Rainfall Distributions

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Session Objectives

- Provide background on rainfall used in hydrologic modeling.
- Identify standard ways of presenting rainfall data.
- Introduce various techniques for determining the temporal distribution of rainfall.
- Examples and comparisons.
Hydrologic Modeling

- Estimate runoff:
  - Design of improvements
  - Determine flood risk for a location
  - Replicate an observed event

- Based on an acceptable level of risk

- Annual Exceedance Probability, the likelihood a flowrate will be equaled or exceeded in any given year, $1/Tr$
How much rainfall runs off?
How long does it take for the rainfall-runoff transformation/translation to occur?

The key input elements in hydrologic analysis are:
- Rainfall
- Watershed physical characteristics
Rainfall Characteristics

- Depth
- Duration
- Temporal Distribution
- Frequency, statistics
- Spatial Distribution
Rainfall Characteristics

- Short duration, high intensity, smaller coverage area, typically associated with thunderstorms.
- Longer duration, lower intensity, greater depths, larger coverage area, typically associated with frontal storms.
Precipitation Data Sources

- Rainfall frequency data are published on-line by the National Oceanic and Atmospheric Administration (NOAA). Missouri data is included in Atlas 14, Region 8.
- Historical observed data records are also maintained by NOAA.
- Probable Maximum Precipitation estimates are available in National Weather Service Hydrometeorological Report 51 (HMR 51).
- Doppler estimates are available from the National Weather Service.
Design Storms

Most jurisdictions in this region use the design storm approach to hydrologic modeling for design and analysis.

A design storm is a way of representing storm rainfall with respect to depth, duration, temporal distribution, frequency and spatial distribution.

Based on the assumption that, under average conditions, a rainfall of a given frequency will produce runoff of the same frequency.
Representation of Rainfall

- Total depth
- Incremental depth or intensity per time period
- Cumulative mass curve
- Depth or Intensity hyetograph
- Intensity-Duration-Frequency curves
- Depth-Duration-Frequency curves
Rainfall
Intensity-Duration-Frequency
National Weather Service Station 23-7263
University of Missouri-Rolla
NOAA Atlas 14, Region 8
4/25/2013

Legend
- 1% AEP
- 2% AEP
- 4% AEP
- 10% AEP
- 20% AEP
- 50% AEP
- 99.99% AEP

*Annual Exceedance Probability

Hydro Division
Rolla, MO
DDF Curve

Rainfall
Depth-Duration-Frequency
Joplin, Missouri

Annual Exceedance Probability
1 %
2 %
4 %
10 %
20 %
50 %
99.99%

Depth, Inches
0  1  2  3  4  5  6  7  8  9 10
Duration, Hours
0  3  6  9 12 15 18 21 24

Data Source:
Joplin Regional Airport
NOAA, Alls 10, Region 8
4/26/2013

Hydro Division
Rolla, MO
Depth vs. Area

Ratio of Areal to Point Rainfall for a Given Area

Graphical Rainfall Depiction

Hyetograph

Cumulative Mass Curve
The selected design storm for hydrologic modeling has a significant impact on the computed results. Rainfall Distributions are generally categorized as:

- Distributed in a “reasonable manner”
- Statistical analysis of a gage network
- Nested intensity
Example Distributions

- Uniform
- Yen-Chow
- Alternating Block
- Keifer & Chu (Chicago Method)
- Pilgrim-Cordery distribution
- SCS Distributions
- Huff’s Quartile Distributions
- NOAA Atlas 14 Temporal Distributions
Uniform Distribution

- Uniform Distribution assumes rainfall is constant over the duration of the event.
- Uniform distribution is generally used with the rational method.
- Unsuitable for use in hydrograph modeling.
Nested Intensity

Nested intensity hyetographs contain the desired AEP intensity for any given duration within the storm.

Example: for a 24-hour storm, 1% AEP event, there is a 10-minute period that has the 10-minute, 1% AEP intensity, a 30-minute period that contains the 30-minute, 1% AEP intensity and so on...
Alternating Block Method

Is a nested intensity method
Alternating Block

**Advantages**
- Derived from local data
- Applicable to multiple durations

**Disadvantages**
- Naturally occurring storms do not occur in this manner
- Yields relatively high peak discharges
Kiefer & Chu (Chicago Method)

- Nested Intensity, limited to maximum duration of 3-hours.
- Intensity based on a power curve, IDF relationship.
- Location parameter, advance, ratio of the time to the most intense period of rainfall to the storm duration.
- Advance varies by location, computed from observed rainfall, for Chicago 0.375, for Rolla 0.42.
Kiefer & Chu (Chicago Method)

Figure 6 - Synthetic Storm Pattern Hyetographs of Three-Eighths Advanced Type

\[ I(t) = \begin{cases} \frac{90 \left( \frac{8}{3} t \right)^9 + 11}{\left( \frac{8}{3} t \right)^9 + 11} & \text{before the peak} \\ \frac{90 \left( \frac{8}{5} t \right)^9 + 11}{\left( \frac{8}{5} t \right)^9 + 11} & \text{after the peak} \end{cases} \]
Chicago Method

Advantages
- Derived from local data

Disadvantages
- Original method investigated for up to 3-hour duration
- Requires statistical analysis of local rainfall to determine parameters
NRCS 24-Hour Distributions

- Nested Intensity
- Developed by SCS using rural gauges, expanded on work by Hershfield, 1961
NRCS 24-Hour Type II

- Nested Intensity.
- 44% of storm rainfall occurs in less than one hour.
- A time transform for 6-hr, 12-hr and 18-hr durations is available from NRCS.
SCS Type II

Advantages
- Applicable to various durations.
- Widely accepted.

Disadvantages
- Yields high peak discharge rates.
- Significantly over-predicts frequent events.
- Observed rainfall events do not occur in this manner.
Pilgrim-Cordery Method

- Ranking Method.
- Arbitrary number of severe storms selected.
- Storm periods ranked by order of occurrence and by percent of overall storm depth.
### Pilgrim-Cordery

| STORM | TOTAL | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | EVENT | PE | FINAL ORDER |
|-------|-------|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|--------|
| 486L  | 2.70  | 1     | 1  | 2     | 1  | 3     | 1  | 4     | 1  | 5     | 1  | 20    | 1  | 20    | 1  | 18    | 1  | 17    | 1  | 15    | 1  | 10    | 1  | 16%    |
| 734S  | 2.72  | 4     | 2  | 3     | 2  | 3     | 2  | 3     | 2  | 3     | 2  | 23    | 2  | 19    | 2  | 16    | 2  | 16    | 2  | 14    | 2  | 12    | 2  | 9%     |
| 837S  | 3.08  | 4     | 4  | 1     | 4  | 1     | 4  | 3     | 4  | 1     | 4  | 49    | 4  | 42    | 4  | 3     | 4  | 3     | 4  | 2     | 4  | 2%     |
| 68S   | 3.16  | 1     | 5  | 2     | 5  | 3     | 5  | 3     | 5  | 3     | 5  | 27    | 5  | 23    | 5  | 18    | 5  | 15    | 5  | 11    | 5  | 5%     |
| 567S  | 3.32  | 4     | 6  | 2     | 6  | 2     | 6  | 2     | 6  | 2     | 6  | 37    | 6  | 28    | 6  | 25    | 6  | 7%     | 6  | 2%     | 6  | 1      |
| 867S  | 3.49  | 4     | 7  | 5     | 7  | 5     | 7  | 5     | 7  | 5     | 7  | 39    | 7  | 26    | 7  | 14    | 7  | 9%     | 7  | 7%     | 7  | 5%     |
| 644S  | 3.82  | 6     | 8  | 5     | 8  | 5     | 8  | 5     | 8  | 5     | 8  | 39    | 8  | 26    | 8  | 14    | 8  | 9%     | 8  | 7%     | 8  | 5%     |
| 583S  | 3.86  | 3     | 9  | 2     | 9  | 2     | 9  | 2     | 9  | 2     | 9  | 37    | 9  | 28    | 9  | 25    | 9  | 7%     | 9  | 2%     | 9  | 1%     |
| 486S  | 4.26  | 2     | 10 | 1     | 10 | 1     | 10 | 1     | 10 | 1     | 10 | 39    | 10 | 26    | 10 | 14    | 10 | 9%     | 10 | 7%     | 10 | 5%     |
| 751S  | 4.38  | 0.63  | 11 | 0.29  | 11 | 0.29  | 11 | 0.29  | 11 | 0.29  | 11 | 0.63  | 11 | 1.12  | 11 | 1.71  | 11 | 0.41  | 11 | 0.22  |

**FINAL ORDER**

- 16%
- 24%
- 9%
- 35%
- 11%
- 5%
Pilgrim-Cordery Distribution

Pilgrim and Cordery, Journal of the Hydraulics Division, ASCE, 1975

Regional Applicability of Synthetic Rainfall Distribution, J.P. Wilson, University of Missouri-Rolla, 1992
Pilgrim-Cordery

Advantages
- Derived from local data.
- Looks like observed rainfall.
- Produces results comparable to results from observed events.
- Distribution varies by duration

Disadvantages
- Requires duration sensitivity analysis.
- Requires analysis of local rainfall.
Yen-Chow

Statistically based on method of moments, results in a triangular hyetograph.
Yen-Chow

Advantages
- Derived from local data.
- Relatively easy to use.

Disadvantages
- Requires duration sensitivity analysis.
- Requires analysis of local rainfall.
- Produces peak flows lower than observed values.
Huff’s Quartile Distributions

- Huff analyzed a network of 49 raingages.
- Concluded that the majority of rainfall occurred in a relatively short period of time compared to the overall storm duration.
- Classified storms based on the quarter of the storm containing the most rainfall.
Source: Time Distribution of Heavy Rainstorms in Illinois, Floyd A. Huff, 1990
1st Quartile

Time Distribution of Heavy Rainstorms in Illinois, Floyd A. Huff, 1990
Huff’s continued

1\textsuperscript{st} quartile storms tended to have a duration of six or less hours.
2\textsuperscript{nd} quartile twelve or less.
3\textsuperscript{rd} quartile 24 or less.
4\textsuperscript{th} quartile greater than 24 hours.
Huff's Quartile Distributions for Point Rainfall

Legend
- 1st Quartile
- 2nd Quartile
- 3rd Quartile
- 4th Quartile

Median Curves Shown

Huff’s Quartile Distributions

Advantages

- Derived from regional data
- Produces results consistent with observed data
- Distribution varies by duration

Disadvantages

- Requires duration sensitivity analysis
So what?

- Compare the distributions
- Example: Runoff model showing the impact on results.
8.02 inches in 24-hours
1% AEP event

Rainfall Hyetographs
8.02 inches in 24-hours
1% AEP event
Comparison of NRCS Type II Distribution and Alternating Block Distribution for Rolla, MO
Dutro Carter Creek
EXAMPLE
Dutro Carter Creek Watershed 6.0 Sq. Miles
Modeling

- Observed event, 3.13 inches in 18 hrs.
- This corresponds to an event with a 50%-20% AEP.
- Modeled same depth/duration using:
  - Huff’s Quartile
  - NRCS Type II
  - Rolla Alternating Block (nested intensity)
Subbasin "DUT250" Results for Run "Huff's"

Legend (Compute Time: 25Jan2013, 19:34:46)
- Run Huff's Element DUT250 Result Precipitation
- Run Huff's Element DUT250 Result Precipitation Loss
- Run Huff's Element DUT250 Result Baseflow
- Run Huff's Element DUT250 Result Outflow
Maximum depth in Observed event
MODELED HYDROGRAPH FROM OBSERVED RAINFALL

18-HOUR STORM
PRECIPITATION = 3.13 INCHES
20% < AEP < 50%
RUNOFF HYDROGRAPH FROM HUFF’S 3RD QUARTILE DISTRIBUTION
RUNOFF HYDROGRAPH FROM OBSERVED RAINFALL

18-HOUR STORM
PRECIPITATION = 3.13 INCHES
20% < AEP < 50%
RUNOFF HYDROGRAPH FROM ROLLA 2-YR NESTED INTENSITY
RUNOFF HYDROGRAPH FROM HUFF’S 3RD QUARTILE DISTRIBUTION
RUNOFF HYDROGRAPH FROM OBSERVED RAINFALL

18-HOUR STORM
PRECIPITATION = 3.13 INCHES
20% < AEP < 50%
RUNOFF HYDROGRAPHS

18-HOUR STORM
PRECIPITATION = 3.13 INCHES
20% < AEP < 50%
Discuss among yourselves

- A higher computed peak flowrate is conservative.
  - Yes,
  - no,
  - it depends...
- What about systems with storage?
- Comparing pre-project with post-project conditions?
Example 2, Small Watershed

Small watershed response time is dominated by the overland flow component of runoff.

128 acres, Curve Number 85.
Results

3.13 inches in 18 hours, 50% > AEP > 20%
  - Observed, 40 cfs
  - Huff’s, 42 cfs
  - Rolla Nested Intensity, 64 cfs
  - SCS, 112 cfs

7.2 inches in 24 hours, 1% AEP
  - Huff’s, 85 cfs
  - SCS, 332 cfs
Advantages and Disadvantages

Uniform Distribution

- Easy to apply.
- Does not represent observed rainfall.
- Not suitable for most design situations.
Advantages and Disadvantages

Nested Intensity Distributions

- Rainfall does not generally occur in this manner.
- Avoids multiple runs to determine critical storm duration.
- Tends to overestimate intensities, particularly for frequent events.
- Can be derived from local data.
Advantages and Disadvantages

Statistical Analysis

- Generally requires a substantial amount of analysis to initially determine the shape parameters of the distribution.
- Is appropriate for the region.
- Most methods require critical duration analysis while modeling.
- Typically produce the most realistic results.
A Comparison of Temporal Distributions:

ATLAS 14

VS.

HUFF’S QUARTILE
Atlas 14 vs. Huff’s Quartile

Topics for Comparison
- Data
- Methodology
- Design
What is Atlas 14?

- Precipitation-Frequency Atlas of the United States

- Published by the National Oceanic and Atmospheric Administration
What is Atlas 14?

- Missouri rainfall frequency estimates are included in Atlas 14, Volume 8, Version 2.0, released April 2013.
- Supersedes Bulletin 71 for rainfall frequency data in Missouri.
- What about the temporal distributions in Atlas 14?
Figure 4.1.2. Four climate regions delineated for NOAA Atlas 14 Volume 8.
Atlas 14 vs. Huff’s Quartile

Huff’s Quartile
- 49 rural gages in a 400-square-mile network (east-central Illinois)

12 additional urban gages in Champaign-Urbana area
Atlas 14 vs. Huff’s Quartile

**Atlas 14**
- 4309 gages reporting at least hourly
- 11,918 gages reporting daily
- 857,000-square-mile network
## Atlas 14 vs. Huff’s Quartile

<table>
<thead>
<tr>
<th>Atlas 14</th>
<th>Huff’s Quartile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geography: Highly varied, divided into 4 regions</td>
<td>Geography: Flat plains</td>
</tr>
<tr>
<td>19-69 year period of record for hourly gages, ending in 2011 or 2012</td>
<td>12-year period of record (1955-1967)</td>
</tr>
<tr>
<td>111,732 “precipitation cases” analyzed</td>
<td>261 storms analyzed</td>
</tr>
</tbody>
</table>
Methodology – Storms Used in Study

**Atlas 14**
- Exceeded 50% AEP (2-yr)

**Huff’s Quartile**
- One or more gages recorded more than 1 inch.
- Network mean rainfall exceeded 0.5 inch.
Methodology – Definition of “Quartile”

- Storms (or cases) were grouped into four categories by the quartile in which the greatest percentage of the total precipitation occurred.

- Atlas 14: 6-hr storm was not divided into even quartiles.
Methodology –

Huff’s Quartile

**Single Storm approach**

- “…a rain period separated from preceding and succeeding rainfall by 6 hours or more.”

- A period of **continuous** precipitation
Methodology –

Atlas 14

**NOT a Single Storm approach**

- “...computed as the total accumulation over a specific duration.” (set time period)

- “...may contain parts of one or more storms.”

- Not necessarily a period of continuous precipitation
Methodology – Definition of “Storm Event”
Methodology – "Storm Event"

Definition of 'Storm Event':

- 12-hour storm
- 6-hour storm

Huff’s Quartile
Methodology – Definition of “Storm Event”

Huff’s Quartile
Methodology – Definition of “Storm Event”

Huff’s Quartile

12-hour storm
6-hour storm
1-hour storm
1-hour storm
6-hour storm
Methodology – Definition of “Storm Event”
Methodology – Definition of “Storm Event”

Atlas 14

12-hour storm
Methodology – Definition of “Storm Event”

Atlas 14
Methodology – "Storm Event"

Atlas 14

Definition of 24-hour storm

RAINFALL, INCHES

TIME, HOURS

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2

0 3 6 9 12 15 18 21 24 27 30 33 36
Methodology – So What?

Atlas 14

- Set-time-period approach
  - May contain long periods of no precipitation
  - May contain parts of one or more storm
  - More front-loaded cases (first quartile dominant)!!

Huff’s Quartile

- Single-storm approach
  - Looks at storm (or most intense portion) as a whole
  - Dominant quartile varied by storm duration
Design – Guidance (or lack thereof)

Atlas 14

Use Atlas 14 for your rainfall frequency data

Atlas 14 temporal distributions are not recommended for design purposes.

- No guidance in Atlas 14 for use in design
- Presented as informational only
Design — Guidance

Huff’s Quartile

“It is recommended...for runoff computations related to the design and operation of runoff control structures.”

- Provides guidance on which temporal distribution to use:
  - First Quartile for storm durations of 6 hours or less
  - Second Quartile for storm durations 6.1 through 12.0 hours
  - Third Quartile for storm durations 12.1 through 24.0 hours
  - Fourth Quartile for storm durations over 24.1 hours
Conclusions — Atlas 14 vs. Huff’s Quartile

Use the right tool for the job:
- Rainfall frequency data: Atlas 14
- Temporal Distribution: Huff’s Quartile
Summary

- Design storms will continue to be used in routine design.
- A design storm must be appropriate for:
  - The region
  - The objective
- Method that yields the highest discharge is not always conservative.
- Atlas 14 temporal distributions are more informational in nature, not design oriented.
Questions?