Multivariate drought risk analysis for California

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Outline

• What is a drought?
• Why analyze droughts?
• How to analyze droughts?
• Impact of a changing climate on drought
• Take-Away
What is a drought?

• Period of prolonged deficit in precipitation, soil moisture, or flow
• Natural, recurring, inevitable process
• Experienced by all climate regions
• “Creeping phenomena”
• Impact can be:
  • Economic
  • Social
  • Environmental
• Multiple physical manifestations
• **Meteorological drought:** Precipitation deficit from the norm

• **Agricultural drought:** Soil lacks moisture that a specific crop need at a specific time

• **Hydrologic drought:** lack of sufficient surface and/or sub-surface water
Natural/human-induced climate variability

Precipitation deficiency (amount, intensity, timing)

Reduced infiltration, runoff, deep percolation, and GW recharge

High T, winds, low relative humidity, greater sunshine

Increased evaporation and transpiration

Soil water deficiency

Plant water stress, reduced biomass and yield

Reduced streamflow, inflow to reservoir, lakes, reduced wetlands, wildlife habitat

Meteorological drought

Agricultural drought

Hydrologic drought

Economic impacts

Social impacts

Environmental impacts
Why droughts are unique among natural disasters?

- No precise and universally accepted definition
  - Quantification of impact and mitigation much more difficult
- Onset and end of drought difficult to determine
- Longer recovery time – impacts may linger for years
- Non-structural impacts and spread over a large geographic area
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Motivation

• Wide spread social, economical, and ecological impact
• **Costliest natural hazard** - $6-8 billion annual damage to US (FEMA)

• Importance of studying droughts in California:
  • Major contributor of fruits, nuts, vegetables, and livestock/dairy
  • 2015 California drought alone caused an economic loss of $2.7 billion
  • Changing climate likely to cause more severe, more frequent droughts in future
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How to analyze droughts?

1. Define drought events
2. Quantify drought properties: severity and duration
3. Fit marginal distributions to severity and duration
4. Joint and conditional distributions of drought properties – severity and duration
5. Derivation of drought frequency curves
6. Plot drought atlas
63 rim watersheds and 30 WBAs to represent Sacramento Valley floor

Data source: Rim inflows from CalSim3.0 input file
WBA surface runoff from CalSim3.0 Output
How to analyze droughts?

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Step 1: Definition of drought events

- Use drought indicators for defining drought events
- Numerous standardized drought indices like Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized Runoff Index (SRI)
- Choice of index depends on purpose of study
- We use SRI for hydrologic drought analysis.
Standardized Runoff Index (SRI)

- Probability based drought indicator
  - Runoff time series for each month is fitted to either a parametric or non-parametric distribution.
  - Calculate the cumulative probabilities for runoff values
  - Convert the cumulative probability to a standard normal distribution variate (with zero mean and unit variance).
  - The standard normal variate is SRI.
SRI values on normal curve

<table>
<thead>
<tr>
<th>SRI values</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater than 2.0</td>
<td>Extremely wet</td>
</tr>
<tr>
<td>1.5 to 1.99</td>
<td>Very wet</td>
</tr>
<tr>
<td>1.0 to 1.49</td>
<td>Moderately wet</td>
</tr>
<tr>
<td>-0.99 to 0.99</td>
<td>Near normal</td>
</tr>
<tr>
<td>-1.0 to -1.49</td>
<td>Moderately dry</td>
</tr>
<tr>
<td>-1.5 to -1.99</td>
<td>Severely dry</td>
</tr>
<tr>
<td>Less than -2.0</td>
<td>Extremely dry</td>
</tr>
</tbody>
</table>
How to analyze droughts?

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Step 2: Quantify drought properties

- Drought events characterized by: severity, duration
- Theory of runs: An event is defined as drought when the value of interest (SRI) falls below a specified threshold.
- Drought event when SRI falls below -0.99
Each drought event characterized by:
- Severity – cumulative SRI for each drought event
- Duration – length for which SRI continuously stays below threshold

Worst drought in 2012-2015 dry period

Strong dependence between severity and duration
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Step 3: Marginal distributions for drought properties

<table>
<thead>
<tr>
<th>Drought property</th>
<th>Distribution</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severity</td>
<td>Log-normal</td>
<td>$\mu = 0.9078$, $\sigma = 0.898$</td>
</tr>
<tr>
<td>Duration</td>
<td>Exponential</td>
<td>$\mu = 2.8194$</td>
</tr>
</tbody>
</table>
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Step 4: Joint distribution of severity and duration

- Marginal distributions for severity and duration belong to different families
- Use an approach called copula to construct joint distribution
- Copulas are mapping functions that preserves the dependence structure between severity and duration
- Different families of copula functions available to develop joint distribution
- Choose the best-fit copula for the data using metrics like log-likelihood estimate
<table>
<thead>
<tr>
<th>Copula family</th>
<th>Function parameter</th>
<th>Log-likelihood estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clayton</td>
<td>4.414</td>
<td>39.13</td>
</tr>
<tr>
<td>Frank</td>
<td>10.892</td>
<td>45.76</td>
</tr>
<tr>
<td><strong>Gumbel</strong></td>
<td><strong>3.207</strong></td>
<td><strong>46.26</strong></td>
</tr>
<tr>
<td>Gaussian</td>
<td>0.883</td>
<td>39.43</td>
</tr>
</tbody>
</table>

Cumulative joint probability plot
How to analyze droughts?

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Step 5: Derivation of drought frequency curves

- Establishes relationship between severity, duration, and frequency
- Analogous to precipitation I-D-F curves
- Useful for drought risk assessment, water resources planning, ecosystem rehabilitation
- S-D-F curves based on conditional return period or recurrence interval

\[ T_{S/D}(s/d) = \frac{N}{n(1 - F_{S/D}(s/d))} \]

Where S and D indicate drought severity and duration, \( F_{S/D}(s/d) \) is conditional distribution of severity and duration, \( n = \) total number of drought events, \( N = \) total length of SRI time series, \( T_{S/D}(s/d) \) is the conditional recurrence interval of S given D=d
• Conditional distribution obtained from joint and marginal distributions
• Recurrence interval calculated based on conditional distribution
How to analyze droughts?

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Step 6: Drought atlas

- Compilation of design drought S-D-F curves for different locations
- Useful for spatial drought analysis
- Example drought map shows the spatial variation of drought severity for a 100-yr return period drought of 12-month duration.
- Series of drought maps for a range of return periods and/or drought durations can be constructed.
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How climate change affects droughts

- Growing evidence on climate change leading to more severe and frequent droughts
- Anticipated reduction in precipitation and increase in temperature
- As a case in point, we compare the worst drought in 2012-2015 dry period under current versus mid-century climatology (2045-2074).
- 2012-2015 considered one of the driest period in the history of California
- We considered the worst case scenario in terms of greenhouse gas concentration (RCP 8.5).
- Climate models chosen from CCTAG recommended list
- Rim inflow perturbed for each climate model projection to generate “climate change rim inflows”
Return period for 2012-2015 drought: 155 yrs

Return period for 2012-2015 drought: 108 yrs

For the same drought, the recurrence interval reduces from 155 to 108 years due to climate change.
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Take-Away

- Understanding drought properties and their joint behavior essential for drought management and mitigation.
- Bivariate computational framework for return period analysis is of key importance in drought risk assessment.
- We also highlight the importance of considering the effect of changing climate on drought properties.
- Significant escalation in the frequency of occurrence of droughts in future.
Thank You!
Disclaimer for analyses

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This presentation is of a framework for multivariate drought risk analysis in California, which represents and is limited by the study/model design, including model assumptions. It has not been Q/A, Q/C by the DWR and is being shared to illustrate the importance of incorporating a multivariate perspective in drought analysis.

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• Any quantitative analyses presented are driven by specific assumptions and the values and trends they show are subject to change with any new or changed assumption.

• The findings presented in these research products are limited to the results shown here.

• CalSim 3 is still in Beta-Release form and not final.