Estimating Design Rainfalls Using Dynamical Downscaling Data

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Outline

• Introduction
• GEV modeling of the extreme values
• Mixture distribution of order statistics
• Demonstration by stochastic simulation
• Demonstration using observed rainfall data in Taiwan
• Conclusions
Introduction

• Design rainfalls
  – Design rainfalls represent rainfall depths of specific storm durations (e.g., 1, 2, 6, 12, 24, 48, 72 hours) which, on average, occur once in every T (5, 20, 100, 200, 1000) years.
  – Design rainfalls are essential for hydrological modeling and water resources planning and engineering design.
  – Estimation of design rainfalls under climate change requires downscaling GCM rainfall outputs to hourly (or even sub-hourly) scale.
• Previous work – Stochastic Storm Rainfall Simulation Model (SSRSM)
  
  – Annual count of storm occurrences (Poisson distribution)
  
  – Bivariate distribution of storm duration and event-total rainfall depth (Non-Gaussian bivariate distribution)
  
  – Temporal variation of hourly rainfalls of individual storms (Bivariate truncated-gamma distribution + Markov process)
  
  – Meiyu (MCS), summer convective storms, typhoons, and winter frontal rainfalls are treated separately.
Annual counts of storm events estimated by ANN

Frontal

Maiyu

Typhoon

Convective

10/03/2017

International Workshop on Climate Downscaling Studies
2017
Storm characteristics (average duration of typhoon)

Gauge observations


MRI (2015 – 2039)

MRI (2075 - 2099)

Source: NCDR, Taiwan
Storm characteristics (average event-total rainfalls of typhoon)

Gauge observations


MRI (2015 – 2039)

MRI (2075 - 2099)

Source: NCDR, Taiwan

10/03/2017
Storm characteristics
• Duration
• Event-total depth
• Inter-arrival (or inter-event) time
• Time variation of rain-rates

Stochastic storm rainfall process

Inter-arrival time

Total depth

Duration

Rainrate

Time(hr)
Season-specific storm characteristics

<table>
<thead>
<tr>
<th>Storm type</th>
<th>Period</th>
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</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>Nov - April</td>
</tr>
<tr>
<td>Mei-Yu</td>
<td>May - June</td>
</tr>
<tr>
<td>Convective</td>
<td>July - October</td>
</tr>
<tr>
<td>Typhoon</td>
<td>July - October</td>
</tr>
</tbody>
</table>

International Workshop on Climate Downscaling Studies
2017
Each simulation run yields an annual sequence of hourly rainfalls. 500 runs were generated for each rainfall station.

Time of storm occurrences

(Duration, total depth) bivariate simulation

first-order Truncated Gamma-Markov simulation

Hourly rainfall sequence
Examples of hourly rainfall sequence (Kaoshiung)
Hyetograph Simulation results (Typhoons)

* Historical  ○ simulated
Time-to-peak and peak rainfall percentage (Typhoons)

- Empirical cumulative distribution functions
Impact on design storm depths

(Projection period: 2020-2039)
Introduction

• Most rainfall frequency analyses were conducted using annual maximum series. However, for stations with short record length, i.e. small sample size, (for example, less than 30 years) and with presence of outliers, results of rainfall frequency analysis will be less reliable.

• Annual maximum rainfalls of longer durations (> 12 hours) in Taiwan were mostly produced by typhoon or meiyu events.
• We propose using event-maximum rainfalls for rainfall frequency analysis.

• By using the event-maximum rainfalls (of various design durations), the sample size can be increased.

• The annual count of events (in our case, typhoons) can vary from one year to another and can be considered as a Poisson random variable.
• The average annual count of typhoons in Taiwan is roughly 3.4 (depending on locations). Mean value of the Poisson distribution.

• The basic idea is to base our rainfall frequency analysis on the probability distribution of t-hr event-maximum rainfalls and the Poisson distribution which characterizes the occurrence of typhoons. [A mixture distribution]

Can be readily provided by high resolution dynamic downscaling data.
• For stations whose annual maximum rainfalls were produced by different storm types (typhoons and meiyu events), a storm-type mixture of mixture distributions needs to be considered.
GEV modeling of the extreme values

**Extremal Type Theorem**

**Type I:**

\[ G_1(x) = \exp(-\exp(-x)), \quad -\infty < x < \infty \]

**Type II:**

\[ G_2(x) = \begin{cases} 
0 & \text{if } x \leq 0, \\
\exp(-x^{-\alpha}) & \text{if } x > 0, \quad \alpha > 0 .
\end{cases} \]

**Type III:**

\[ G_3(x) = \begin{cases} 
\exp(-(-x)^{\alpha}) & \text{if } x \leq 0, \\
0 & \text{if } x > 0, \quad \alpha > 0 .
\end{cases} \]

\[ G_\eta(x) = \begin{cases} 
\exp\{-1 + \eta [\frac{x-\mu}{\sigma}]^{-1/\eta}\} & \text{if } \eta \neq 0 \\
\exp\{-\exp\left(-\left[\frac{x-\mu}{\sigma}\right]\right)\} & \text{if } \eta = 0
\end{cases} \]
(Extremal types theorem). Let \( (X_n) \) be independent with distribution function \( F \) and let \( X_{(n)} = \max_{1 \leq i \leq n} X(i) \). If there exist constants \( a_n > 0 \) and \( b_n \) and a non-degenerate distribution function \( G \) such that
\[
\mathbb{P}\left( \frac{X_{(n)} - b_n}{a_n} \leq x \right) \overset{d}{\to} G(x),
\]
then \( G \) must be of the same type as one of the three extreme value classes below:

Type I \((\text{Fréchet})\): \( G_{1,\alpha}(x) = \begin{cases} 0 & \text{if } x \leq 0 \\ \exp(-x^{-\alpha}) & \text{if } x > 0 \end{cases} \) for some \( \alpha > 0 \)

Type II \((\text{Negative Weibull})\): \( G_{2,\alpha}(x) = \begin{cases} \exp\{-(x)^\alpha\} & \text{if } x < 0 \\ 1 & \text{if } x \geq 0 \end{cases} \) for some \( \alpha > 0 \)

Type III \((\text{Gumbel})\): \( G_3(x) = \exp(-e^{-x}) \) for \( x \in \mathbb{R} \).

\[
G_\eta(x) = \begin{cases} \exp\{-(1 + \eta[\frac{x-\mu}{\sigma}])^{-1/\eta}\} & \text{if } \eta \neq 0 \\ \exp\{\exp(-[\frac{x-\mu}{\sigma}])\} & \text{if } \eta = 0 \end{cases}
\]
Mixture distribution of order statistics for annual maximum rainfalls

• Order statistic
  – Given a random sample of size \( n \) \((X_1, X_2, \ldots, X_n)\), the max order statistic \( Y_n = \max(X_1, X_2, \ldots, X_n) \) satisfies \( F_{Y_n}(y) = \left[F_X(y)\right]^n \)
  – Annual maximum rainfalls can be considered as the maximum order statistic of individual years.
  – However, the annual count of events has a Poisson distribution. Thus, annual maximum rainfalls of different years have different probability distributions.

\[
F_{Y_{n_1}}(y) = \left[F_X(y)\right]^{n_1} \neq F_{Y_{n_2}}(y) = \left[F_X(y)\right]^{n_2}
\]
– Mixture distribution modeling. Annual count of events \((k)\) has a Poisson distribution.

\[
F_W(w) = \sum_{k=0}^{\infty} [F_{Y_k}(w)] p(k) = \sum_{k=0}^{\infty} [F_X(w)]^k p(k)
\]
• Three approaches (for calculation of T-yr rainfall, \(X_T\))
  
  – Derive the probability distribution of annual maximum rainfalls from the event-maximum rainfalls and then find the \(1-(1/T)\) quantitle of the annual maximum distribution. [Approach 1 - Mixture distribution approach]

  – Calculate \(X_T\) directly from the probability distribution of event-maximum rainfalls [Approach 2 - Adjusted exceedance probability approach]

\[
p_E = \frac{1}{T_E \cdot E(M)}
\]
– Simulate many years (N = 10,000) of typhoon occurrences and event-maximum rainfalls. Extract N annual maximum rainfalls from the simulation results and find $X_T$. [Approach 3 - Simulation approach]
Demonstration by stochastic simulation

- Annual count of events has a Poisson distribution (mean = 3.6)
- 1-hour event-maximum rainfall has a gamma distribution with mean = 96 mm and stdev = 76 mm. (scale = 60, shape = 1.6)
- We simulated 100,000 years of typhoon occurrences and event-maximum rainfalls using R.
Can be considered as the theoretical distribution of annual maximum rainfalls.
• Rainfalls of various return periods (in years) \((\text{seq}(20,200,10))\) \([\text{Approaches 2 and 3}]\)
• Comparison between Approaches 1 and 3
• The above simulation results demonstrate that annual maximum rainfalls are asymptotically and theoretically a mixture distribution of order statistics.
• Practically, dynamic downscaling data are available for 25 or 30-year period.
Demonstration using observed rainfall data in Taiwan (limited record length)

- 44 years of event-maximum rainfalls of typhoons (頭汴坑) in Taiwan.

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</table>

Typhoons-dominated 24-hour Annual maximum rainfalls

AMS-based Return period in years
Mixture distribution - Poisson distribution of annual count of typhoons

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<th>Duration</th>
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Typhoons-dominated 24-hour Annual maximum rainfalls
Typhoons-dominated
24-hour Annual maximum rainfalls
Demonstration using observed rainfall data in Taiwan (limited record length)

- 42 years of event-maximum rainfalls of typhoons (Jia-Yi) in Taiwan.

<table>
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Typhoons and Meiyu mixture of 24-hour annual maximum rainfalls

\[ P(\text{typhoon}) = 0.64, \quad P(\text{meiyu}) = 0.36 \quad (tr=24) \]
A mixture of mixture distributions of typhoons and meiyu event-maximum rainfalls.

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</tbody>
</table>
Typhoons and Meiyu mixture of 24-hour Annual maximum rainfalls

\[ P(\text{typhoon}) = 0.64, \ P(\text{meiyu}) = 0.36 \ (tr=24) \]
Conclusions

• We demonstrate that the annual maximum rainfalls in Taiwan (which are produced by typhoons or meiyu events) can be characterized by a mixture distribution.

• For stations with short record length, using event-maximum rainfalls for rainfall frequency analysis can provide good estimates of design rainfalls.

• By adopting the proposed approach, design rainfalls of the projection period can be derived from high resolution dynamic downscaling data.
Thanks for your attention.
Design rainfall depths
For example, 24-hr, 100-year rainfall depth
Characteristics of extreme storm events

24 GCMs
Projections in coarse spatial and time scales.
(200 – 300 km; monthly)

RCM
Projections in finer spatial scale.
(5km; monthly)

From GCM outputs to design storm depths – a problem of scale mismatch (both temporal and spatial)
• Characteristics of storm events
  • Number of storm events
  • Duration of a storm event
  • Total rainfall depth
  • Time variation of rainfall intensities

• These characteristics are random in nature and can be described by certain probability distributions.

• Although the realized values of these storm characteristics of individual storm events represent weather observations, their probability distributions are climate (long term and ensemble) properties.
• A GCM – stochastic model integrated approach
  – Climatological projection by GCMs
    • Changes in the **means** of storm characteristics
    • For examples,
      – Average number of typhoons per year
      – Average duration of typhoons
      – Average event-total rainfall of typhoons
  – Hydrological projection by a stochastic storm rainfall simulation model
    • Generating realizations of storm rainfall process using storm characteristics which are representative of the projection period.
    • Preserving statistical properties of the all storm characteristics.
Characteristics of storm events

1. Number of storm events
2. Onset of storm occurrences
3. Duration of a storm event
4. Total rainfall depth
5. Time variation of rainfall intensity

Conceptual flowchart

- 24 GCMs → Projections in coarse spatial and time scales. (200 – 300 km; monthly)
- RCM → Projections in finer spatial scale. (5km; monthly)
- Weather Generator (Richardson type) → Projections in finer time scale. (5km; daily)
- ANN

Design rainfall depths
For example, 24-hr, 100-year rainfall depth

Characteristics of extreme storm events
Climate change scenarios and GCM outputs

• Emission scenario: A1B
• Baseline period: 1980 – 1999
• Projection period
  – Near future: 2020 – 2039
  – End of century: 2080 – 2099
• GCM model: 24 GCMs statistical downscaling
• Hydrological scenario: changes in storm characteristics
Changes in monthly rainfalls (Statistical downscaling, Ensemble average with standard deviation adjustment) Taipei area

Near future (2020 – 2039)  
Near future (2080 – 2099)
Stochastic Storm Rainfall Simulation Model (SSRSM)

- Simulating occurrences of storms and their rainfall rates
  - Preserving seasonal variation and temporal autocorrelation of rainfall process.
- Duration and event-total depth
- Inter-event times
- Percentage of total rainfalls in individual intervals (Storm hyetographs)
• Simulating occurrences of storm events of various storm types
  – Number of events per year
    • Poisson distribution for typhoon and Mei-Yu
  – Inter-event time
    • Gamma or log-normal distributions
• Simulating joint distribution of duration and event-total depth

  – Bivariate gamma distribution (e.g. typhoons)
  – Log-normal-Gamma bivariate
  – Non-Gaussian bivariate distribution was transformed to a corresponding bivariate standard normal distribution with desired correlation matrix.
\( \rho_{XY} \sim \rho_{UV} \) Conversion

\[
\rho_{XY} \approx \left( A_X A_Y - 3 A_X C_Y - 3 C_X A_Y + 9 C_X C_Y \right) \rho_{UV} \\
+ 2 B_X B_Y \rho_{UV}^2 + 6 C_X C_Y \rho_{UV}^3
\]

\[
A_X = 1 + \left( \frac{\gamma_X}{6} \right)^4 \\
B_X = \frac{\gamma_X}{6} - \left( \frac{\gamma_X}{6} \right)^3 \\
C_X = \frac{1}{3} \left( \frac{\gamma_X}{6} \right)^2
\]

\[
A_Y = 1 + \left( \frac{\gamma_Y}{6} \right)^4 \\
B_Y = \frac{\gamma_Y}{6} - \left( \frac{\gamma_Y}{6} \right)^3 \\
C_Y = \frac{1}{3} \left( \frac{\gamma_Y}{6} \right)^2
\]

Bivariate gamma \((X,Y)\)
• Simulating percentages of total rainfalls in individual intervals (Simulation of storm hyetographs)
  – Based on the simple scaling property
    • Durations of all events of the same storm types are divided into a fixed number of intervals (e.g. 24 intervals).
    • For a specific interval, rainfall percentages of different events are identically and independently distributed (IID).
    • Rainfall percentages of adjacent intervals are correlated.
Modeling the storm hyetograph

An example of dimensionless hyetograph of a storm of 24 hours duration.

Probability density of $x(15)$
Taking all the above properties into account, we propose to model the dimensionless hyetograph by a truncated gamma Markov process.

- Properties:
  1. $0 < x(t) \leq 100\%$, $t = 1, 2, \ldots, 24$.
  2. $X$'s can be described by gamma distributions.
  3. $\sum_{t=1}^{24} x(t) = 100$
  4. Lag-1 autocorrelation coefficients are significantly different from 0. For example, $\text{Correl}(x(t), x(t+1)) > 0.5$.

- It is unlikely that rainfall percentage of any particular hour will exceed a level (for example, 30%) which is significantly lower than the ultimate upper level of 100%. Thus, rainfall percentage of any particular hour is modeled as having a truncated gamma distribution (truncated from above).
An example of dimensionless hyetograph of a storm of 24 hours duration.

Probability density of $x(15)$

Truncated gamma density (parameters estimation, including the truncation level)
– Rainfall percentages should sum to 100%
  • Truncated gamma distributions
  • Conditional simulation is necessary
  • 1st order Markov process

— Conditional simulation of first order truncated gamma Markov process
More than 400 automated rainfall stations established since early 1990.

Until now, most stations have record length less than or close to 20 years.

If rainfall frequency analysis requires at least 40 years of annual maximum rainfalls, then we have to wait for another 20 years.
### Beginning Dates of Some Annual Maximum Events in Taiwan.

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