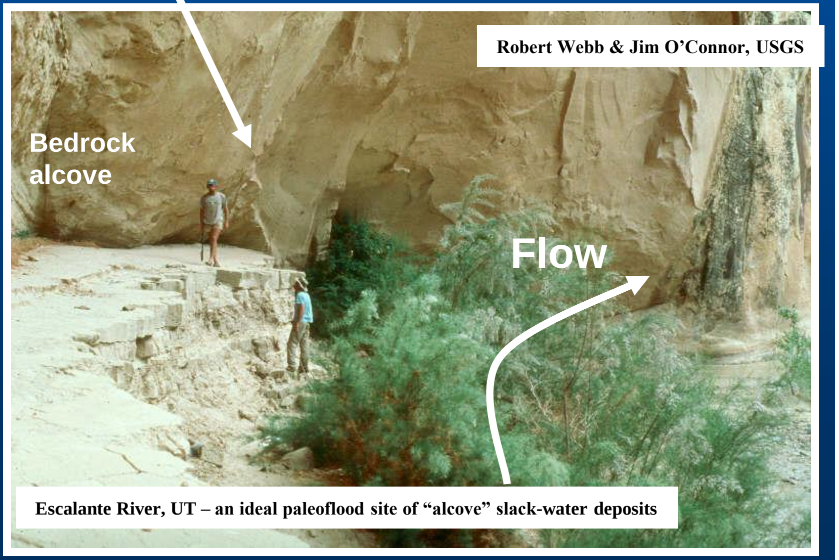
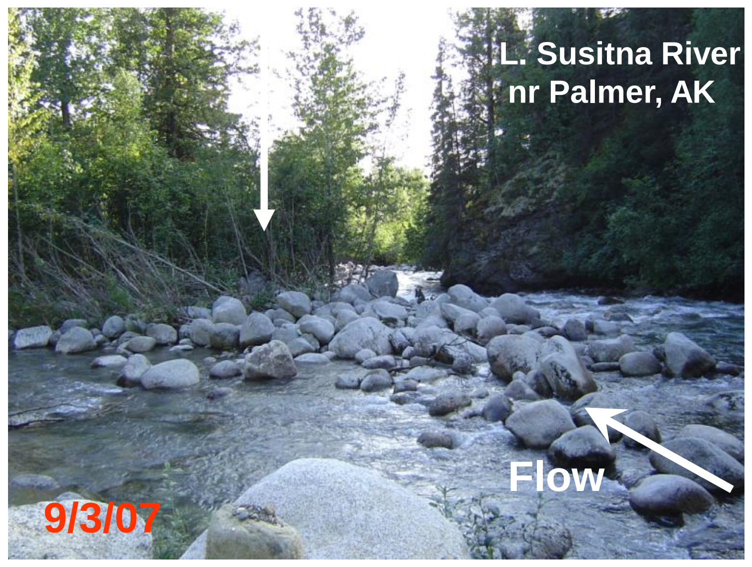
August 1976 - what do these flood sediments have to say?

Types and locations of PaleoStage Indicators (PSIs)







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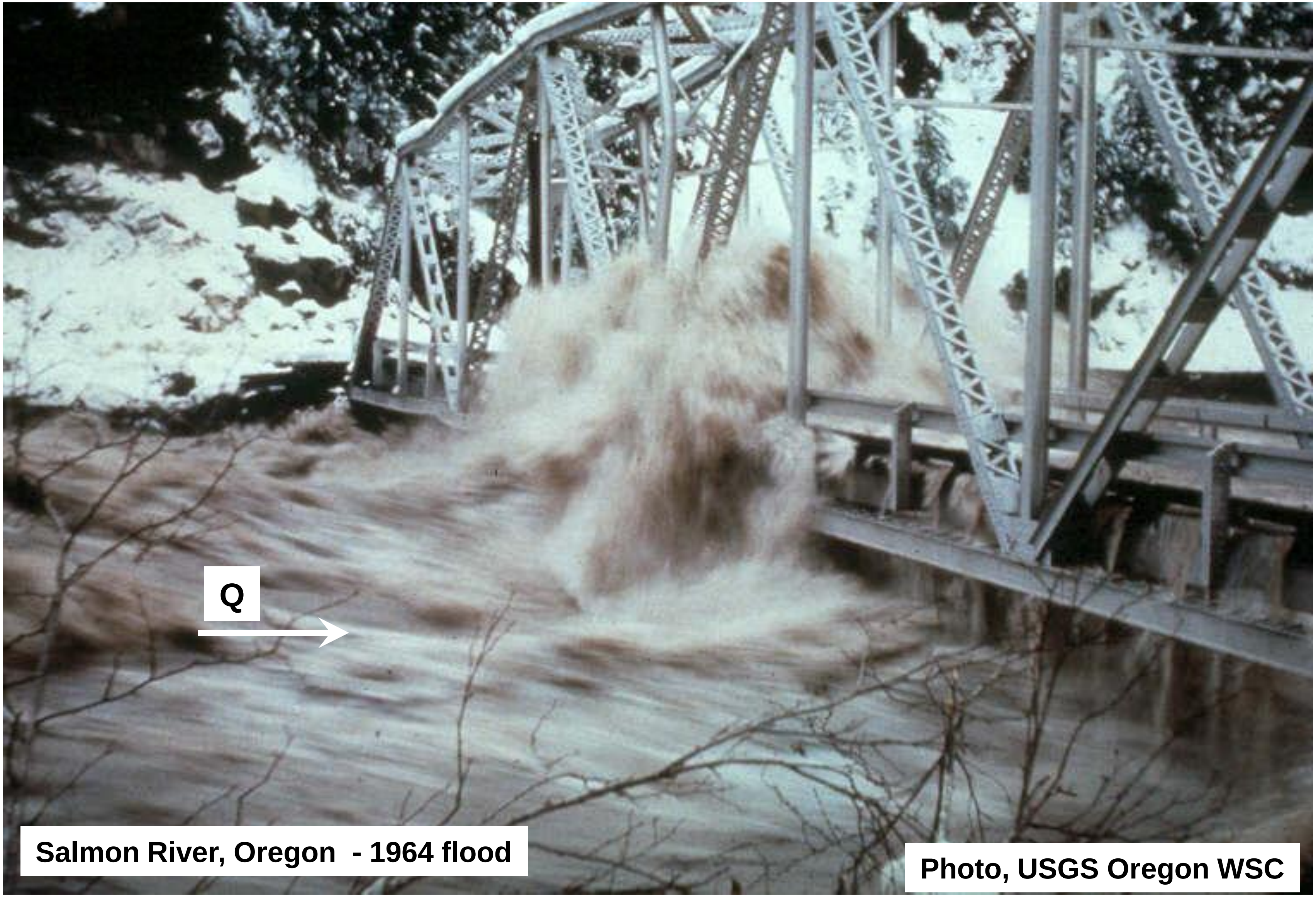
Topic 1--What is the relation of flood deposits and flood height?



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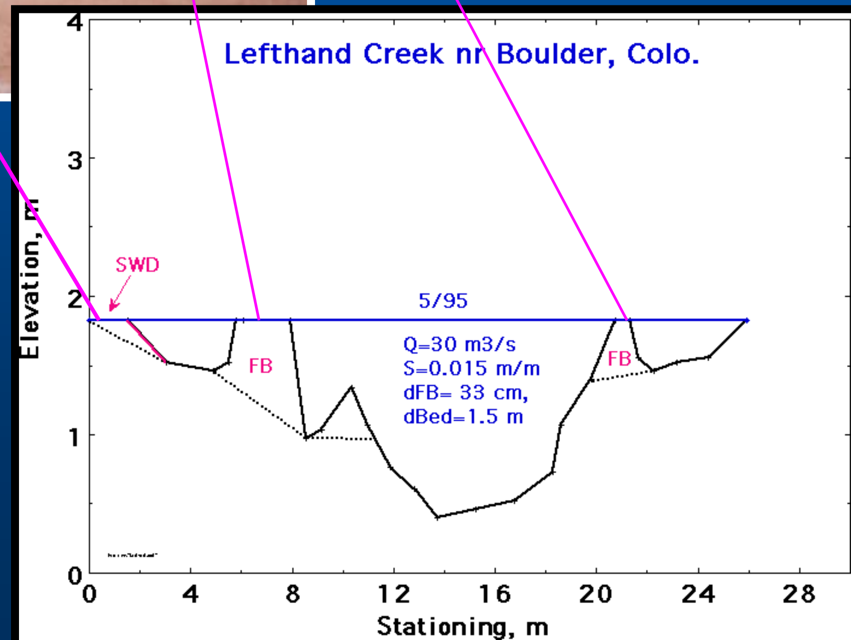
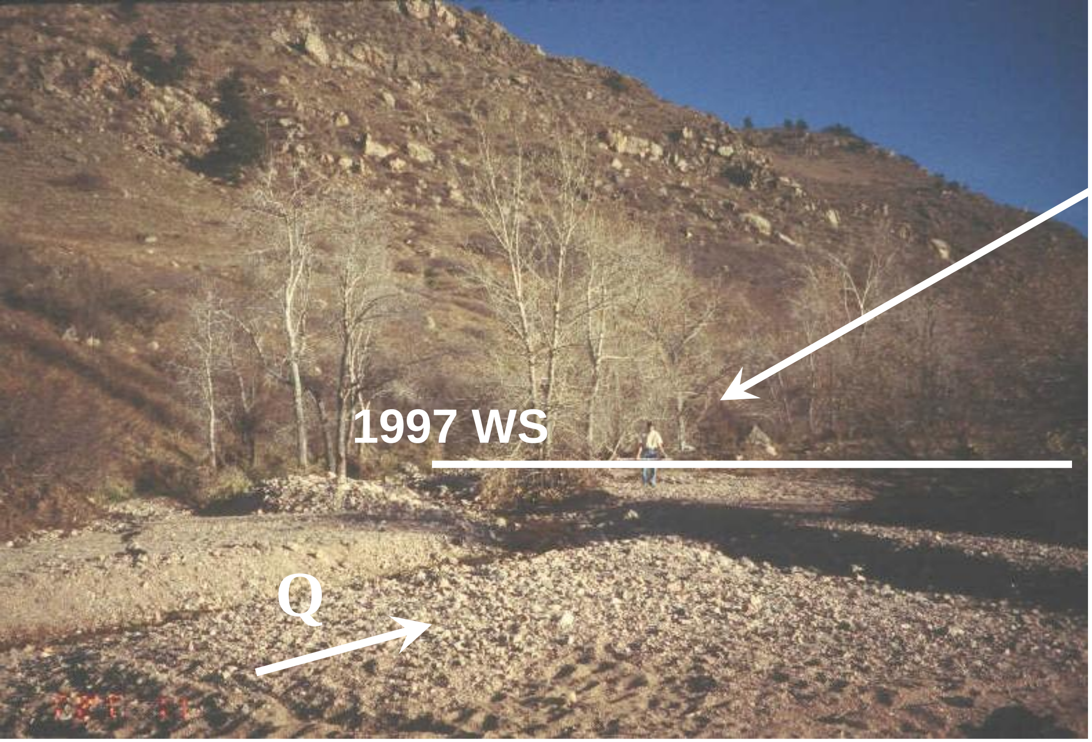
1995 to 2002 -- studied over 200 rivers with recent large floods

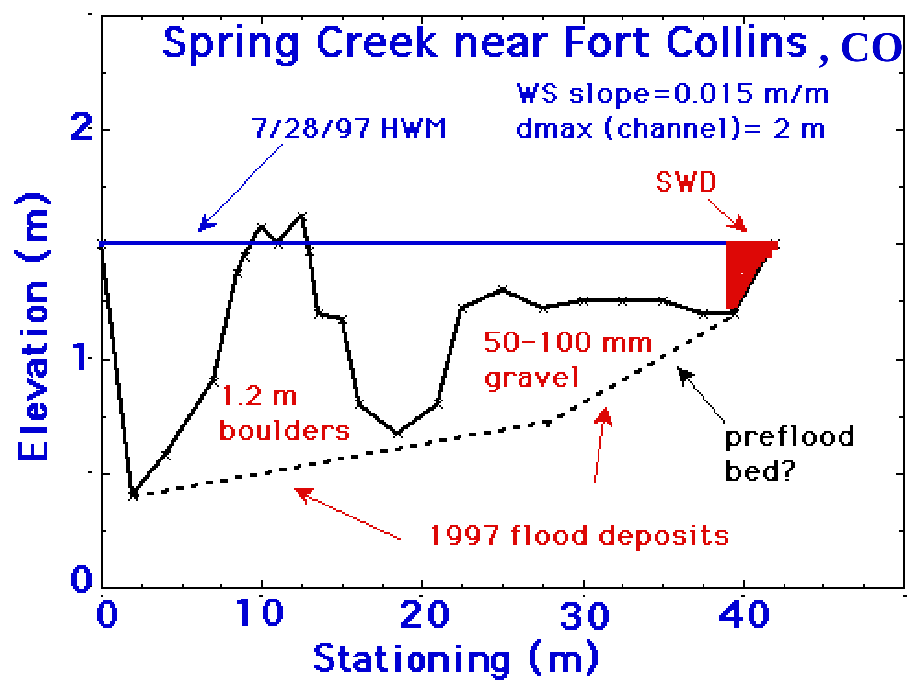
May 1995 (~1 hr after peak)

“Flood chasing 101”





Dan Cenderelli, USFS



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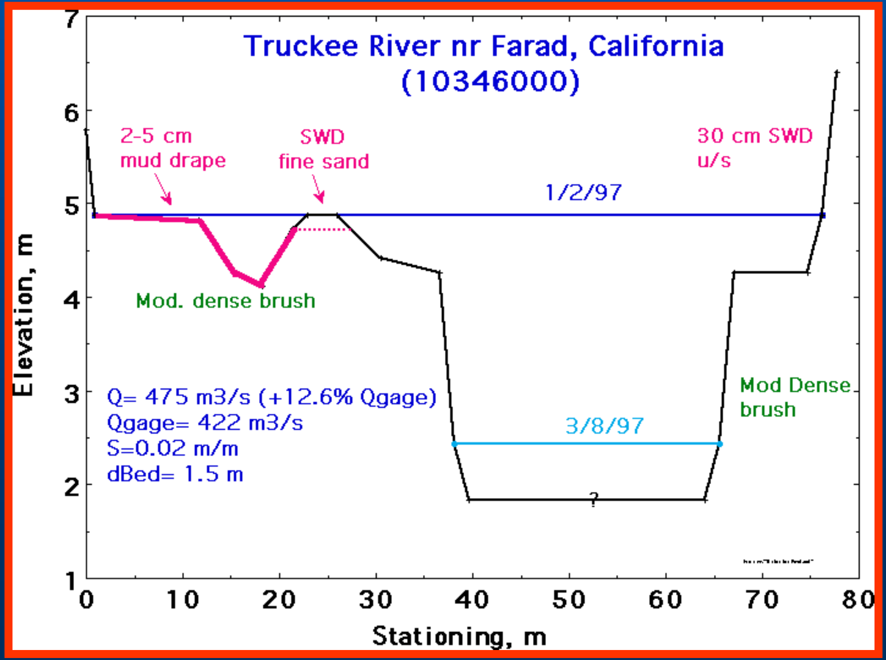

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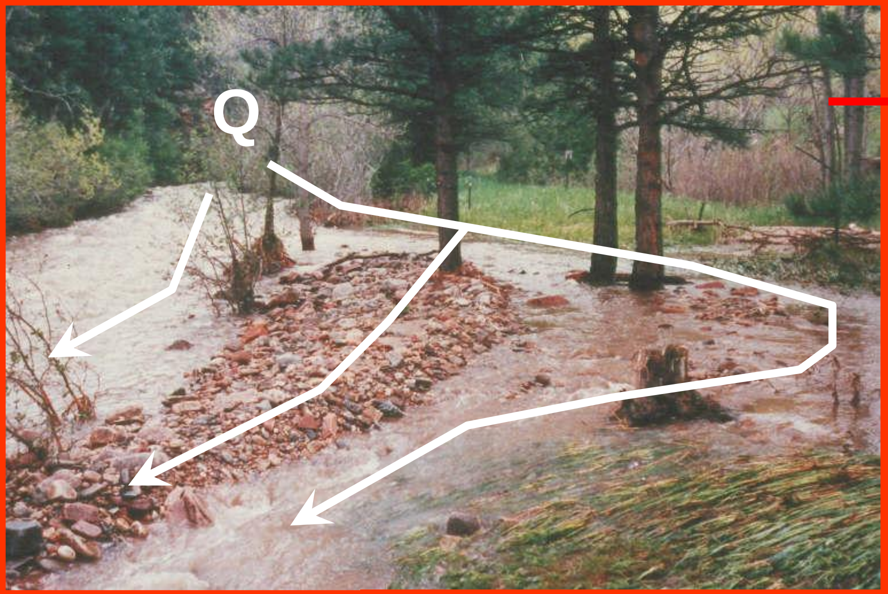
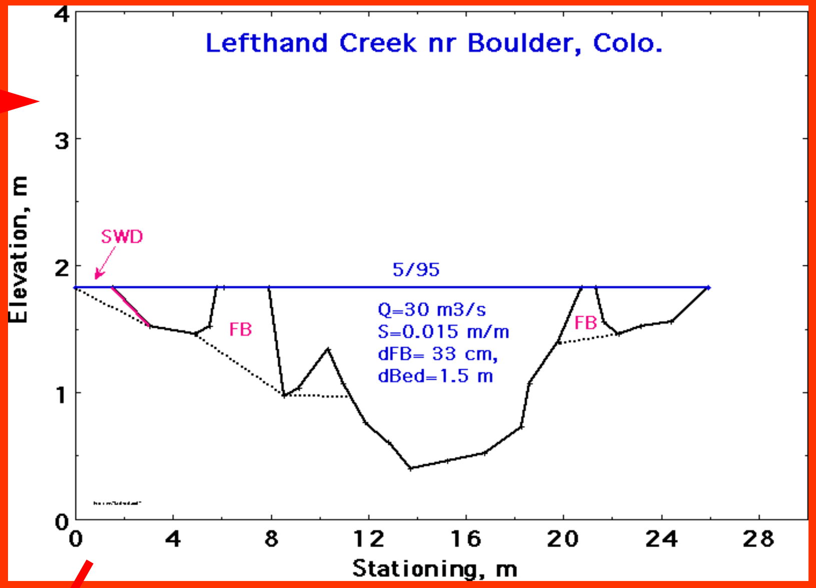
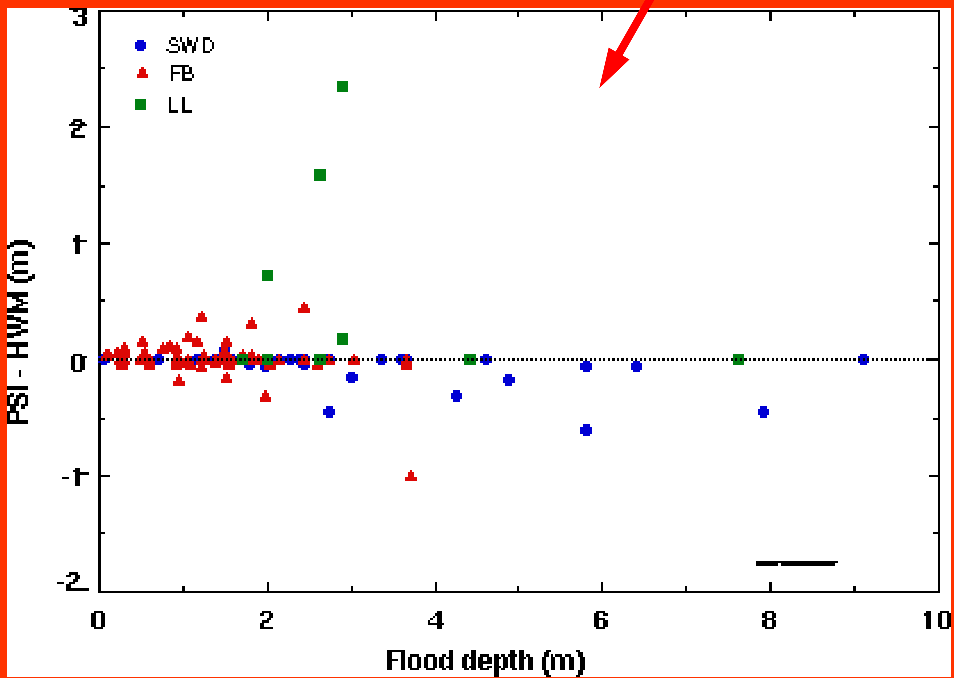
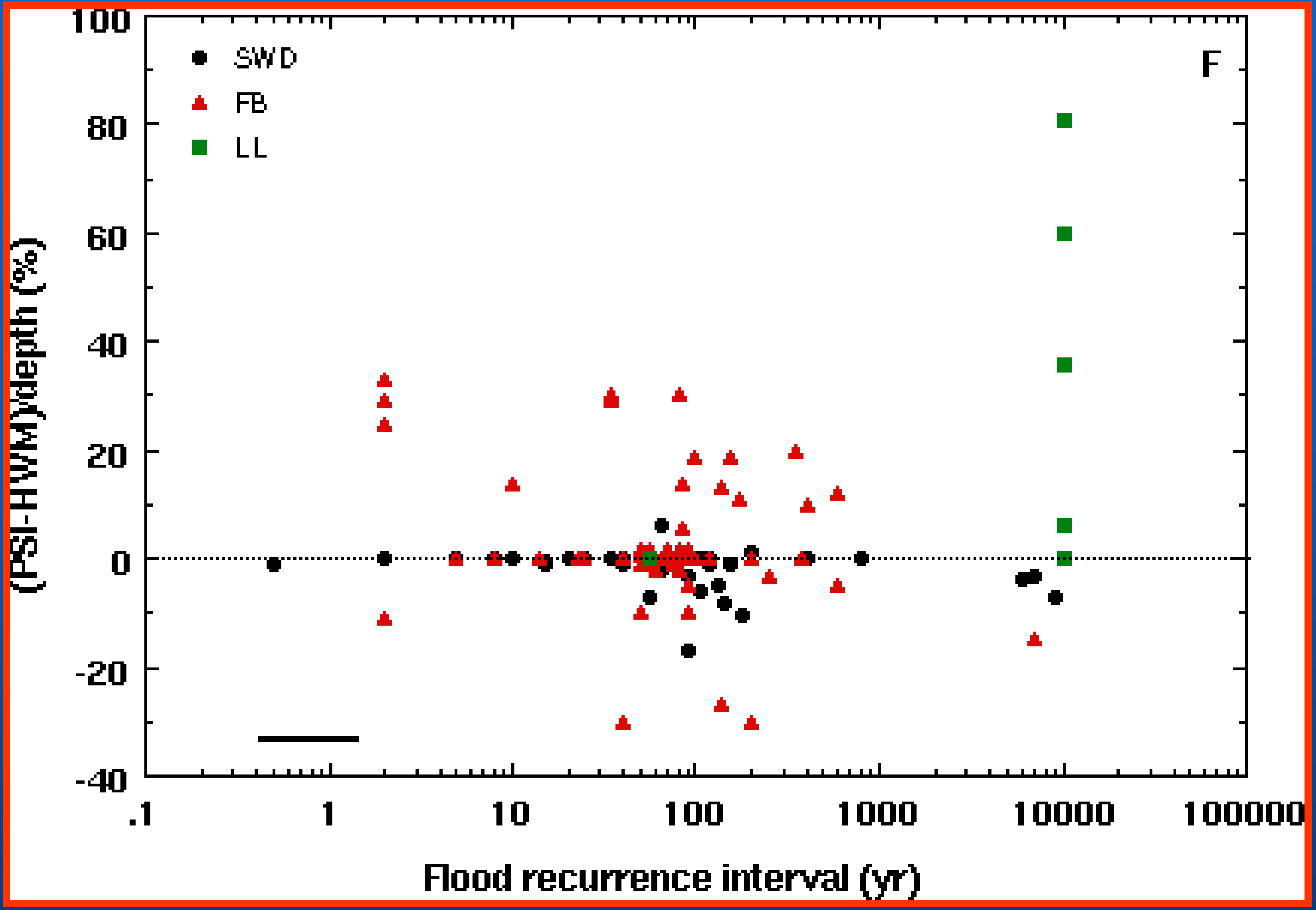
Lefthand Cr nr Boulder, CO (~1 hour after peak; 5/95)





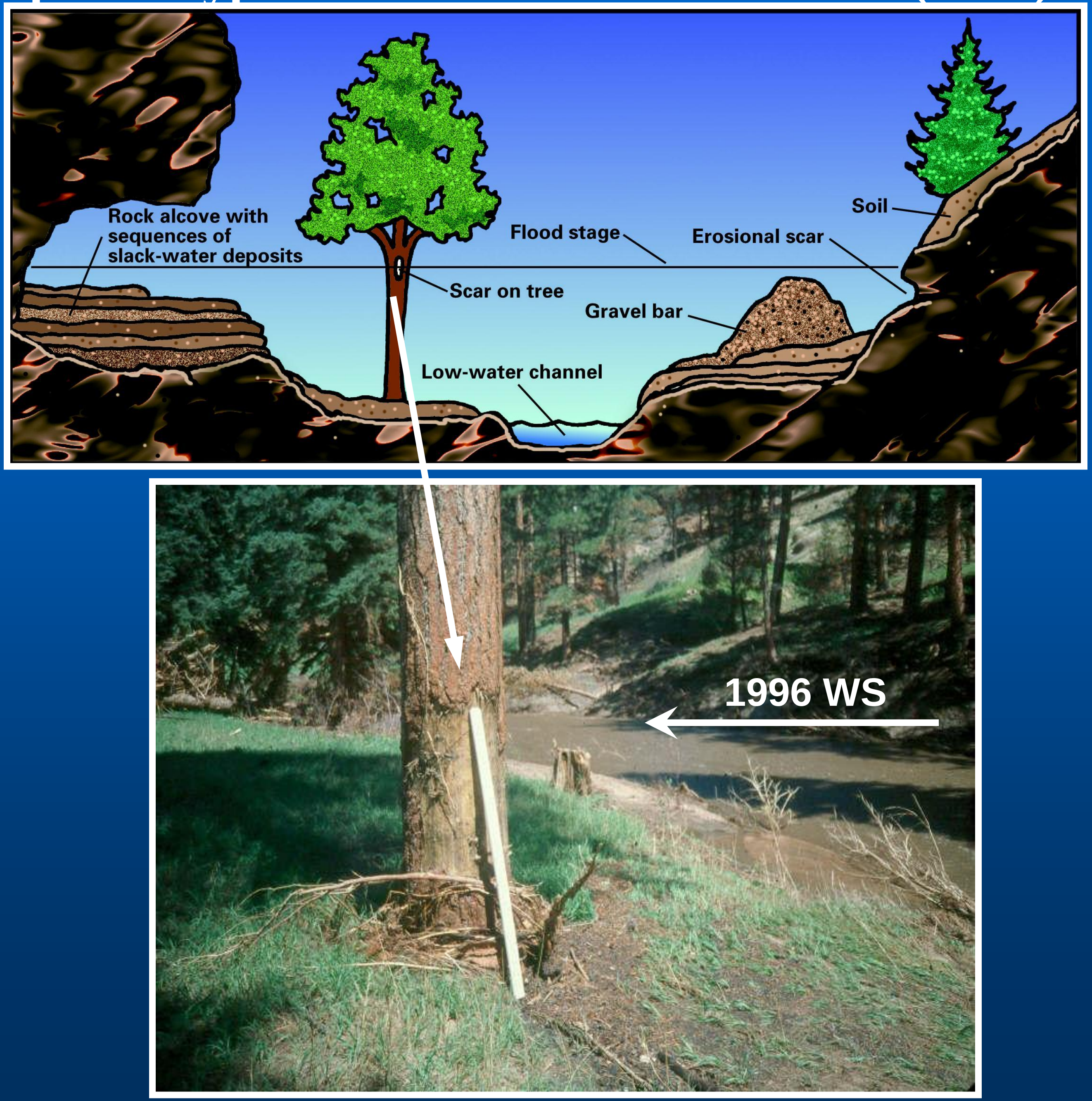




Average recurrence interval ~75 years for all sites

Conclusion: The study of over 200 flooded rivers demonstrated that the maximum height of fresh deposits of flood sediments approximately equal maximum flood height or high-water marks. Thus, paleostage indicators (sediment deposits) of past floods can be used to estimate the approximate flood height of paleofloods and their associated discharge.

Topic 2--Types and locations of tree scars (PSIs)



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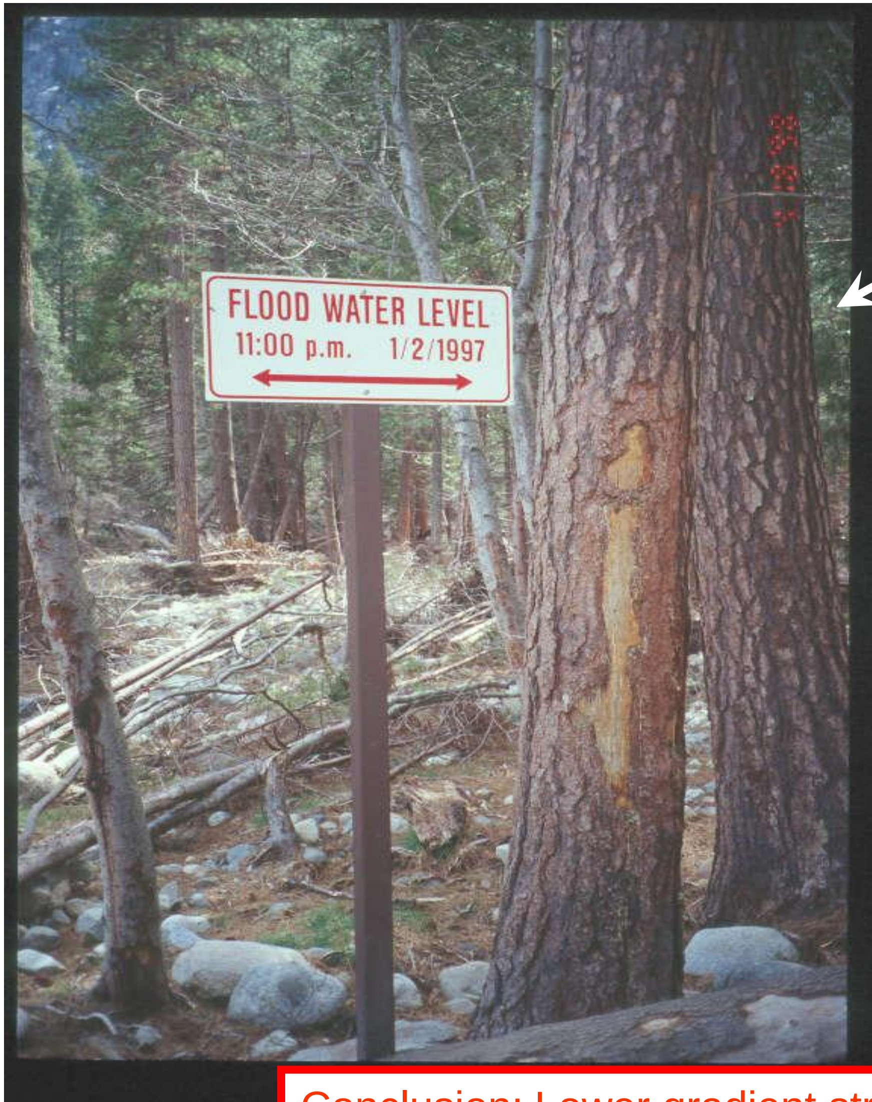
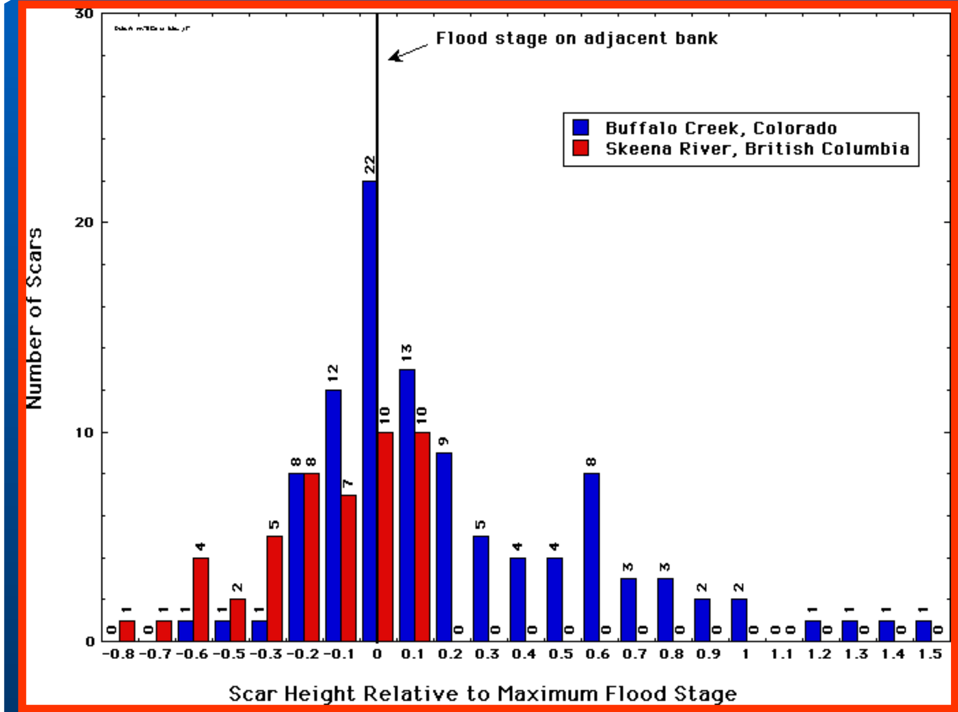
What is the relation of flood scars and flood height?



Merced River, Yosemite National Park, CA



Yanosky and Jarrett, 2002

Conclusion: Lower gradient streams produce flood scars (red) at or somewhat below the maximum water surface; in higher gradient streams, flood scars (blue) are produced at or higher than the maximum water surface.

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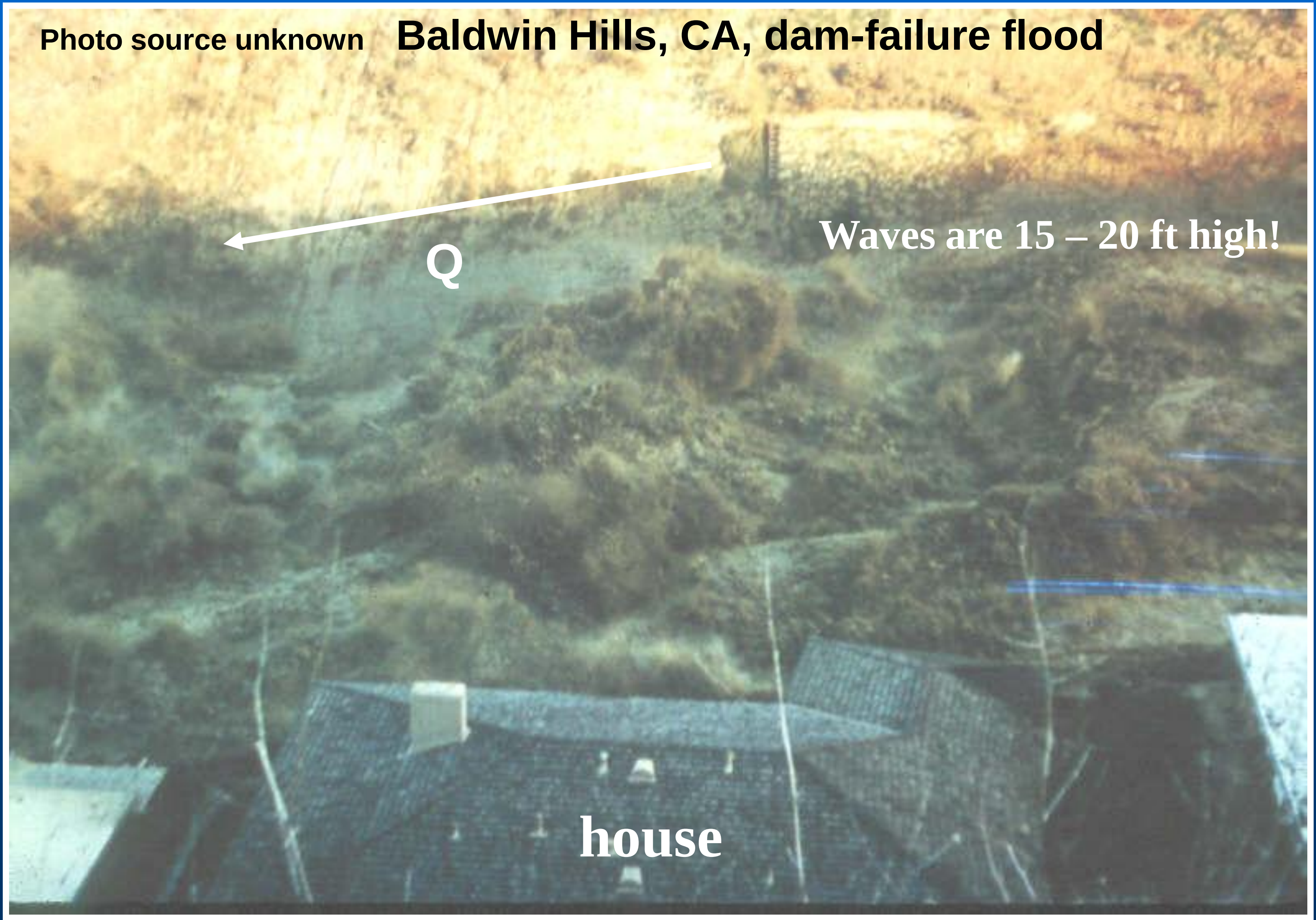
How reliable are methods for estimating extreme flood discharge?



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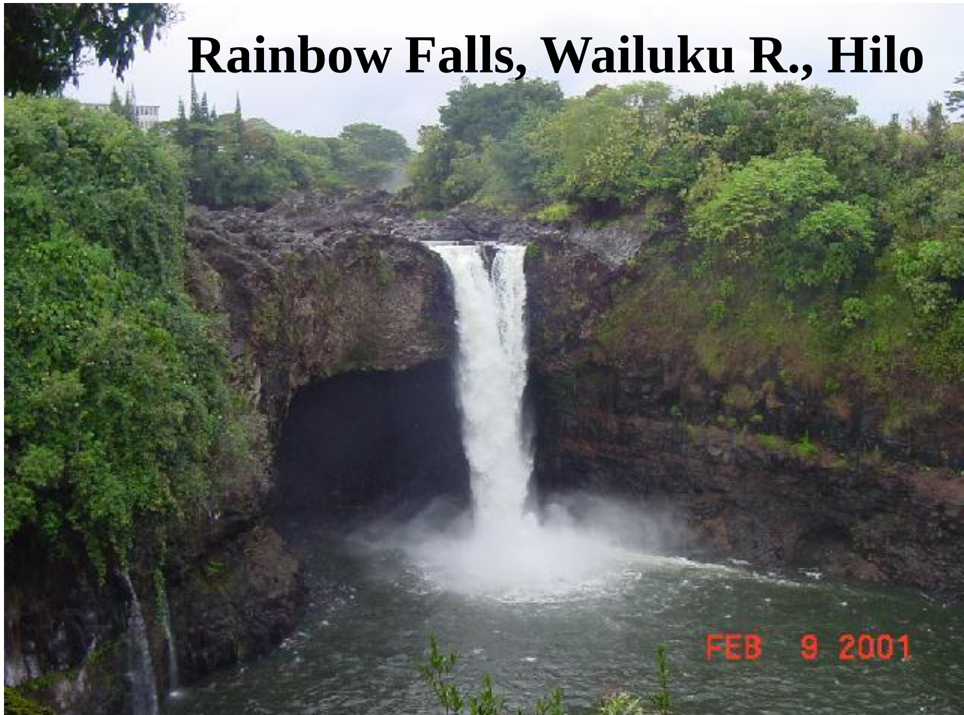
Topic 3 --Critical-depth method for reliable discharges

Critical-depth sites

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

Surveying

- CD-cross section
- Approach cross section
  (~4x "CD" distance upstream)



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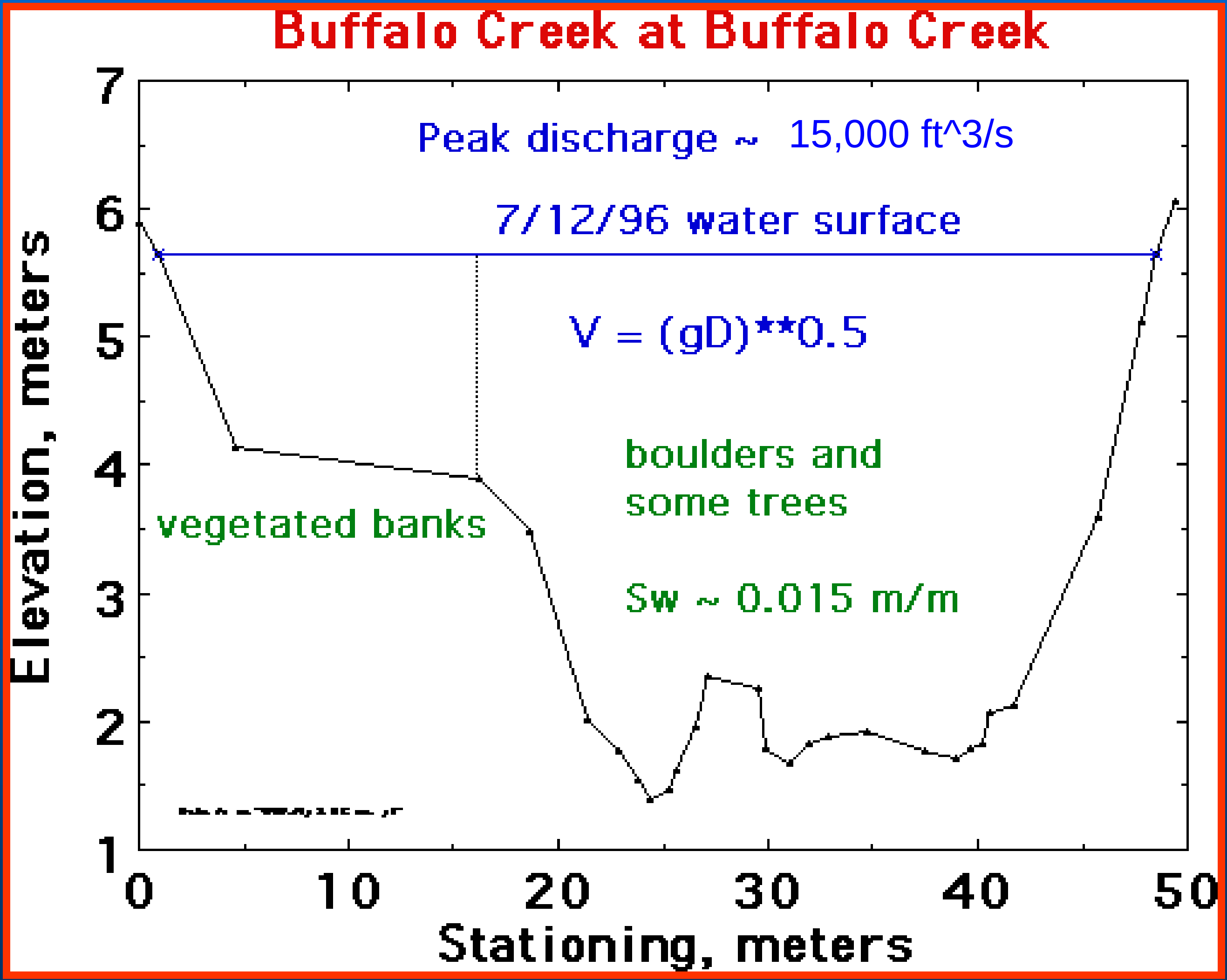
Arkansas River near Buena Vista, CO

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

Critical-Depth Method



- Validate at Qgage sites

* Assume F~1

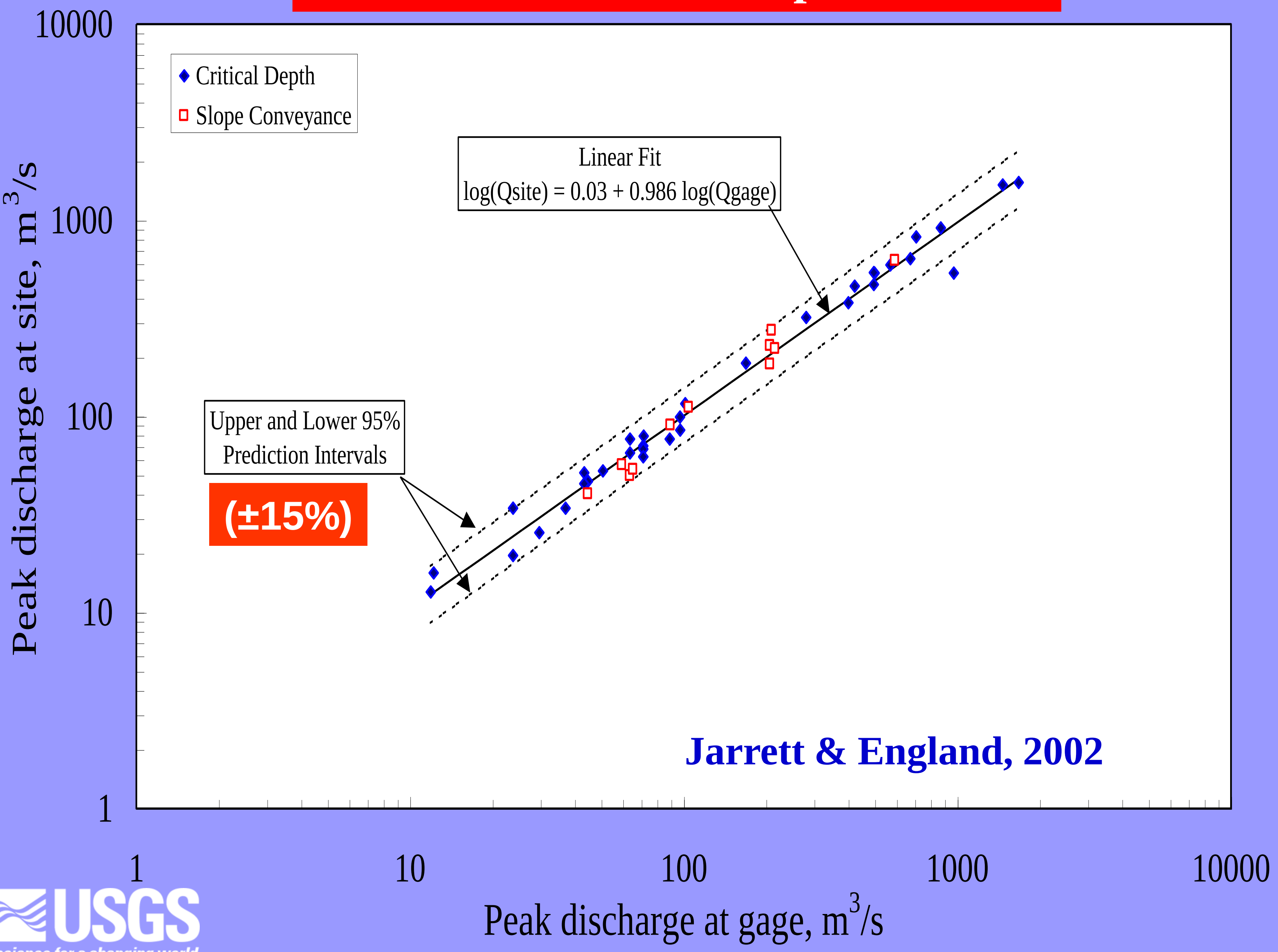
* Independent of n-value

* Natural rivers slopes > ~1% to 7%

- Jarrett & England, 2002

* Grant, 1997

Validation of critical-depth method



Research topic 4 - Estimating the Age of Paleofloods

Description of Relative Dating Methods for Paleoflood Deposits.

Type of Relative Dating Method1	0	2	4	6	8	10
Soil horizons	C (no O/A)		O/A/C			O/A/Btj/C
Rock weathering	fresh		partly weathered			weathered
pitting	<10% rare/incipient		50%			75% common
grain relief	<0.5 mm		0.5-1 mm			2 mm
Boulder burial	0%	25%	50%	75%		>90% buried
Surface morphology						
terrace-scarp slope	Steep angular	slightly muted			well-rounded and muted	
terrace tread flood evidence	fresh longitudinal				extensive transverse rills and gullies	
Lichenometry						
largest thalli	0 mm	50 mm	100 mm			>150 mm
rock coverage	0 %	25 %	50 %			>75 %

1 A rating of 0 is modern or 0 years, 10 is early Holocene or older or 10,000 years.

Jarrett & Tomlinson (2000)

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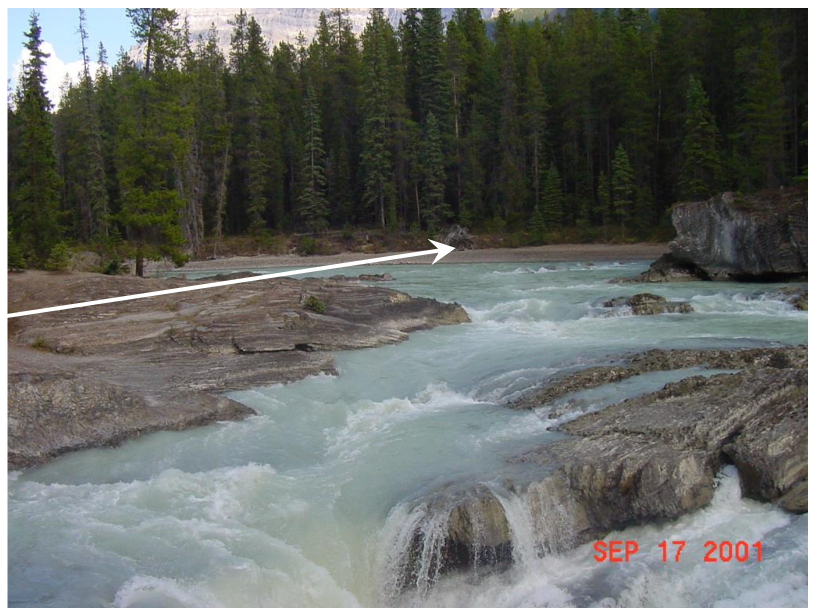
Benefits of Paleoflood Hydrology

- Can provide flood data for thousands of years
- Complements existing streamflow gage data
- Improves the reliability of flood estimates
- More robust flood-frequency estimates
- Can evaluate effects of climate change on maximum flooding
- Can be used in many water-resources studies

Upper Columbia River, Canada -
"An ideal paleoflood site."
Bedrock channel with ~10,000 years of paleoflood deposits



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Types of Paleoflood studies

1976 Big Thompson Flood damage

- Lack of data available for water-resources investigations

- Flood-plain management
- Design in infrastructure in flood plains
- Risk assessments of dam safety
- Wildland fire hydrology
- Determine rainfall amounts and thresholds of flash flooding for National Weather Service
- River "restoration"
- Debris-flow hazard assessment

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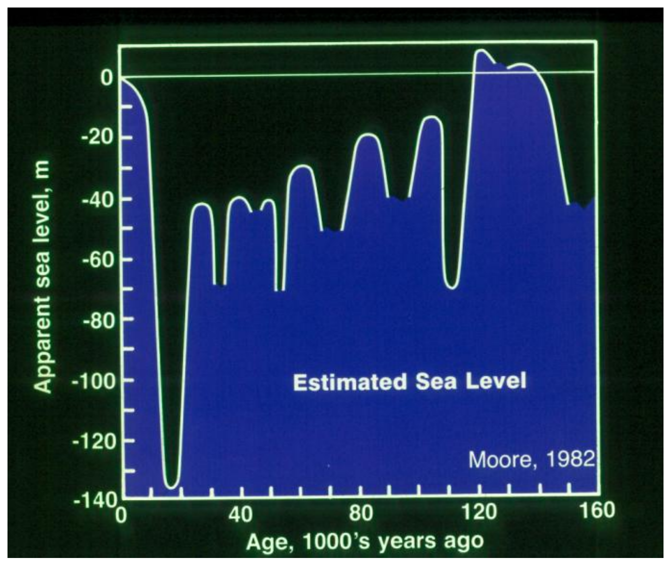
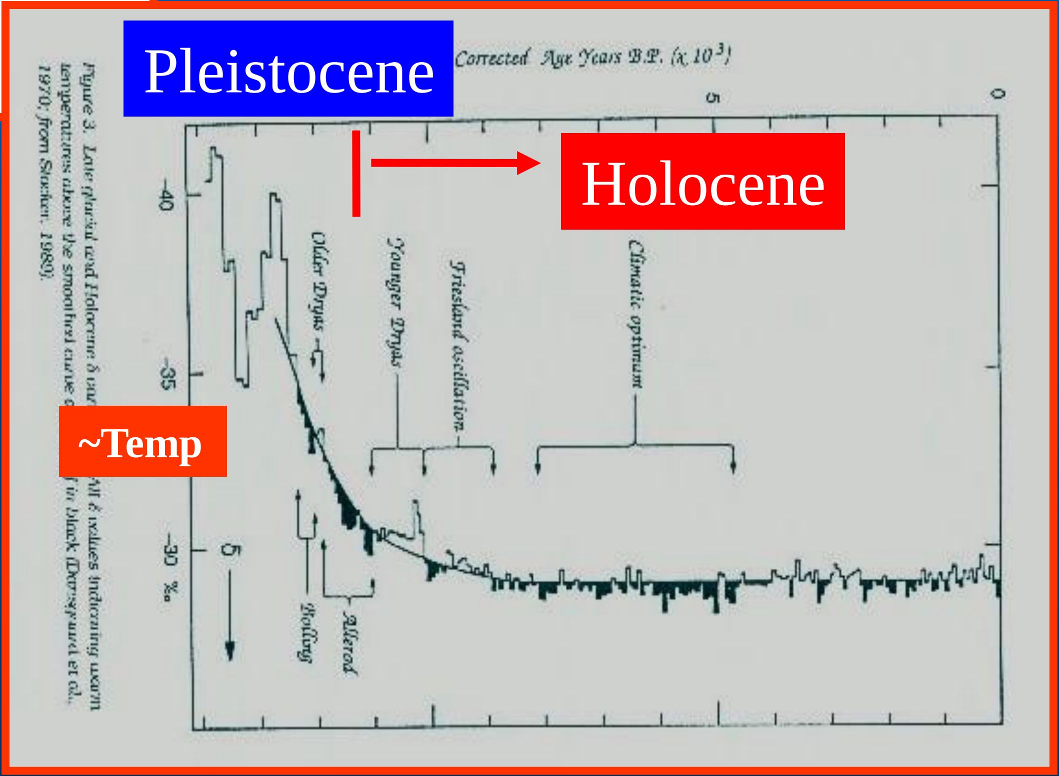
Paleoflood Research to Improve Flood Science

- Introduction
- Overview of paleoflood hydrology
- Recent paleoflood research topics
- Examples
  - Dam safety
  - Climate change and maximum flooding
- Concluding remarks





Holocene climate has been relatively constant with moderate HC variability

Issues & Examples

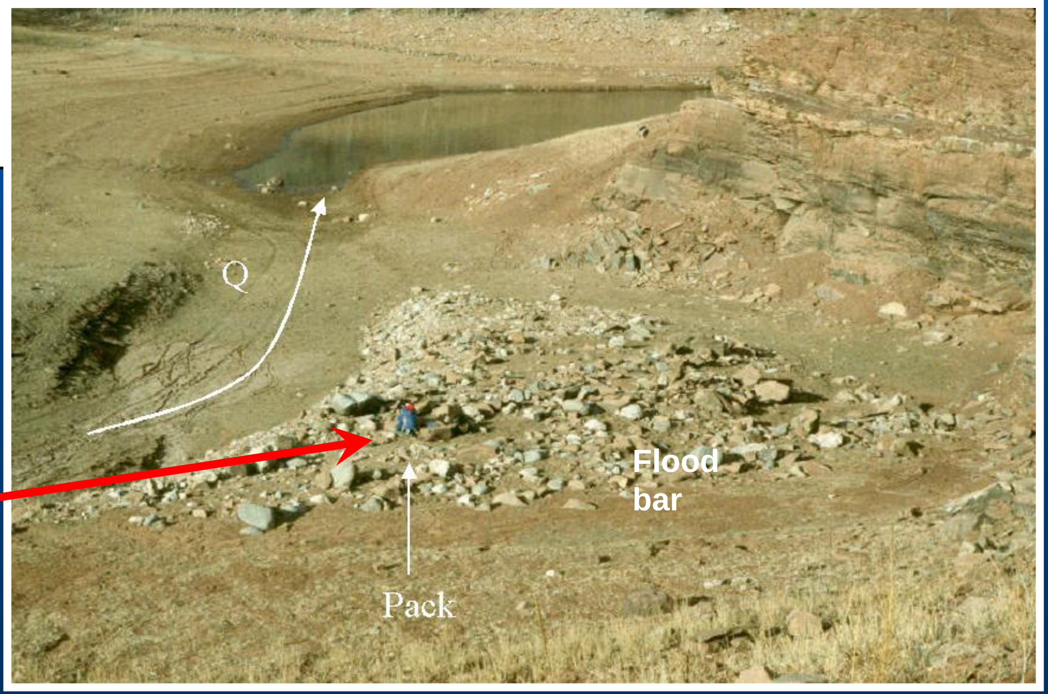
Where do you look for evidence of change?

What defines a representative study site and regional area?

How reliable are flood data?

What is the "detection criteria for climate variability?"

Arthurs Rock Gulch at Horsetooth Reservoir Fort Collins, CO



Largest paleoflood ~5,000 yrs old

Waythomas and Jarrett, 1994

East Cascades, Washington

Northwestern Montana

Northwestern Colorado

Central Idaho

Eastern Colorado

Arizona (Enzel et al.)

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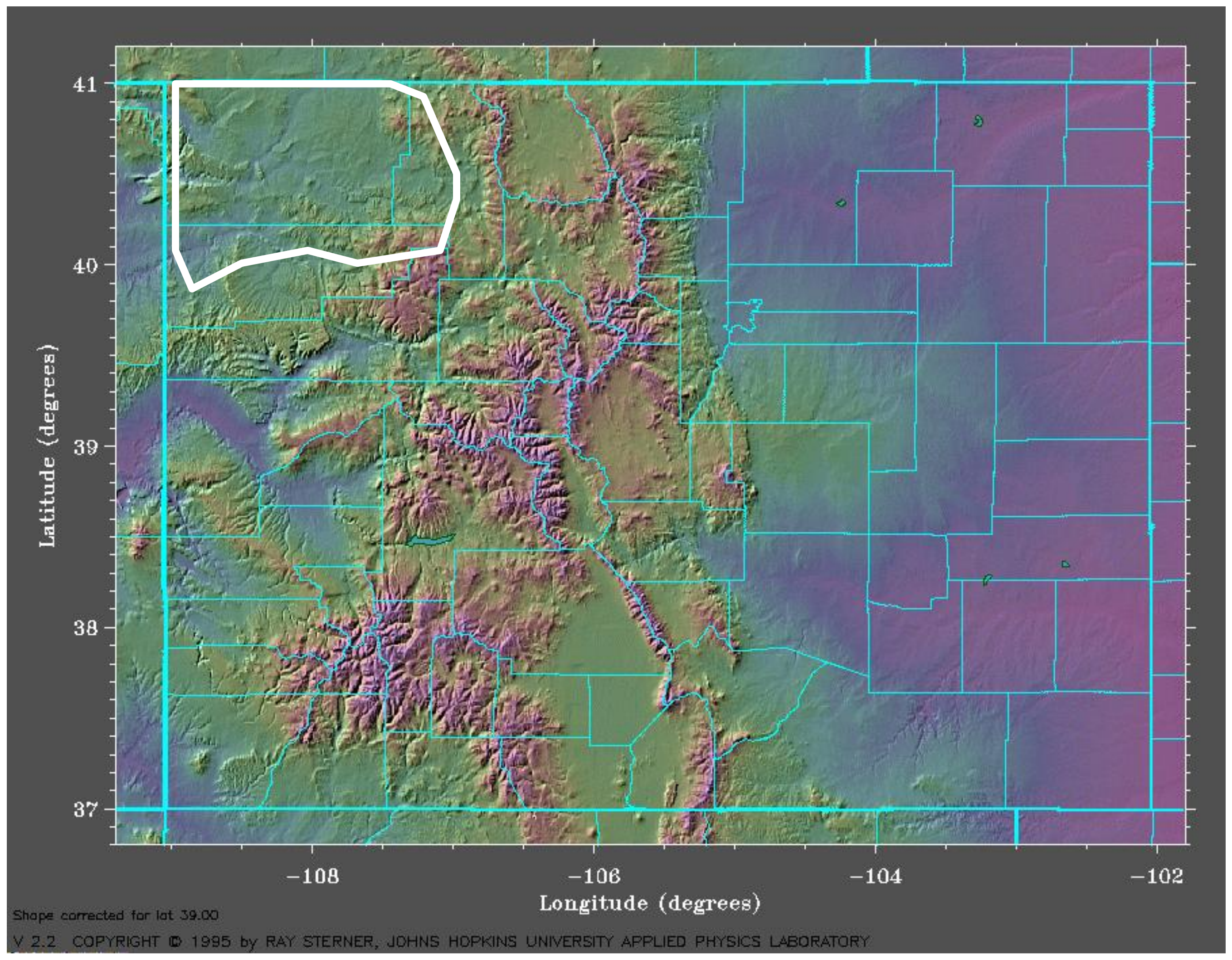
Regional Paleoflood Studies for Dam Safety Assessments

Northwestern Colorado



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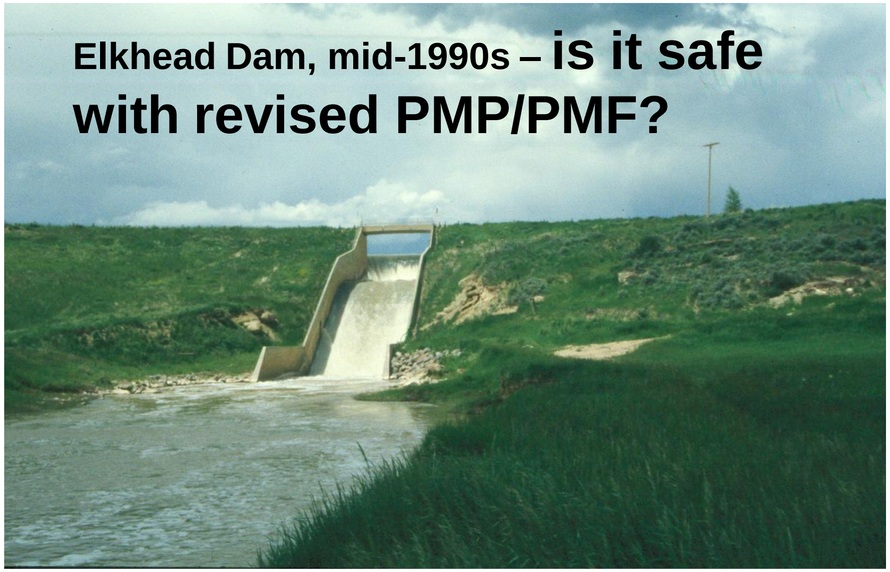
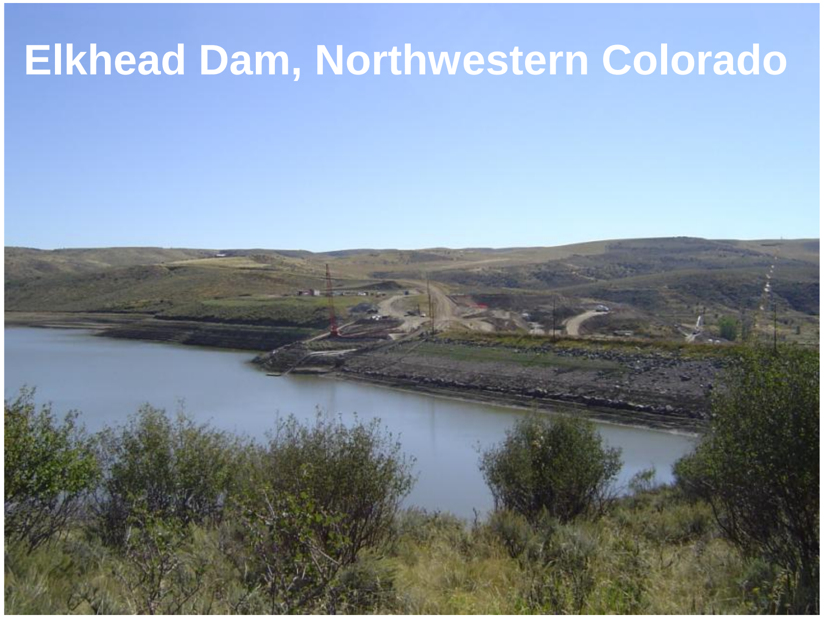
Snowmelt runoff and small thunderstorms

Hydrologic Aspects of Dam Safety in the Rocky Mountains

- New PMP/PMF estimates 1980s
- Need to estimate small probabilities (AEPs from 10^{-2} to 10^{-4})
- Poor understanding of flooding
- Lack of hydrometeorologic data for extreme floods for dam safety



Elkhead Dam, mid-1990s – **is it safe with revised PMP/PMF?**



Elkhead Dam, Northwestern Colorado

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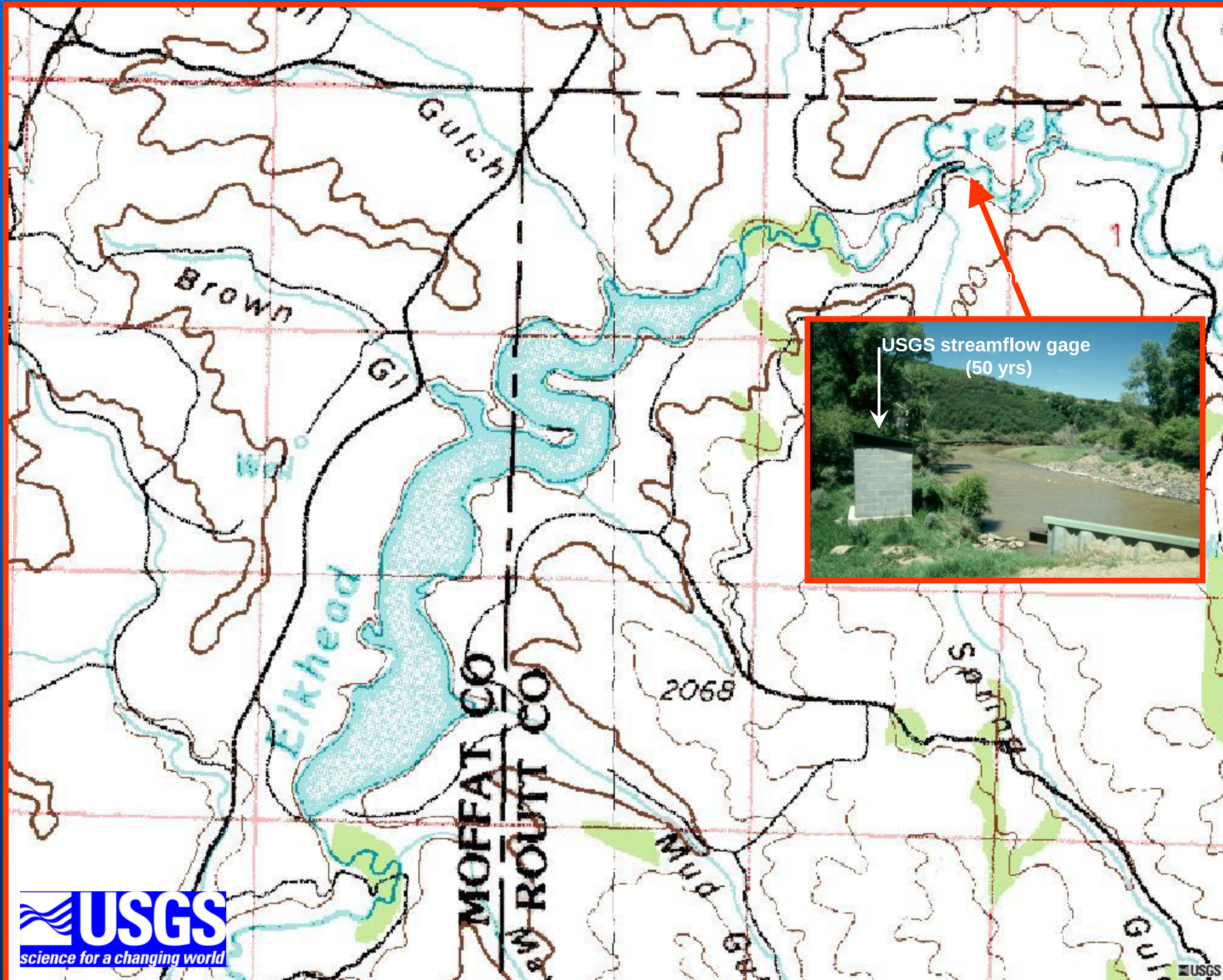

Gulch
Brown
Gl
Creek
Elkhead
MOFFAT CO
ROUTT CO
2068
Mud
USGS streamflow gage
(50 yrs)
USGS
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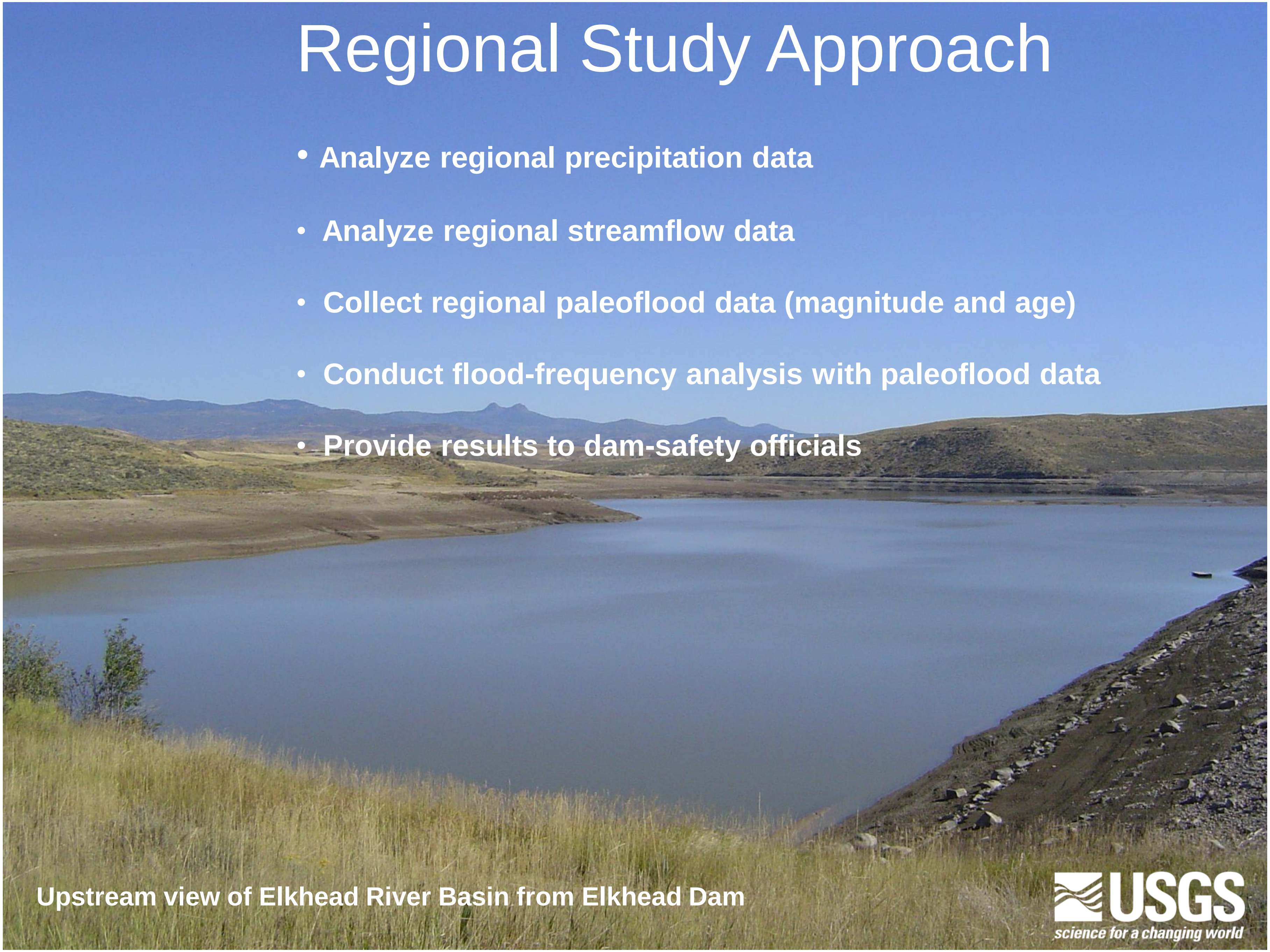
Regional Study Approach

- Analyze regional precipitation data
- Analyze regional streamflow data
- Collect regional paleoflood data (magnitude and age)
- Conduct flood-frequency analysis with paleoflood data
- Provide results to dam-safety officials



Upstream view of Elkhead River Basin from Elkhead Dam

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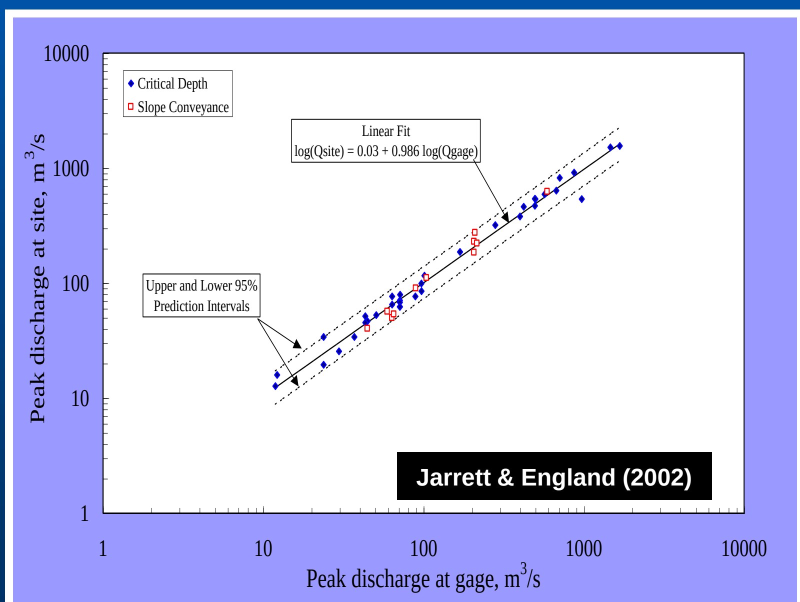
Paleoflood Methods

Flood Discharge

Validation of flood discharge methods

(15 percent)



Age of Paleofloods

- **Absolute dating methods**

  e.g., ^{14}C, trees on flood bars

- **Relative dating methods**

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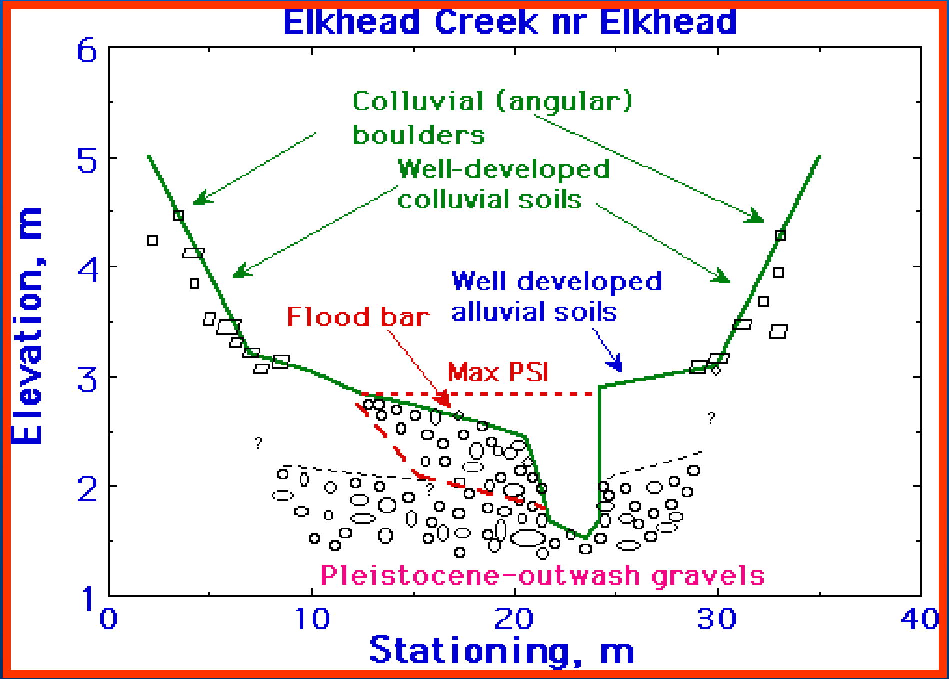
Determine paleoflood discharges at 93 sites in Northwestern Colorado



Elkhead Creek upstream from Elkhead Reservoir

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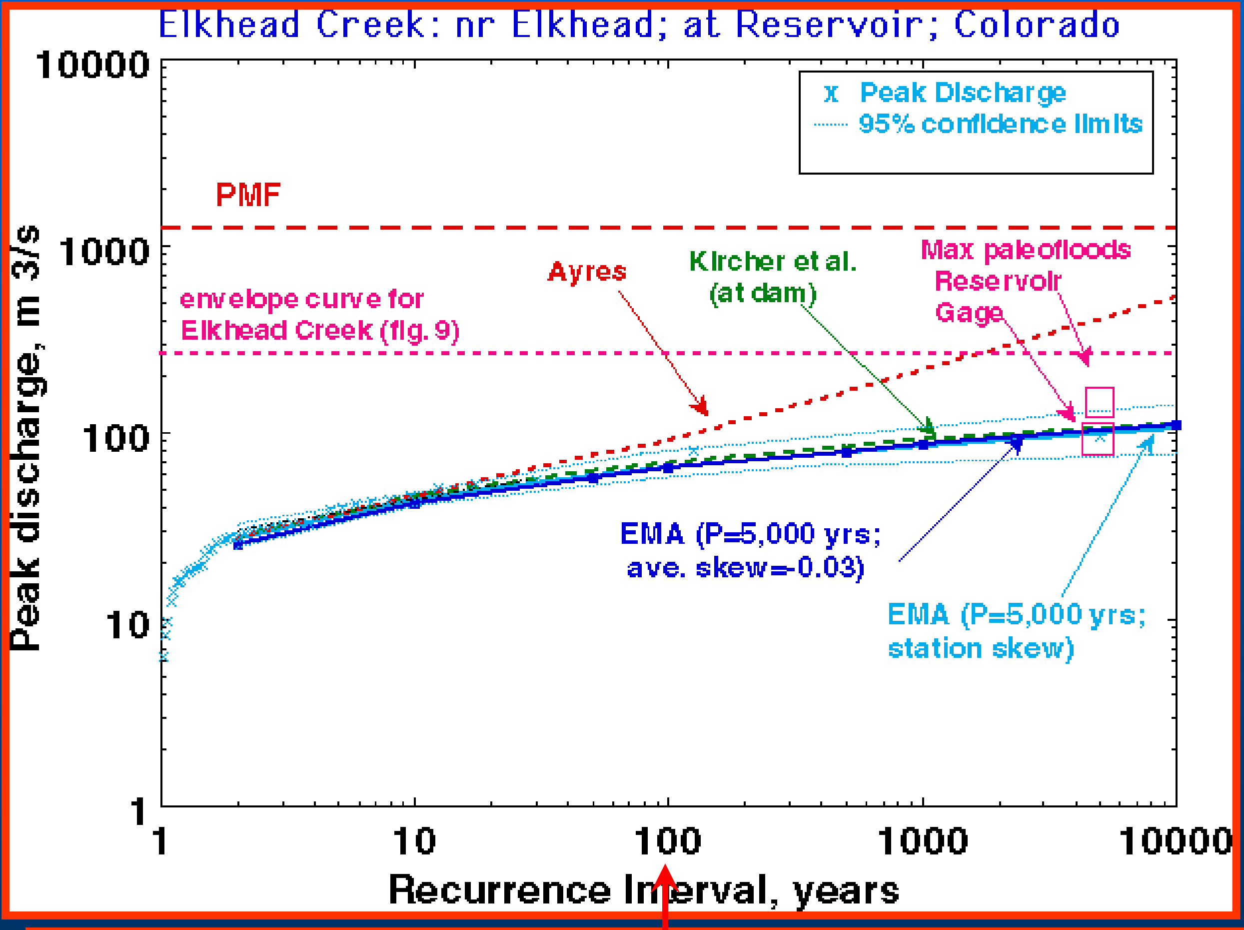
Paleoflood data allows flood-frequency estimates for flood recurrence intervals up to 10,000 years to help with dam safety evaluations and other water-resources issues



Jarrett and Tomlinson, 2000

Importance: standard flood-frequency analysis can only provide estimates up to the 100-year flood or less

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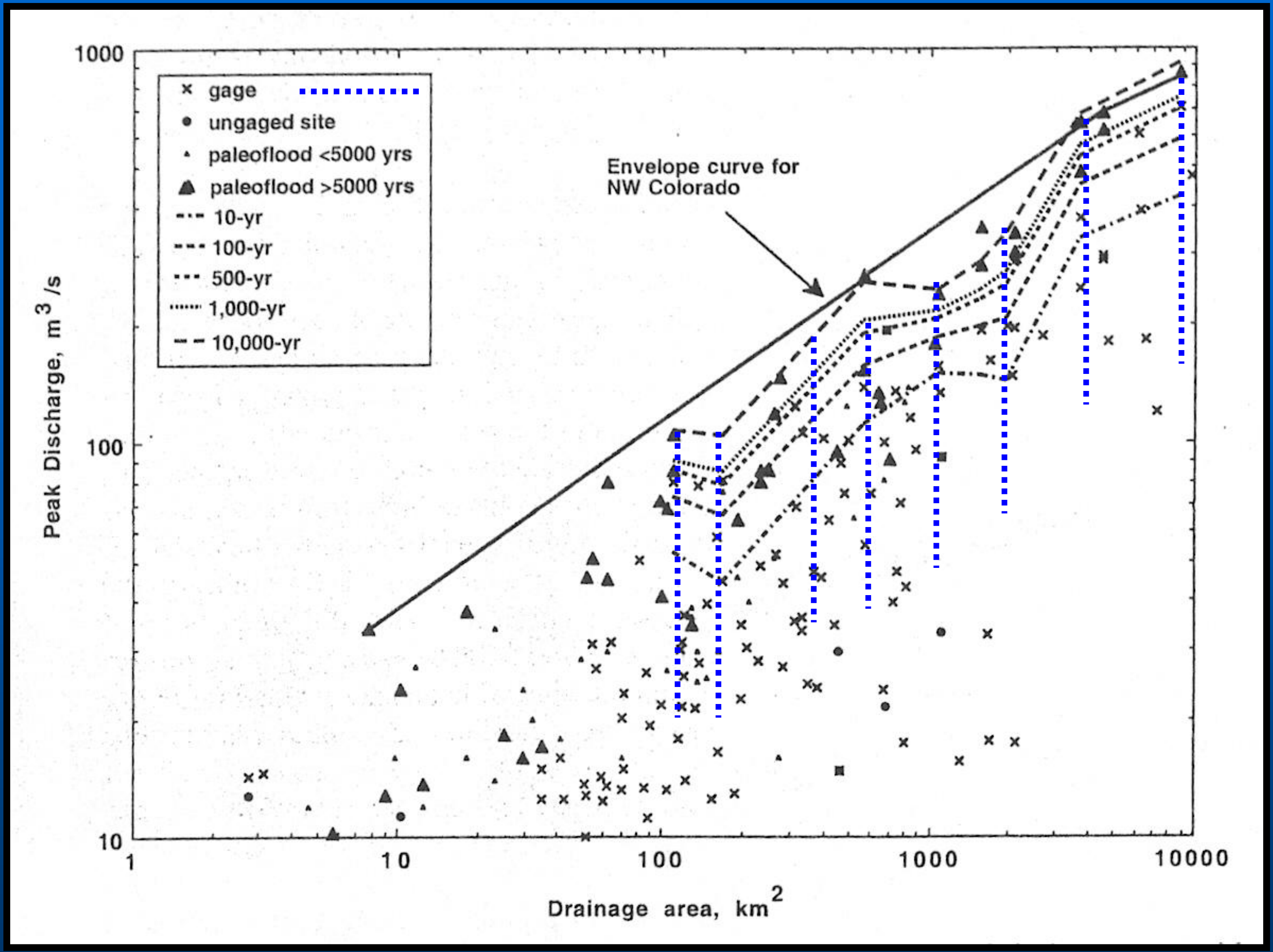

Relation between contemporary and paleofloods and drainage area with eight flood-frequency curves superimposed for NW, CO (Jarrett and Tomlinson, 2000).

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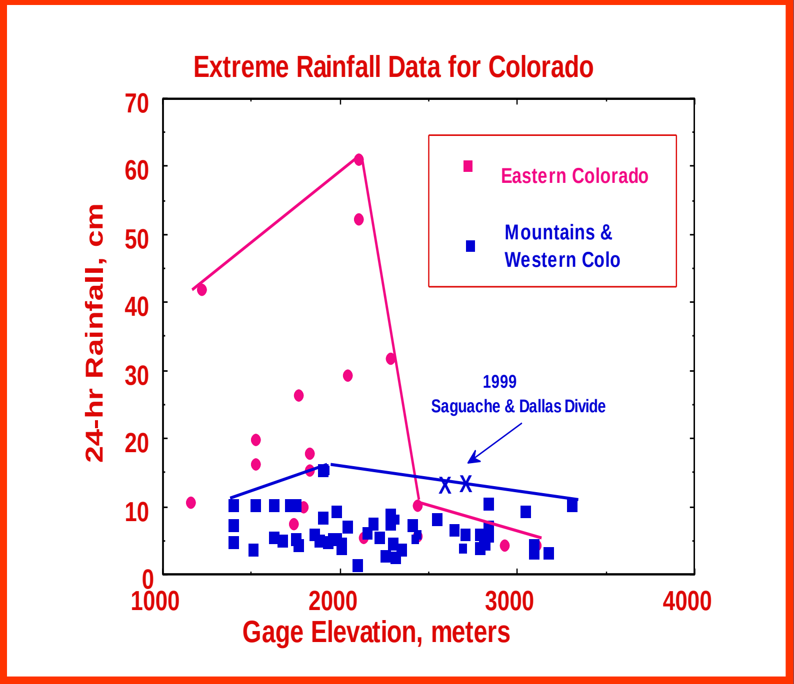

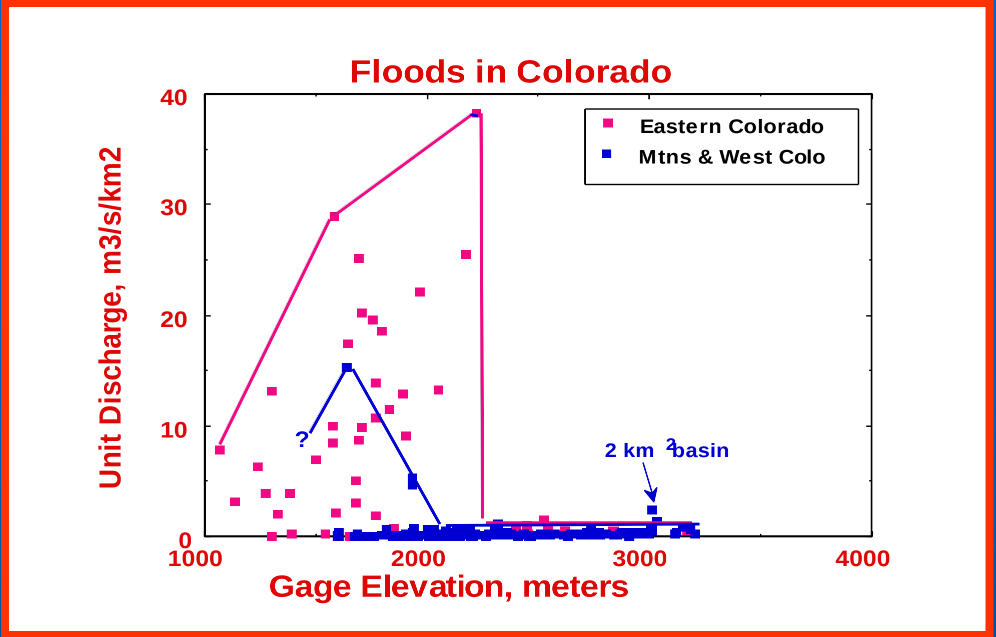

Regional Analyses of Storms and Floods

- smaller rain and floods >7,500 ft
- storm footprint in mountains <50 mi^2
- rapid transition to large rain floods <7,500 ft

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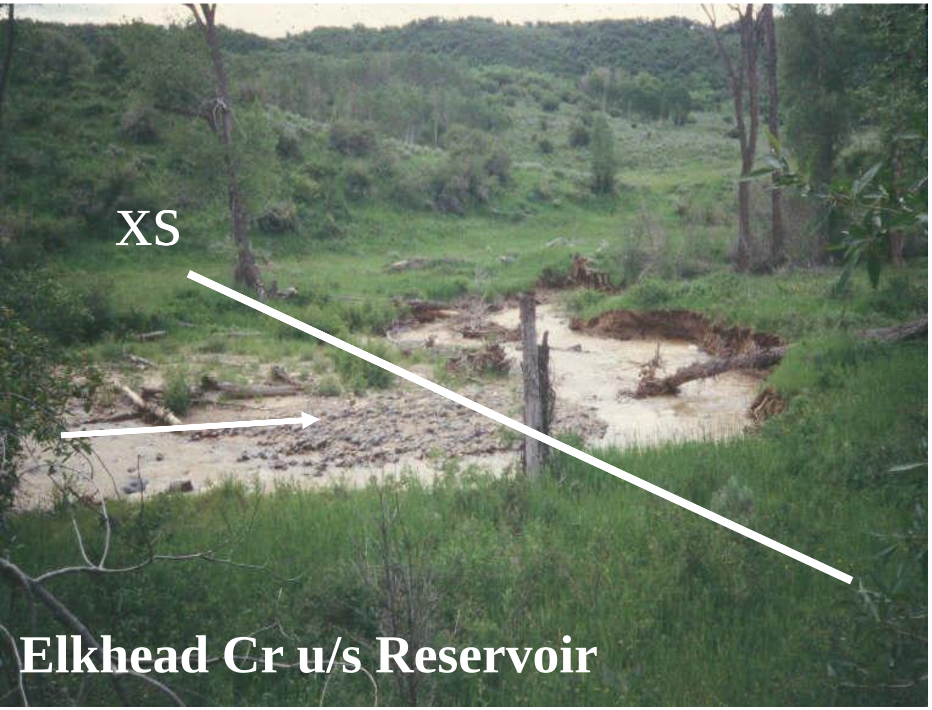
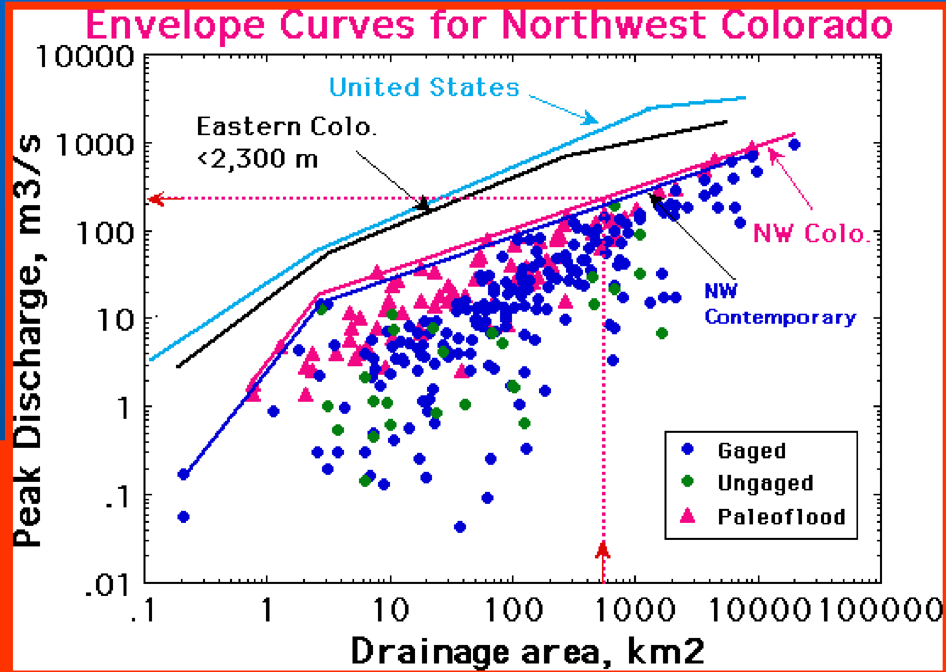
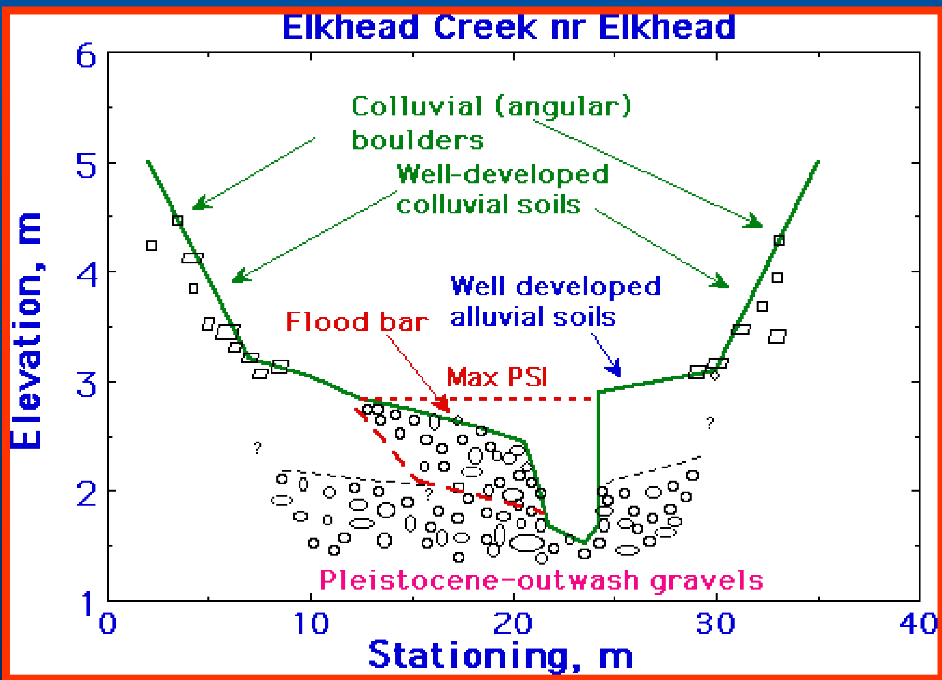
Snowmelt and small convective storms

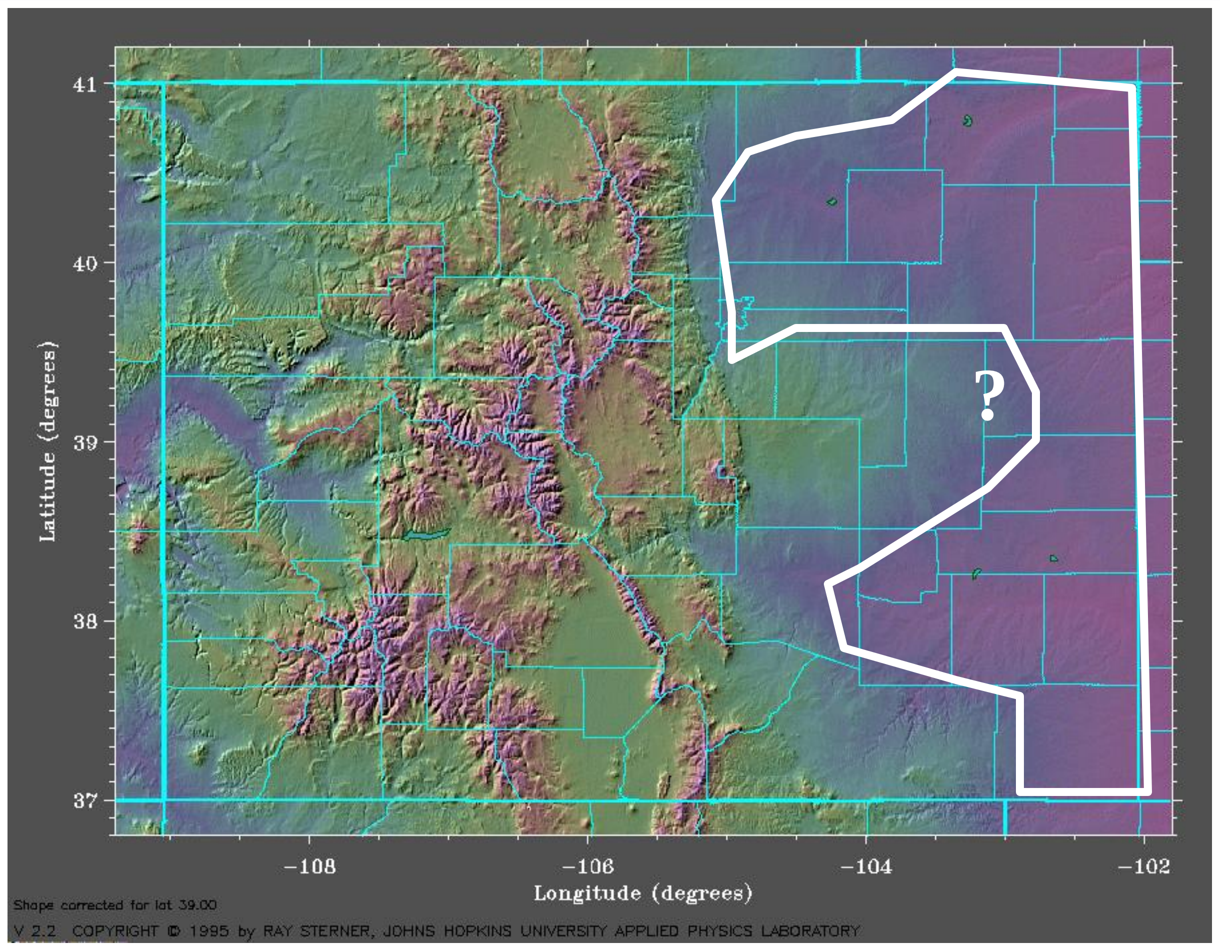






*** Paleofloods (5-10k years) are ~25% larger than contemporary floods**

Low topographic relief areas of Eastern Colorado
Flood Safety of Cherry Creek Dam in Denver



Jarrett, 2001

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Paleoflood Hydrology: Cherry Creek Dam

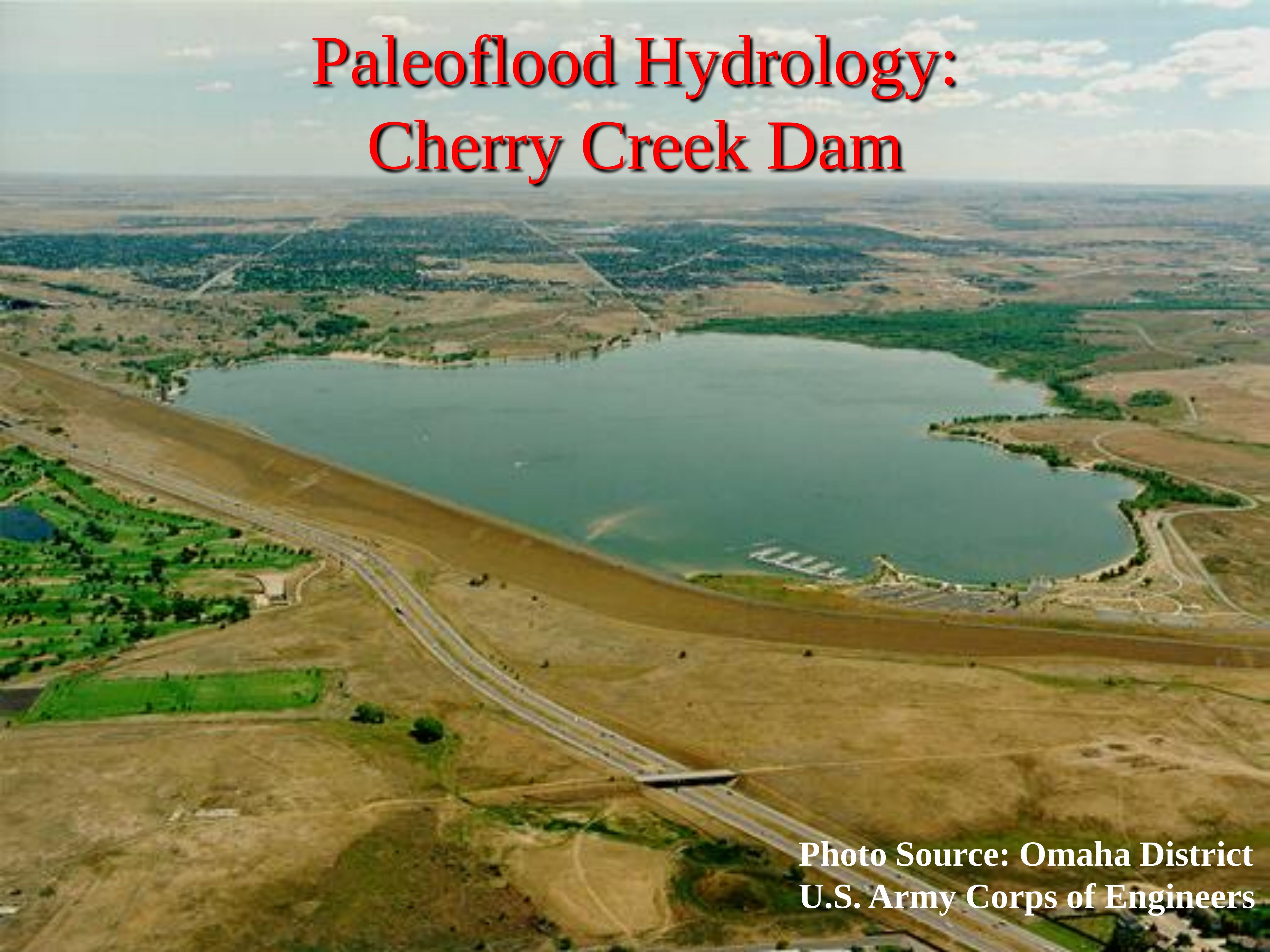
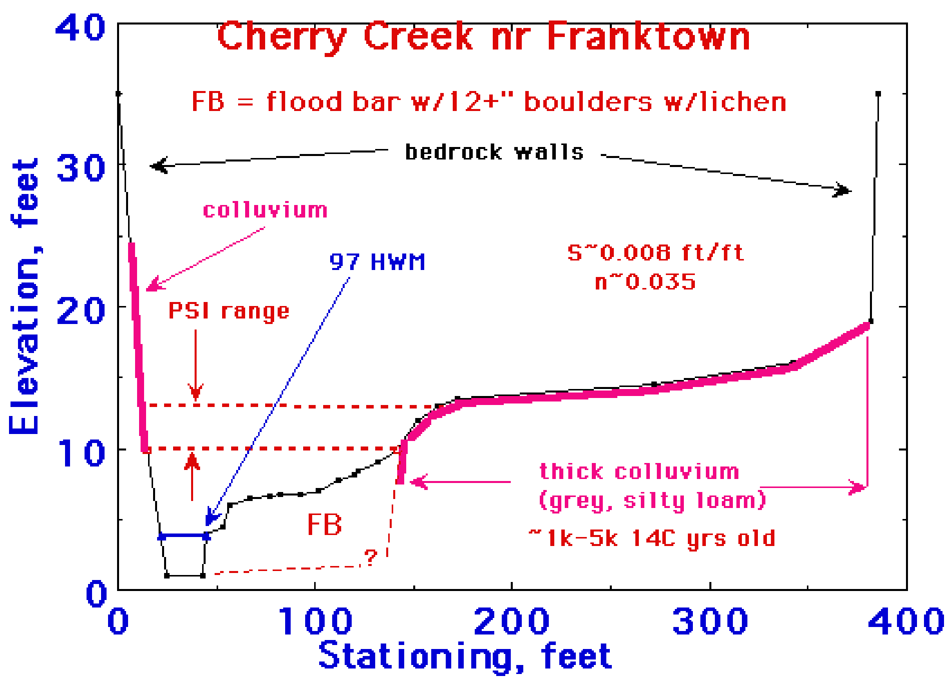
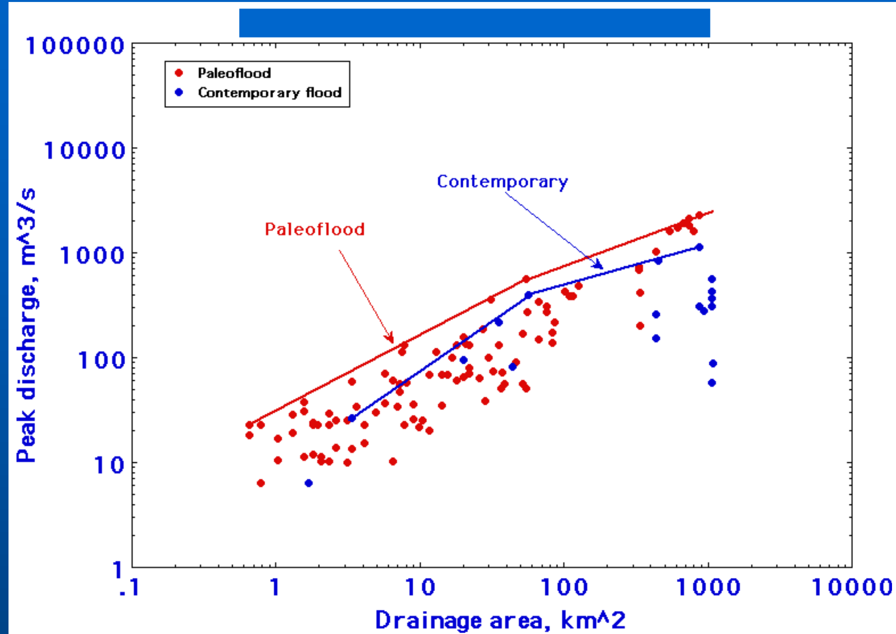


Photo Source: Omaha District U.S. Army Corps of Engineers

Large convective storms





*Paleoflood (~5,000 years) range from 20-40 % larger than contemporary floods

* Overlapping confidence limits

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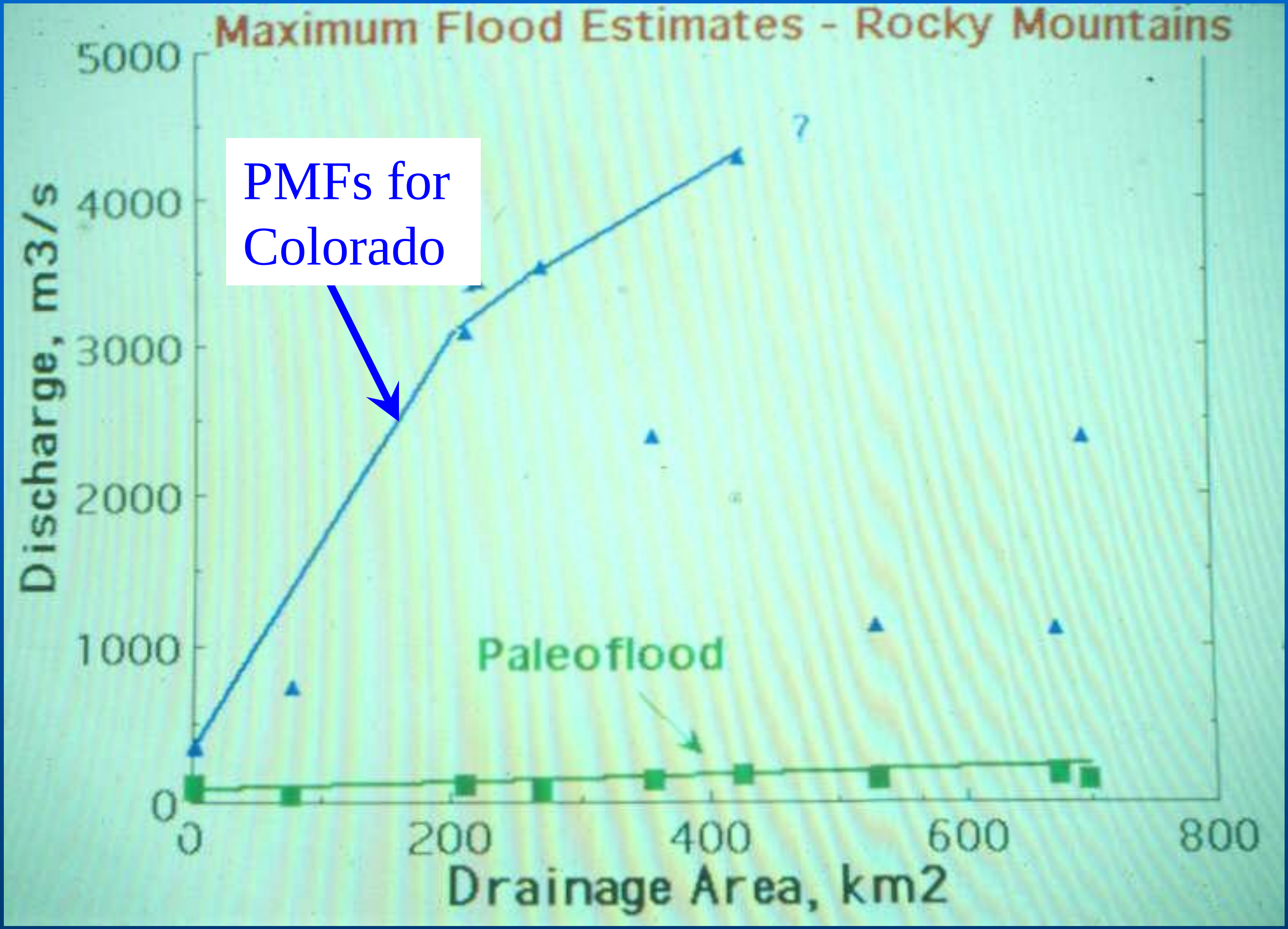
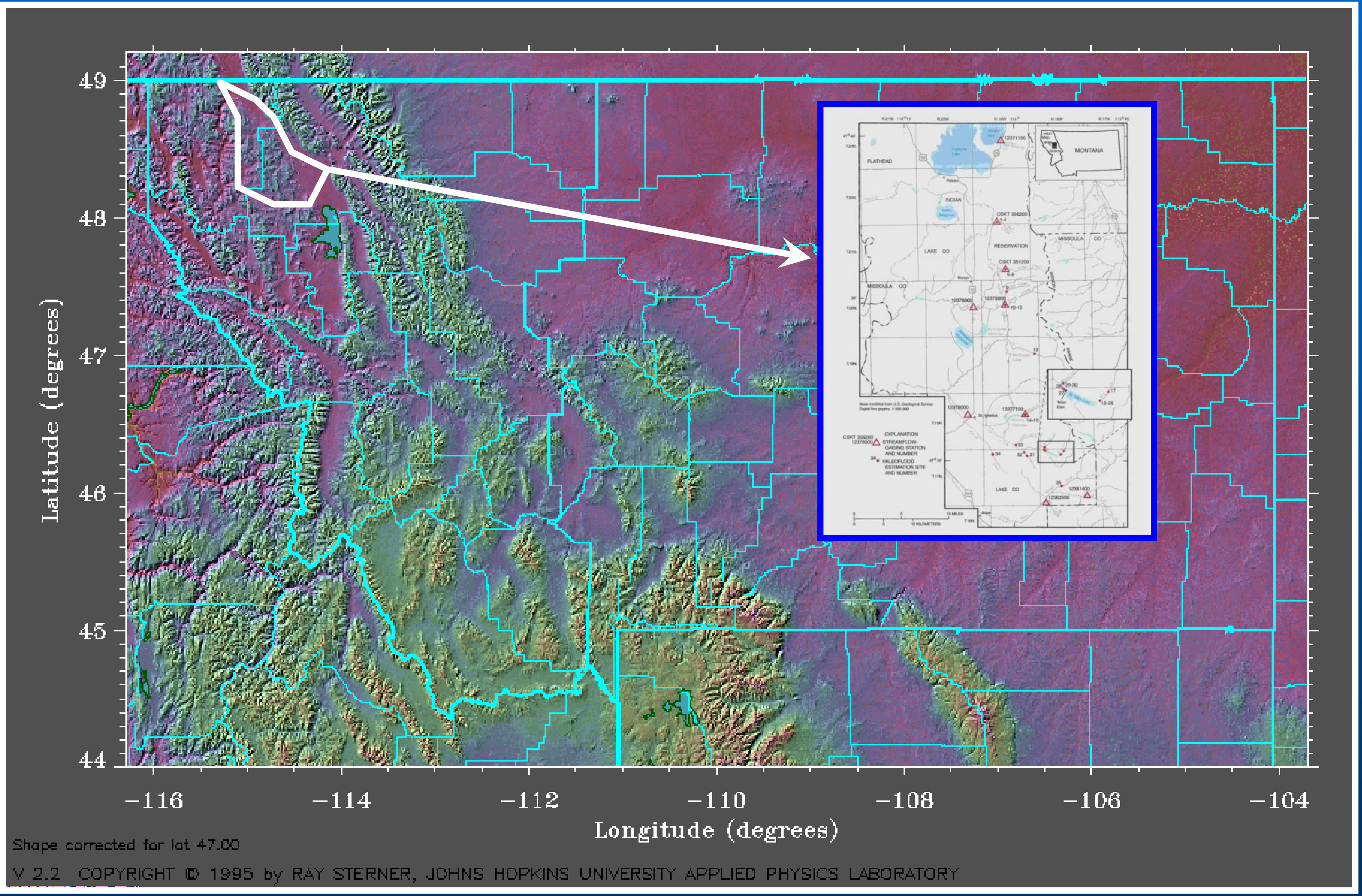


- **Why are the largest paleofloods in last ~10k years so much smaller than PMFs?**

Mission Range, Northwestern Montana



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Mazama ash layer (Crater Lake, Oregon) ~6,850 years ago

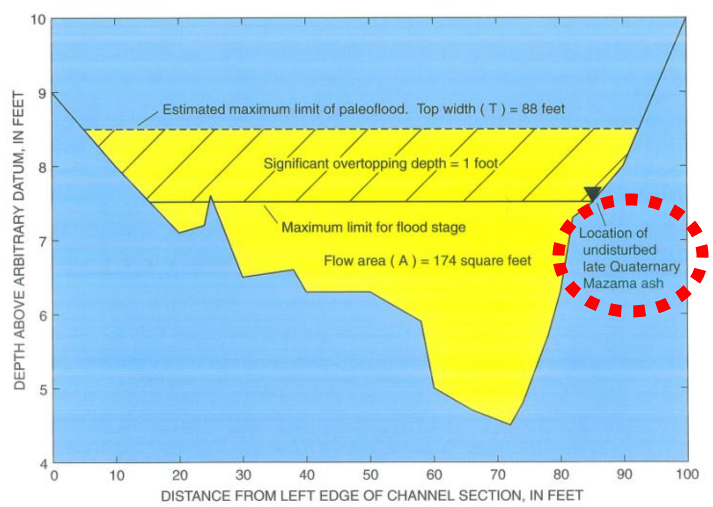

Figure 4. Channel geometry of Dry Creek above St. Mary Lake at paleoflood estimation site 17, Montana.

- Max paleofloods (~7,000 years) ~ 30% larger than contemporary floods
- RF-RO modeling w/ 5,000-yr RF ~ maximum paleoflood

Parrett & Jarrett (2000)

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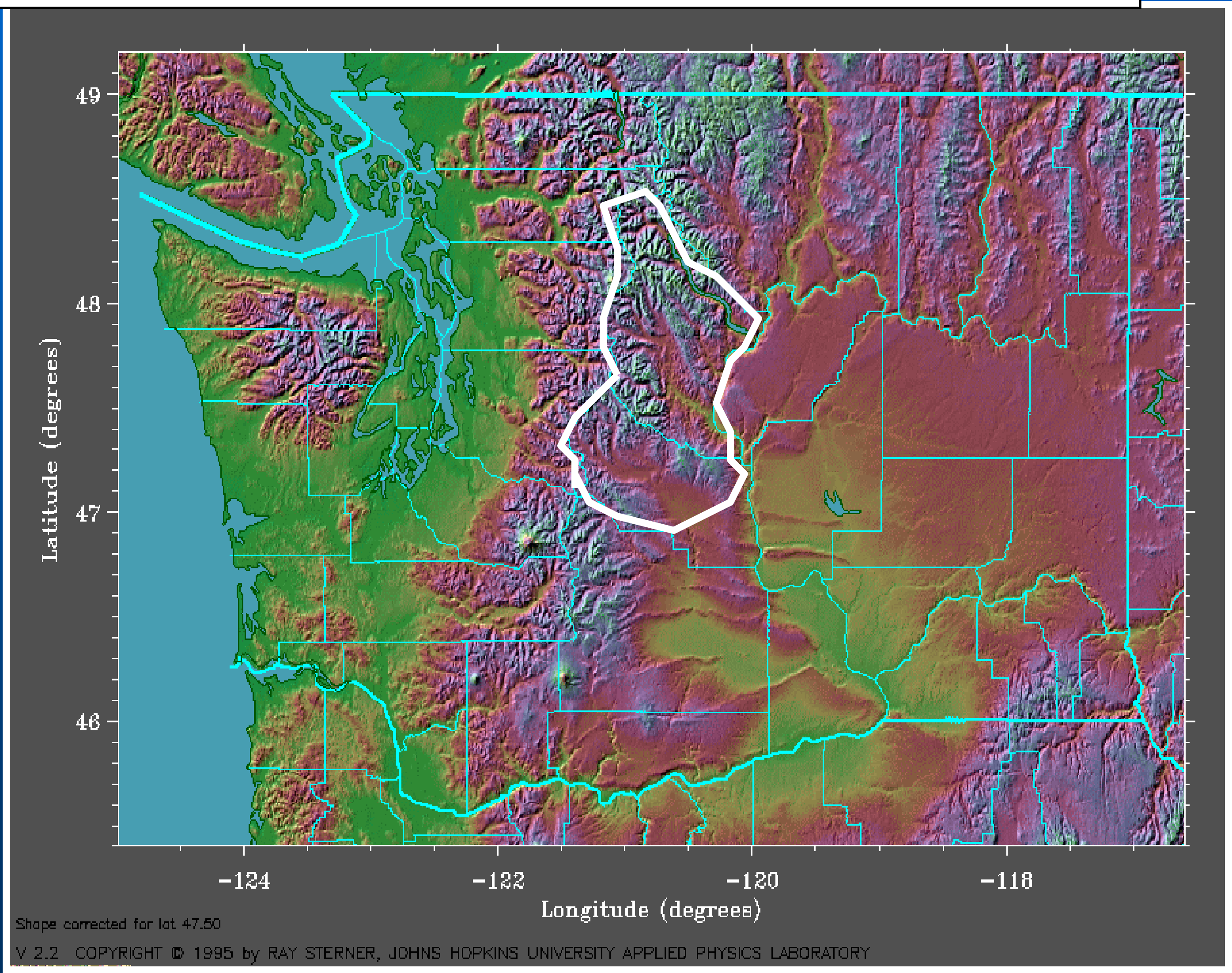
North Cascades, WA



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Stehekin River Basin - Chelan Dam Safety Analysis

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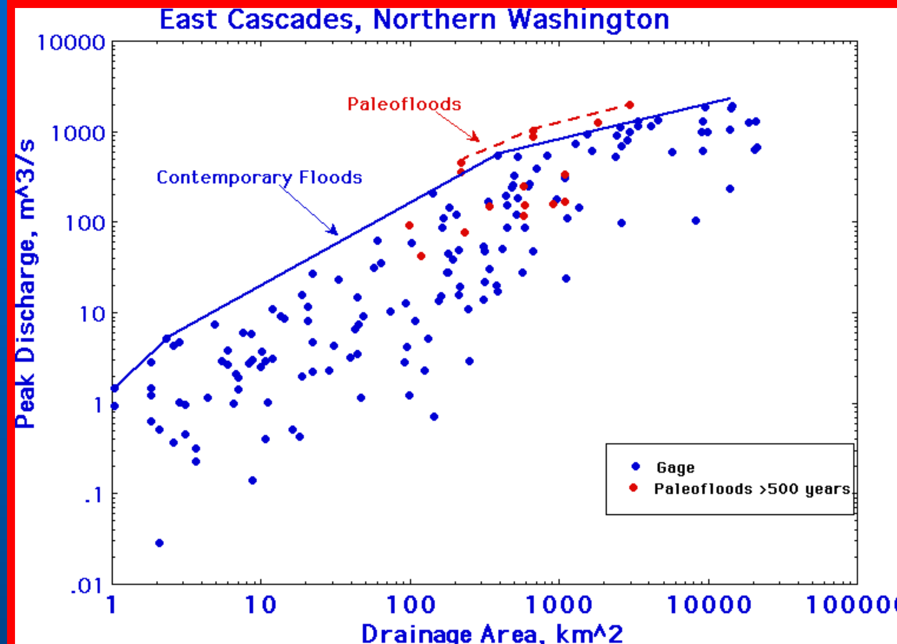
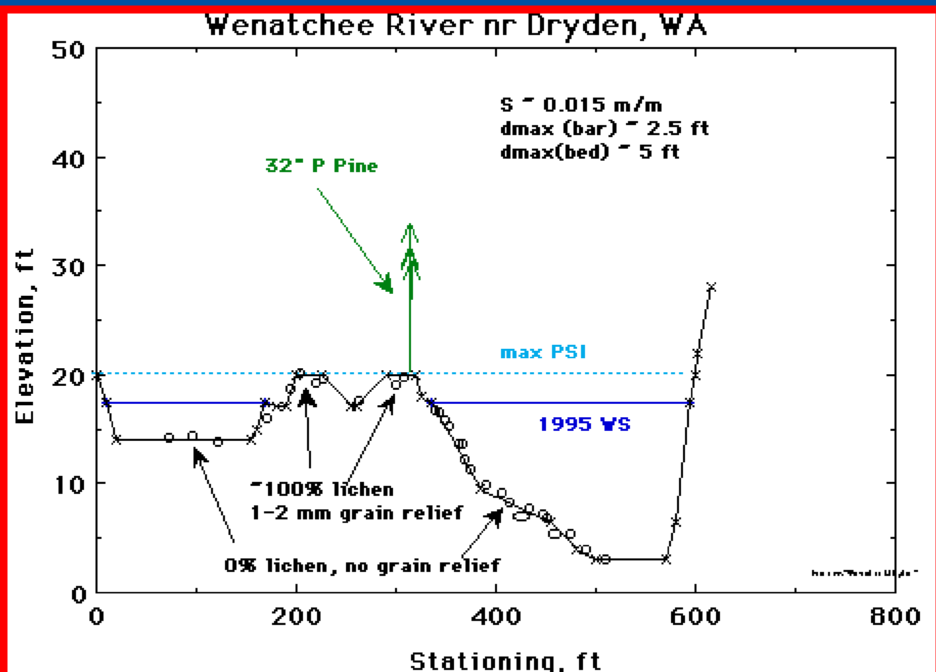
Rain-on-snow floods

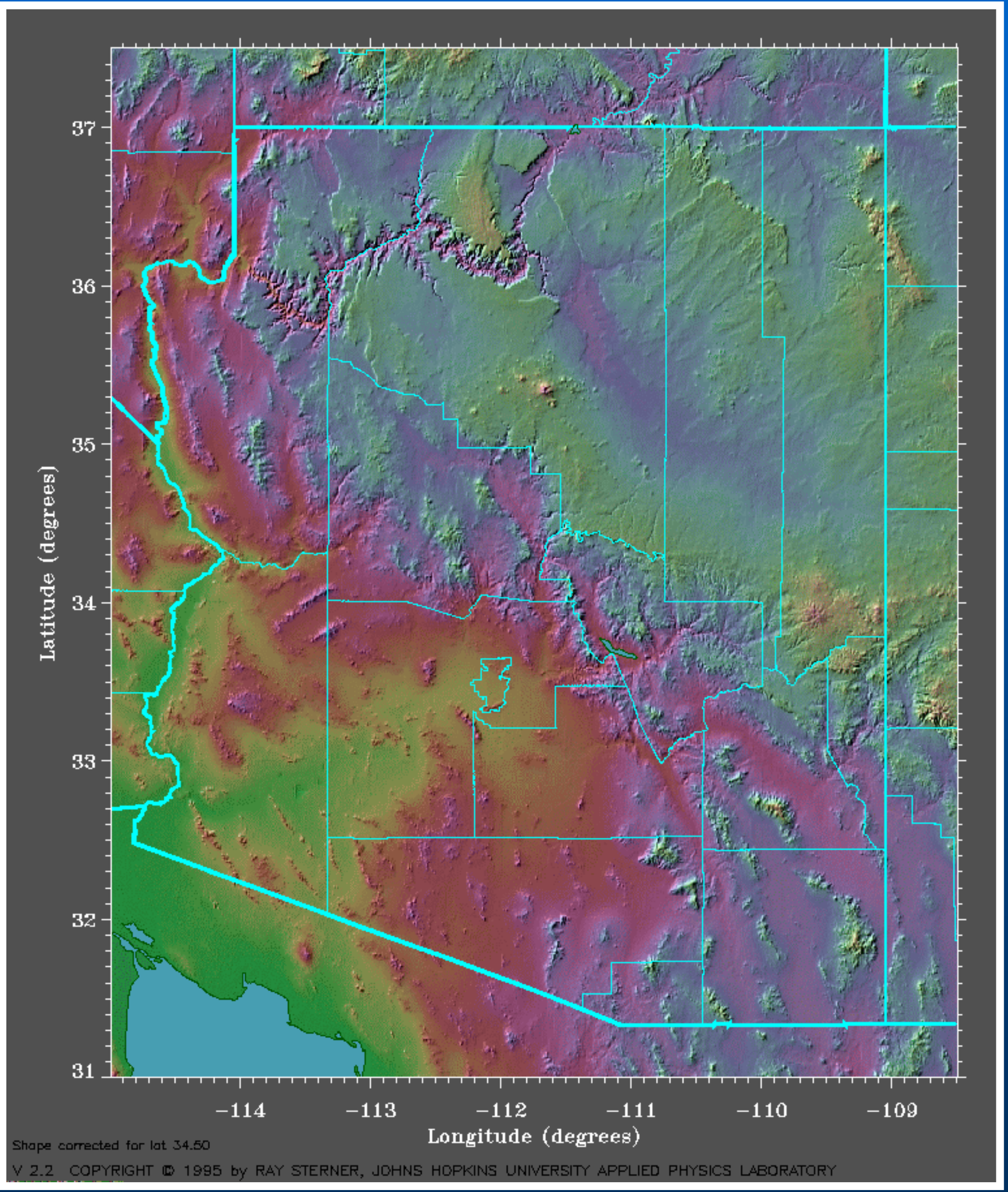
Stehekin R. at Lake Chelan,
North Cascade National Park





- Paleofloods (~5,000 years) are ~35% larger than contemporary floods
- Preliminary results
- Addt'l 75 paleoflood sites

Arizona and S. Utah



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Enzel et al., 1993

Mixed-population: Large convective,tropical, and frontal storms

ENZEL ET AL.: EVIDENCE FOR A NATURAL UPPER BOUND TO FLOOD MAGNITUDES

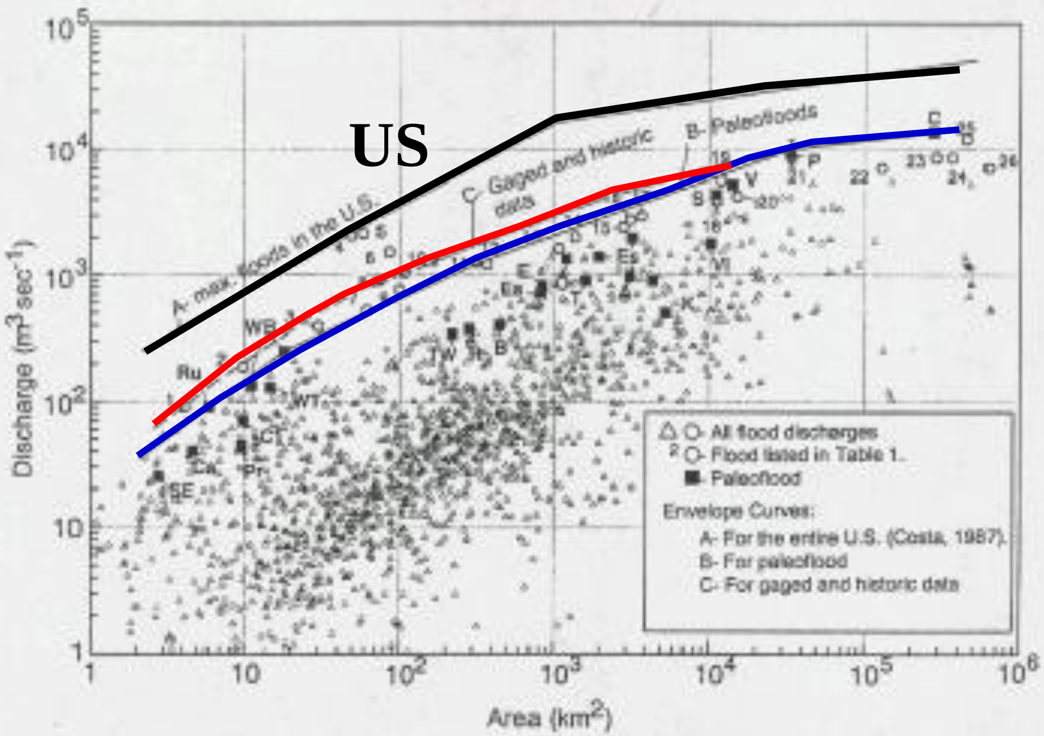

Fig. 2. Largest modern, historical, and paleoflood peak discharge data for each station or site in the Colorado River basin and the envelope curves: the entire United States (curve A) the paleoflood data (curve B), and the Colorado River drainage basin (curve C) from *U.S. Bureau of Reclamation* [1990], which constructed the curve for drainage basins with areas >250 km^2. We extended the curve (dashed line) to encompass basins with smaller drainage areas. Triangles and circles denote all the data available for the largest flood magnitudes at each gaged or ungaged site; circles denote those data points which can affect the envelope curves (Table 1, Figure 1). Solid squares denote the paleoflood data (Table 2, Figure 1).

Enzel et al. (1993)

Paleofloods ~ contemporary floods

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Climate Change & Flooding Summary

- Noise "questionable" peak discharges make it difficult to detect the signal "change" in floods.
- Defining hydrologically homogeneous regions.
- Regional paleoflood approach is one of several approaches that can be used to answer critical water-resources issues.
- Appears to be a variable flood response to past climate change.

Paleoflood Research to Improve Flood Science

Introduction

Overview of paleoflood hydrology

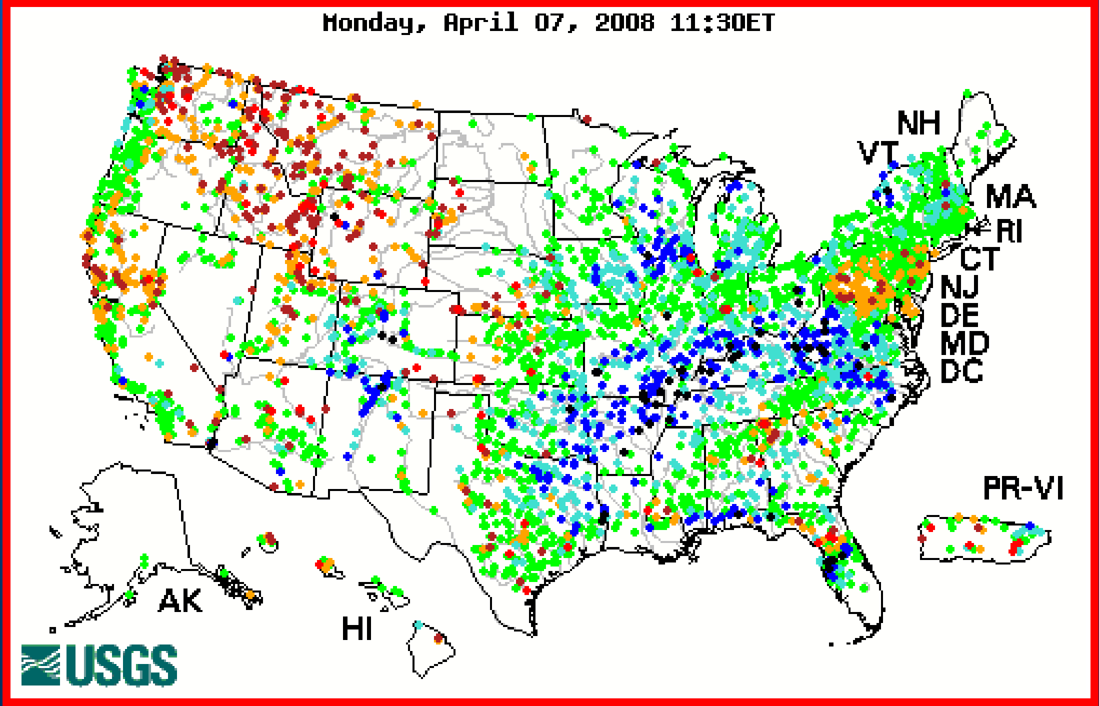
Recent paleoflood research topics

Examples

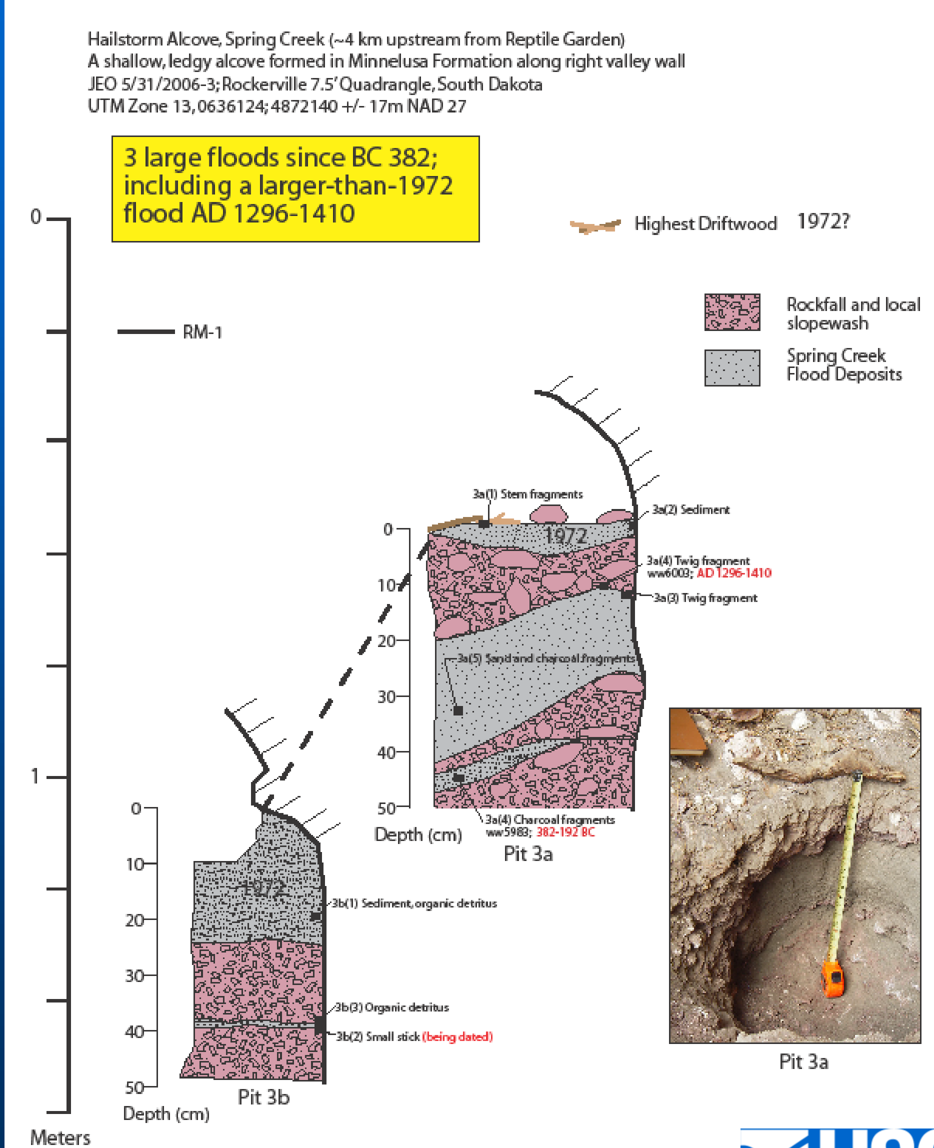
Concluding remarks

How to define flood risk with limited gaged data?

Paleoflood hydrology can provide information about the number, magnitude, and frequency of flooding in basins with limited or no data



Box Elder Cr nr Rapid City, SD



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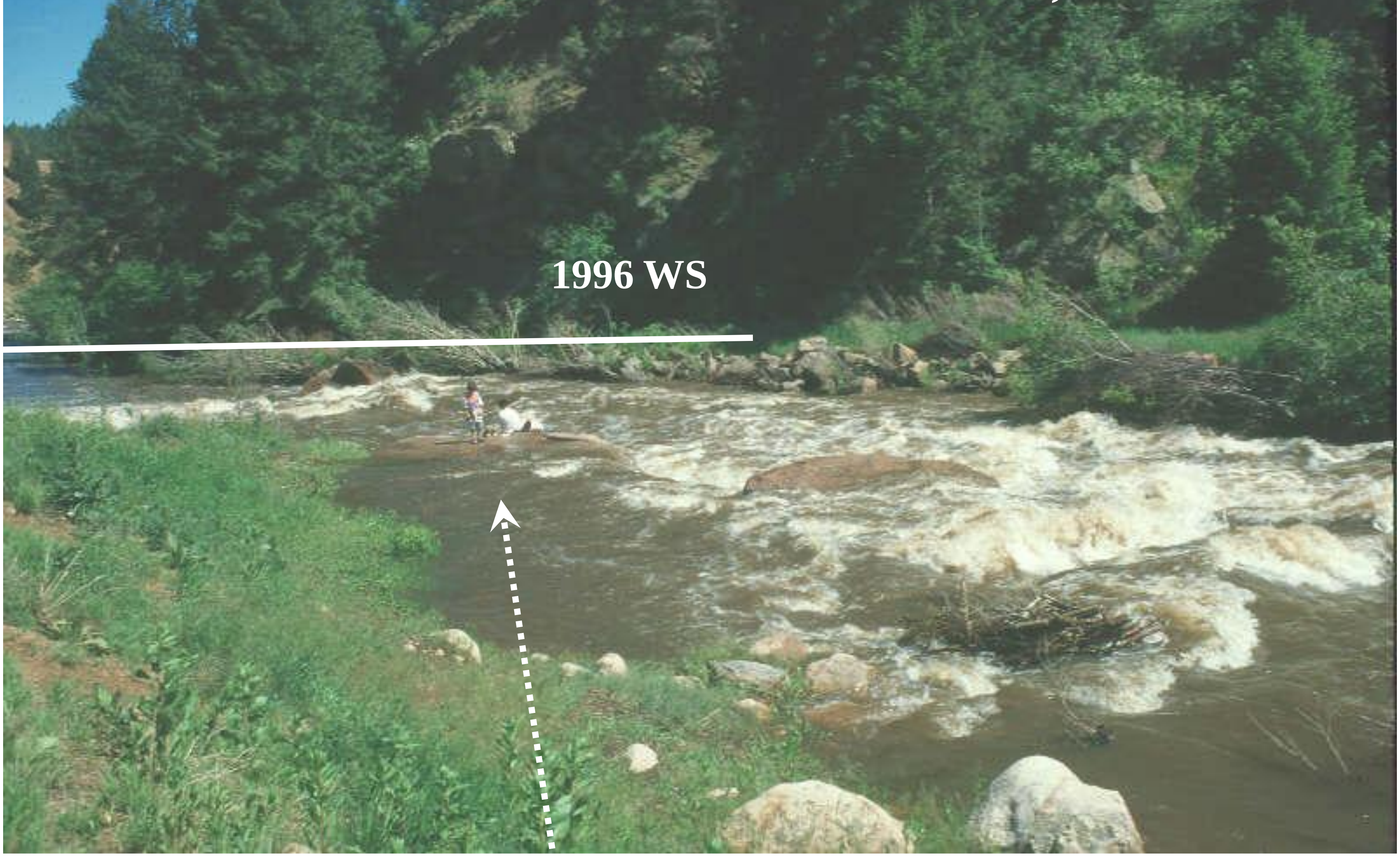
In remote mountain areas, NWS watches and warnings & cell phones may not be available

North Fork South Platte River d/s Buffalo Creek, CO: late-1996



Parents w/ ~5-yr old. How to best convey flood risk?

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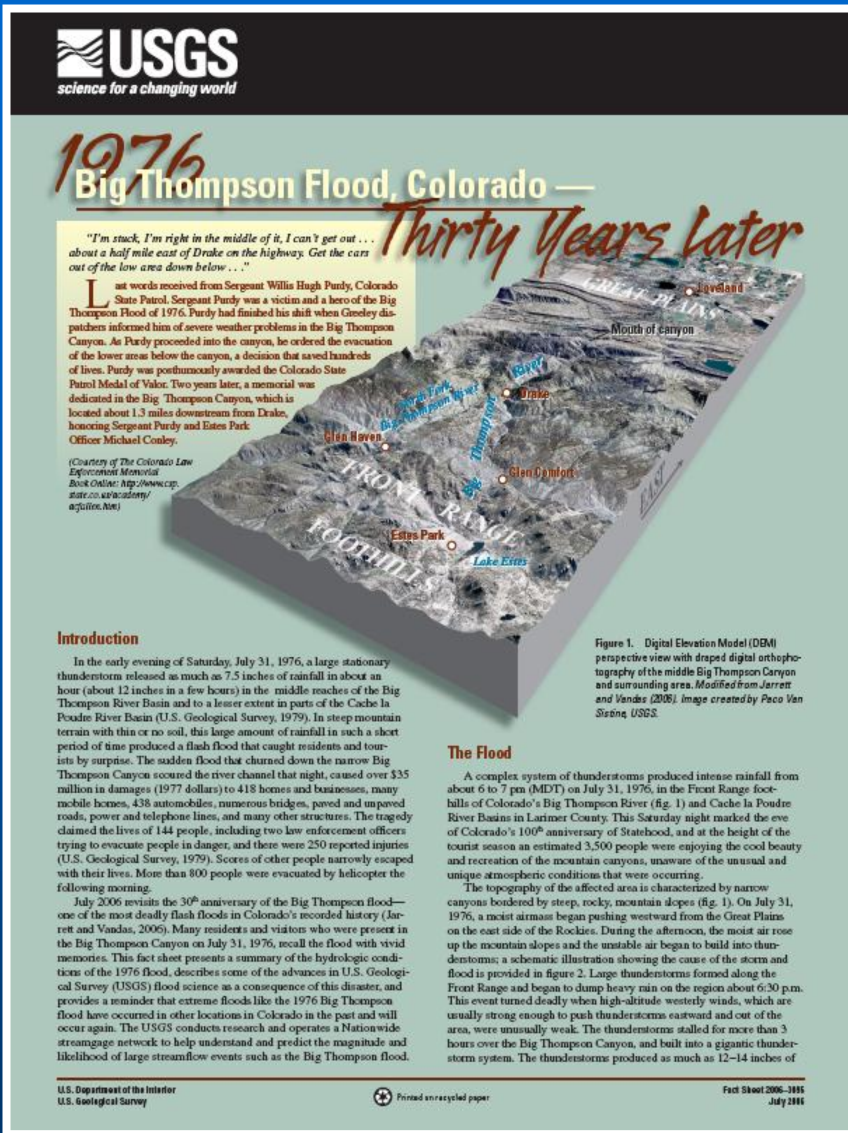
Thus, people need to be aware of nature’s environmental warning signs

- **Dark clouds**
- **Heavy rain**
- **Lightning**
- **Wind**
- **Sounds—trees breaking and loud roars**

Photograph by Lester Zins, University Corporation for Atmospheric Research



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1976 Big Thompson Flood, Colorado — Thirty Years Later

"I'm stuck, I'm right in the middle of it, I can't get out . . . about a half mile east of Drake on the highway. Get the cars out of the low area down below . . ."

Last words received from Sergeant Willis Hugh Purdy, Colorado State Patrol. Sergeant Purdy was a victim and a hero of the Big Thompson Flood of 1976. Purdy had finished his shift when Greeley dispatchers informed him of severe weather problems in the Big Thompson Canyon. As Purdy proceeded into the canyon, he ordered the evacuation of the lower areas below the canyon, a decision that saved hundreds of lives. Purdy was posthumously awarded the Colorado State Patrol Medal of Valor. Two years later, a memorial was dedicated in the Big Thompson Canyon, which is located about 1.3 miles downstream from Drake, honoring Sergeant Purdy and Estes Park Officer Michael Conley.

(Courtesy of The Colorado Law Enforcement Memorial Book Online: http://www.csp.state.co.us/academy/acfullen.htm)

Figure 1. Digital Elevation Model (DEM) perspective view with draped digital orthophotography of the middle Big Thompson Canyon and surrounding area. *Modified from Jarrett and Vandas (2006). Image created by Paco Van Sistine, USGS.*

Introduction

In the early evening of Saturday, July 31, 1976, a large stationary thunderstorm released as much as 7.5 inches of rainfall in about an hour (about 12 inches in a few hours) in the middle reaches of the Big Thompson River Basin and to a lesser extent in parts of the Cache la Poudre River Basin (U.S. Geological Survey, 1979). In steep mountain terrain with thin or no soil, this large amount of rainfall in such a short period of time produced a flash flood that caught residents and tourists by surprise. The sudden flood that churned down the narrow Big Thompson Canyon scoured the river channel that night, caused over $35 million in damages (1977 dollars) to 418 homes and businesses, many mobile homes, 438 automobiles, numerous bridges, paved and unpaved roads, power and telephone lines, and many other structures. The tragedy claimed the lives of 144 people, including two law enforcement officers trying to evacuate people in danger, and there were 250 reported injuries (U.S. Geological Survey, 1979). Scores of other people narrowly escaped with their lives. More than 800 people were evacuated by helicopter the following morning.

July 2006 revisits the 30th anniversary of the Big Thompson flood—one of the most deadly flash floods in Colorado's recorded history (Jarrett and Vandas, 2006). Many residents and visitors who were present in the Big Thompson Canyon on July 31, 1976, recall the flood with vivid memories. This fact sheet presents a summary of the hydrologic conditions of the 1976 flood, describes some of the advances in U.S. Geological Survey (USGS) flood science as a consequence of this disaster, and provides a reminder that extreme floods like the 1976 Big Thompson flood have occurred in other locations in Colorado in the past and will occur again. The USGS conducts research and operates a Nationwide streamgage network to help understand and predict the magnitude and likelihood of large streamflow events such as the Big Thompson flood.

The Flood

A complex system of thunderstorms produced intense rainfall from about 6 to 7 pm (MDT) on July 31, 1976, in the Front Range foothills of Colorado's Big Thompson River (fig. 1) and Cache la Poudre River Basins in Larimer County. This Saturday night marked the eve of Colorado's 100th anniversary of Statehood, and at the height of the tourist season an estimated 3,500 people were enjoying the cool beauty and recreation of the mountain canyons, unaware of the unusual and unique atmospheric conditions that were occurring.

The topography of the affected area is characterized by narrow canyons bordered by steep, rocky, mountain slopes (fig. 1). On July 31, 1976, a moist airmass began pushing westward from the Great Plains on the east side of the Rockies. During the afternoon, the moist air rose up the mountain slopes and the unstable air began to build into thunderstorms; a schematic illustration showing the cause of the storm and flood is provided in figure 2. Large thunderstorms formed along the Front Range and began to dump heavy rain on the region about 6:30 p.m. This event turned deadly when high-altitude westerly winds, which are usually strong enough to push thunderstorms eastward and out of the area, were unusually weak. The thunderstorms stalled for more than 3 hours over the Big Thompson Canyon, and built into a gigantic thunderstorm system. The thunderstorms produced as much as 12–14 inches of

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U.S. Geological Survey

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Fact Sheet 2006–3095
July 2006

USGS Fact Sheet 2006-3095 (Jarrett and Costa, 2006)

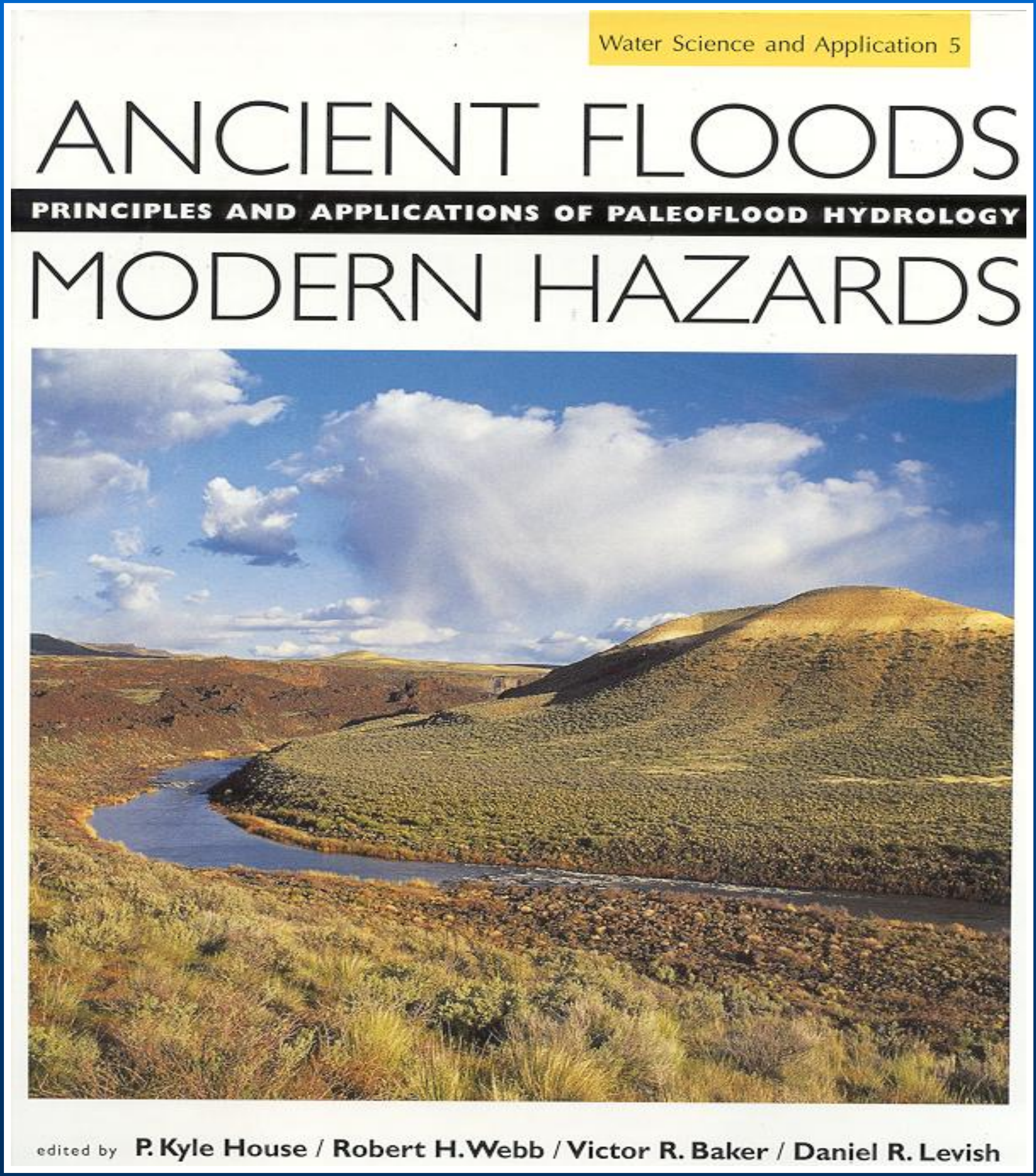
http://pubs.usgs.gov/fs/2006/3095/pdf/FS06-3095_508.pdf

USGS General Information Product 35, Flood Poster (Jarrett and Vandas, 2006)

Additional Information on Paleoflood Science

Main conclusion

Paleoflood data complement short gaged records and provide data in ungaged rivers



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Additional Information

Collins, D.L., Doesken, N.J., and Stanton, W.P., 1991, Colorado floods and droughts: U.S. Geological Survey Water Supply Paper 2375, p. 207–214.
Costa, J.E., 1978, Colorado Big Thompson flood—Geologic evidence of a rare hydrologic event: Geology, v. 6, no. 10, p. 617–620.
Costa, J.E., and Jarrett, R.D., 1981, Debris flows in small mountain stream channels of Colorado and their hydrologic implications: Association of Engineering Geologists Bulletin, v. 18, p. 309–322.
England, J.F. Jr., Jarrett, R.D., Salas, J.D., 2003, Data-based comparisons of moments estimators using historical and paleoflood data: Journal of Hydrology, v. 278, p. 172-196.
Enzel, Y., Ely, L.L., House, P.K., Webb, R.H., and Baker, V.R., 1993,Paleoflood evidence for a natural upper bound to flood magnitudes in the Colorado River Basin, Water Resour. Res., v. 29, pp. 2287-2297.
Gruntfest, E.C., 1977, What people did during the Big Thompson Flood: Natural Hazards Research and Applications Information Center, Working Paper, 62 p.
House, K.P., 2002, Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology, AGU's Water Science and Application Series, v. 5, 385 p., with additional supporting data and information on cd-rom.
Jarrett, R.D., 1984, Hydraulics of high-gradient streams: American Society of Civil Engineers, Journal of Hydraulic Engineering, v. 110, no. 1, p. 1519-1939.
Jarrett, R.D., 1987, Peak discharge errors in slope-area computation in mountain streams: Journal of Hydrology, v. 96, no. 1–4, p. 53–67.
Jarrett, R.D., 2000, Paleoflood investigations for Cherry Creek basin, Eastern Colorado, in Hotchkiss, R.H., and Glade, Michael, editors, Building Partnerships, Proceeding of the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management, July 30-August 2, 2000, Minneapolis, MN, American Society of Civil Engineers, Reston, VA, p. 1-10.
Jarrett, R.D., and Costa, J.E., 1986, Hydrology, geomorphology, and dam break modeling of the July 15, 1982, Lawn Lake Dam and Cascade Lake Dam Failures, Larimer County, Colorado: U.S. Geological Survey Professional Paper 1369, 79 p.
Jarrett, R.D., and Costa, J.E., 1988, Evaluation of the flood hydrology in the Colorado Front Range using streamflow records and paleohydrologic data for the Big Thompson River Basin: U.S. Geological Survey Water-Resources Investigations Report 87–4117, 37 p.
Jarrett, R.D.,and Costa, J.E., 2006, 1976 Big Thompson Flood, Colorado – Thirty Years Later: U.S. Geological Survey Fact Sheet 2006-3095, 6 pages.
Jarrett, R. D., and England, J. F., Jr., 2002, Reliability of paleostage indicators for paleoflood studies: Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology, AGU's Water Science and Application Series, vol. 5, p. 91-109.
Jarrett, R.D., and Tomlinson, E.M., 2000, Regional interdisciplinary paleoflood approach to assess extreme flood potential: Water Resources Research, vol. 36, no. 10, p. 2957-2984.
Jarrett, R.D., and Vandas, S.J. (compilers), 2006, 1976 Big Thompson Flood, Colorado: U.S. Geological Survey General Information Product 35, 1 sheet (poster).
Webb, R. H. and Jarrett, R. D., 2002, One-dimensional estimation techniques for discharges of paleofloods and historical floods: Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology, AGU's Water Science and Application Series, vol. 5, p. 111-125.
Parrett, Charles, and Jarrett, R.D., 2000, Flood hydrology for Dry Creek, Lake County, Northwestern Montana: U.S Geological Survey Water Resources Investigations Report 00-4069, 12 p.
Patton, P.C., and Baker, V.R., 1977, Geomorphic response of central Texas streams to catastrophic rainfall and runoff, in Doehring, D.O., ed, Geomorphology in Arid and Semi-Arid Regions, Publ. in Geomorphology, State Univ., New York, Binghamton, N.Y., p. 189-217.
Simons, D.B., Nelson, J.D., Reiter, E.R., and Barkau, R.L., 1978, Flood of 31 July 1976 in Big Thompson Canyon, Colorado: National Academy of Sciences, Washington, D.C., 85 p.
U.S. Geological Survey, 1979, Storm and flood of July 31–August 1, 1976, in the Big Thompson River and Cache la Poudre River Basins, Larimer and Weld Counties, Colorado: U.S. Geological Survey Professional Paper 1115, 152 p.
Waythomas, C.F., and Jarrett, R.D., 1994, Flood geomorphology of Arthurs Rock Gulch, Colorado, paleoflood history: Geomorphology, v. 11, p. 15-40.
Yanosky, T. M. and Jarrett, R. D., 2002, Dendrochronologic evidence for the frequency and magnitude of paleofloods: Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology, AGU's Water Science and Application Series, vol. 5, p. 77-89.

For more information on USGS science: http://www.usgs.gov; http://water.usgs.gov/osw/; http://ks.water.usgs.gov/Kansas/floodsummary; http://water.usgs.gov/usgs/osw/FS-List-2003.html; http://pubs.usgs.gov/fs/2006/3095/pdf/FS06-3095_508.pdf

For more information on flood hydrology: http://www.noaa.gov; http://www.roc.noaa.gov/; www.nwrfc.noaa.gov/misc/rfcs.cgi; http://ccc.atmos.colostate.edu/~odie/rain.html; http://co.water.usgs.gov/); http://water.state.co.us/; http://www.fema.gov; http://www.usace.army.mil; http://www.usbr.gov/pmts/flood/; http://www.udfcd.org/; http://cwcb.state.co.us; http://www.casfm.org; http://floodsafety.org/colorado/index.htm

The fact sheet (FS-2006–3096) and accompanying poster (General Information Product 35) on the July 31, 1976, Big Thompson Flood, Colorado, and other publications can be ordered from the USGS Store at http://store.usgs.gov or call 1-888-ASK-USGS (1-888-275-8747).

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