Constraining Flood Probabilities with Hydroclimatic & Paleohydrological Information

Katie Hirschboeck
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.

National Research Council
1988
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.”
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
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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

“Normals”

“Indices”
#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 Geomorphology (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
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

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

Water Year

Discharge in (cfs)

Convective
Tropical Storm
Synoptic

52700 (cfs)
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
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
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 Hydroclimatolgy:

Western Type III Pattern linked to flash flooding in CA

Based on: Maddox et al. 1980

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

Source: Hirschboeck 1988

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

“Atmospheric river” linked to flooding in Russian R

Source: Ralph et al. 2006
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.

MIGHT THIS BE A WAY TO ADDRESS THE NONSTATIONARITY ISSUE?
Increasingly Important Research Need:

**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
#3 A deeper understanding of flood-climate linkages can be obtained by examining all 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.
#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)

Discharge in Cu Meters per Sec

Drainage Area in Sq. Km

10,000

1,000

100,000

1,000,000

10,000

100

1,000

10,000

100,000

1,000,000

10

100

1,000

10,000

100

10

1

Brazil

China

India

S. Korea

China

Mississippi

Johnstown

Rapid City

Big Thompson

Telon

New Caledonia

Taiwan

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11

12

13

14

15

16

17

18

19

20

21

1

10

1,000

10,000

100,000

1,000,000

Drainage Area in Sq. Km

Discharge in Cu Meters per Sec

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.

Jimmy Camp Creek flood of 1965

Spring 1973 Mississippi River Basin floods
In addition, extreme flow events can emerge from synergism 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 characteristics . . . . and . . .
... let the rivers “speak for themselves” about how they respond to climate!
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Closing Thoughts
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 . . .

especially to understand and evaluate extreme 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 . . . .

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

(Source: Jarrett 1991, modified from Baker 1987)
Example peak discharge time series with historical period and discharge threshold $Q_0$: The shaded area represents floods of unknown magnitude less than $Q_0$. 

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)
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.

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?

Lower Colorado Basin Envelope Curve
(with 1993 Flood Peaks and Paleoflood estimates plotted)

Envelope curve for Arizona peak flows

Envelopes of largest rainfall-runoff floods in the Lower Colorado River Basin (modified from Enzel et al., 1993)

1993 Record Flood Discharges
Paleoflood Estimates

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 sensitive
• 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


- No corresponding peaks in streamflow reconstruction for paleofloods of 1862 & 1891
- 1868 peak = has a corresponding paleoflood

Our new Verde reconstruction awaits analysis!
Process-based evaluation of relationship between mean annual flow & instantaneous peaks . . .

Verde River Basin Comparison: Observed, Reconstructed, & Instantaneous Peak Flows

Note vertically exaggerated scale on this axis

Water Year

Instantaneous Peak Flow (cms)

Mean Annual Flow (cms)

Instantaneous Peak Discharge

Observed Annual flow

Reconstructed Annual Flow
Verde River Basin
Instantaneous Peak Flows
Classified by Synoptic Type

<table>
<thead>
<tr>
<th>Water Year</th>
<th>Synoptic</th>
<th>Convective</th>
<th>Tropical Storm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec / Jan 1952</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
| Sep 1970 | | | TS Norma
| Winters of 1978-80 | | | |
| Jan 1993 | | | |
| Feb 1995 | | | |
| Dec / Jan 2005 | | | |

. . . combined with flood hydroclimatology info . . .
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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Closing Thoughts
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?