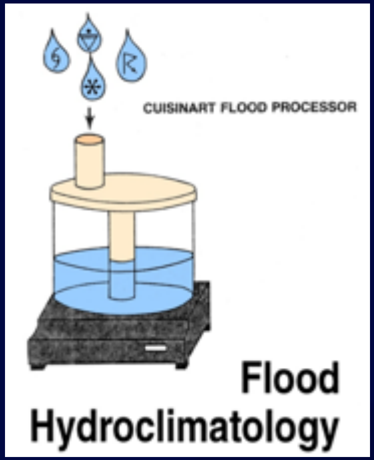
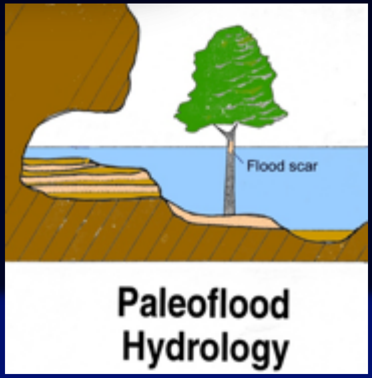
Workshop on Hydrologic Extremes
and Water Management in a Warmer World – California Perspective
May 19-20, 2011

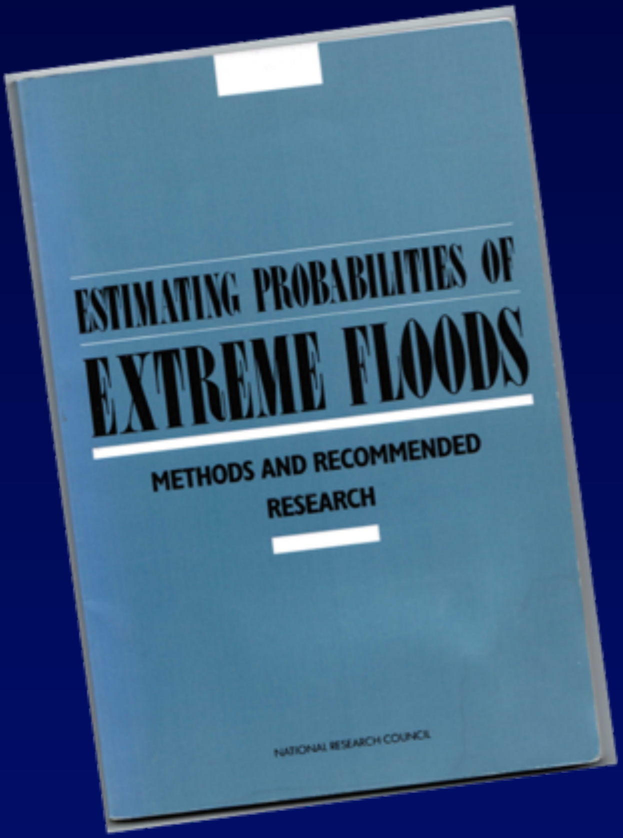
Constraining Flood Probabilities with Hydroclimatic & Paleohydrological Information





Katie Hirschboeck

CLIMAS Climate Assessment for the Southwest
The University of Arizona
The Laboratory of Tree-Ring Research



ESTIMATING PROBABILITIES OF

EXTREME FLOODS

METHODS AND RECOMMENDED RESEARCH

NATIONAL RESEARCH COUNCIL

National Research Council
1988

“The committee endorses the concept that the objective of flood studies should be to generate as much information as practicable about the range of flood potential at a site.”

ESTIMATING PROBABILITIES OF
EXTREME FLOODS
METHODS AND RECOMMENDED RESEARCH

THREE PRINCIPLES:

(1) Substitution of space for time (regionalization)

(2) Introduction of more "structure" into the models (alternative distributions)

(3) Focus on extremes or "tails" as opposed to, or even to the exclusion of, central characteristics (censored data, paleofloods)

> *". . . based on the observation that hydrometeorological and watershed processes during extreme events are likely to be quite different from those same processes during more common events."*

report details

Constraining Flood Probabilities with Hydroclimatic & Paleohydrological Information

I. Insights from “Flood Hydroclimatology”” on the Probability of Extremes

II. The Potential of Paleoflood Information

Closing Thoughts

Constraining Flood Probabilities with Hydroclimatic & Paleohydrological Information

I. Insights from “Flood Hydroclimatology”” on the Probability of Extremes

II. The Potential of Paleoflood Information

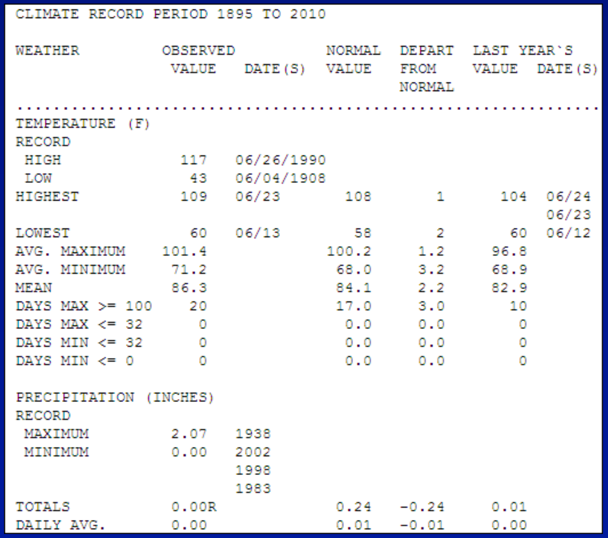
Closing Thoughts

5 Insights on Ways to Identify Flood-Climate Linkages That Might Otherwise Be Missed

1. **Expanded understanding of climate**
2. **Process-sensitive "bottom-up" approach**
3. **Peaks-above base vs. annual maxima**
4. **Regions of flood sensitivity to climate**
5. **Storm type, hierarchy, and basin scale**

ARE WE THINKING ABOUT CLIMATE IN THE BEST WAY ?

> ***“Climate is what you expect, weather is what you get.”***
>
> **Robert A. Heinlein**



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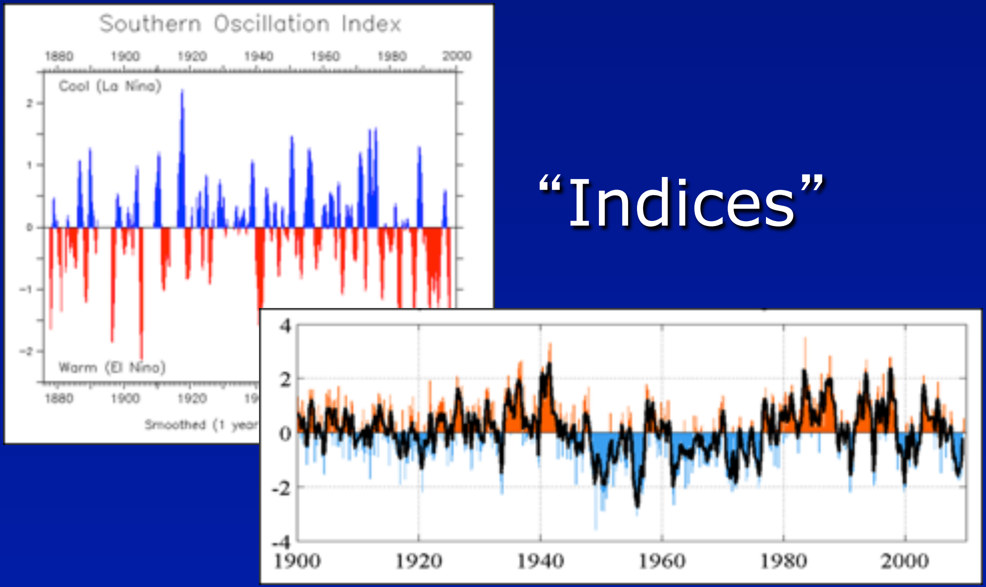
CLIMATE RECORD PERIOD 1895 TO 2010

WEATHER         OBSERVED          NORMAL  DEPART  LAST YEAR`S
                 VALUE   DATE(S)  VALUE   FROM    VALUE  DATE(S)
                                          NORMAL
................................................................
TEMPERATURE (F)
RECORD
 HIGH             117   06/26/1990
 LOW               43   06/04/1908
HIGHEST           109   06/23       108       1     104  06/24
                                                          06/23
LOWEST             60   06/13        58       2      60  06/12
AVG. MAXIMUM    101.4             100.2     1.2    96.8
AVG. MINIMUM     71.2              68.0     3.2    68.9
MEAN             86.3              84.1     2.2    82.9
DAYS MAX >= 100    20              17.0     3.0      10
DAYS MAX <= 32      0               0.0     0.0       0
DAYS MIN <= 32      0               0.0     0.0       0
DAYS MIN <= 0       0               0.0     0.0       0

PRECIPITATION (INCHES)
RECORD
 MAXIMUM         2.07   1938
 MINIMUM         0.00   2002
                        1998
                        1983
TOTALS           0.00R             0.24   -0.24    0.01
DAILY AVG.       0.00              0.01   -0.01    0.00
```

“Normals”



“Indices”

HOW CAN WE THINK ABOUT CLIMATE DIFFERENTLY ?

#1 Our understanding of climate / climate variability should be expanded beyond statistical definitions to include mechanistic, event-based, weather components.

HYDROMETEOROLOGY

- Weather, short time scales
- Local / regional spatial scales
- Forecasts, real-time warnings

vs.

HYDROCLIMATOLOGY

- Seasonal / long-term perspective
- Site-specific and regional synthesis of flood-causing weather scenarios
- Regional linkages/differences identified
- Entire flood history context → benchmarks for future events

FLOOD HYDROCLIMATOLOGY

is the analysis of flood events within the context of their history of variation

- in magnitude, frequency, seasonality

- over a relatively long period of time

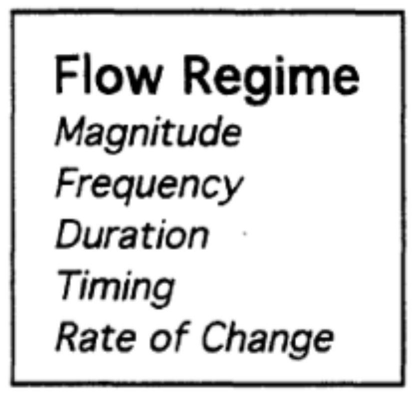
- analyzed within the spatial framework of changing combinations of meteorological causative mechanisms

"Flood Hydroclimatology" in Flood Geopmorphology (1988)

FLOOD HYDROCLIMATOLOGY:

1) Different types of FLOODS

2) Different types of SEASONAL FLOW REGIMES:



Flow Regime

Magnitude

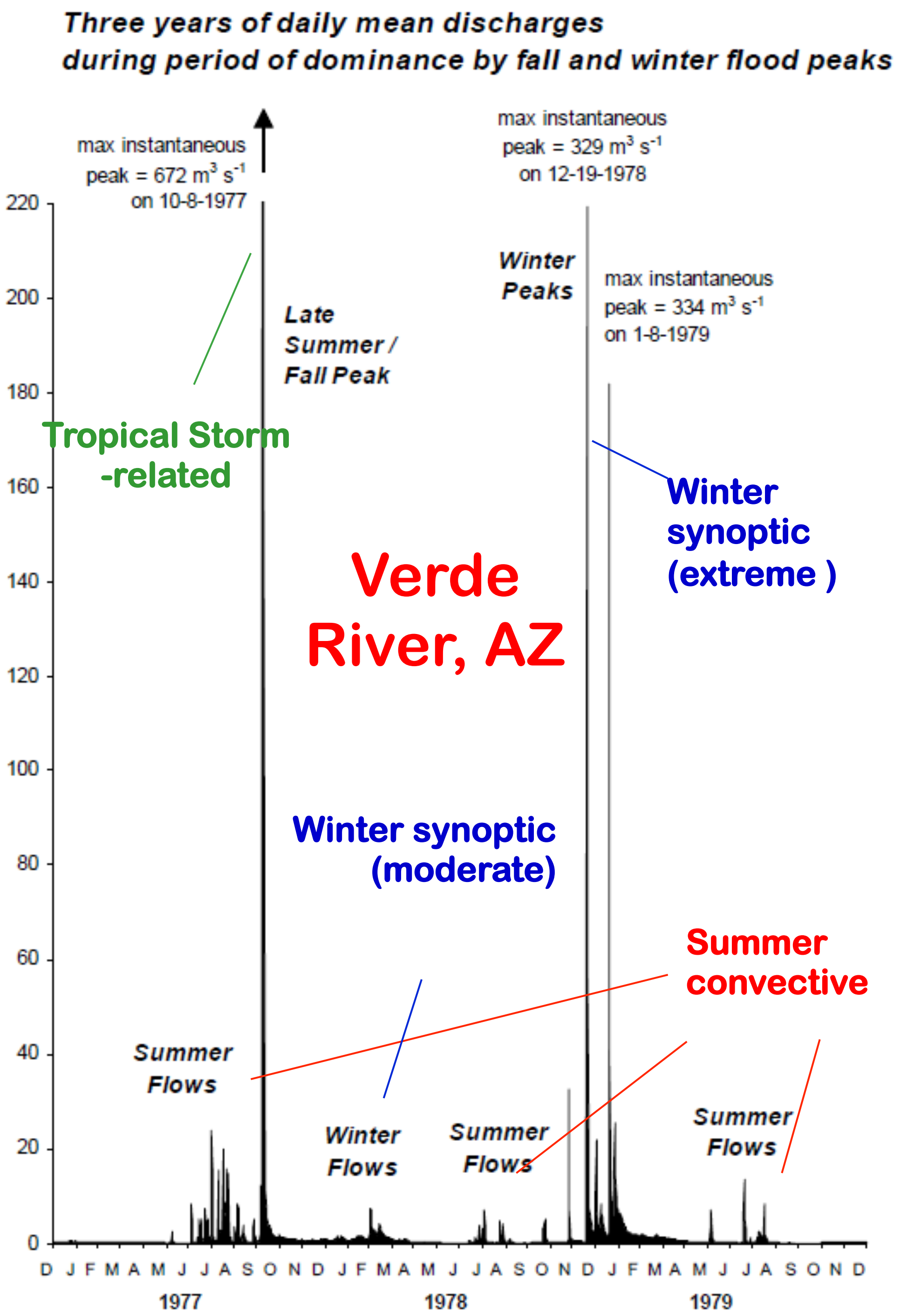
Frequency

Duration

Timing

Rate of Change

Some or all of these factors are likely to shift with a changing climate



Three years of daily mean discharges during period of dominance by fall and winter flood peaks

Tropical Storm -related

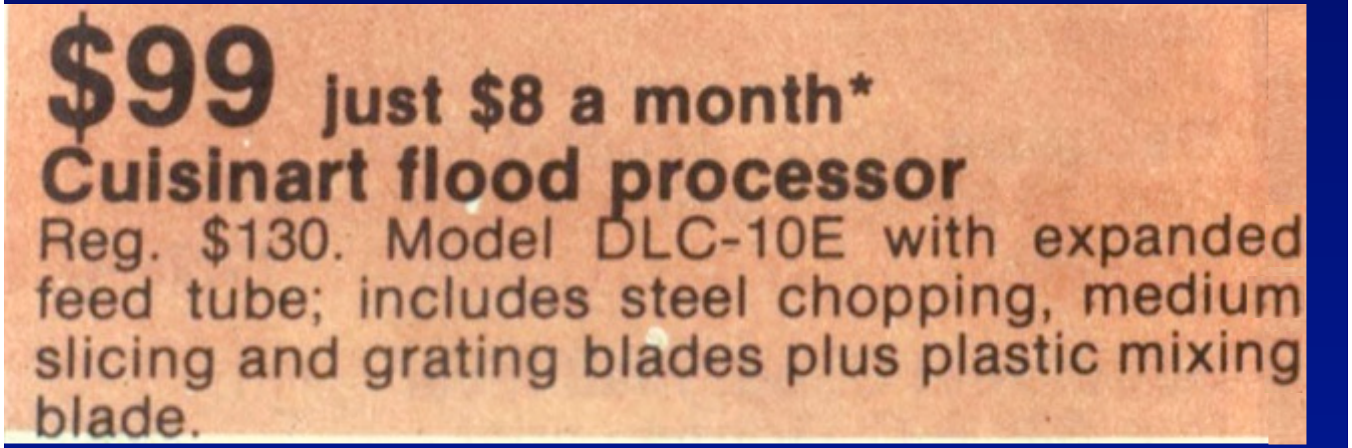
Verde River, AZ

Winter synoptic (extreme)

Winter synoptic (moderate)

Summer convective

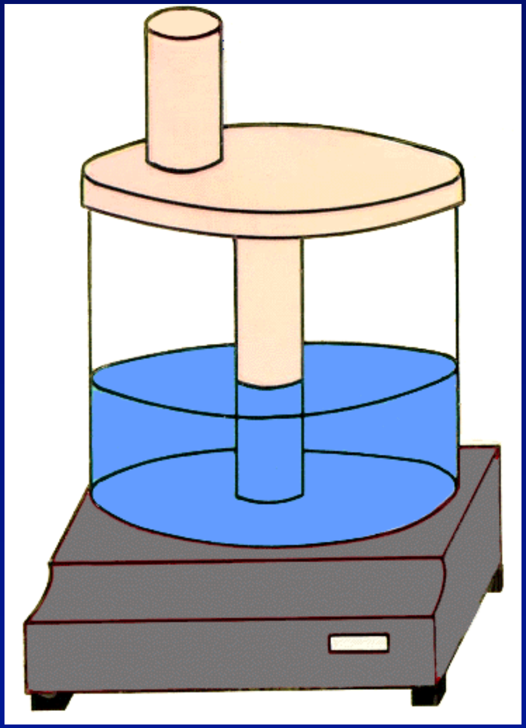
Newspaper ad . . . .



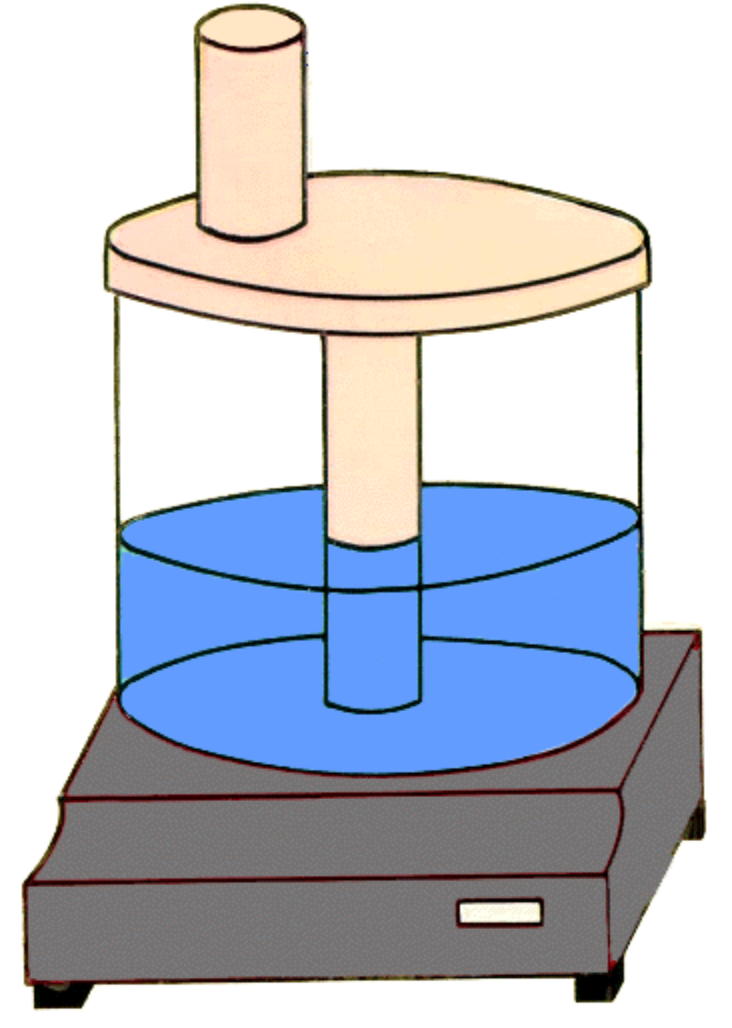
$99 **just $8 a month***

Cuisinart flood processor

Reg. $130. Model DLC-10E with expanded feed tube; includes steel chopping, medium slicing and grating blades plus plastic mixing blade.



Standard approach analyzes floods using "CUISINART" HYDROLOGY!



"FLOOD PROCESSOR"

With expanded feed tube

– for entering all kinds of flood data

including steel chopping, slicing & grating blades

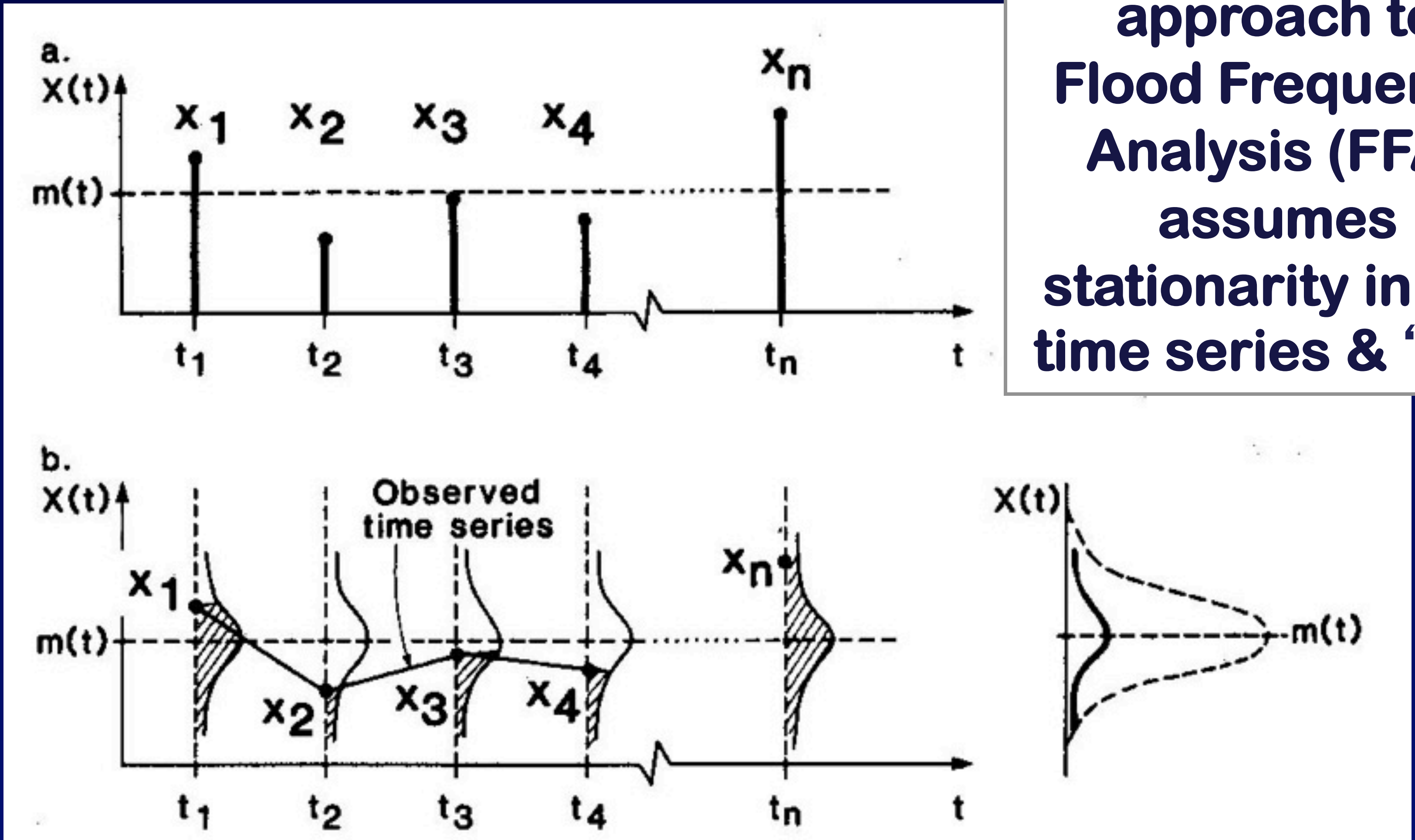
– for removing unique physical characteristics, climatic information, and outliers

plus plastic mixing blade

– to mix the populations together

The Standard iid Assumption for FFA

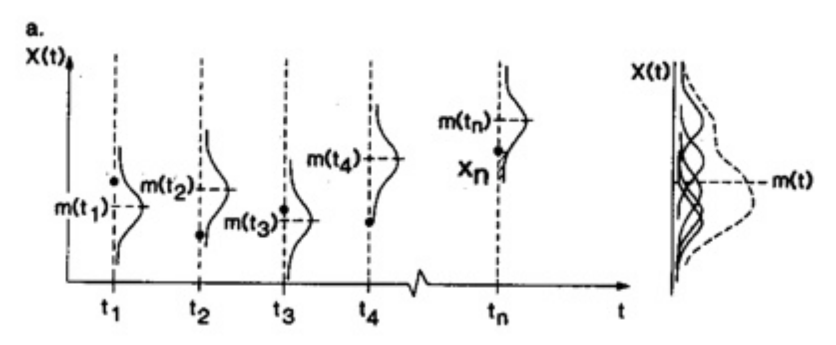
The standard approach to Flood Frequency Analysis (FFA) assumes stationarity in the time series & “iid”



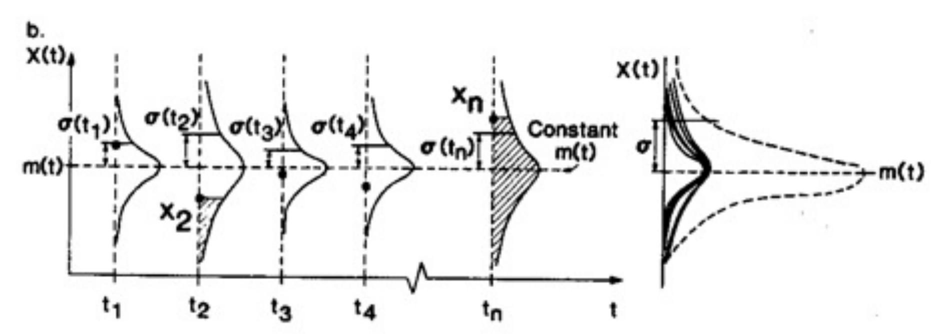
“ iid ” assumption: independently, identically distributed

Alternative Conceptual Framework:

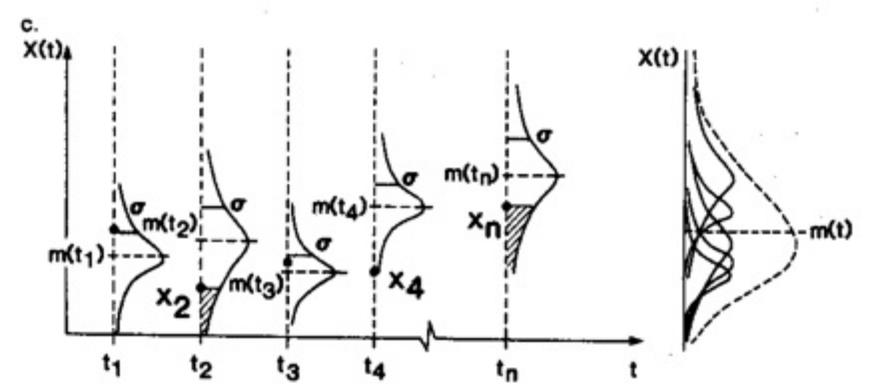
Time-varying means



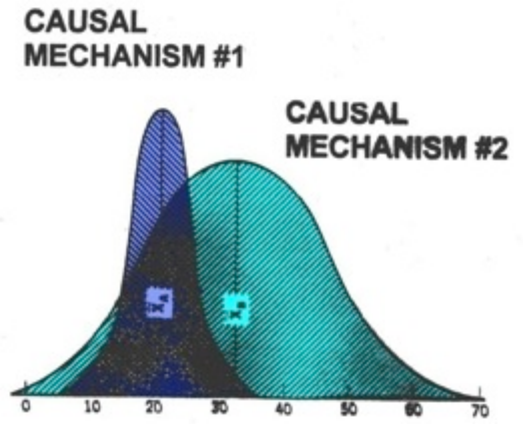
Time-varying variances



Both

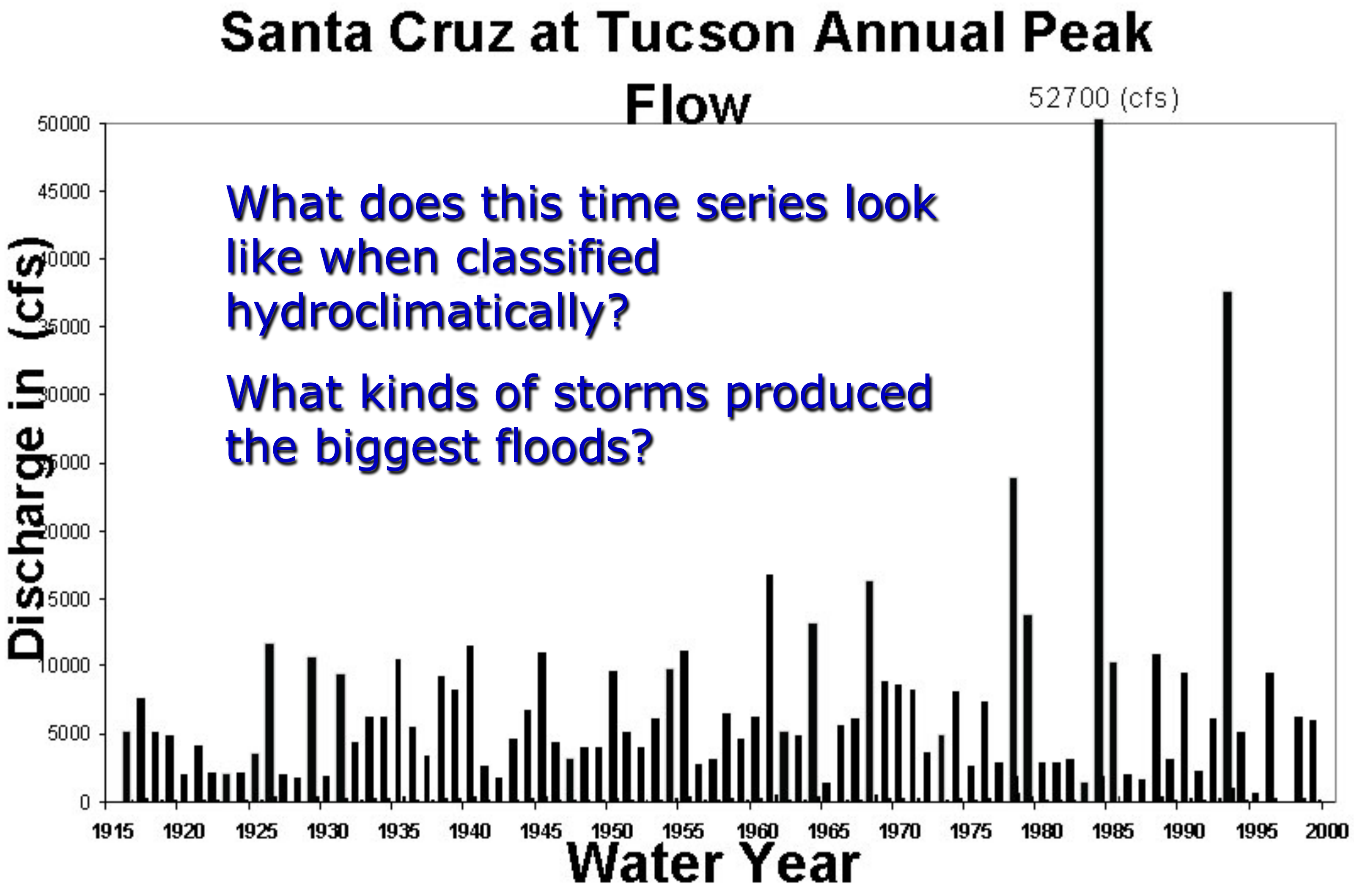


SOURCE: Hirschboeck, 1988



Mixed frequency distributions may arise from:

- storm types
- synoptic patterns
- ENSO, etc. teleconnections
- multi-decadal circulation +/or SST regimes

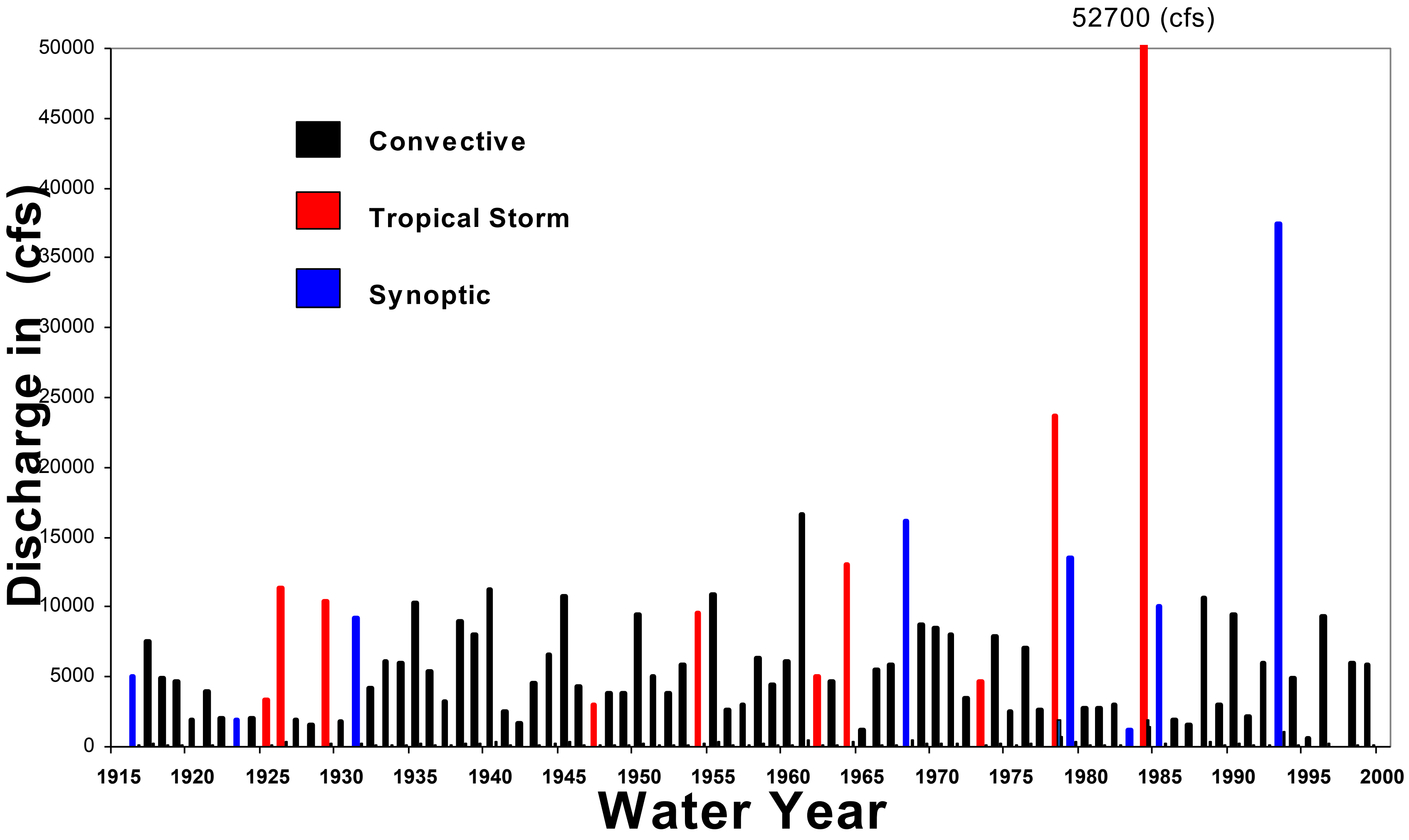


What does this time series look like when classified hydroclimatically?

What kinds of storms produced the biggest floods?

Hydroclimatically classified time series . . .

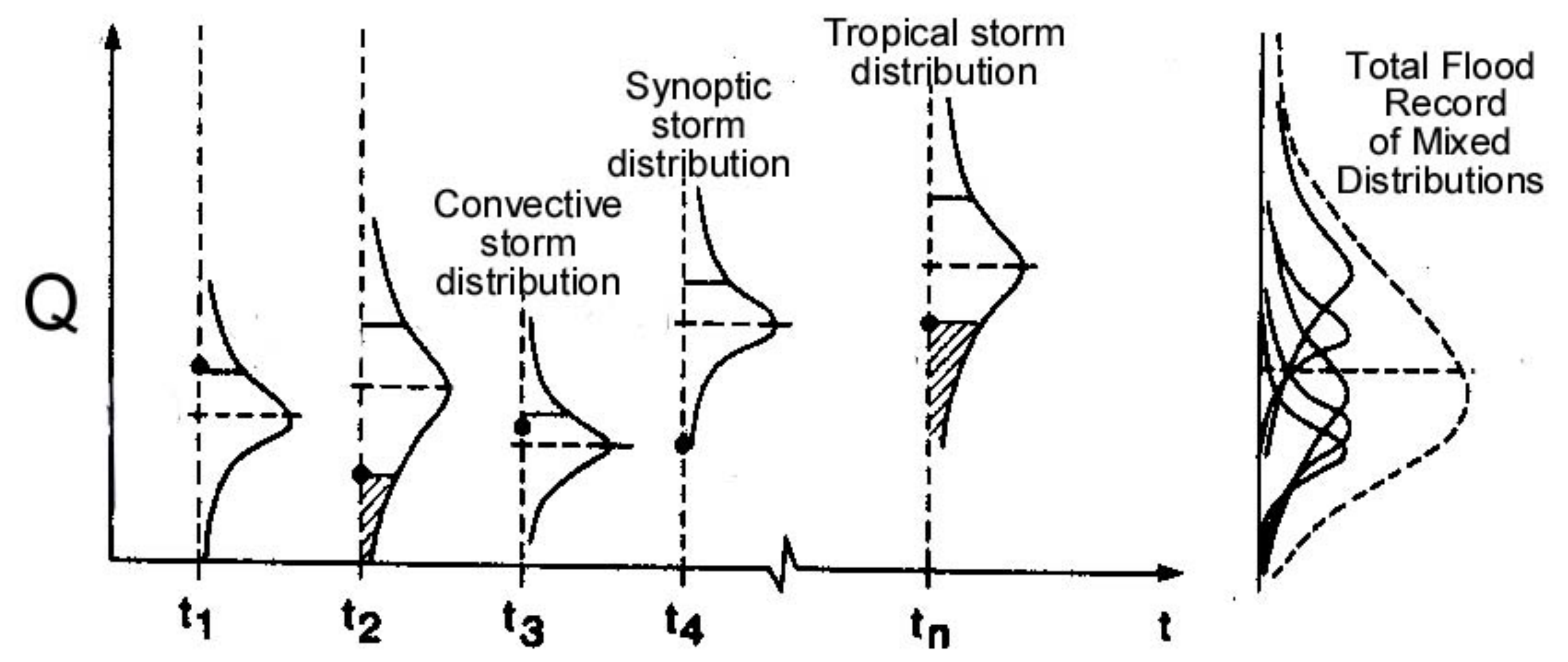
Santa Cruz at Tucson



. . . but this:

Alternative Model to Explain How Flood Magnitudes Vary over Time

Schematic for Arizona floods based on different storm types

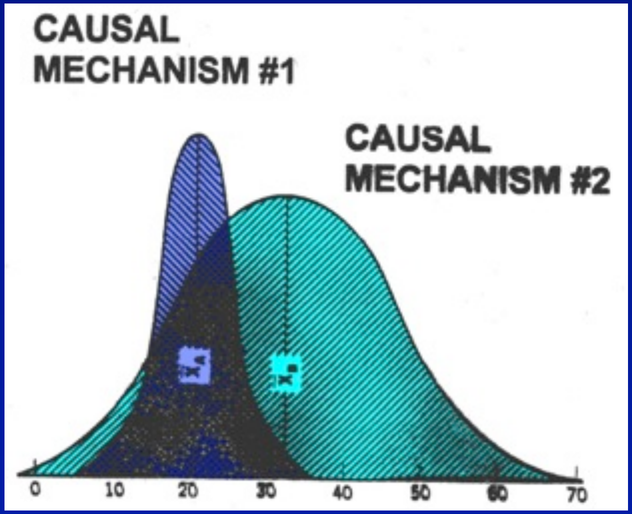


Varying mean and standard deviations due to different causal mechanisms

Moving Beyond “Cuisinart” Hydrology . . . .

A Mixture of Flood Causes:

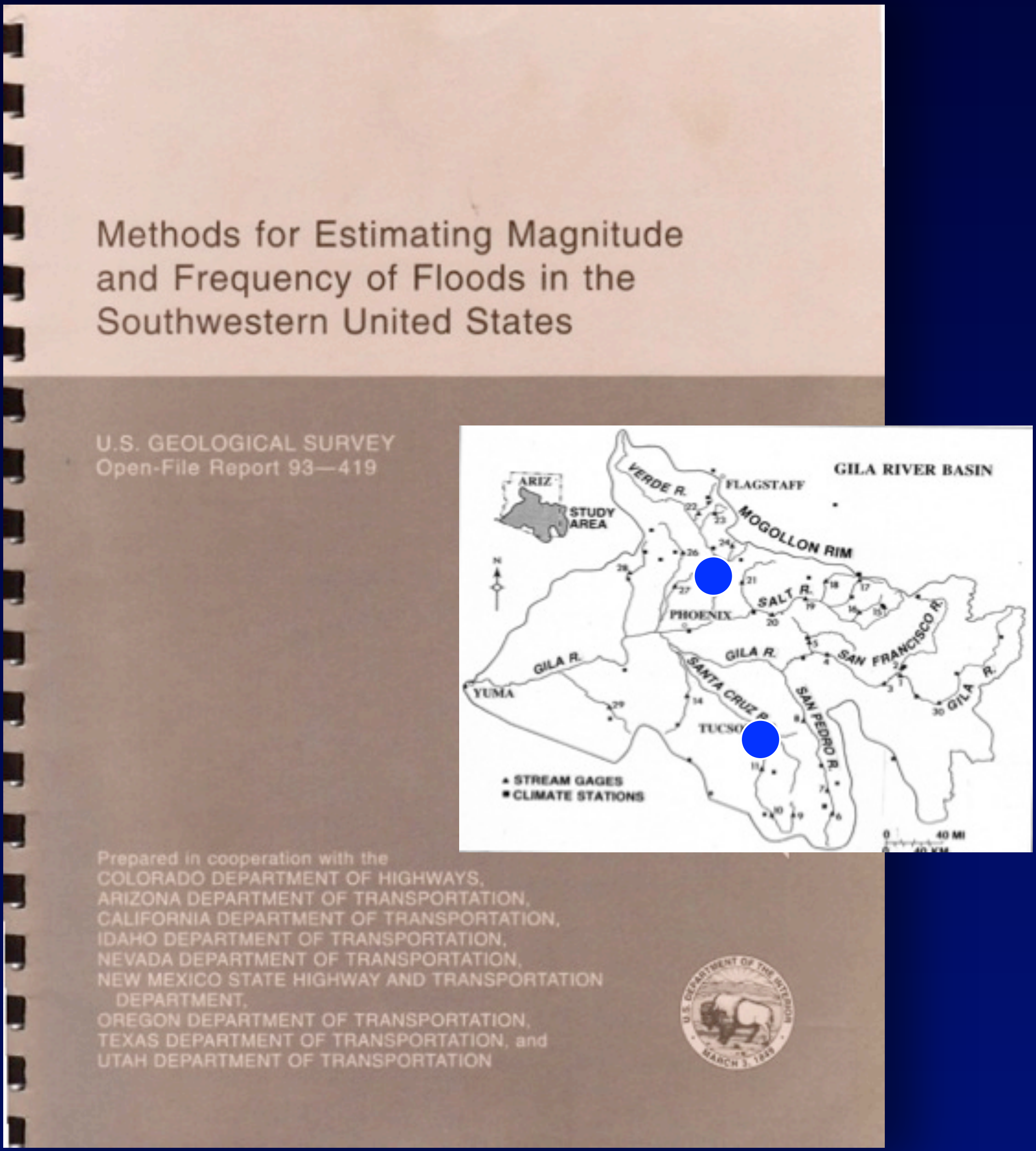
Data from key flood subgroups may be better for estimating the probability and type of extremely rare floods than a single “100-Year Flood” calculated from all the flood data combined



-- Useful for defining regions

-- Can then be used to estimate flow behavior in ungaged basins

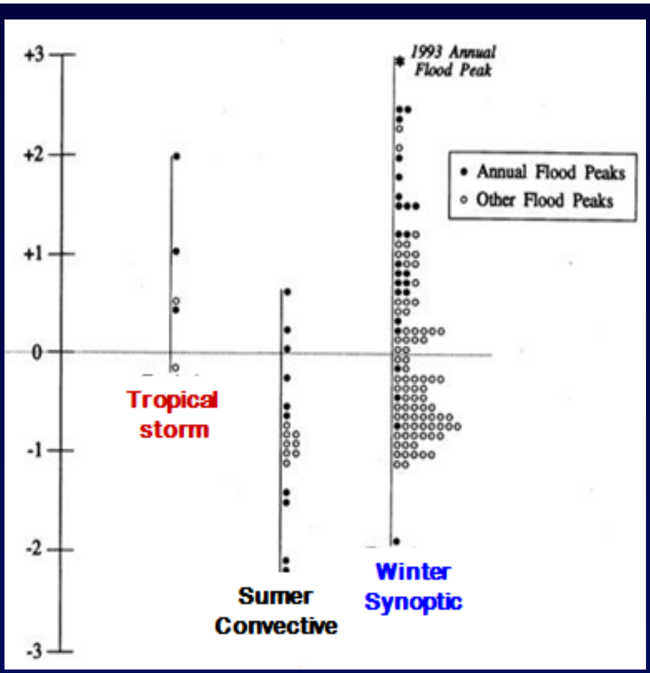
(new USGS collaboration)

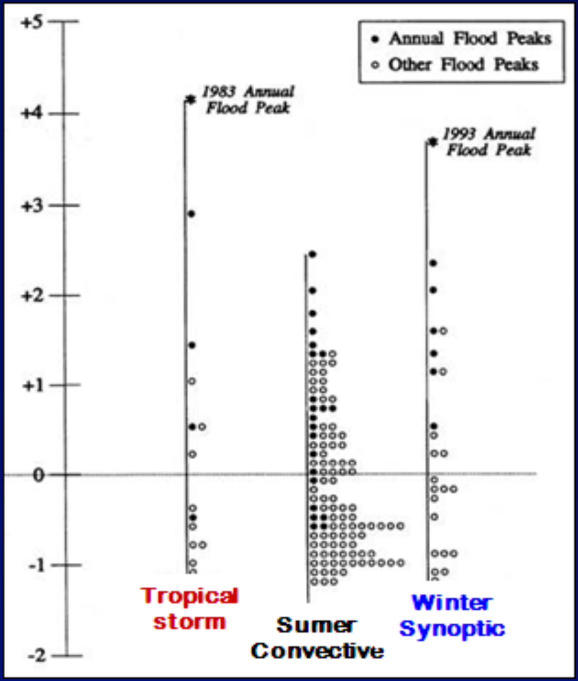


Methods for Estimating Magnitude
and Frequency of Floods in the
Southwestern United States

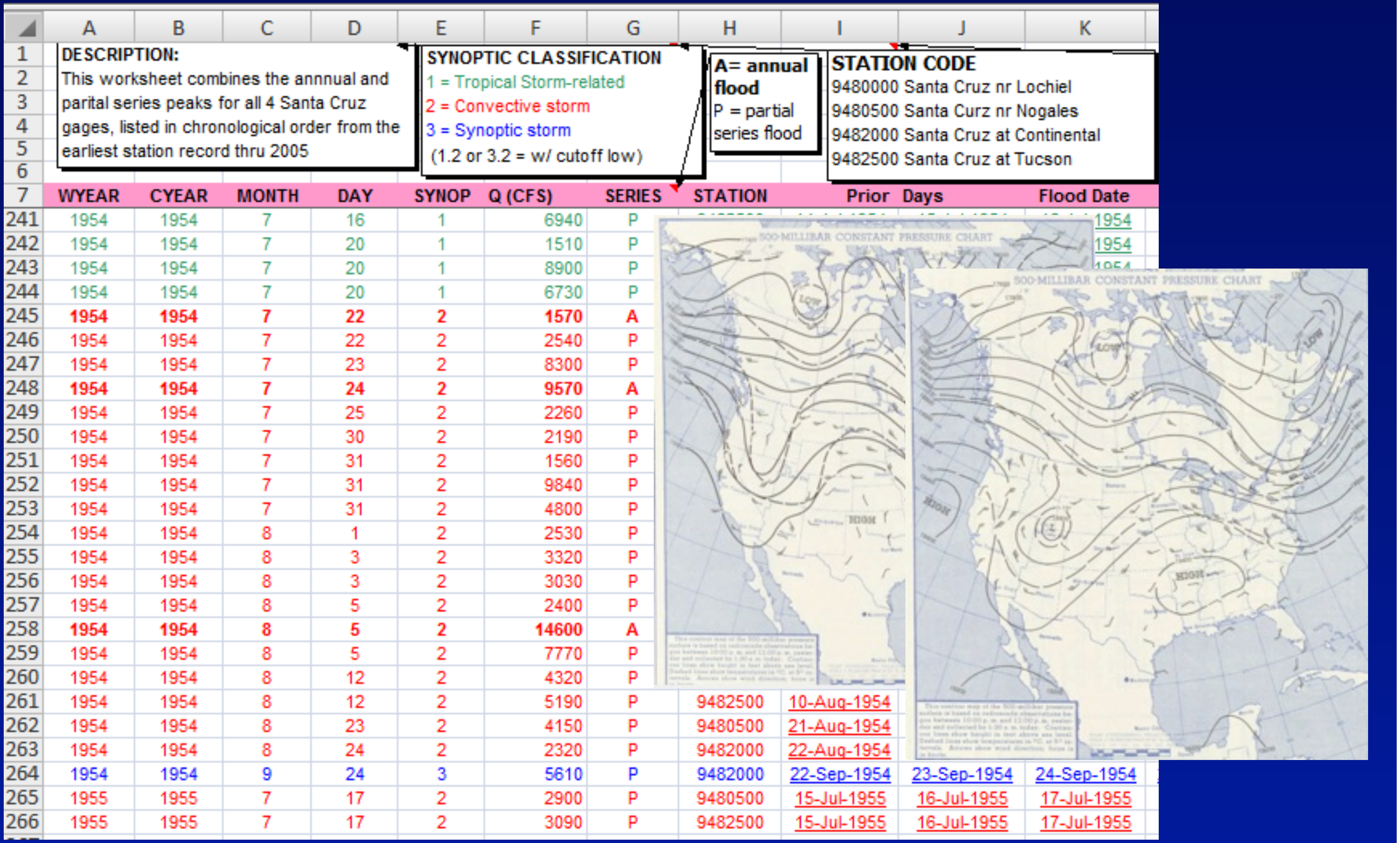
U.S. GEOLOGICAL SURVEY
Open-File Report 93—419

Prepared in cooperation with the
COLORADO DEPARTMENT OF HIGHWAYS,
ARIZONA DEPARTMENT OF TRANSPORTATION,
CALIFORNIA DEPARTMENT OF TRANSPORTATION,
IDAHO DEPARTMENT OF TRANSPORTATION,
NEVADA DEPARTMENT OF TRANSPORTATION,
NEW MEXICO STATE HIGHWAY AND TRANSPORTATION
DEPARTMENT,
OREGON DEPARTMENT OF TRANSPORTATION,
TEXAS DEPARTMENT OF TRANSPORTATION, and
UTAH DEPARTMENT OF TRANSPORTATION





Flood Hydroclimatology Database



DESCRIPTION:
This worksheet combines the annnual and parital series peaks for all 4 Santa Cruz gages, listed in chronological order from the earliest station record thru 2005

SYNOPTIC CLASSIFICATION
1 = Tropical Storm-related
2 = Convective storm
3 = Synoptic storm
(1.2 or 3.2 = w/ cutoff low)

A= annual flood
P = partial series flood

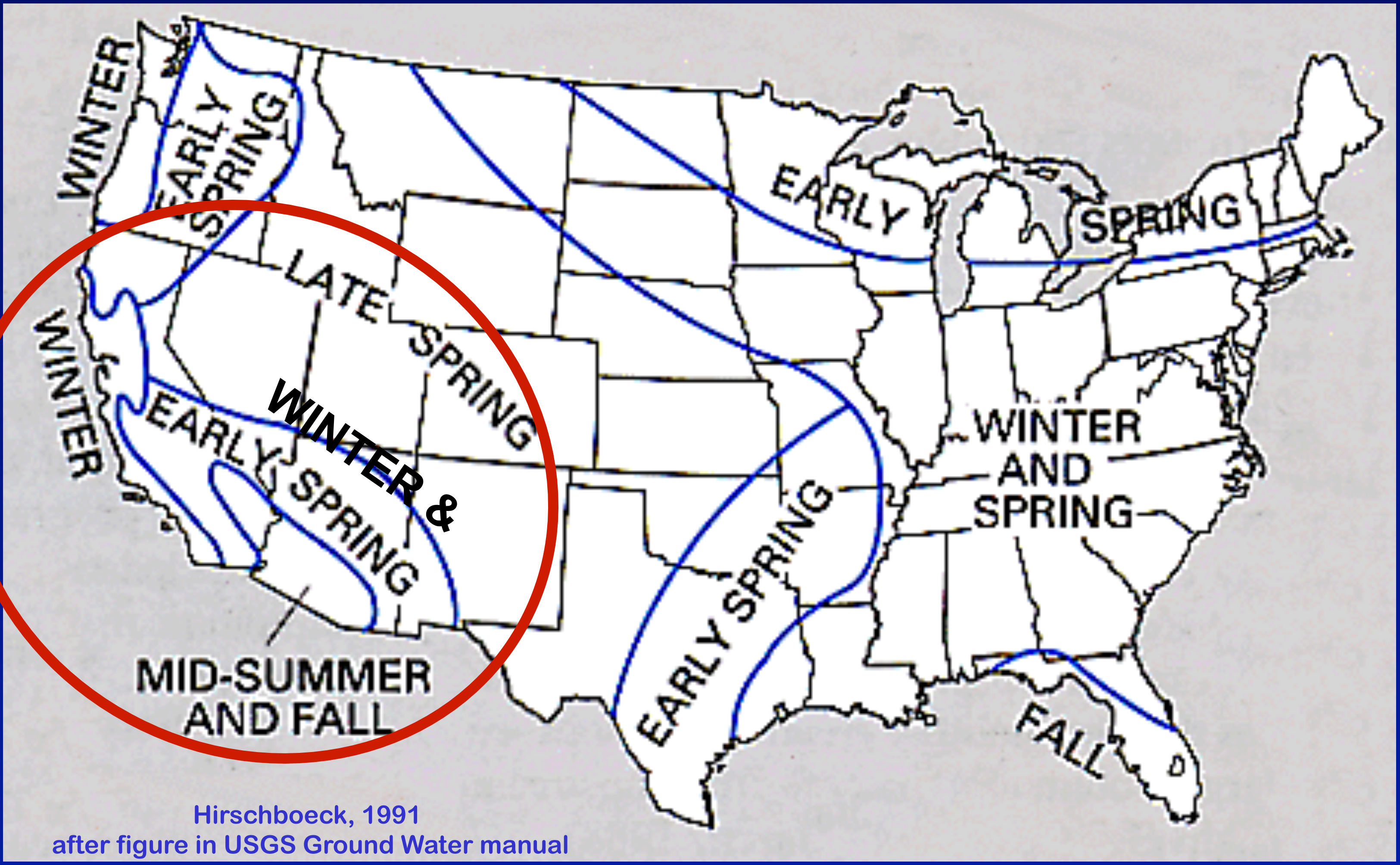
STATION CODE
9480000 Santa Cruz nr Lochiel
9480500 Santa Curz nr Nogales
9482000 Santa Cruz at Continental
9482500 Santa Cruz at Tucson

	WYEAR	CYEAR	MONTH	DAY	SYNOP	Q (CFS)	SERIES	STATION	Prior	Days	Flood Date
241	1954	1954	7	16	1	6940	P				1954
242	1954	1954	7	20	1	1510	P				1954
243	1954	1954	7	20	1	8900	P				
244	1954	1954	7	20	1	6730	P				
245	**1954**	**1954**	**7**	**22**	**2**	**1570**	**A**				
246	1954	1954	7	22	2	2540	P				
247	1954	1954	7	23	2	8300	P				
248	**1954**	**1954**	**7**	**24**	**2**	**9570**	**A**				
249	1954	1954	7	25	2	2260	P				
250	1954	1954	7	30	2	2190	P				
251	1954	1954	7	31	2	1560	P				
252	1954	1954	7	31	2	9840	P				
253	1954	1954	7	31	2	4800	P				
254	1954	1954	8	1	2	2530	P				
255	1954	1954	8	3	2	3320	P				
256	1954	1954	8	3	2	3030	P				
257	1954	1954	8	5	2	2400	P				
258	**1954**	**1954**	**8**	**5**	**2**	**14600**	**A**				
259	1954	1954	8	5	2	7770	P				
260	1954	1954	8	12	2	4320	P				
261	1954	1954	8	12	2	5190	P	9482500	10-Aug-1954		
262	1954	1954	8	23	2	4150	P	9480500	21-Aug-1954		
263	1954	1954	8	24	2	2320	P	9482000	22-Aug-1954		
264	1954	1954	9	24	3	5610	P	9482000	22-Sep-1954	23-Sep-1954	24-Sep-1954
265	1955	1955	7	17	2	2900	P	9480500	15-Jul-1955	16-Jul-1955	17-Jul-1955
266	1955	1955	7	17	2	3090	P	9482500	15-Jul-1955	16-Jul-1955	17-Jul-1955

Based on USGS "peaks-above-base" record (annual & partial series)

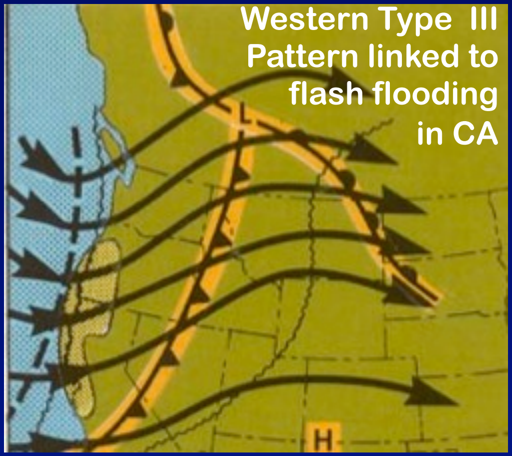
PURPOSE: to determine hydroclimatic context for causes of floods in AZ watersheds

Generalized Seasonality of Peak Flooding: California vs Arizona



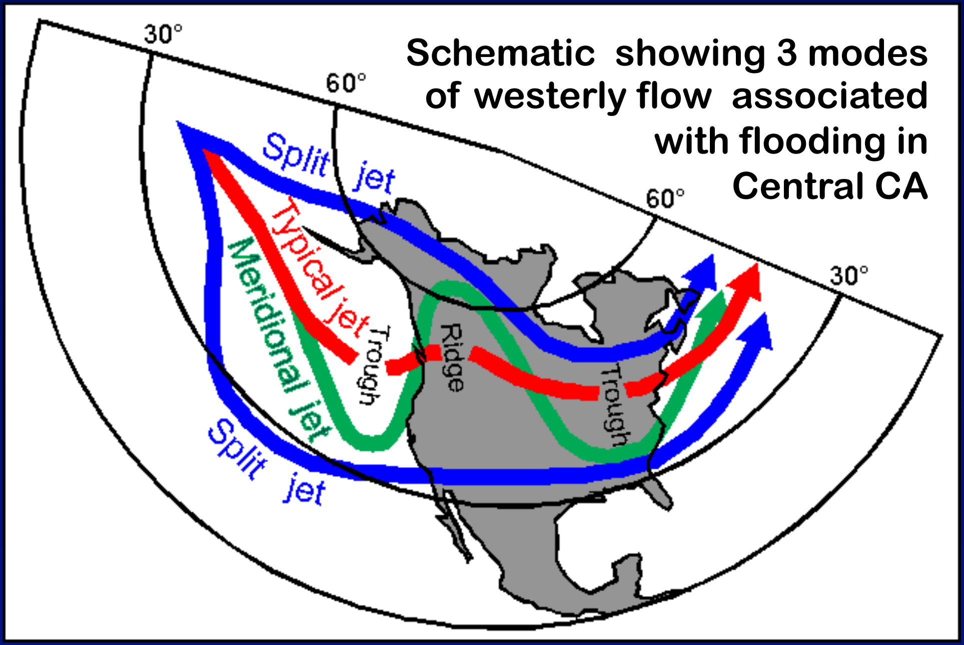
Hirschboeck, 1991
after figure in USGS Ground Water manual

CALIFORNIA
Flood Hydroclimatology:

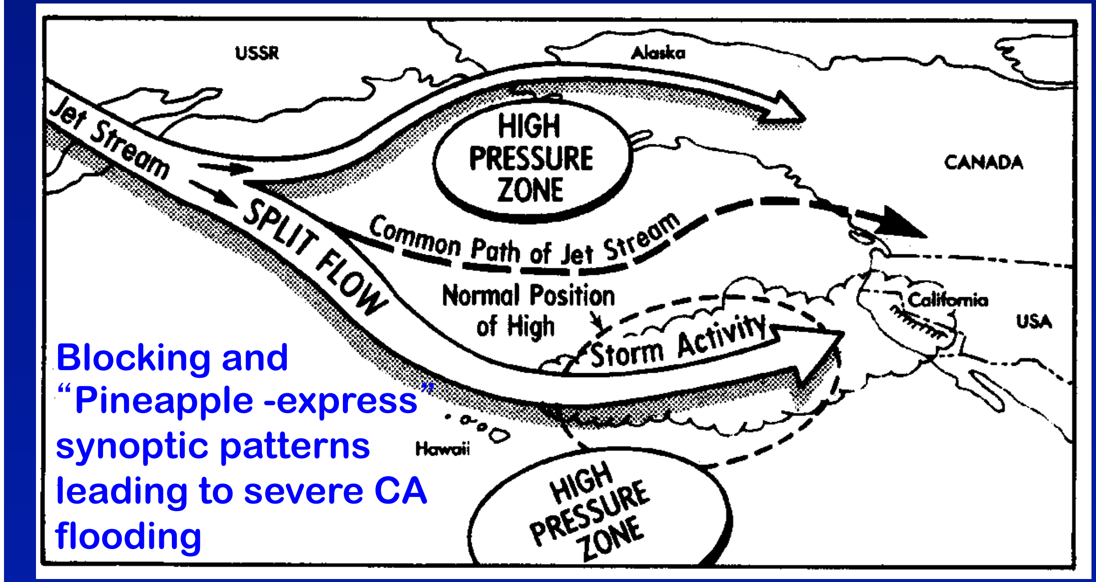


Western Type III Pattern linked to flash flooding in CA

Based on: Maddox et al. 1980

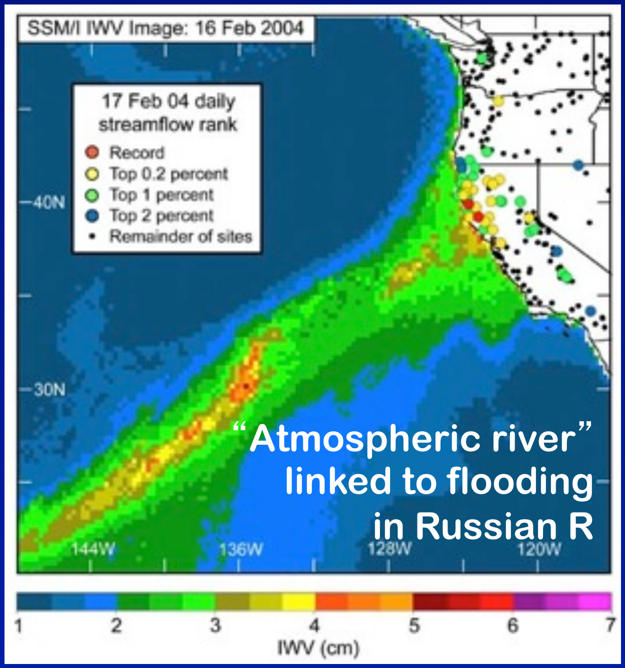


Schematic showing 3 modes of westerly flow associated with flooding in Central CA



Blocking and "Pineapple -express" synoptic patterns leading to severe CA flooding

Source: Hirschboeck 1988



"Atmospheric river" linked to flooding in Russian R

Source: Ralph et al. 2006

MIGHT THIS BE A WAY TO ADDRESS THE NONSTATIONARITY ISSUE?

 # 2 This expanded understanding of climate can be linked to flooding both deterministically and probabilistically through a process-sensitive "bottom up" approach in which individual peaks are grouped according to their flood-causing storm types and circulation patterns.

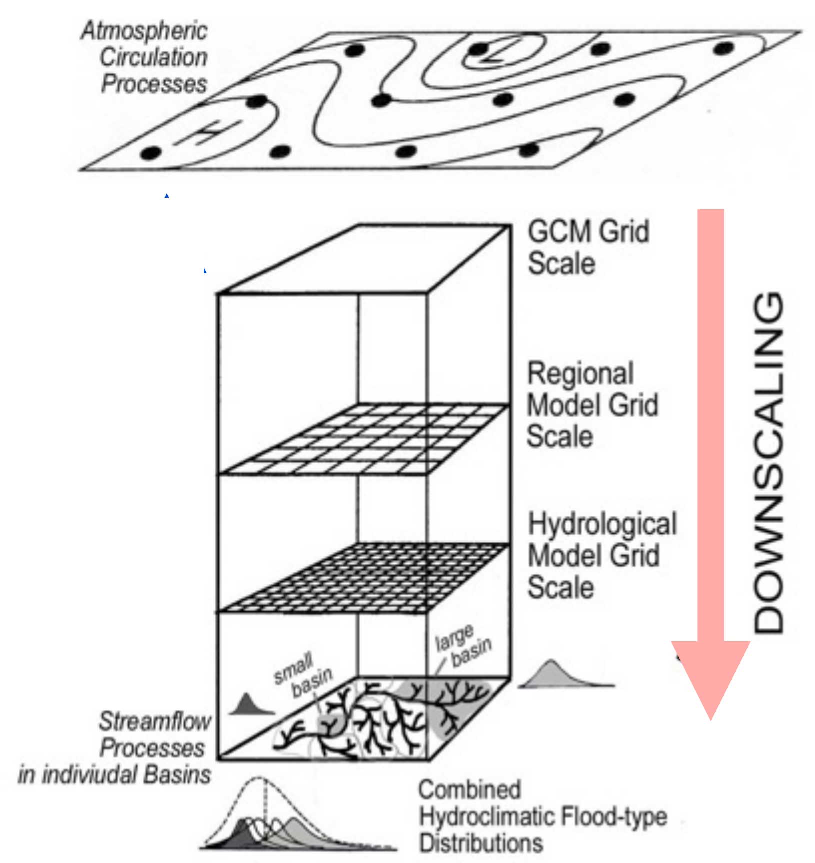
Increasingly Important Research Need:

Model runs to link surface hydrology with scenario-driven atmospheric circulation

DOWNSCALING . . .

-- “scaling up from local data is as important as scaling down from globally forced regional models.”

-- regionally tailored indices may be better than the latest “index-de-jour”



. . . Coupled with PROCESS-SENSITIVE UPSCALING

Process studies at the watershed scale to specify climate linkages

RATIONALE FOR
PROCESS-SENSITIVE UPSCALING:

Attention to climatic driving forces & causes:

- -- storm type seasonality
- -- atmospheric circulation patterns

with respect to:

- -- basin size
- -- watershed boundary / drainage divide
- -- geographic setting (moisture sources, etc.)

. . . can provide a basis for a cross-scale linkage
of GLOBAL climate variability
with LOCAL hydrologic variations
at the individual basin scale . . .

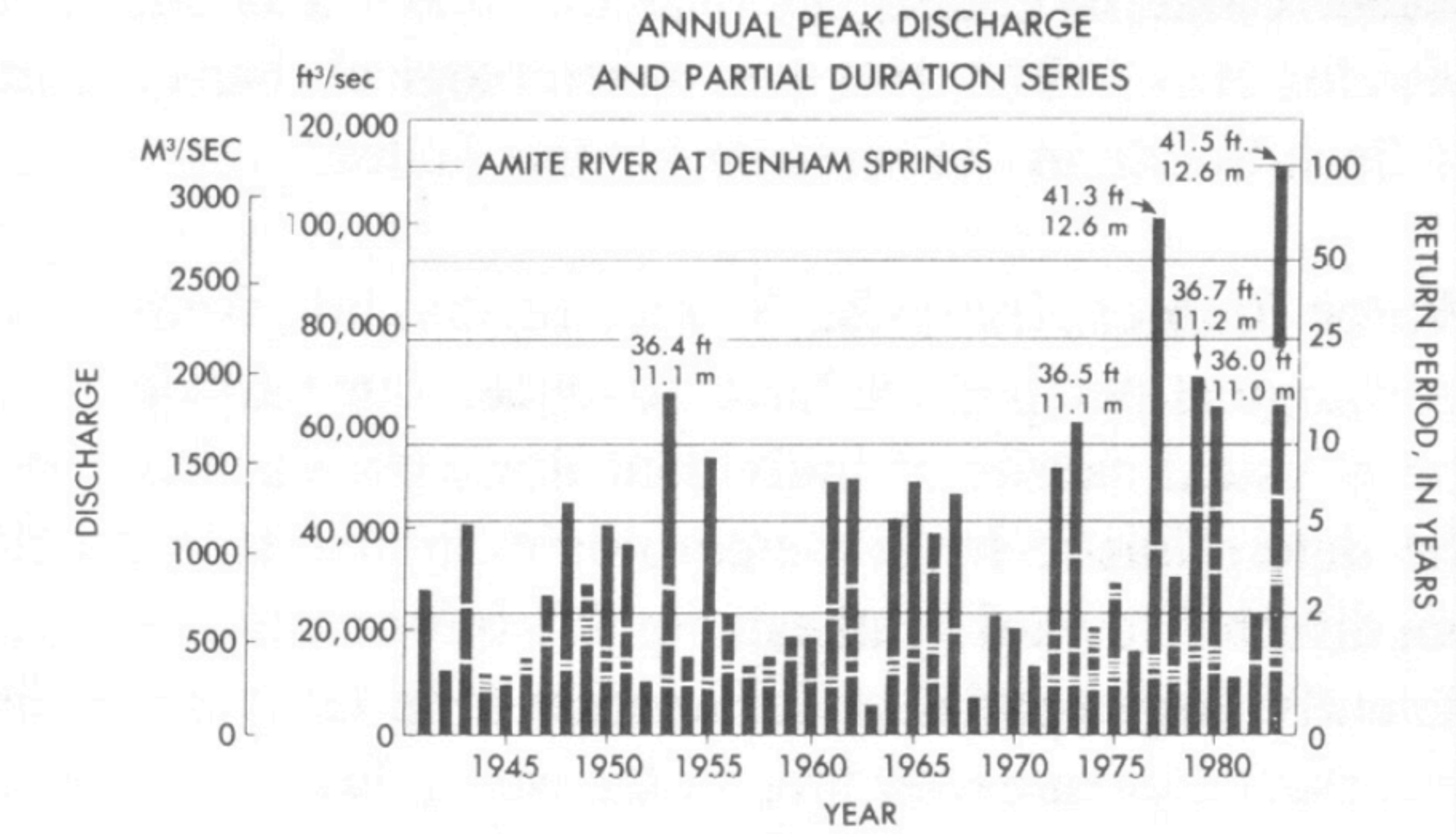
- Process-sensitive upscaling . . .
can define relationships that may not be detected via precipitation downscaling

- Allows the imprint of a drainage basin's characteristic mode of interacting with precipitation in a given storm type to be incorporated into the statistics of the flow event's probability distribution as it is "scaled up" and linked to model output and /or a larger scale flow-generating circulation pattern

CAN WE GET MORE OUT OF THE RECORDS WE HAVE?

#3 A deeper understanding of flood-climate linkages can be obtained by examining <u>all</u> observed flood peaks at a given gauge (e.g., the peaks-above-base record), not just the annual flood series.

EXAMPLE: Some years have many partial peaks, others few . . .



Climate variability may manifest itself in a shift to more frequent, smaller floods in a given year

. . . which would be missed in the annual series or a selection of the most extreme floods.

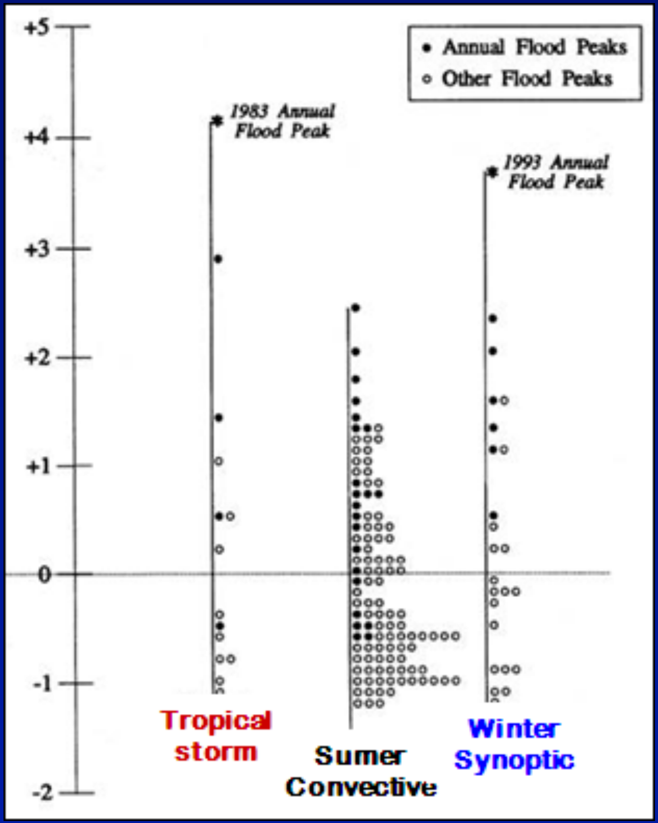
CAN WE TARGET OUR EXPLORATION MORE STRATEGICALLY REGIONALLY?

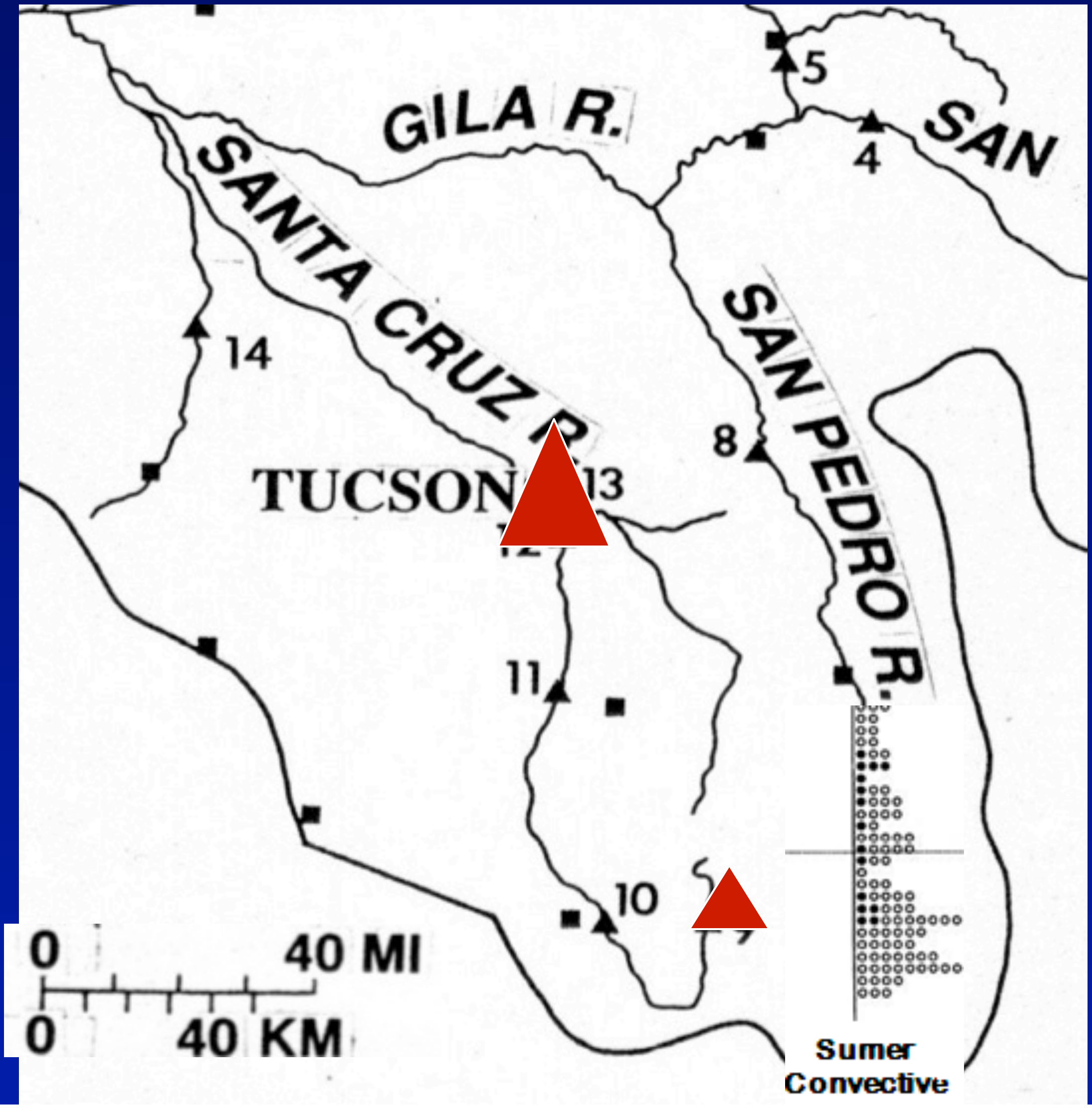
#4 Watersheds located in transition zones between climate regions, or at the margins of influence by a specific storm type are likely to exhibit the greatest sensitivity to climatic variability.

ARE THERE UNTAPPED CLIMATE-RELATED EXPLANATIONS FOR WATERSHED RESPONSE, PARTITIONING, & SCALING THEORY?

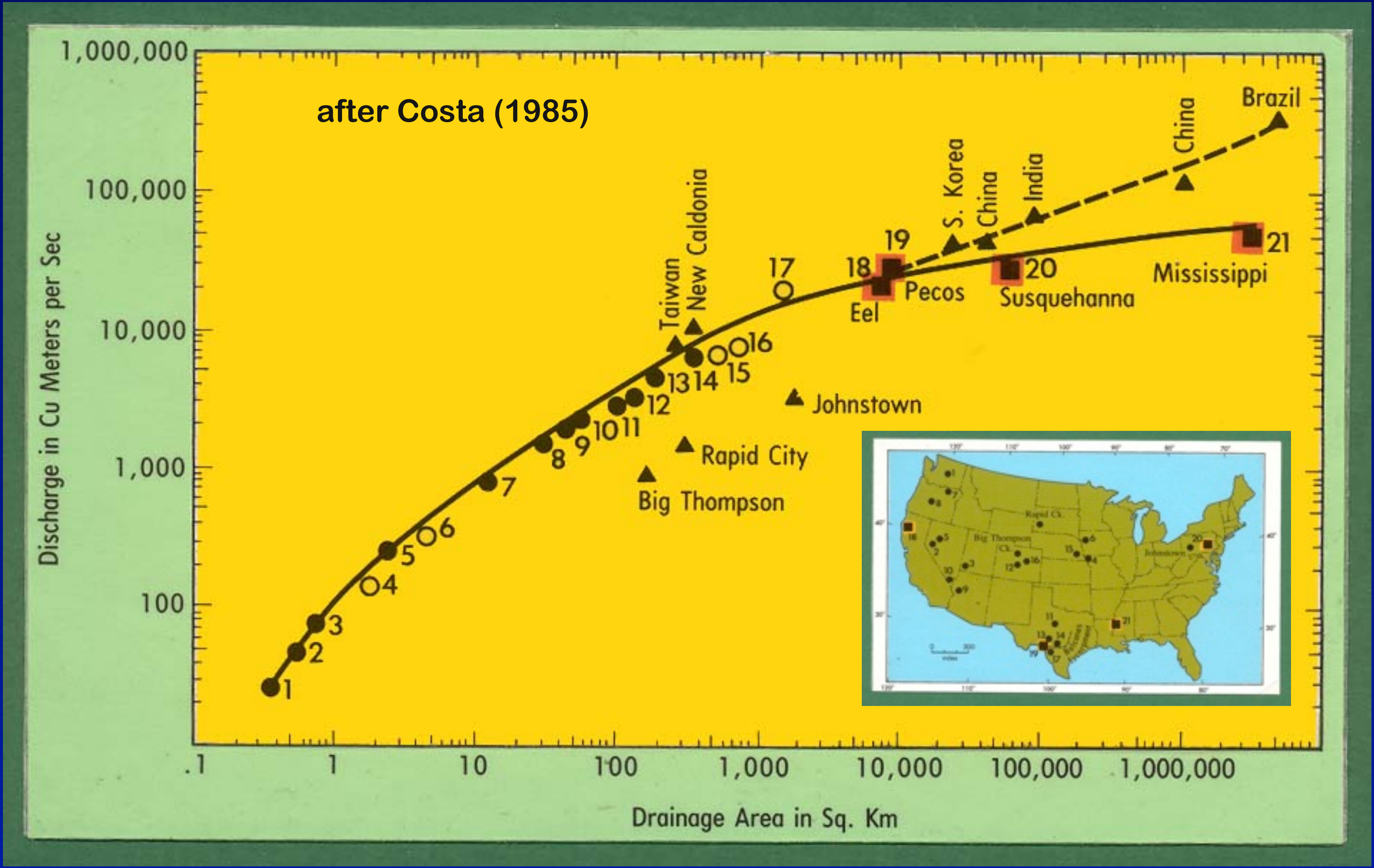
#5 The dominant flood-producing storm type can vary with basin size, elevation, and orographic influence, resulting in a varied response to climatic variability depending on a basin’s scale and hierarchical position.

Response to weather & climate varies with basin size (e.g. convective events are more important flood producers in small drainage basins)





Flood Hydroclimatology for Floods of Record



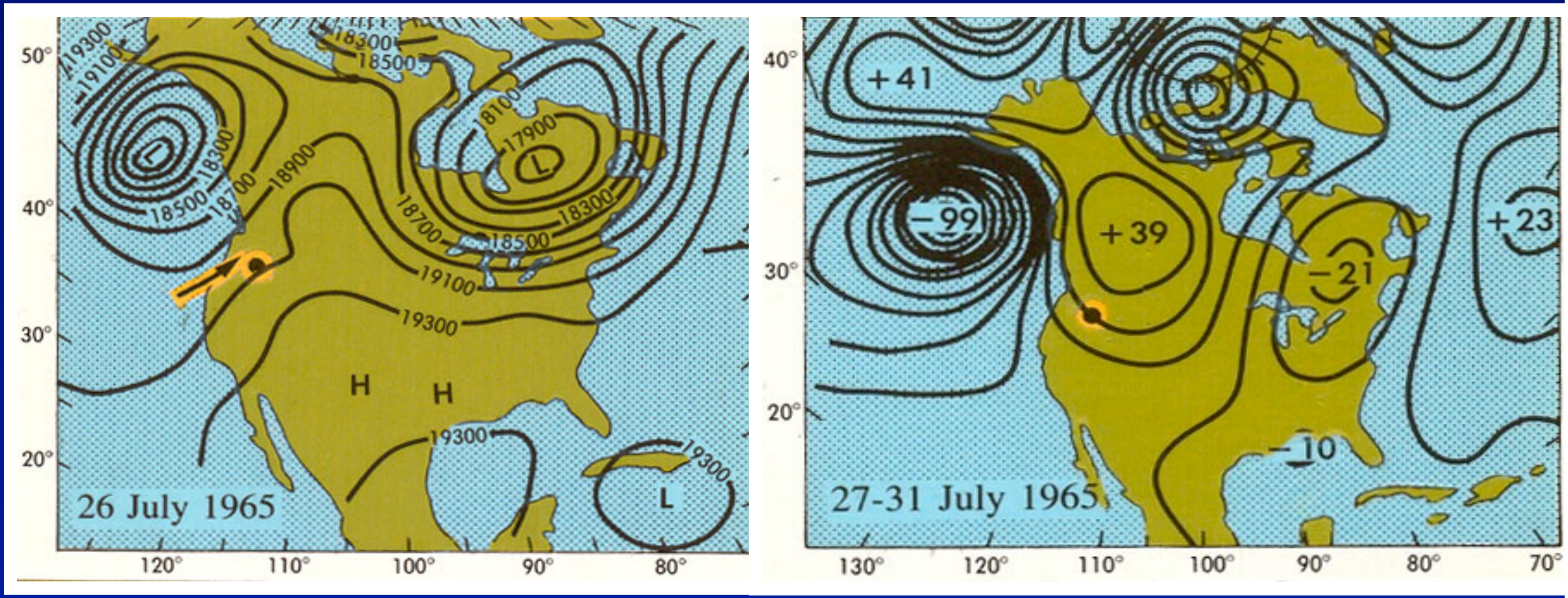
after Costa (1985)

The Most Extreme Floods Evolve From:

- uncommon (or unseasonable) locations of typical circulation features
(a future manifestation of climate change?)
- unusual combinations of atmospheric processes
- rare configurations in circulation patterns (e.g. extreme blocking)
- exceptional persistence of a specific circulation pattern.

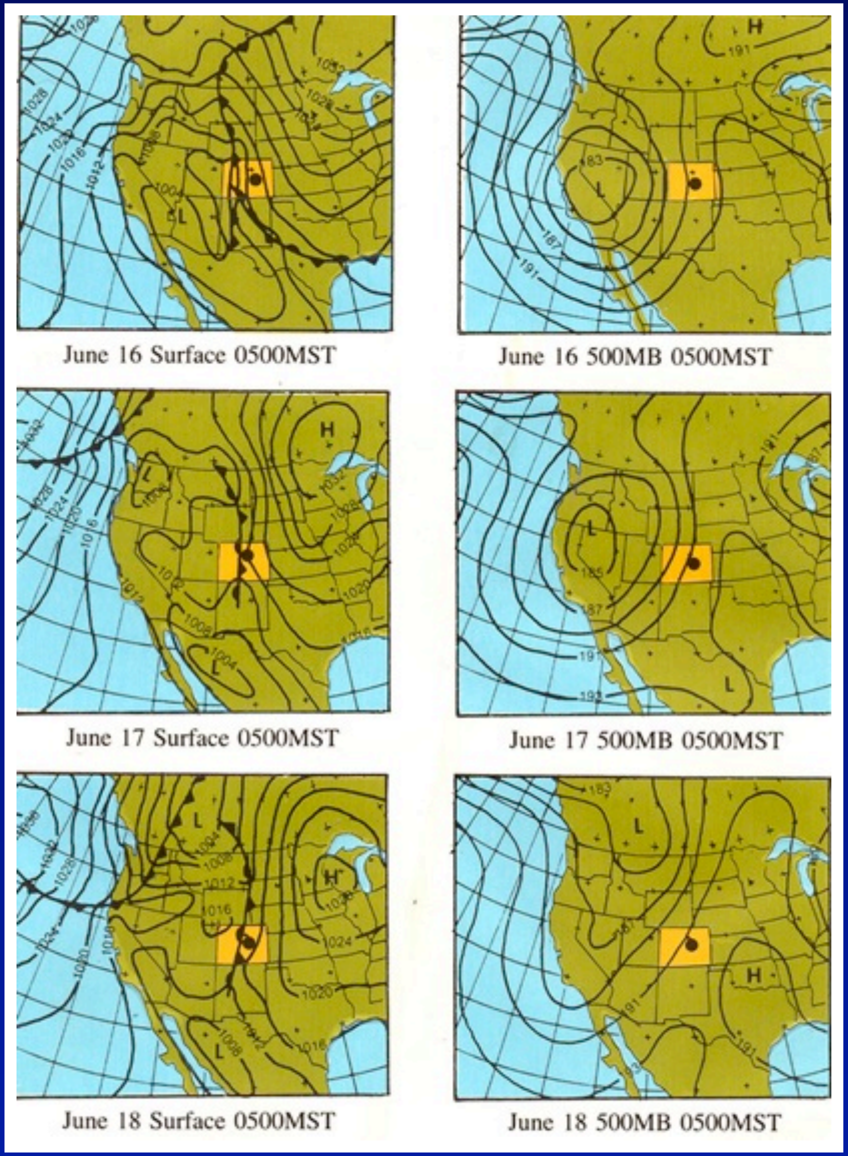
EXAMPLE:

Rare configurations in circulation patterns (extreme blocking)



Lane Canyon flash flood

EXAMPLES: exceptional persistence of a specific circulation pattern.



June 16 Surface 0500MST

June 16 500MB 0500MST

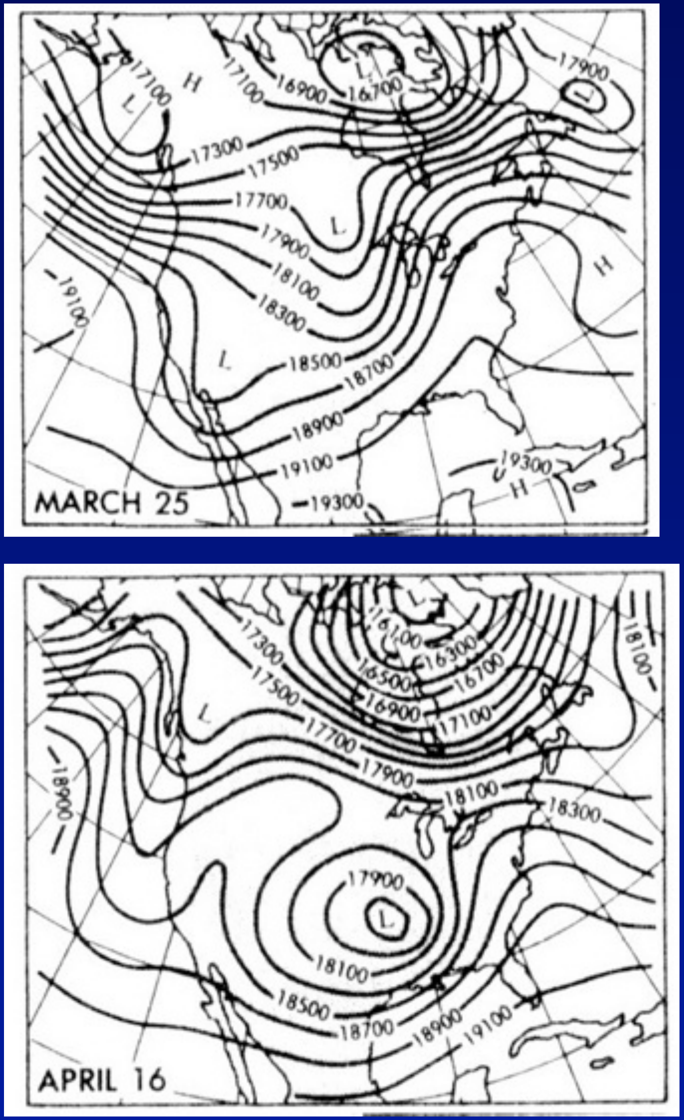
June 17 Surface 0500MST

June 17 500MB 0500MST

June 18 Surface 0500MST

June 18 500MB 0500MST

Jimmy Camp Creek flood of 1965

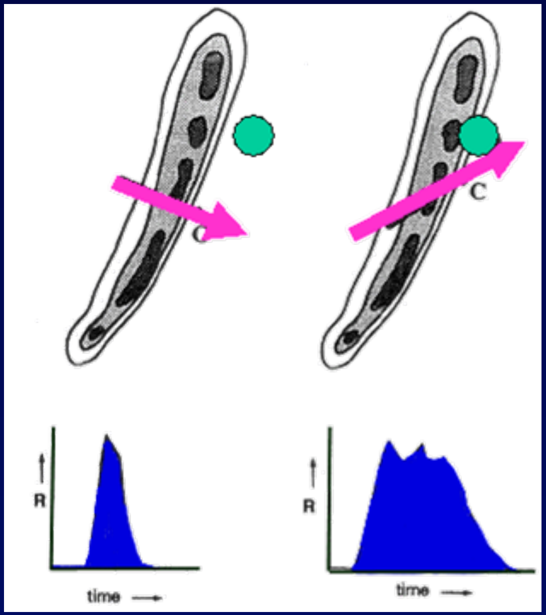


Spring 1973 Mississippi River Basin floods

In addition, extreme flow events can emerge from <u>synergism</u> in:

The way in which rainfall or snow is delivered

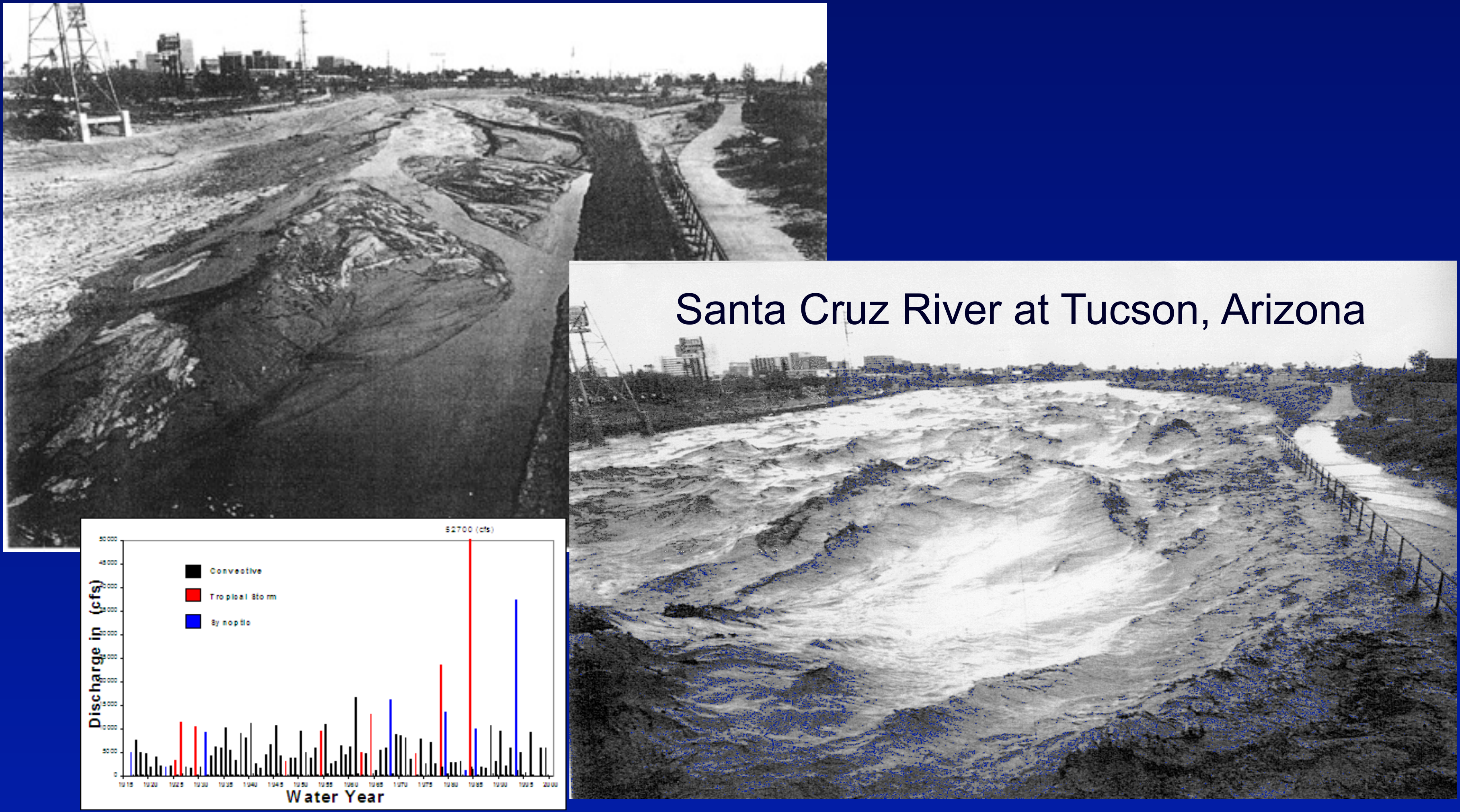
- in both space (e.g., storm movement, direction)
- and time (e.g., rainfall rate, intensity)
- over drainage basins of different sizes & orographies



from Doswell et al. (1996)

1. Expand mechanistic understanding of climate
2. Use a process-sensitive “bottom-up” approach
3. Take full advantage of peaks-above base records
4. Target regions of flood sensitivity to climate
5. Link all of the above to watershed characteristcs . . . . and . . .

. . . let the rivers "speak for themselves" about how <u>they</u> respond to climate !



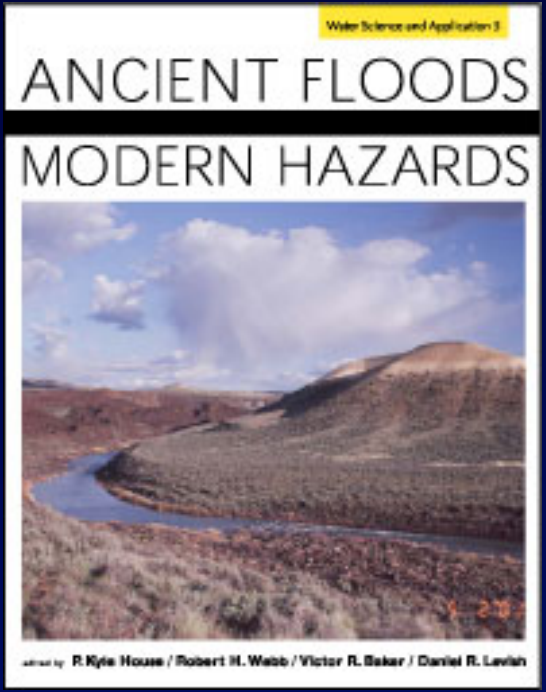
Santa Cruz River at Tucson, Arizona

Constraining Flood Probabilities with Hydroclimatic & Paleohydrological Information

I. Insights from "Flood Hydroclimatology"" "on the Probability of Extremes

II. The Potential of Paleoflood Information

Closing Thoughts



Water Science and Application 5

ANCIENT FLOODS

MODERN HAZARDS

edited by P. Kyle House / Robert H. Webb / Victor R. Baker / Daniel R. Levish

House, Webb, Baker
& Levish (2002)
American Geophysical Union

ADVANTAGES OF EXPLORING HOW FLOODS ARE REPRESENTED IN THE PALEORECORD

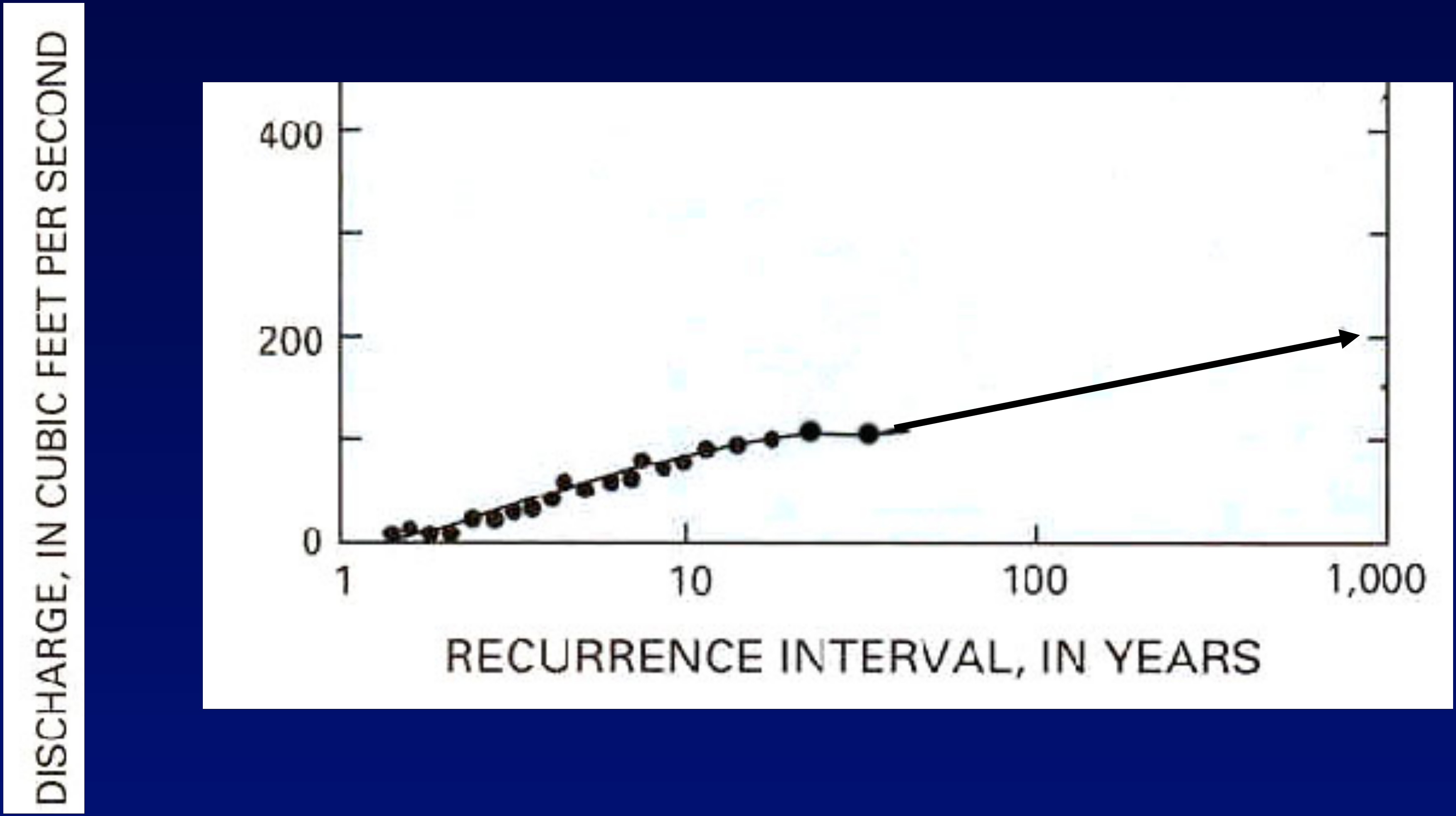
To fully understand flood variability, the longest record possible is the ideal . . .

<u>especially</u> to understand and evaluate <u>extreme</u> flooding!

By definition extreme events are rare . . .
hence gaged streamflow records capture only a recent sample of the full range of extremes that have been experienced by a given watershed.

Flood Frequency Analysis:

Straightforward extrapolation . . . .

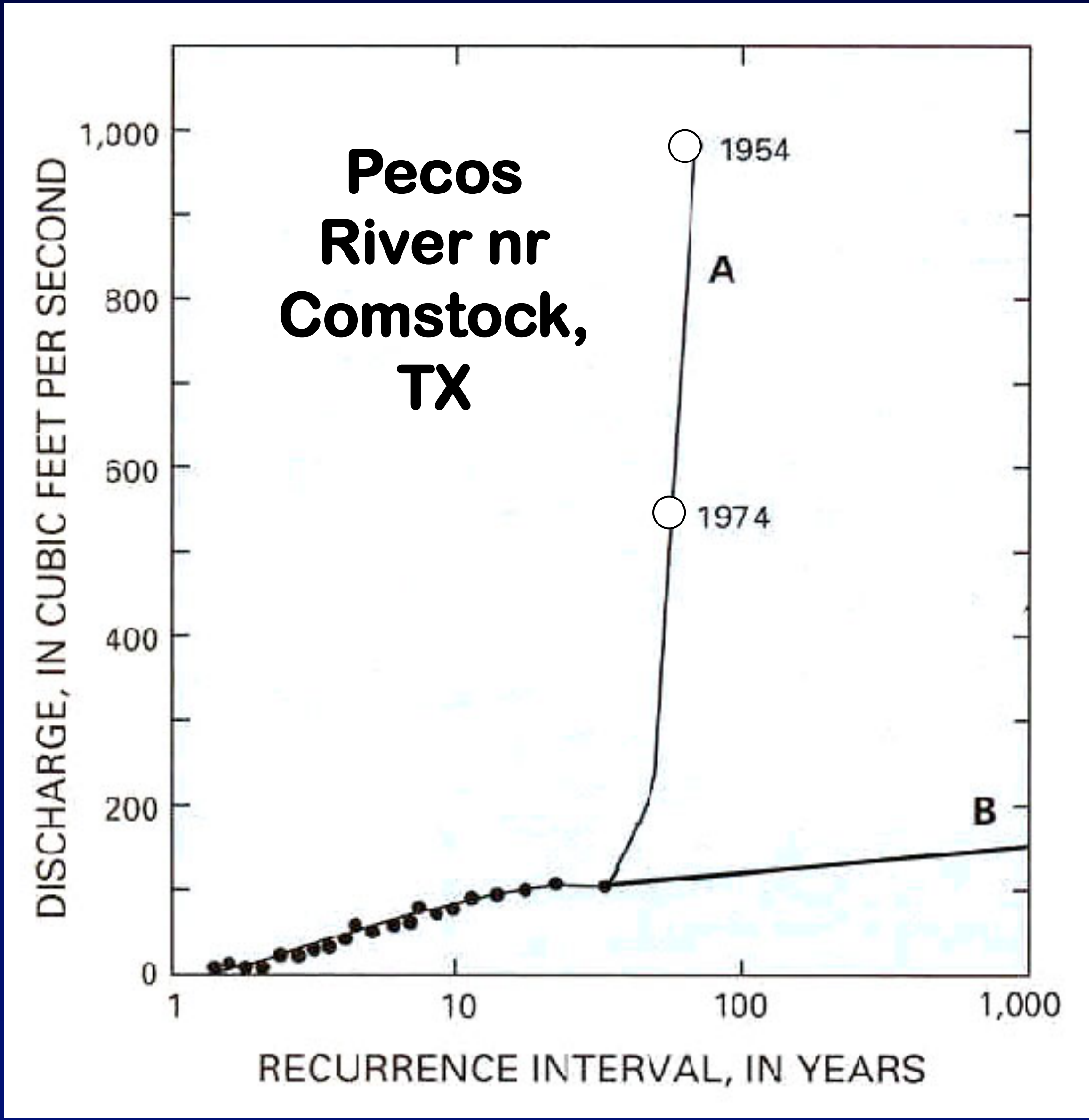


(SOURCE: modified from Jarrett, 1991 after Patton & Baker, 1977)

The Challenge of the "Upper Tails"

. . . can fail when "outlier" floods occur !

Curves A & B indicate the range (uncertainty) of results obtained by using conventional analysis of outliers for 1954 & 1974 floods.



SOURCE: modified from Jarrett, 1991, after Patton & Baker, 1977

Using Paleo-stage Indicators & Paleoflood Deposits . . .

-- ***direct*** **physical evidence of extreme hydrologic events**

-- selectively preserve evidence of only the largest floods . . .

. . . this is precisely the information that is lacking in the short gaged discharge records of the observational period

- Paleoflood evidence provides information about the upper discharge and stage limits of the most extreme floods (and by inference, the flood-generating precipitation) and their likely return periods.
- this type of information is not available in any other source of paleoenvironmental data.

Flood Frequency Analysis

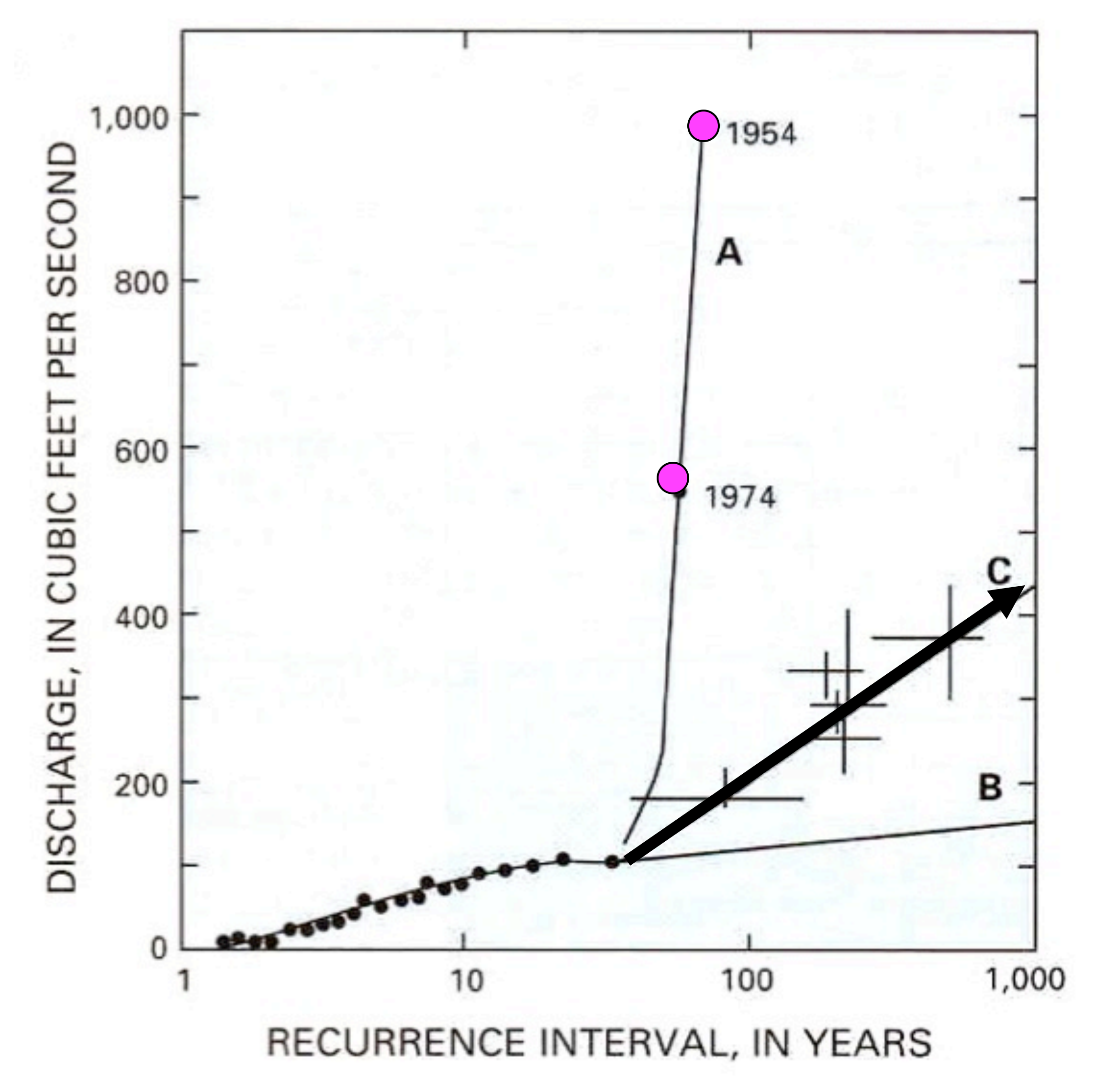
Curves A & B indicate range (uncertainty) of results obtained by using conventional analysis of outliers for 1954 & 1974 floods.

Curve C is from analyses of paleoflood data.

| Q (discharge) uncertainty

— R.I. uncertainty

(SOURCE: Jarrett, 1991 after Patton & Baker, 1977)



Not all Paleofloods are "Paleo" . . .

- PALEOFLOOD

A past or ancient flood event which occurred prior to the time of human observation or direct measurement by modern hydrological procedures.

- HISTORICAL FLOOD

Flood events documented by human observation and recorded prior to the development of systematic streamflow measurements

- EXTREME FLOODS IN UNGAGED WATERSHEDS

For comparison & benchmarks:
GAGED HYDROLOGICAL RECORDS *are often combined, but ...*

. . . unlike systematic gaged data, paleoflood information is collected and reported in different ways, leading to different "data types" . . .

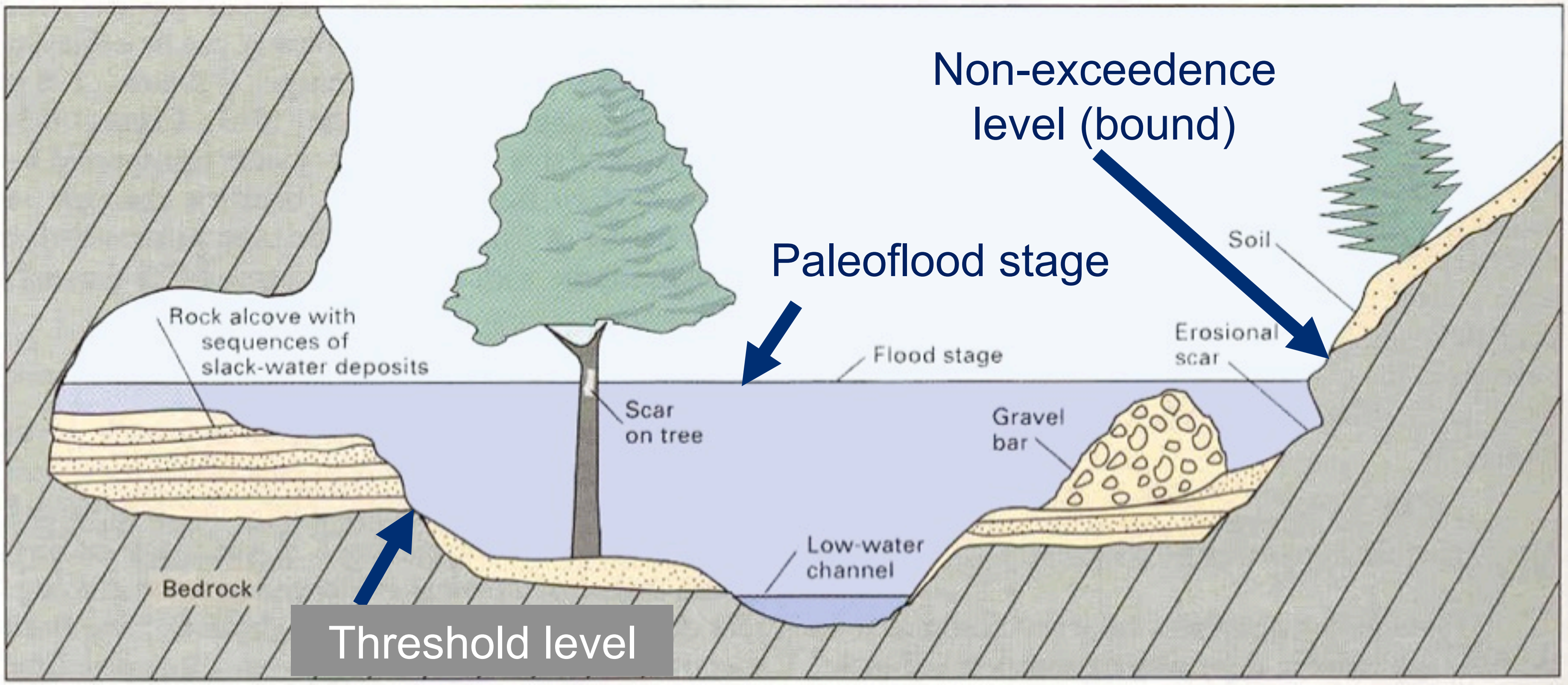
- Paleofloods (w/ stage +/or discharge)
  ("paleo-stage indicator" = PSI)
- Thresholds
- Non-exceedence bounds

Paleoflood = discrete flood / paleoflood stage or discharge estimate

Threshold = a stage or discharge level below which floods are not preserved; only floods which overtop the threshold level leave evidence; smaller events not preserved (over specific time interval)

Non-exceedence bound = a stage or discharge level which has either never been exceeded, or has not been exceeded during a specific time interval

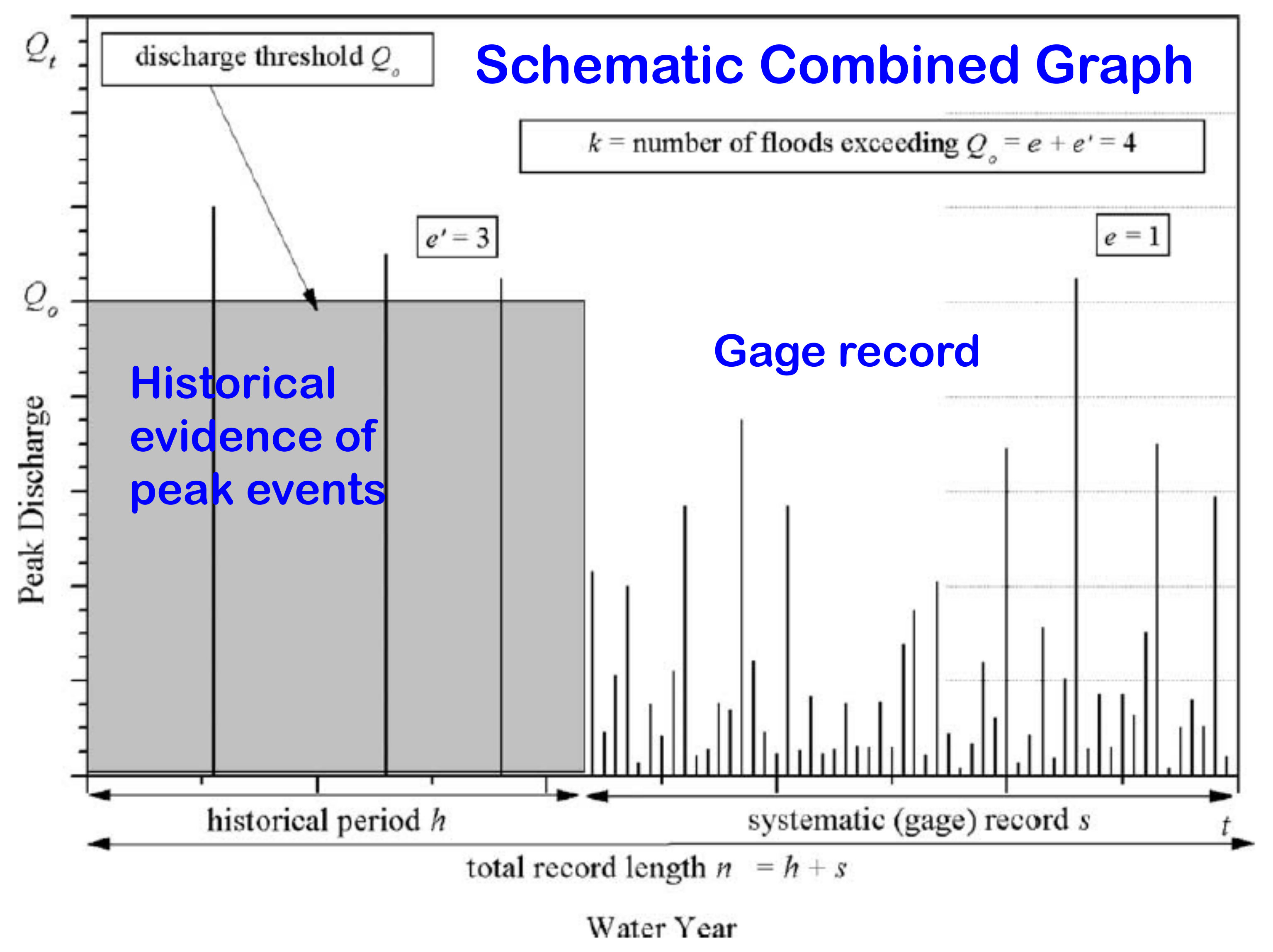
Paleoflood Data Types:



Diagrammatic section across a stream channel showing a flood stage and various features

(Source: Jarrett 1991, modified from Baker 1987)

Schematic Combined Graph

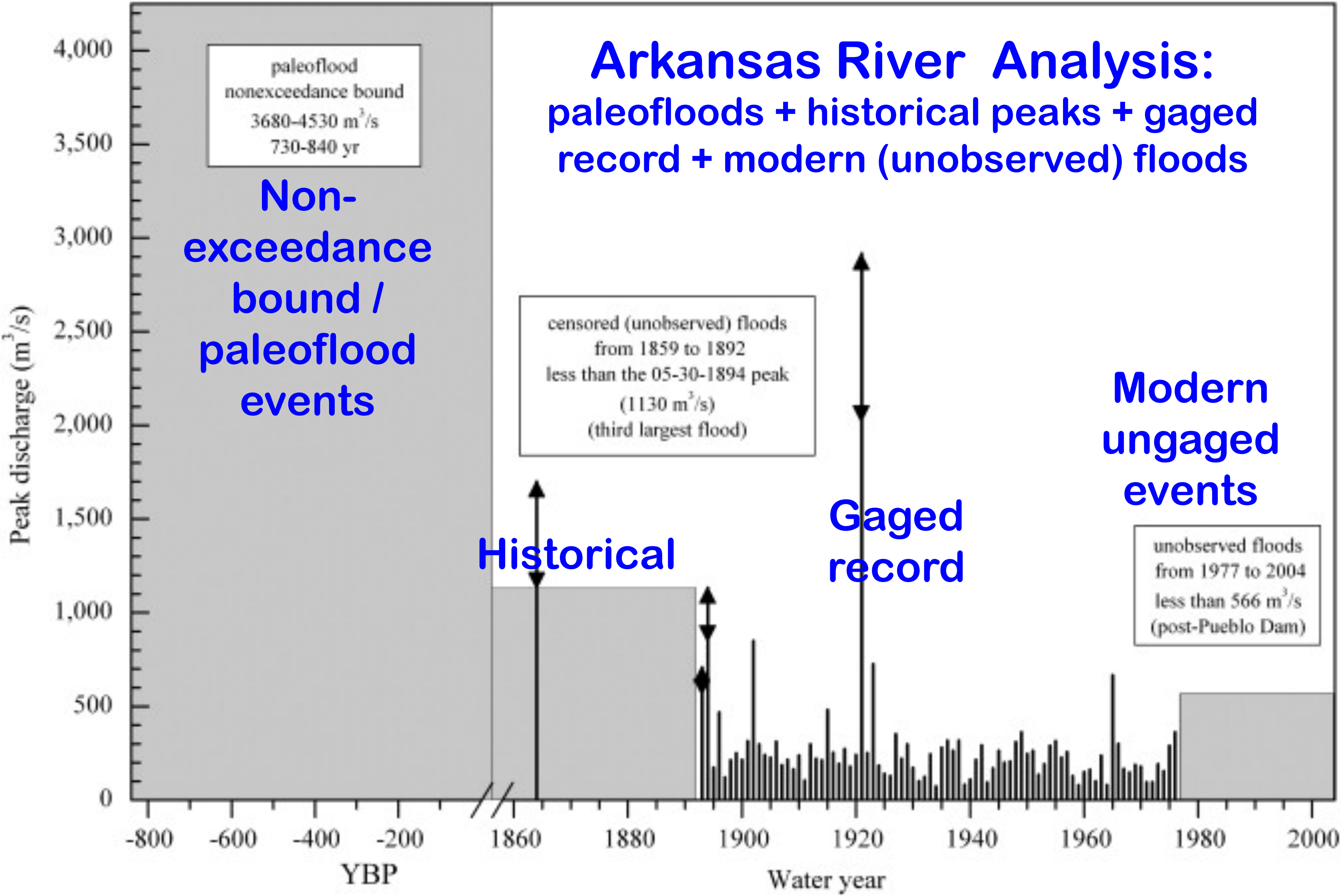


Example peak discharge time series with historical period and discharge threshold Q_0: The shaded area represents floods of unknown magnitude less than Q_0.

Source: England, Jarrett and Salas (2003)

Arkansas River Analysis:

paleofloods + historical peaks + gaged record + modern (unobserved) floods

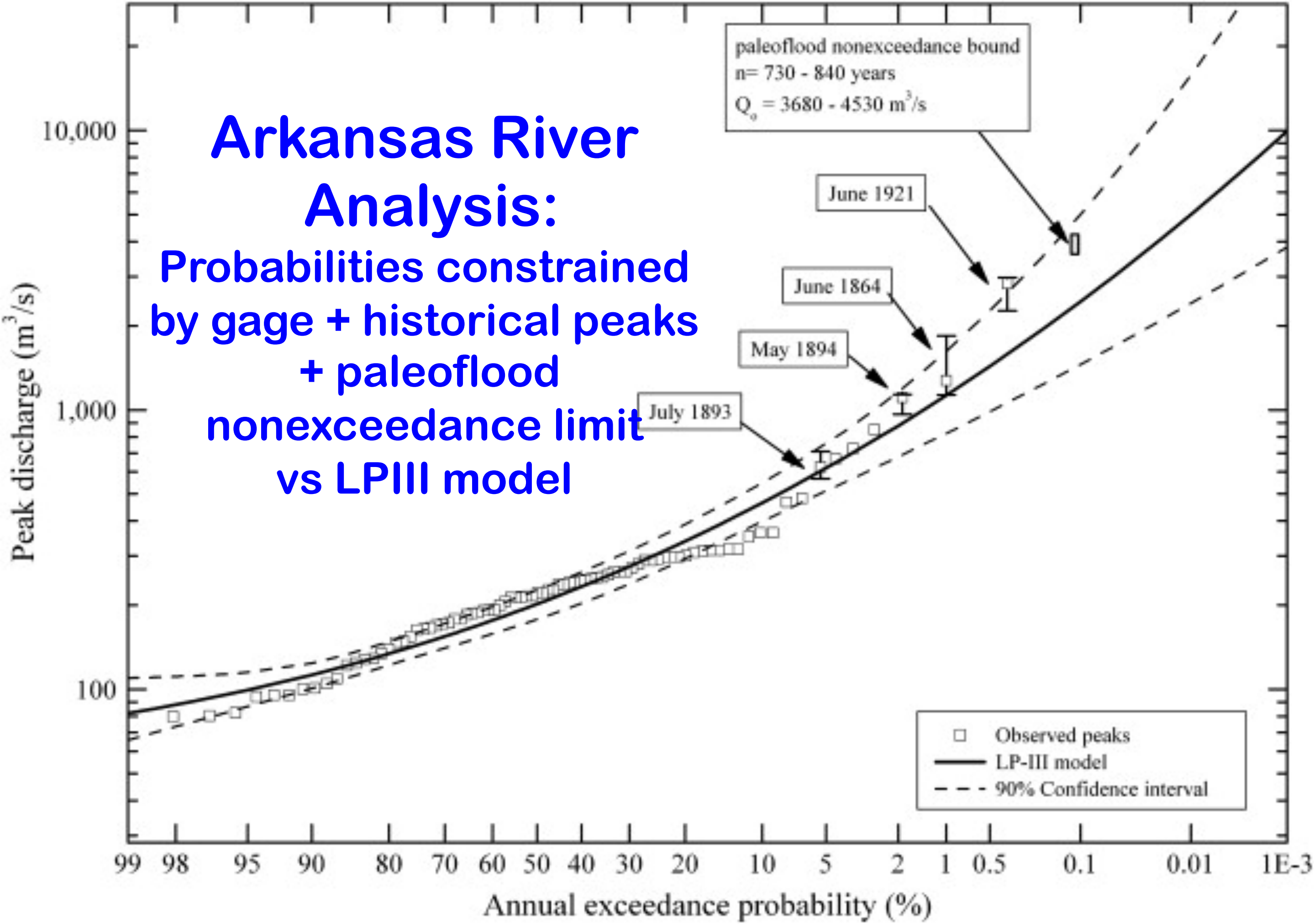


Peak discharge, historical, and paleoflood estimates, Arkansas River at Pueblo State Park. A scale break is used to separate the gage and historical data from the longer paleoflood record. Arrows on the 1864, 1893, 1894, and 1921 floods indicate floods in a range.

Source: England, et al. (2010)

Arkansas River Analysis:

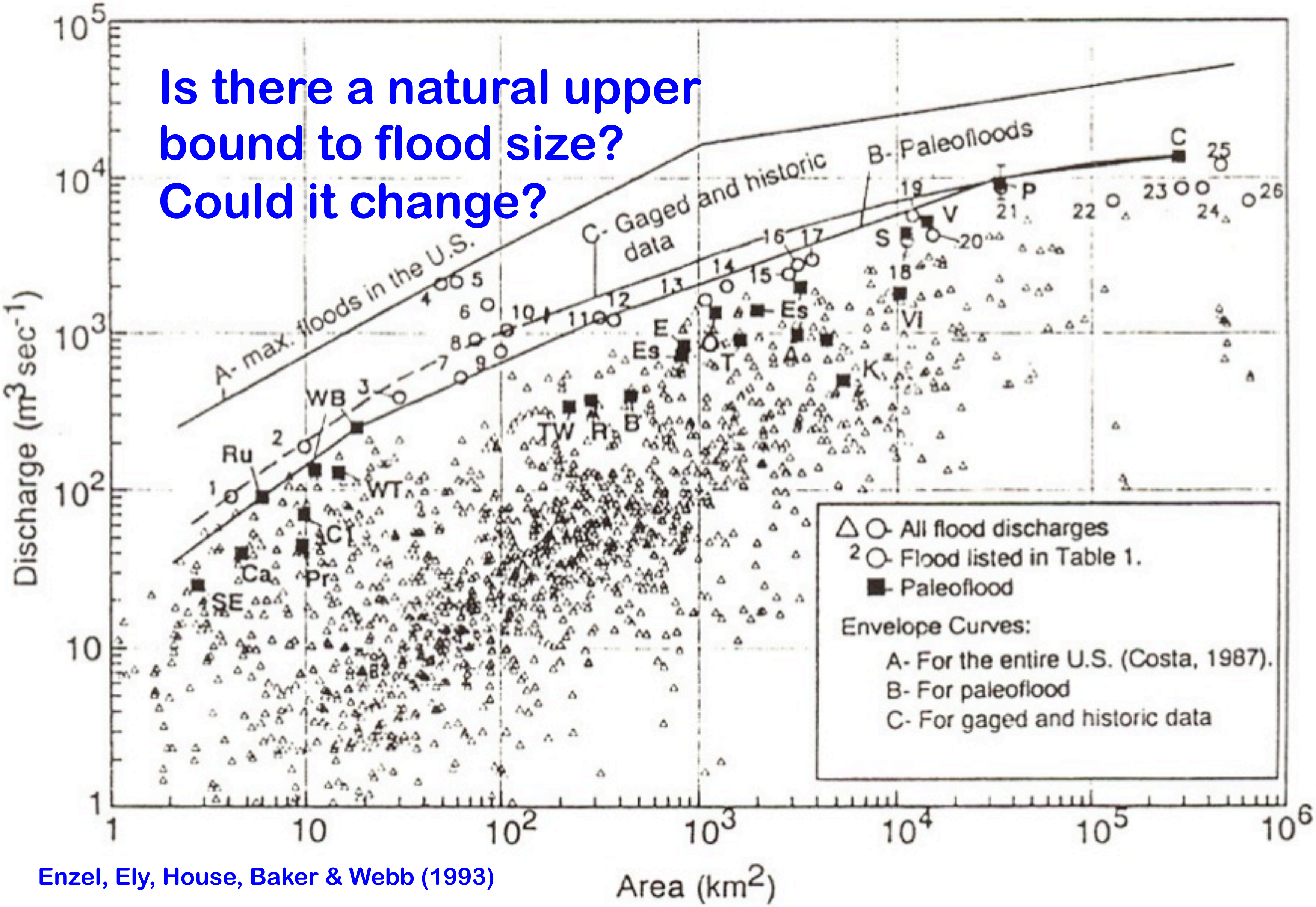
Probabilities constrained by gage + historical peaks + paleoflood nonexceedance limit vs LPIII model



Peak discharge frequency curve, Arkansas River at Pueblo State Park, including gage, historical, and paleoflood data. Peak discharge estimates from the gage are shown as open squares; vertical bars represent estimated data uncertainty for some of the largest floods. Paleoflood nonexceedance bound shown as a grey box.

Source: England, et al. (2010)

Paleoflood evidence for a natural upper bound to flood magnitudes in the Colorado River Basin

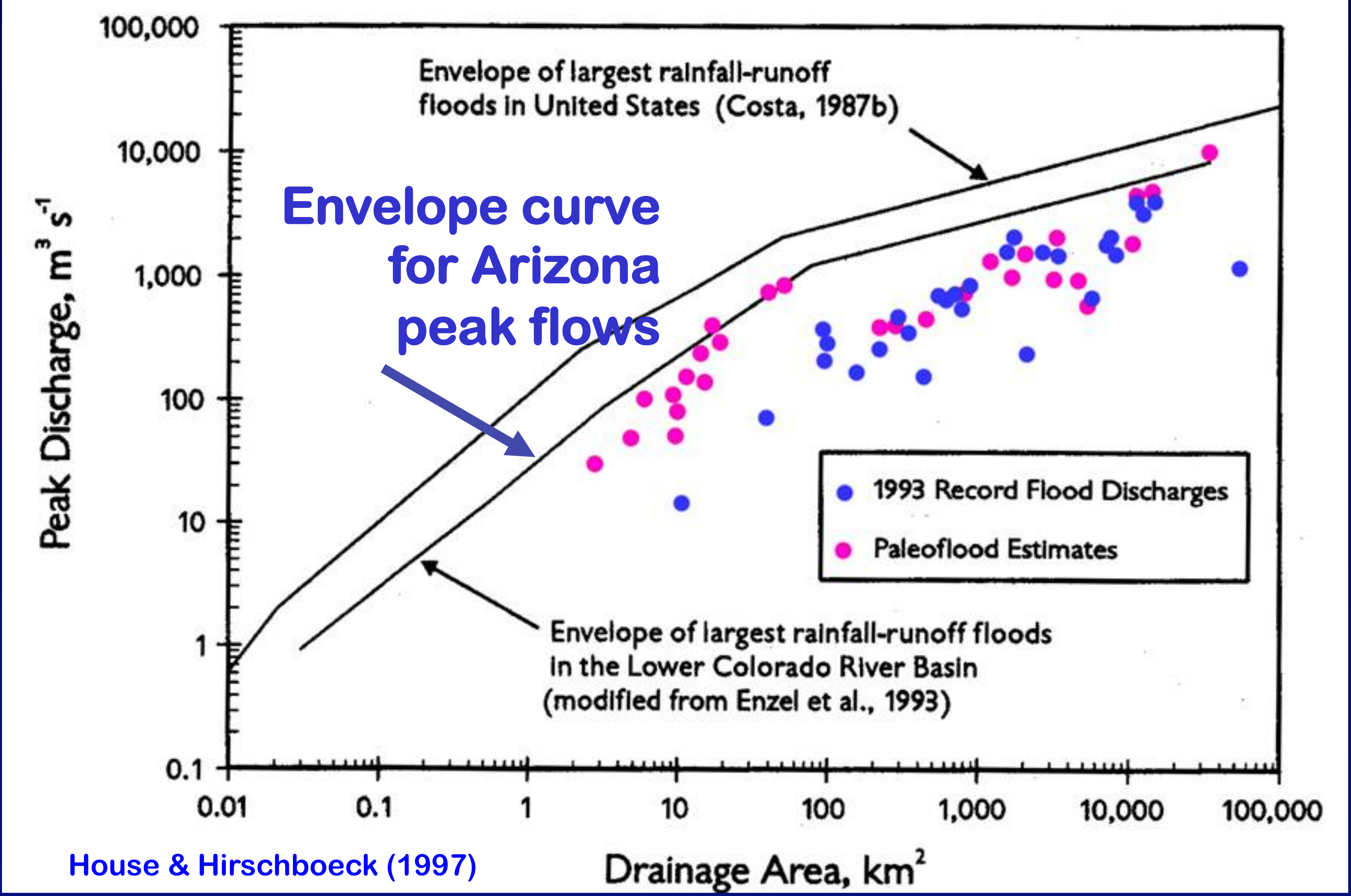


Is there a natural upper bound to flood size?
Could it change?

Enzel, Ely, House, Baker & Webb (1993)

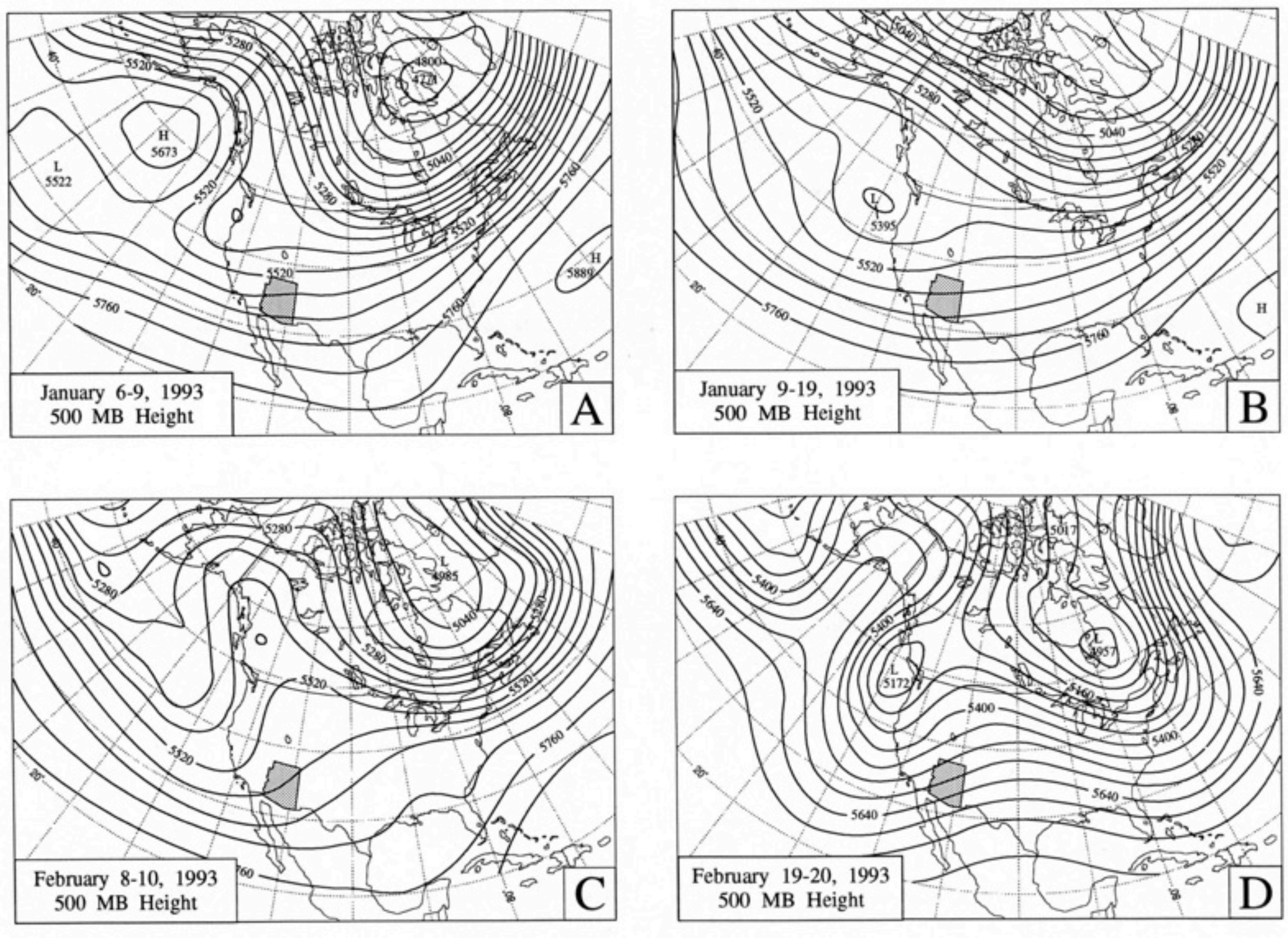
Lower Colorado Basin Envelope Curve

(with 1993 Flood Peaks and Paleoflood estimates plotted)



Envelope curve for Arizona peak flows

House & Hirschboeck (1997)



Record-breaking floods of winter 1992-93 in Arizona

Questions to ponder . . .

- **How useful are paleoflood data for water management planning?**

  for water supply, for floods?

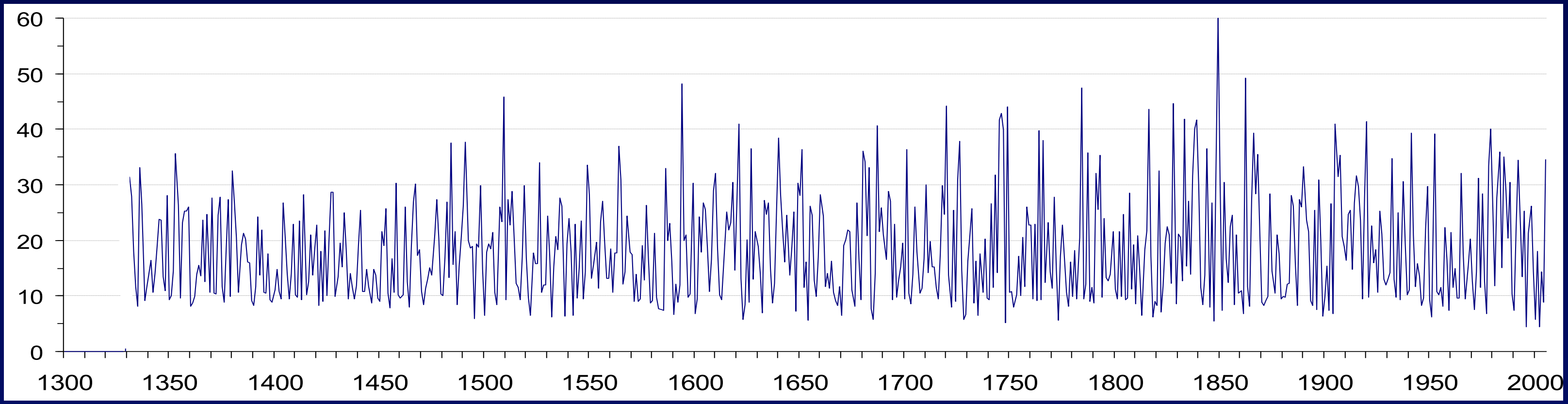
- **What format would be the most useful?**

- **To what degree do peak events influence the annual (or seasonal) flow of a river?**

  . . . . if they do . . . . ➔

Another question:

Are extreme floods and peak flows identifiable in a Tree-Ring Reconstruction?

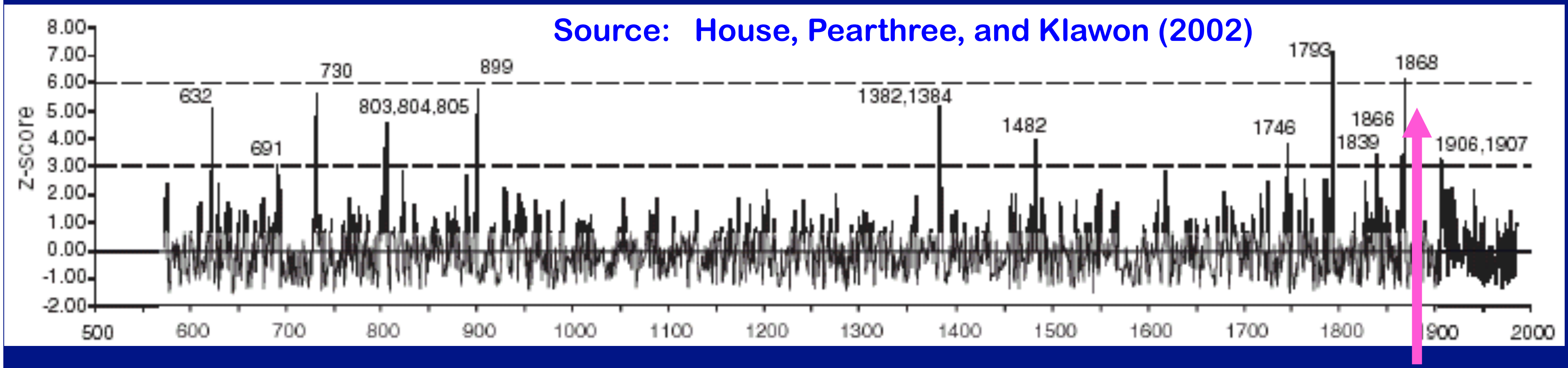


ISSUES:

- **trees tend to be more drought senstitive**
- **extreme floods / paleofloods are intermittent**
- **paleofloods cannot be archived as continuous annually resolved chronologies**

Can paleofloods be “seen” in tree-ring streamflow reconstructions? *(answer = mixed results)*

Verde River, AZ: Paleoflood Data Vs. Tree-ring Based Annual Streamflow Reconstruction



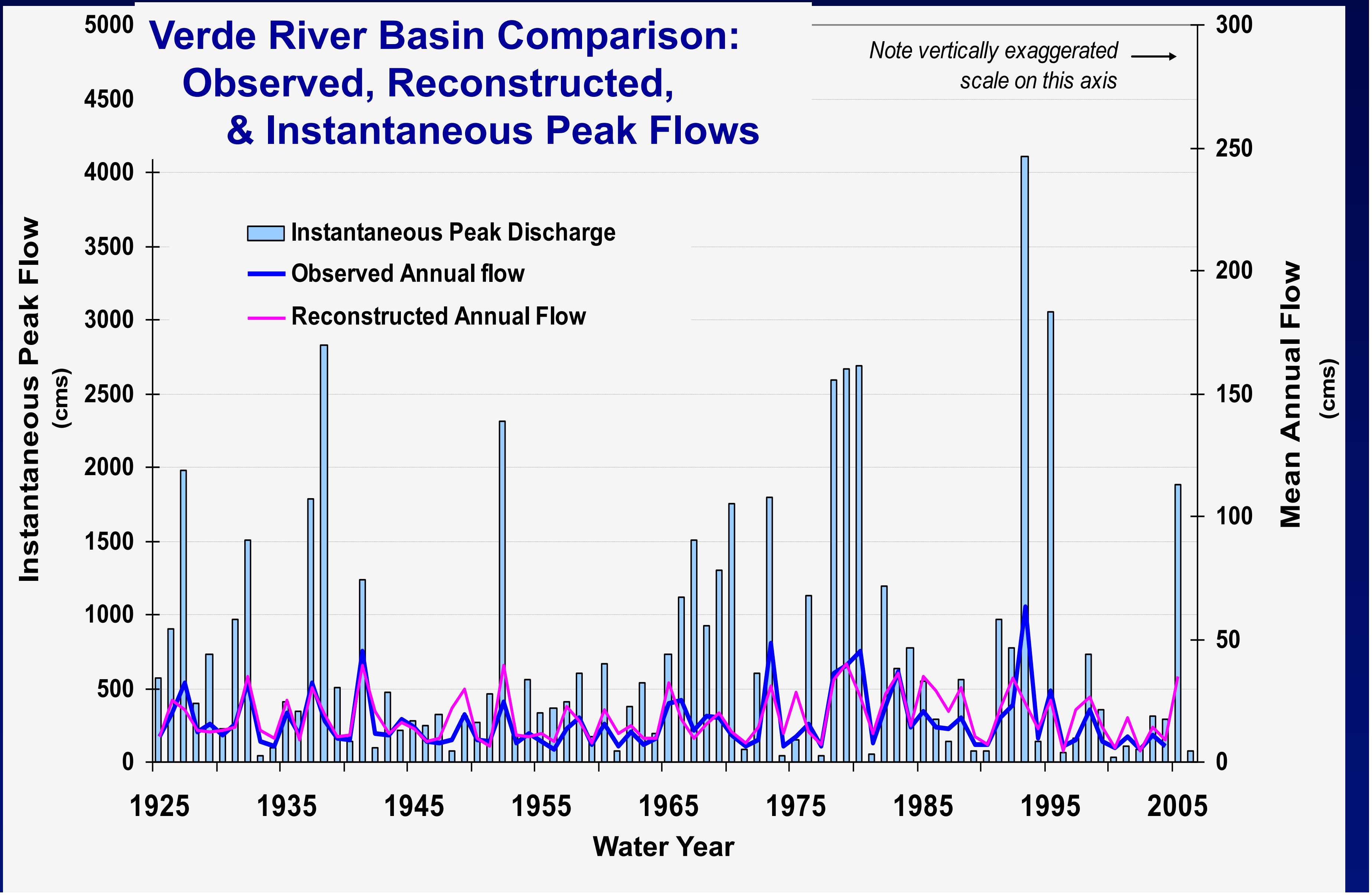
Source: House, Pearthree, and Klawon (2002)

<u>No</u> corresponding peaks in streamflow reconstruction for paleofloods of 1862 & 1891

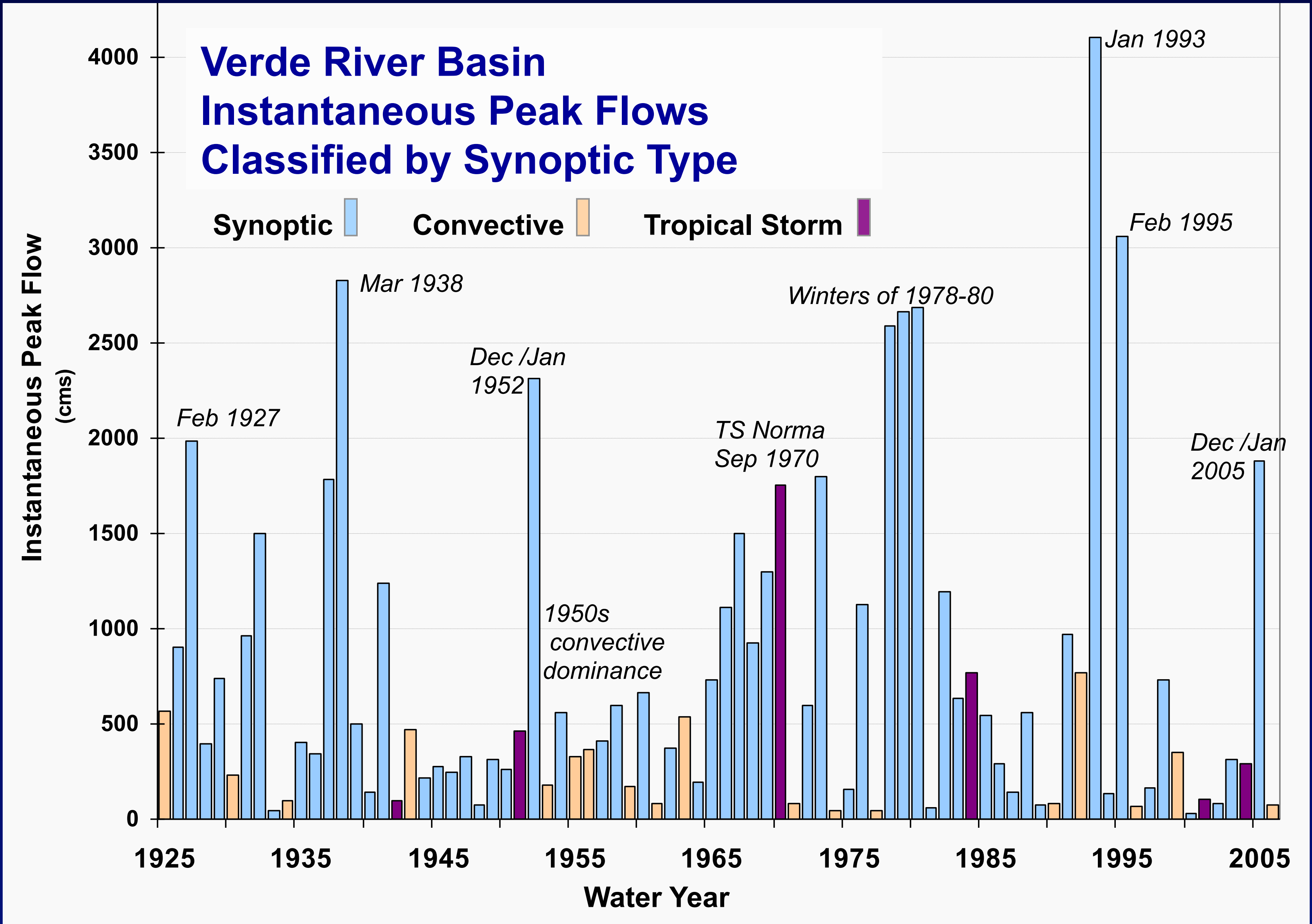
1868 peak = <u>has</u> a corresponding paleoflood

Our new Verde reconstruction awaits analysis!

Process-based evaluation of relationship between mean annual flow & instantaneous peaks . . .



. . . combined with flood hydroclimatology info . . .

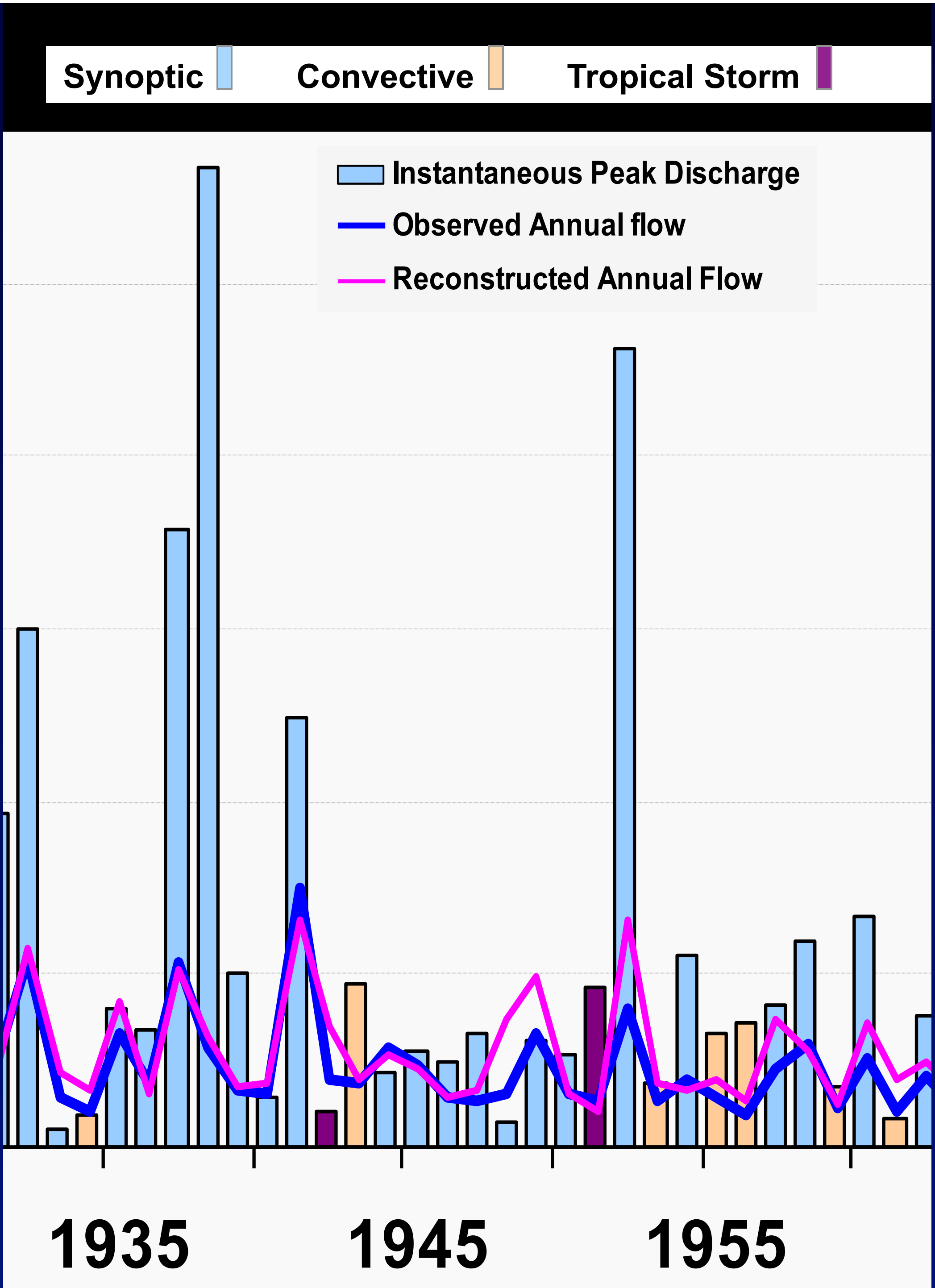


Verde River Basin
Instantaneous Peak Flows
Classified by Synoptic Type

. . . and analyzed mechanistically

INSIGHTS:

Both reconstructed & observed annual flows track the magnitude of the instantaneous peak better during synoptic (winter) events



POTENTIAL USES OF PALEOFLOOD INFO

- Seasonal / long-term / extreme event perspective
- Site-specific and regional synthesis of extremes
- Regional linkages / differences identified
- Entire flood history context → benchmarks of extreme events for monitoring future climate change
- Reference database for near-real time assessment of developing events
- Link to other forms of paleodata (i.e. tree-ring streamflow reconstructions)

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HOW MIGHT CLIMATE CHANGE AFFECT THESE DISTRIBUTIONS?

1. The impact of climate change on a flood distribution is likely to be more complex than a simple shift in mean or variance

2. Climatic changes can be conceptualized as time-varying atmospheric circulation regimes that generate a mix of shifting streamflow probability distributions over time

Recommendation: We need to continue to develop new and evolving statistical tools that can address this behavior.

3. The interactions between storm properties and drainage basin properties also play an important role in the occurrence and magnitude of large floods both regionally and seasonally.

Recommendation:

Watershed–based hydrometeorology studies should continue to be a key component of watershed and flood management practice.

4. Shifts in storm track locations and other anomalous circulation behavior are clearly linked to unusual flood (and drought) behavior.

They are likely to be the factors most *directly* responsible for projected increases in hydrologic extremes under a changing climate.

Recommendation: Use process-sensitive upscaling to link circulation patterns directly to flood–producing mechanisms and to complement downscaling

5. In the largest and most extreme floods studied, PERSISTENCE was always a factor

- Persistence of INGREDIENTS (e.g., deep moist convection environment) was most important at small scales (flash floods)
- Persistence of PATTERN was most important at larger scales (basin-wide / regional floods)
- Quasi-stationary patterns such as blocking ridges and cutoff lows in the middle-level flow were linked to extreme events in all sizes of basins

- Process-sensitive upscaling . . .
can define relationships that may not be detected via precipitation downscaling

- Allows the imprint of a drainage basin's characteristic mode of interacting with precipitation in a given storm type to be incorporated into the statistics of the flow event's probability distribution as it is "scaled up" and linked to model output and /or a larger scale flow-generating circulation pattern

Thank you!

Questions?