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A New Approach of Rainfall Frequency Analysis Using Event-Maximum Rainfalls

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Outline

- Introduction
- Annual maximum rainfalls (AMRs)
- Extremal types theorem and the GEV distribution
- Mixture distribution modeling of AMRs
- Demonstration by stochastic simulation
- Demonstration using observed rainfall data in Taiwan
- Conclusions

Introduction

- Rainfall frequency analyses are often conducted using annual maximum rainfalls. However, for stations with short record length, i.e. sample size, (for example, less than 30 years) and with presence of extreme outliers, results of rainfall frequency analysis are likely to be associated with very high uncertainties.

- Extreme rainfalls produced by Typhoon Morakot

表 4.1 莫拉克颱風高屏溪各雨量站不同降雨延時降雨量頻率分析結果表

流域	雨量站	鄉鎮名稱	24-hour rainfall	Return Period	48 小時		72 小時		累積雨量	Record length
					實測雨量	相當重限期(年)	實測雨量(mm)	相當重限期(年)		
高屏溪	屏東(5)	屏東縣屏東市	667.0	141	886.0	124	947.0	159	959.0	38
	美濃(2)	高雄縣美濃鎮	507.0	>2000	749.0	>2000	828.0	>2000	871.0	19
	屏東	屏東縣屏東市	666.0	140	906.0	143	974.5	197	990.0	38
	溪埔	高雄縣大樹鄉	729.5	271	994.5	265	1057.5	378	1076.5	38
	旗山	高雄縣旗山鎮	621.0	>2000	813.0	>2000	854.5	>2000	881.0	15
	尾寮山	屏東縣三地門	1414.5	>2000	2215.5	>2000	2564.0	>2000	2701.0	21
	甲仙	**高雄縣甲仙鄉**	**1077.5**	>2000	**1601.0**	>2000	**1856.0**	>2000	**1916.0**	25
	古夏	屏東縣三地門鄉	683.5	>2000	946.0	>2000	1061.5	>2000	1127.0	25
	美濃	高雄縣美濃鎮	633.5	>2000	878	>2000	955.5	>2000	989.5	15
	里港	屏東縣里港鄉	710.5	>2000	955.5	>2000	1018	>2000	1039.5	15
	上德文	屏東縣三地門鄉	1185.5	>2000	1968.0	>2000	2194.5	>2000	2255.0	25
	新圍	屏東縣鹽埔鄉	578.0	148	757.5	>2000	806.5	565	830.5	25
	月眉	高雄縣杉林鄉	744.0	>2000	1081.0	>2000	1205.0	>2000	1246.5	19
	吉東	高雄縣美濃鎮	547.5	>2000	728.0	>2000	789.0	>2000	820.5	19
	大津	高雄縣六龜鄉	738.5	>2000	1072.0	>2000	1241.0	>2000	1314.0	21

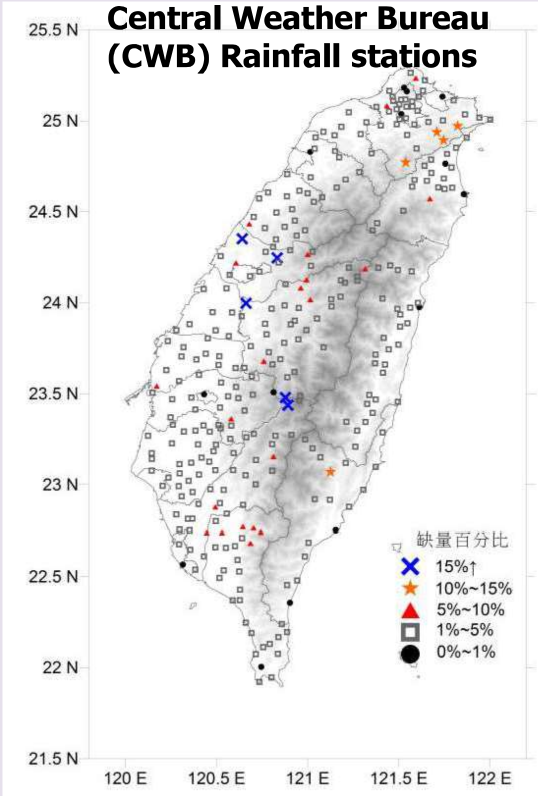
資料來源：「莫拉克颱風暴雨量及洪流量分析」，經濟部水利署，民國98年9月。原資料尚有濁水溪、北港溪、朴子溪、八掌溪、急水溪、曾文溪、鹽水溪、二仁溪、東港溪、四重溪、林邊溪、知本溪等各雨量站不同降雨延時降雨量頻率分析結果。

CWB Raingauge Network

More than 400 automated rainfall stations established since early 1990.

Until now, most stations have record length less than or close to 25 years.

If rainfall frequency analysis requires at least 40 years of annual maximum rainfalls, then we have to wait for another 15 to 20 years.



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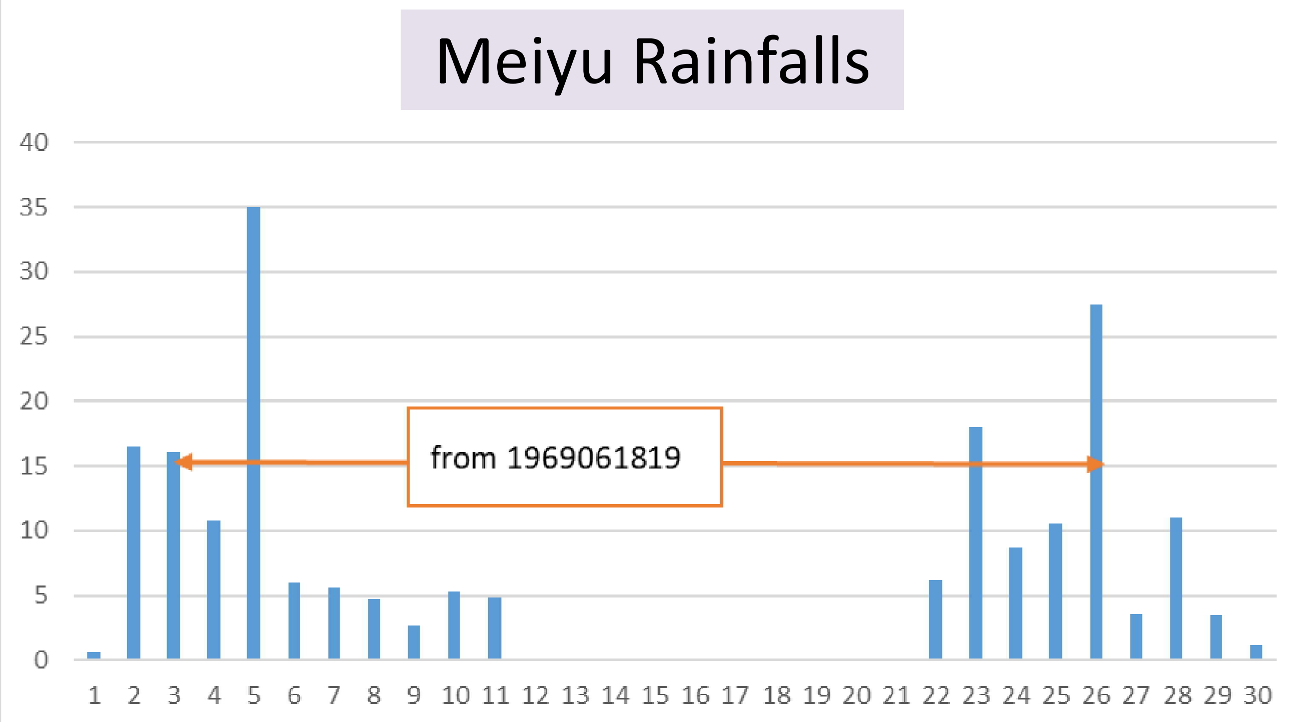
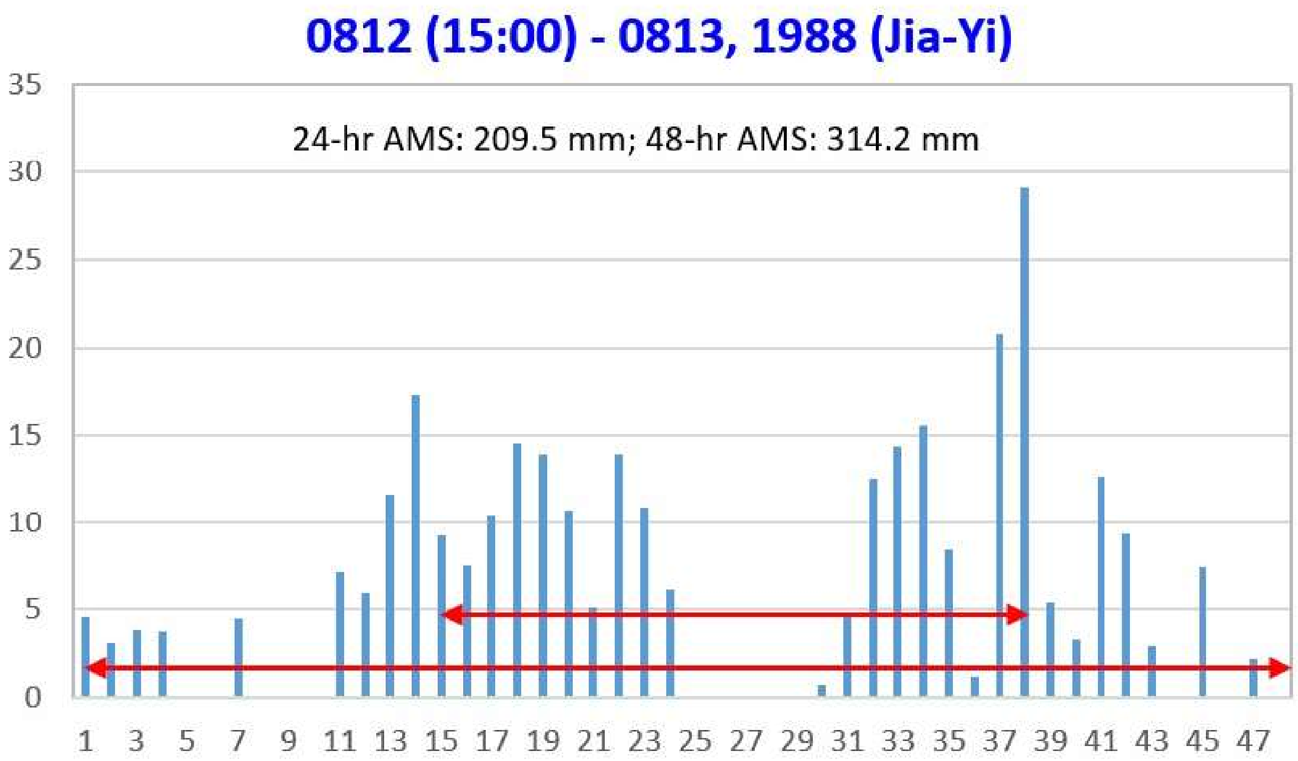
Annual maximum rainfalls (AMRs)

- **Duration-specific**
  - Design durations of 1, 2, 6, 12, 24, 48, 72 hours are often adopted.
- **Loss of information**
  - The 2nd or 3rd highest rainfalls in one year may exceed the annual maximum of another year, but are not included in the AMR series.
- **For longer durations (e.g. 48 and 72 hours), the AMR amounts may include rainfalls of different storm events.**

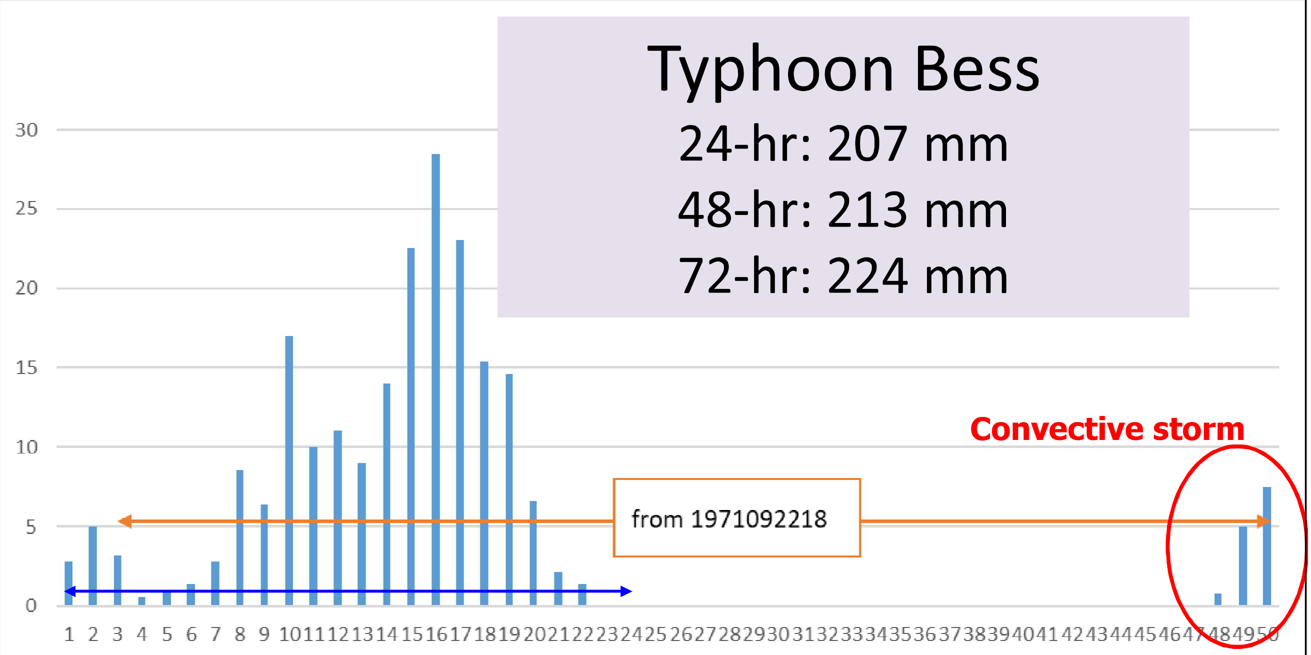
24-hr Annual Maximum Rainfall 1969, Jia-Yi Station (164.3mm)



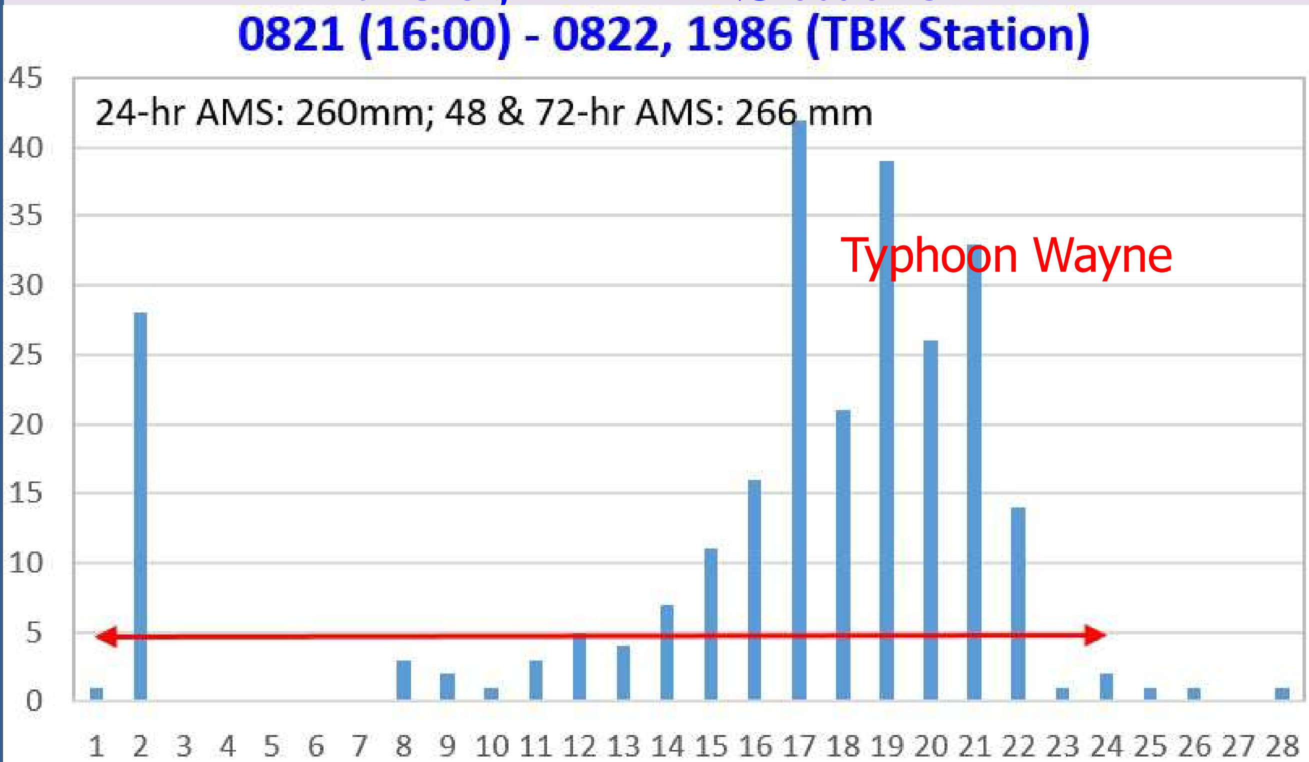
24 & 48-hr Annual Maximum Rainfalls, 1988, Jia-Yi Station



Annual Maximum Rainfalls 1971, TBK Station



Annual Maximum Rainfalls 1986, TBK Station



- **Thus, we propose using the event-maximum rainfalls (EMRs) for rainfall frequency analysis.**
  - **We calculated t-hr (1, 2, 3, 6, 12, 24, 48, and 72 hours) event-maximum rainfalls of individual storm events.**
  - **Storm events are grouped into 4 categories: Meiyu, convective storms, typhoons, and winter frontal rainfalls**
- **By using EMRs of various durations, the sample size can be significantly increased.**
- **The annual count of storm events varies from one year to another and can be characterized by a Poisson distribution.**

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Extremal Types Theorem

Probability framework for block maxima distribution

☐ Let $X_1, \ldots, X_n \overset{\text{iid}}{\sim} F$ and define

$$M_n = \max\{X_1, \ldots, X_n\}.$$

Then the distribution function of M_n is

$$\begin{aligned} \Pr\{M_n \leq x\} &= \Pr\{X_1 \leq x, \ldots, X_n \leq x\} \\ &= \Pr\{X_1 \leq x\} \times \cdots \times \Pr\{X_n \leq x\} \\ &= F(x)^n. \end{aligned}$$

☐ But F is unknown, so approximate F^n by limit distributions as $n \to \infty$.

☐ What distributions can arise?

☐ Obviously, if $F(x) < 1$, then $F(x)^n \to 0$, as $n \to \infty$.

Statistical Modelling of Extreme Values

Stuart Coles and Anthony Davison ©2008

CLT & ETT

Classical limit laws

M_n will converge to the upper endpoint of the distribution of X as $n \to \infty$.

- recall the Central Limit Theorem: with $\mu_n = \mu$ and $\sigma_n = \sigma/\sqrt{n}$,

$$\frac{\overline{X}_n - \mu_n}{\sigma_n} \to N(0,1),$$

so rescaling is needed to obtain a non-degenerate limit.

- Same applies here: we seek limits of

$$\frac{M_n - b_n}{a_n}$$

Approximation to the limit distribution is good only when the sample size is large enough.

for suitable sequences $\{a_n\} > 0$ and $\{b_n\}$.

Statistical Modelling of Extreme Values

Stuart Coles and Anthony Davison ©2008

Extremal types theorem

If there exist sequences of constants $a_n > 0$ and b_n such that, as $n \to \infty$,

$$\Pr\{(M_n - b_n)/a_n \le x\} \to G(x)$$

for some non–degenerate distribution G, then G has the same type as one of the following distributions:

$$I : G(x) = \exp\{-\exp(-x)\}, \quad -\infty < x < \infty;$$

$$II : G(x) = \begin{cases} 0, & x \le 0, \\ \exp(-x^{-\alpha}), & x > 0, \alpha > 0; \end{cases}$$

$$III : G(x) = \begin{cases} \exp\{-(-x)^{\alpha}\}, & x < 0, \alpha > 0, \\ 1, & x \ge 0. \end{cases}$$

Conversely, each of these G's may appear as a limit for the distribution of $(M_n - b_n)/a_n$, and does so when G itself is the distribution of X.

Statistical Modelling of Extreme Values

Stuart Coles and Anthony Davison ©2008

GEV Distribution

Generalized extreme value distribution

This family encompasses all three of the previous extreme value limit families:

$$G(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]_+^{-1/\xi}\right\},$$

defined on $\{x : 1 + \xi(x-\mu)/\sigma > 0\}$.

$x_+ = \max(x, 0)$.

μ and σ are location and scale parameters

ξ is a shape parameter determining the rate of tail decay, with

- $\xi > 0$ giving the heavy-tailed (Fréchet) case
- $\xi = 0$ giving the light-tailed (Gumbel) case
- $\xi < 0$ giving the short-tailed (negative Weibull) case

Speed of convergence to the limiting distribution

- **The speed of convergence of M_n to the limiting GEV distribution depends on the underlying distribution *F* - for example, convergence is slow for maxima of *n* Gaussian variables (Coles and Davison, 2008).**

Problems of GEV approximation of AMRs

- **AMRs are mostly resulted from events of dominant storm types (typhoons and Meiyu in East Asia).**
- **Annual count of typhoon (or Meiyu) events varies. Thus, AMRs are block maxima of different block sizes.**
- **Block sizes (*n*, number of events in a year) are generally small and, therefore, GEV approximation of AMRs distribution may not be appropriate.**

24-hr AMRs
Jia-Yi
(44 years)

starting time	rainfall (mm)	event
1969061819	164.3	2 meiyu rains, interval of 10 hours
1970090622	208.8	Typhoon (FRAN)
1971060614	262.5	Meiyu
1972060516	257.2	Meiyu
1973051812	115.6	2 meiyu rains, interval of 17 hours
1974060205	208	Meiyu
1975081613	380.7	Typhoon
1976052724	165.7	Meiyu
1977072516	423.5	Typhoon (THELMA)
1978060104	131.8	Meiyu
1979082417	235.4	Typhoon (JUDY)
1980082716	194	Typhoon (NORRIS)
1981090213	420.3	Typhoon
1982072918	167.5	Typhoon (ANDY)
1983053117	158.5	3 meiyu rains, interval of 8 and 5 hours
1984060924	101	Meiyu
1985062613	138.8	2 meiyu rains, interval of 4 hours
1986082120	212.6	Typhoon (WAYNE)
1987072703	215.4	Typhoon (ALEX)
1988081305	210.1	2 Typhoons, interval of 5 hours
1989091202	310	Typhoon (SARAH)
1990062316	139.8	Typhoon (OFELIA)
1991072922	175.9	Convective storm and typhoon, interval of 4 hours
1992083009	214.1	Typhoon (POLLY)
1993052613	130.5	Meiyu
1994081113	305.5	Typhoon and convective storm, interval of 6 hours
1995060815	123.5	Meiyu and Typhoon (DEANNA), interval of 6 hours
1996073116	347.5	Typhoon (HERB)
1997080614	218	Convrctive storm and typhoon, interval of 14 hours
1998080410	241	Typhoon (OTTO)
1999081121	112.5	Typhoon
2000082220	213.8	Typhoon (BILIS)
2001091718	871	Typhoon (NARI)
2002071618	98.2	2 convective storms, interval of 10 hours
2003060620	84.1	Meiyu
2004070207	454	Typhoon (MINDULLE)
2005061406	319	Meiyu
2006060905	401.5	Meiyu
2007081819	229.2	Typhoon (SEPAT)
2008071715	344.5	Typhoon (KALMAEGI)
2009080814	526	Typhoon (MORAKOT)
2010072616	210	Convective storm and typhoon, interval of 4 hours
2011110918	114.7	Frontal rain
2012080121	179	Typhoon (SAOLA)

24-hr AMRs
Wu-Duh
(32 years)

starting time	rainfall (mm)	event
1970081110	103.3	Typhoon (WILDA)
1974101113	296.5	Typhoon (BESS)
1975101322	120.5	Convective storm
1983101118	168	Typhoon
1984080622	210	Typhoon (FREDA)
1985082219	210	Typhoon (NELSON)
1986091816	290	Typhoon (ABBY)
1987102324	924	Typhoon (LYNN)
1988091904	341	Typhoon
1989072803	312	Typhoon
1990090718	214	Typhoon (DOT)
1991062024	183	Meiyu
1992092002	156	Typhoon (TED)
1993092404	212	Typhoon
1994091206	280	Typhoon
1995092104	173	Typhoon (RYAN)
1996092716	236	Typhoon (ZANE)
1997081717	337	Typhoon (WINNIE)
1998101516	492	Typhoon (ZEB)
1999031205	319	Frontal rain
2000103024	252	Typhoon (XANGSANE)
2001091611	782	Typhoon (NARI)
2002061104	170	Meiyu
2003112605	141	Frontal rain
2004091018	416	Typhoon (HAIMA)
2005083116	250	Typhoon (TALIM)
2006091007	223	Typhoon
2007100605	270	Typhoon (KROSA)
2008110811	301	Frontal rain
2009060405	180	Meiyu
2010102022	268	Typhoon (MEGI)
2011100217	170	Typhoon

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Mixture distribution modeling of AMRs

- Four different storm types
  - Meiyu (May – June)
  - Convective storm (July – October)
  - Typhoon (July – Mid November)
  - Frontal rainfall (November – April)

Mixture distribution modeling of AMRs using event-maximum rainfalls

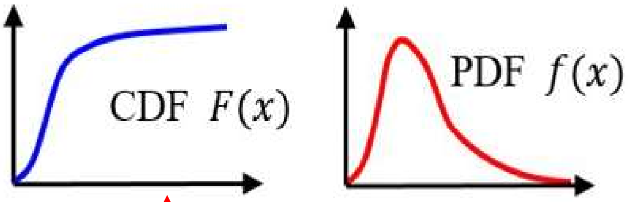
1) Probability distributions of event-maximum rainfalls of individual storm types (Pearson Type III distribution)
2) Poisson distribution for annual occurrences of individual storm types
3) Mixture distribution modeling of AMRs of individual storm types
4) Cumulative distribution of AMRs of all storm types

Storm-type-specific EMRs & AMRs

	Number of storms, n	t-hr EMRs
Year 1	n_1 (3)	x_{11}, x_{12}, x_{13}
Year 2	n_2 (5)	$x_{21}, x_{22}, x_{23}, x_{24}, x_{25}$
	:	:
	:	:
Year j	n_j (0)	none
	:	:
	:	:
Year N	n_N (2)	x_{N1}, x_{N2}

Storm-type-specific EMRs & AMRs

CDF & PDF of EMRs

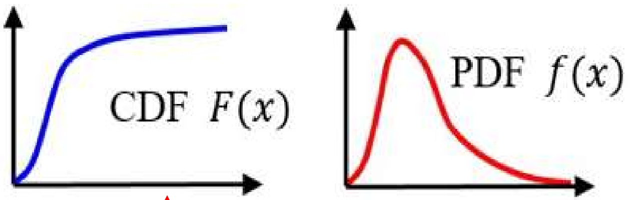


Poisson distribution of annual storm occurrences, **n**

	Number of storms, n	t-hr EMRs
Year 1	n_1 (3)	x_{11}, x_{12}, x_{13}
Year 2	n_2 (5)	$x_{21}, x_{22}, x_{23}, x_{24}, x_{25}$
	:	:
	:	:
Year j	n_j (0)	none
	:	:
	:	:
Year N	n_N (2)	x_{N1}, x_{N2}

Storm-type-specific EMRs & AMRs

CDF & PDF of EMRs

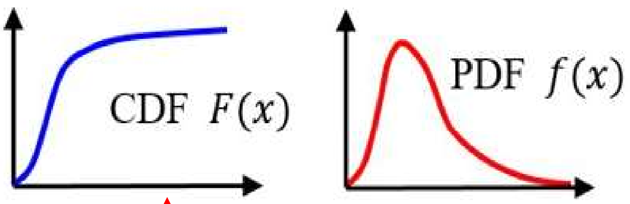


Poisson distribution of annual storm occurrences, **n**

	Number of storms, n	t-hr EMRs	CDF of AMR of individual years
Year 1	n_1 (3)	x_{11}, x_{12}, x_{13}	$[F(x)]^3$
Year 2	n_2 (5)	$x_{21}, x_{22}, x_{23}, x_{24}, x_{25}$	$[F(x)]^5$
	:	:	:
	:	:	:
Year j	n_j (0)	none	$[F(x)]^0 = 1$
	:	:	:
	:	:	:
Year N	n_N (2)	x_{N1}, x_{N2}	$[F(x)]^2$

Storm-type-specific EMRs & AMRs

CDF & PDF of EMRs



Poisson distribution of annual storm occurrences, **n**

	Number of storms, n	t-hr EMRs	CDF of AMR of individual years	Mixture distribution of AMR
Year 1	n_1 (3)	x_{11}, x_{12}, x_{13}	$[F(x)]^3$	Theoretical
Year 2	n_2 (5)	$x_{21}, x_{22}, x_{23}, x_{24}, x_{25}$	$[F(x)]^5$	
	:	:	:	$F_{AMR}(x) = F^*(x) = \sum_{n=0}^{\infty}[F(x)]^n p(n)$
	:	:	:	
Year j	n_j (0)	none	$[F(x)]^0 = 1$	$p(x) = \frac{e^{-\mu}\mu^x}{x!}$ $x = 0, 1, 2, \ldots$
	:	:	:	
	:	:	:	
Year N	n_N (2)	x_{N1}, x_{N2}	$[F(x)]^2$	

CDF of overall-AMRs

- **Cumulative distribution of AMRs of all storm types, *G*(*x*)**
  - **Overall-AMR is the maximum of four storm-type-specific AMRs.**
  - **AMRs mixture distributions of individual storm types are independent.**

$$G(x) = F^*_{Mei}(x) \times F^*_{Con}(x) \times F^*_{Typ}(x) \times F^*_{Frn}(x)$$

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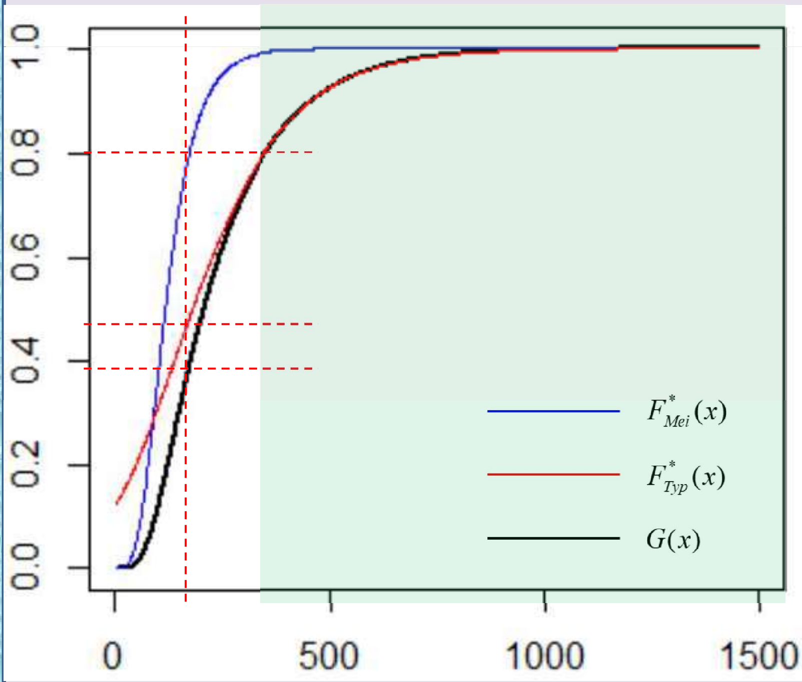
Parameters Setting

- Two dominant storm types: Meiyu, Typhoon
- 24-hour EMRs of typhoon (X_1) & meiyu (X_2)
  - $X_1 \sim Gamma(scale = 141.19, shape = 1.34)$
  - $X_2 \sim Gamma(scale = 53.87, shape = 0.68)$
- Number of storm occurrences in one year
  - $n_1 \sim Poisson(\lambda_1 = 2.09)$
  - $n_2 \sim Poisson(\lambda_2 = 11.45)$
- Record length, N=44 (one block simulation run)
- 10,000 block simulation runs were conducted.

- **Theoretical CDF of annual maximum rainfalls *G*(*x*) can be derived based on the CDF of event maximum rainfalls & Poisson distribution of storm occurrences.**



Return Period (years)	24-hr rainfall (mm)
5	352
10	459
25	596
50	698
100	799
200	899

- **From the results of one block simulation run, there are two approaches to estimate design rainfalls of various return periods**
  - **(1) Event-based approach - Based on EMRs and mixture distribution**
  - **(2) Traditional approach - Based on AMRs**

(1) Event-based approach

- **From the results of one block simulation run**
  - **Estimate distribution parameters of EMRs of individual storm types. [Gamma distribution, Method of L-moments]**
  - **Estimate parameter of the Poisson distribution of storm occurrences of individual storm types.**
  - **Estimate CDF of AMRs [Mixture distribution]**
  - **AMR quantiles of desired returned periods.**

	Number of storms, n	t-hr EMRs	CDF of AMR of individual years	Estimate of Mixture distribution of AMR
Year 1	n_1 (3)	x_{11}, x_{12}, x_{13}	$[F(x)]^3$	$\hat{F}_{AMR}(x) = \hat{F}^*(x) = \sum_{n=0}^{\infty}[\hat{F}(x)]^n \hat{p}(n)$ $\hat{p}_n(x) = \frac{e^{-\hat{\mu}}\hat{\mu}^x}{x!} \quad x = 0, 1, 2, \cdots$
Year 2	n_2 (5)	$x_{21}, x_{22}, x_{23}, x_{24}, x_{25}$	$[F(x)]^5$	
	:	:	:	
	:	:	:	
Year j	n_j (0)	none	$[F(x)]^0 = 1$	
	:	:	:	
	:	:	:	
Year N	n_N (2)	x_{N1}, x_{N2}	$[F(x)]^2$	

$$\hat{G}(x) = \hat{F}^*_{Mei}(x) \times \hat{F}^*_{Typ}(x)$$

	Number of storms, n	t-hr EMRs	CDF of AMR of individual years	Mixture distribution of AMR
Year 1	n_1 (3)	x_{11}, x_{12}, x_{13}	$[F(x)]^3$	Theoretical $F_{AMR}(x) = F^*(x) = \sum_{n=0}^{\infty}[F(x)]^n p(n)$ $p(x) = \frac{e^{-\mu}\mu^x}{x!} \quad x = 0, 1, 2, \ldots$
Year 2	n_2 (5)	$x_{21}, x_{22}, x_{23}, x_{24}, x_{25}$	$[F(x)]^5$	
	:	:	:	
	:	:	:	
Year j	n_j (0)	none	$[F(x)]^0 = 1$	
	:	:	:	
	:	:	:	
Year N	n_N (2)	x_{N1}, x_{N2}	$[F(x)]^2$	

(2) Traditional approach

- From the results of one block simulation run
  - Collect an AMR series (considering all storm types)
  - Estimate distribution parameters of AMRs [Pearson Type III distribution, Method of L-moments]
  - Estimate CDF of AMRs
  - AMR quantiles of desired returned periods.

- Estimates of design rainfalls
  - The 1st block simulation run

Return Period (years)	24-hr rainfall (mm)		
	Theoretical	Event-based	Traditional
5	352	423	422.7886
10	459	557	562.6678
25	596	727	743.2285
50	698	853	877.7817
100	799	978	1011.1386
200	899	1102	1143.5941

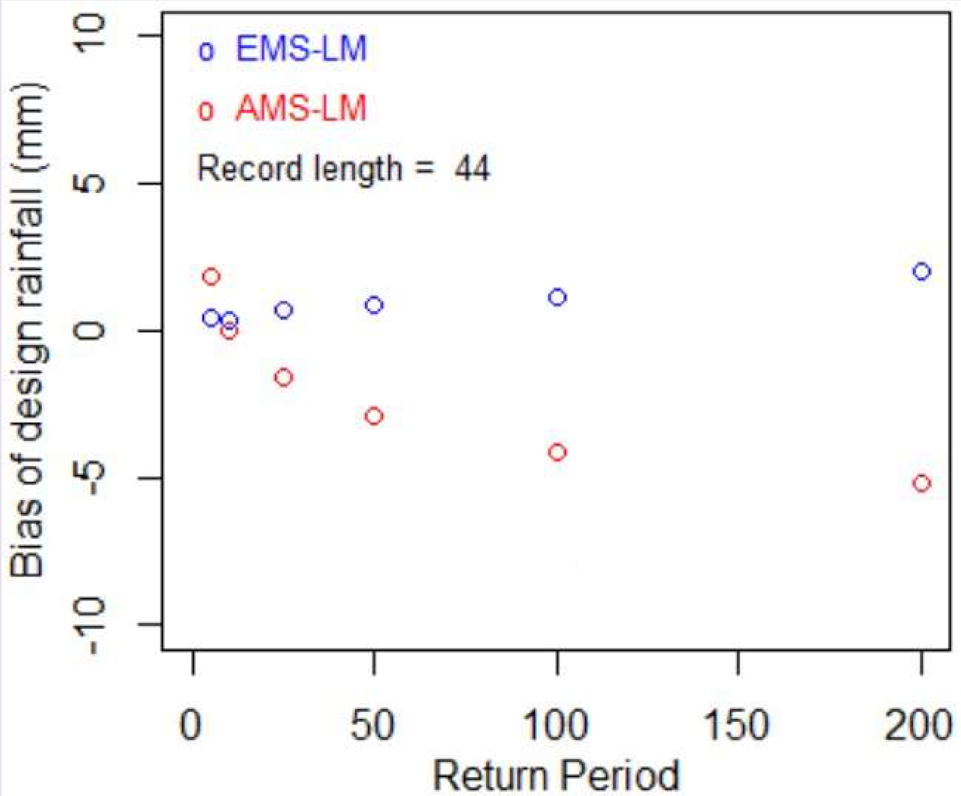
- **Estimates of design rainfalls**
  - **The 100th block simulation run**

Return Period (years)	24-hr rainfall (mm)		
	Theoretical	Event-based	Traditional
5	352	355	363.9645
10	459	464	469.119
25	596	607	605.1704
50	698	715	706.7061
100	799	822	807.4293
200	899	930	907.5403

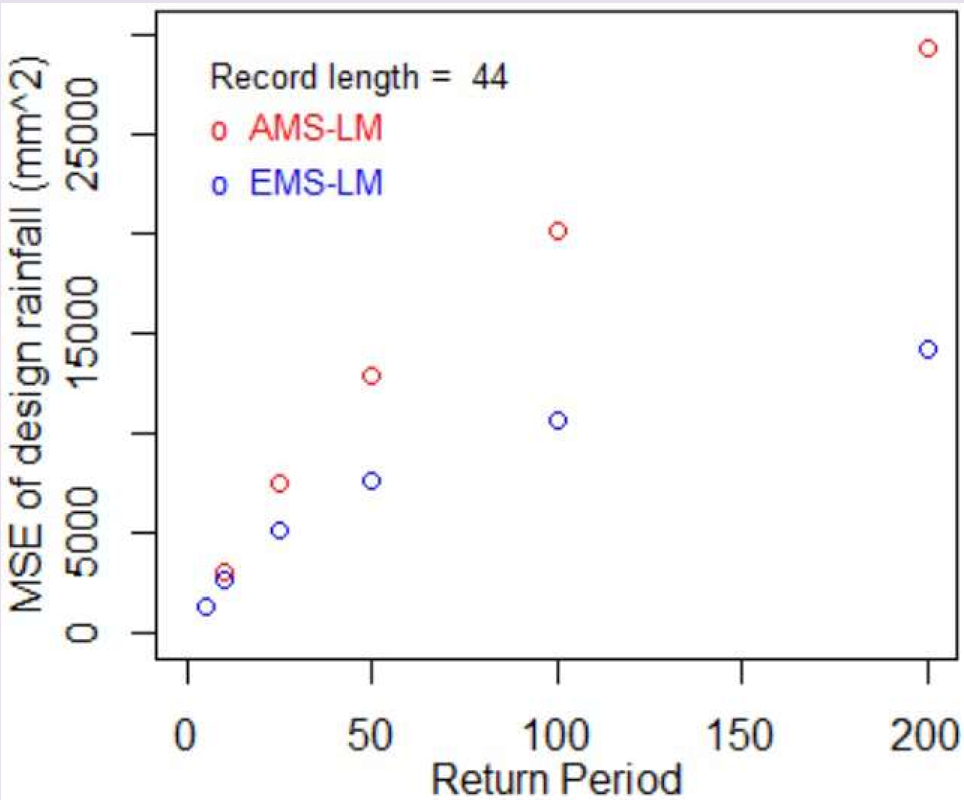
Evaluating the bias and MSE

- **Based on 10,000 block simulation runs, the bias and mean squared error of design rainfall estimates by the event-based approach and the traditional approach were calculated.**
- **Both approaches achieved nearly unbiased estimates, although the event-based approach seemed to perform better.**
- **The event-based approach is superior to the tradition approach in terms of the mean squared errors.**

Bias



Mean squared error



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Observed rainfalls in Taiwan

- Thee stations
  - Wu-Duh (32 years) [Northern Taiwan]
  - TBK (42 years) [Central Taiwan]
  - Jia-Yi (44 years) [Southern Taiwan]
- EMRs and AMRs of 1, 2, 3, 6, 12, 24, 48, and 72-hour durations.
- Types of dominant storms
  - Meiyu
  - Convective rainfalls
  - Typhoons

- **EMRs and AMRs were modeled by the Pearson Type III distribution.**
  - **Parameters estimation by Method of L-moments**
- **Poisson distribution for annual storm occurrences**

Wu-Duh

	Design rainfalls based on annual maximum rainfalls (PE3)					
	5	10	25	50	100	200
1	78.94626	95.73936	117.2391	133.1756	148.9195	164.5181
2	113.2098	133.5616	158.568	176.5966	194.1009	211.2078
3	139.558	167.2692	202.3861	228.2416	253.6794	278.8016
6	196.0209	236.3163	287.6358	325.5457	362.9189	399.887
12	281.2399	357.1421	458.4298	535.4955	612.8213	690.3423
24	370.2707	492.1145	659.349	788.7392	919.8096	1052.135
48	493.3882	660.0997	886.0866	1059.66	1234.765	1411.015
72	556.7683	732.6582	967.7849	1146.873	1326.677	1507.016

	(Mixture distribution, 3 storm types)					
Duration	5	10	25	50	100	200
1	74	85	98	108	118	128
2	110	128	149	165	180	196
3	135	157	183	203	222	241
6	196	231	274	307	339	371
12	280	334	402	453	502	552
24	372	448	543	613	682	752
48	484	596	739	845	950	1055
72	511	631	783	896	1009	1122

TBK

	Design rainfalls based on annual maximum rainfalls (PE3)					
	5	10	25	50	100	200
1	83.05702	110.3765	150.0912	181.8177	214.5183	247.9404
2	118.2606	168.884	248.6744	315.0862	384.9715	457.4031
3	148.4663	209.7813	301.8913	376.7473	454.5879	534.6295
6	217.6051	302.273	422.1546	516.5603	613.125	711.2948
12	300.4476	409.3882	557.8193	672.1691	787.7246	904.1816
24	389.0314	514.8466	680.7289	806.0099	931.1713	1056.243
48	460.4525	599.9898	781.7722	918.033	1053.559	1188.532
72	495.2108	639.6295	827.0582	967.2126	1106.41	1244.887

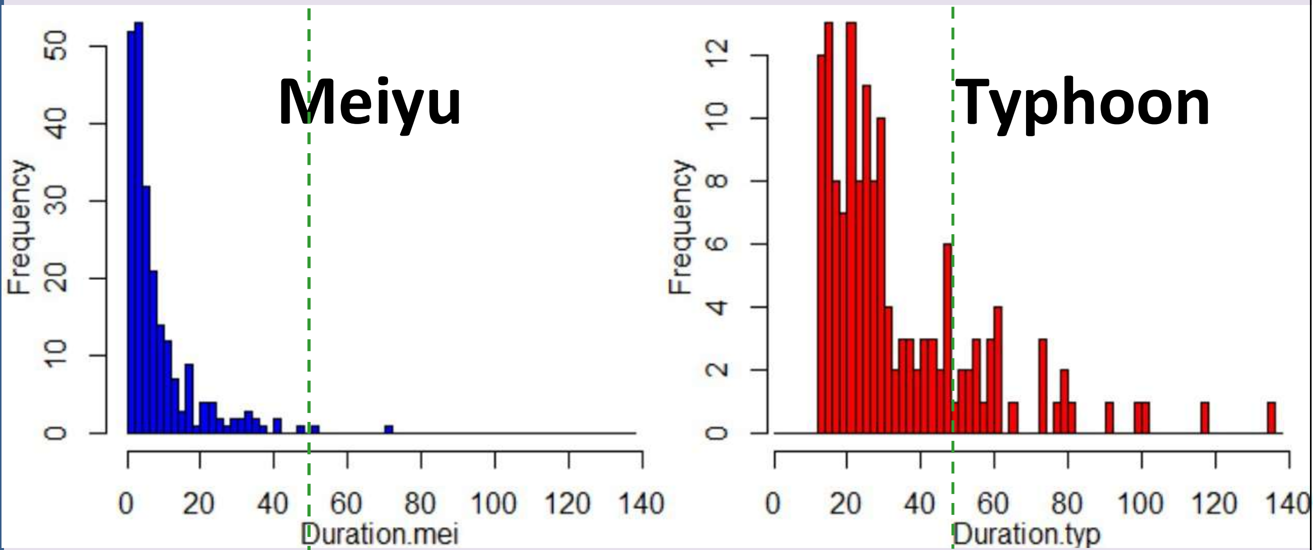
	(Mixture distribution, 3 storm types)					
Duration	5	10	25	50	100	200
1	82	94	109	120	131	142
2	122	140	164	181	198	215
3	147	171	200	222	244	265
6	205	245	296	333	371	408
12	289	356	442	505	567	629
24	379	477	601	693	784	873
48	431	545	691	798	904	1009
72	432	546	692	799	905	1010

Jia-Yi

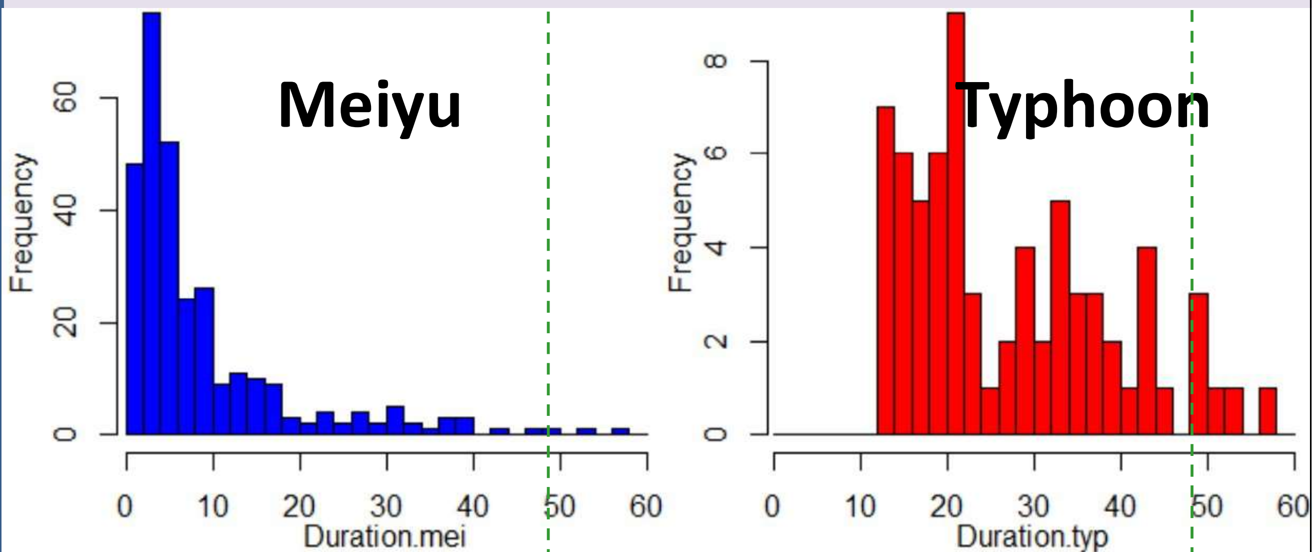
	Design rainfalls based on annual maximum rainfalls (PE3)					
	5	10	25	50	100	200
1	78.47339	99.57152	128.5489	150.9776	173.7026	196.6487
2	112.5002	142.6238	183.5709	215.0724	246.8812	278.9197
3	130.9613	163.2666	206.3612	239.1431	272.0316	305
6	174.9975	215.3053	267.3386	306.1147	344.5469	382.7198
12	244.0945	306.3945	386.6671	446.4158	505.5914	564.335
24	331.7323	428.3877	555.2884	650.8777	746.2281	841.399
48	406.8952	525.8088	684.2436	804.6747	925.4451	1046.47
72	444.4195	564.2938	722.4132	841.8642	961.2203	1080.505

	(Mixture distribution, 3 storm types)					
Duration	5	10	25	50	100	200
1	78	91	111	127	145	166
2	113	134	165	190	219	254
3	131	157	194	224	257	297
6	173	211	263	305	349	401
12	238	298	378	439	504	579
24	313	401	516	605	698	806
48	354	463	608	720	839	977
72	356	466	610	723	842	980

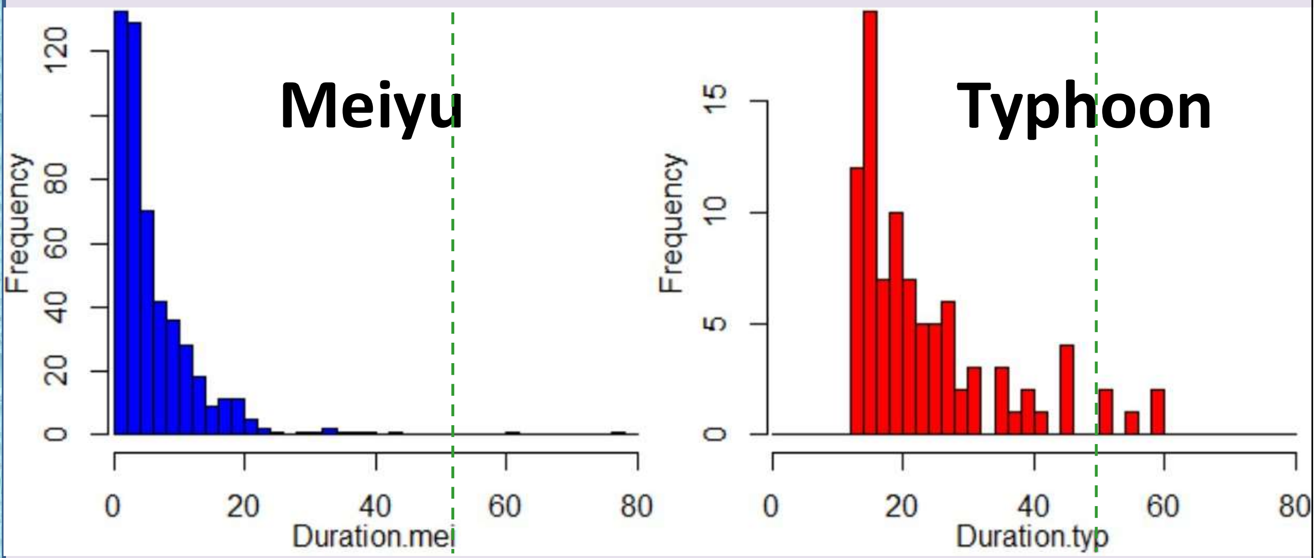
Histogram of event durations Wu-Duh Station



Histogram of event durations TBK Station



Histogram of event durations Jia-Yi Station



Effect of outliers on rainfall frequency analysis (Wu-Duh)

Removal of outlier

Design rainfalls based on annual maximum rainfalls (PE3)

	5	10	25	50	100	200
1	78.94626	95.73936	117.2391	133.1756	148.9195	164.5181
2	113.2098	133.5616	158.568	176.5966	194.1009	211.2078
3	139.558	167.2692	202.3861	228.2416	253.6794	278.8016
6	196.0209	236.3163	287.6358	325.5457	362.9189	399.887
12	281.2399	357.1421	458.4298	535.4955	612.8213	690.3423
24	370.2707	492.1145	659.349	788.7392	919.8096	1052.135
48	493.3882	660.0997	886.0866	1059.66	1234.765	1411.015
72	556.7683	732.6582	967.7849	1146.873	1326.677	1507.016

Design rainfalls based on annual maximum rainfalls (PE3, 1 typho

	5	10	25	50	100	200
1	78.10128	95.3162	117.5662	134.1605	150.6154	166.9653
2	111.8809	132.9205	159.1002	178.1398	196.7284	214.9756
3	136.2523	163.6607	198.6821	224.608	250.2005	275.5414
6	187.879	222.6974	266.3589	298.2798	329.5478	360.322
12	263.1103	320.3148	393.8594	448.5221	502.6136	556.2745
24	339.2505	422.2506	530.1935	611.0175	691.3532	771.3213
48	445.0466	549.1422	680.3696	776.6528	871.1764	964.3701
72	502.8246	610.9091	744.5343	841.2857	935.4801	1027.738

(Mixture distribution, 3 storm types)

Duration	5	10	25	50	100	200
1	74	85	98	108	118	128
2	110	128	149	165	180	196
3	135	157	183	203	222	241
6	196	231	274	307	339	371
12	280	334	402	453	502	552
24	372	448	543	613	682	752
48	484	596	739	845	950	1055
72	511	631	783	896	1009	1122

(Mixture distribution, 3 storm types, 1 typhoon outlier removed)

Duration	5	10	25	50	100	200
1	73	83	97	107	116	126
2	109	126	147	162	177	192
3	133	153	178	196	215	233
6	189	221	260	290	318	347
12	263	309	367	409	451	492
24	340	401	477	532	587	641
48	434	522	633	715	795	875
72	460	556	676	765	853	941

Effect of outliers on rainfall frequency analysis (TBK)

Removal of outlier

Design rainfalls based on annual maximum rainfalls (PE3)

	5	10	25	50	100	200
1	83.05702	110.3765	150.0912	181.8177	214.5183	247.9404
2	118.2606	168.884	248.6744	315.0862	384.9715	457.4031
3	148.4663	209.7813	301.8913	376.7473	454.5879	534.6295
6	217.6051	302.273	422.1546	516.5603	613.125	711.2948
12	300.4476	409.3882	557.8193	672.1691	787.7246	904.1816
24	389.0314	514.8466	680.7289	806.0099	931.1713	1056.243
48	460.4525	599.9898	781.7722	918.033	1053.559	1188.532
72	495.2108	639.6295	827.0582	967.2126	1106.41	1244.887

Design rainfalls based on AMS (PE3, 1 outlier removed)

5	10	25	50	100	200
76.02109	89.74817	107.5395	120.832	134.0269	147.1484
108.7826	132.0299	163.7662	188.2437	212.9953	237.9518
135.3101	167.2984	210.3337	243.239	276.349	309.6125
198.0264	250.8289	320.3221	372.7477	425.0888	477.3665
276.2485	353.8318	454.4323	529.6169	604.263	678.5036
363.774	463.9002	591.8952	686.6765	780.2558	872.9283
434.8072	552.0111	701.456	811.9369	920.9053	1028.732
470.4024	595.5943	755.5525	873.9645	990.8517	1106.589

(Mixture distribution, 3 storm types)

Duration	5	10	25	50	100	200
1	82	94	109	120	131	142
2	122	140	164	181	198	215
3	147	171	200	222	244	265
6	205	245	296	333	371	408
12	289	356	442	505	567	629
24	379	477	601	693	784	873
48	431	545	691	798	904	1009
72	432	546	692	799	905	1010

(Mixture distribution, 3 storm types, 1 meiyu outlier removed)

5	10	25	50	100	200
78	90	105	117	128	139
115	133	156	173	190	206
139	162	192	214	235	257
196	237	289	328	367	405
281	351	439	503	566	628
372	473	600	692	783	873
423	541	688	797	903	1009
424	542	690	798	904	1010

Effect of outliers on rainfall frequency analysis (Jia-Yi)

Removal of outlier

Design rainfalls based on annual maximum rainfalls (PE3)

	5	10	25	50	100	200
1	78.47339	99.57152	128.5489	150.9776	173.7026	196.6487
2	112.5002	142.6238	183.5709	215.0724	246.8812	278.9197
3	130.9613	163.2666	206.3612	239.1431	272.0316	305
6	174.9975	215.3053	267.3386	306.1147	344.5469	382.7198
12	244.0945	306.3945	386.6671	446.4158	505.5914	564.335
24	331.7323	428.3877	555.2884	650.8777	746.2281	841.399
48	406.8952	525.8088	684.2436	804.6747	925.4451	1046.47
72	444.4195	564.2938	722.4132	841.8642	961.2203	1080.505

Design rainfalls based on AMS (PE3, 1 outlier removed)

5	10	25	50	100	200
75.39092	94.09747	119.5949	139.2423	159.0994	179.1133
107.7287	132.9395	166.5035	192.0048	217.5709	243.1858
125.636	152.657	187.9131	214.3663	240.6922	266.9222
167.4199	200.719	242.5871	273.2523	303.324	332.9471
228.1933	272.3134	325.9458	364.322	401.4011	437.4961
308.544	377.76	463.9536	526.6731	587.9276	648.0735
379.5444	464.9235	573.0741	652.68	730.9862	808.3108
417.6516	506.6674	618.9174	701.2927	782.1723	861.9217

(Mixture distribution, 3 storm types)

Duration	5	10	25	50	100	200
1	78	91	111	127	145	166
2	113	134	165	190	219	254
3	131	157	194	224	257	297
6	173	211	263	305	349	401
12	238	298	378	439	504	579
24	313	401	516	605	698	806
48	354	463	608	720	839	977
72	356	466	610	723	842	980

(Mixture distribution, 3 storm types, 1 typhoon outlier removed)

5	10	25	50	100	200
75	88	104	117	131	148
109	127	152	173	195	222
127	149	180	204	231	263
167	199	243	278	315	359
222	269	331	378	428	485
288	356	444	510	580	660
322	406	515	598	685	786
324	408	517	601	689	790

Conclusions

- We developed an event-based rainfall frequency analysis approach.
- For stations with short record length, the EMR-based approach performs better than the AMR-based approach.
- For longer durations (48 and 72 hours), results of AMR-based approach may be unrealistic.

Thank you for listening.
Your comments and suggestions are most welcome.

Events description	48-hr	72-hr	Events durations
4 meiyu rains, interval of 10 、9 、4 hours	225.5	232	11 、9 、3 、5
Typhoon (FRAN)	244.5	277.1	**52**
Meiyu	357.6	398.6	**61**
Meiyu	280.9	292.9	**36**
3 convective rains, interval of 15 、17 hours	175.2	177.1	7 、7 、4
2 meiyu rains, interval of 30 hours	225.1	267.8	11 、2
Typhoon	383.8	384	**25**
2 meiyu rains, interval of 12 hours	200.7	246.1	19 、12
Convective rain and typhoon rain(THELMA), interval of 4 hours	617.4	663.8	8 、46
Meiyu	132.5	186.9	**7**
Typhoon (JUDY)	278.4	289	**46**
Typhoon (NORRIS)	196	196	**26**
2 typhoons, interval of 13 hours	505.8	562.6	36 、22
Typhoon (ANDY)	241.6	260.7	**56**
4 meiyu rains, interval of 8 、5 、14 hours	253.3	308.9	6 、3 、6 、9
2 meiyu rains, interval of 6 hours	128	169.1	5 、37
3 meiyu rains, interval of 9 and 7 hours	159.5	185	5 、19 、4
Typhoon (WAYNE)	213	237.3	**22**
Typhoon rain (ALEX) and convective rain, interval of 8 hours	256.5	264.7	21 、6
2 Typhoons, interval of 5 hours	315.5	345.9	24 、18
Typhoon (SARAH)	374.8	379.1	**45**
Typhoon 、convective and typhoon rains (in YANCY), interval of 4 and 7 hours	224.4	249.9	17 、8 、14
2 convective rains and typhoon, interval of 6 and 4 hours	273.3	311.6	12 、2 、15
Convective rain 、typhoon rain and convective rain, interval of 4 and 13 hours	278.9	364.6	2 、19 、11
Meiyu	158.3	162.7	**34**
2 typhoons and convective rain, interval of 15 and 6 hours	346.5	422.8	15 、16 、5
Meiyu and Typhoon (DEANNA), interval of 6 hours	182.1	235.6	9 、24
Typhoon (HERB)	413	416.5	**46**
Convrctive and typhoon, interval of 14 hours	281.9	376.2	2 、36
Typhoon (OTTO)	244.8	289.7	**20**
Convective rain 、typhoon and convective rain, interval of 12 and 14 hours	173.3	198	6 、16 、5
Typhoon (BILIS) and convective rain, interval of 22 hours	229.8	232.3	20 、2
Typhoon (NARI)	1062.5	1065.5	**42**
3 convective rains, interval of 17 、17 hours	177.2	262.3	3 、7 、5
5 meiyu rains, interval of 5 、6 、5 、6 hours	137	157	3 、10 、4 、2 、8
Typhoon (MINDULLE) and convective rain, interval of 9 hours	489	521.6	26 、3
Meiyu	459	538	**78**
Meiyu	496	515	**39**
Typhoon (SEPAT) and convective rain, interval of 8 hours	318.7	364.8	28 、9
Typhoon (KALMAEGI)	427.5	454.1	**51**
Typhoon (MORAKOT)	646	697.1	**60**
Convective rain and typhoon, interval of 4 hours	311	320	4 、40
Frontal rain	159.7	171.1	**45**
2 convective rains, interval of 19 hours	216.9	217.9	5 、7