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Investigating event-based temporal patterns of design rainfall in a tropical region

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Abstract

This study investigated the temporal rainfall pattern in order to facilitate rainfall design, which normally requires a good understanding of the temporal patterns of rainstorm events. The analysis was based on a storm-event-based approach using the concept of inter-event time definition (IETD) and rainfall depth/duration/intensity thresholds. The 5-min rainfall data at three rain gauge stations were analysed to determine representative quartiles of a design storm in a tropical city. The temporal characteristics of the design storm could be determined from the rainfall depth ratios of consecutive peak rainfalls for each interval of storm duration, and time to the first peak rainfall depending on each quartile's rainstorm events. The determination of the quantile distribution of tropical rainfall could help improve the representativeness of design rainfall and facilitate rainfall-runoff modelling for urban flood control in a tropical region.

***Keywords*:** design storm hyetograph, temporal pattern of rainfall, peak rainfall, urban stormwater infrastructures, tropical region

INTRODUCTION

Flood estimation is essential for many hydrological applications in urban areas such as flood risk mapping, stormwater management, and hydraulic infrastructure design. In engineering practice, the design rainfall is commonly used as input for various rainfall-runoff models, which facilitate the estimation of flood quantiles in urban drainage systems (Varga *et al*. 2009). The magnitude of design rainfall is normally estimated from rainfall depth-duration-frequency (DDF) or intensity-duration-frequency (IDF) curves (Liew 2012), and the temporal patterns of design rainfall are obtained from synthetic hyetographs under various combinations of frequencies and durations (Wenzel 2013). As a design rainfall significantly affects the prediction of runoff characteristics, such as time to peak rainfall and peak runoff rate, its representativeness of the local temporal rainfall pattern is critical to the proper design of urban stormwater management systems (Durkerley 2012; Hu et al., 2021).

Synthetic hyetographs are generally derived from the analysis of observed rainfall data and rainfall IDF relationships by using stochastic or probabilistic approaches (Na and Yoo 2018). Keifer and Chu (1957) proposed the Chicago method to calculate design rainfalls for urban sewer design; the method involves two analytical equations for describing temporal distributions of rainfall depending on the time to peak rainfall rate. Huff (1967) proposed a design approach to model storm distributions in dimensionless forms that could be used to generate rainfall hyetographs using specific storm durations (Bonnin *et al*. 2006; Liew 2012). Pilgrim and Cordery (1975) suggested an order-average hyetograph method focusing on the average rainfall in the rank of each rainfall duration. Yen and Chow (1980) developed a method for producing triangular-shaped hyetographs by considering design rainfall depth, rainfall duration, and the storm advancement coefficient. Chow *et al*. (1988) introduced an alternating block method to derive design hyetographs based on the difference between cumulative depths of successive rainfalls corresponding to specific durations and return periods.

Additionally, a number of studies have analysed the temporal characteristics of rainfall in tropical areas. In Singapore, Chang (1969) examined 377 rainfall events at five gauge stations and found that the temporal pattern of storms could be represented by the storm events from a single station, not correlated with other storm characteristics. Tan and Sia (1997) utilized 5-year rainfall data to develop an algorithm for producing synthetic hyetographs of design rainfall in a tropical region based on a one-step Markov chain model. Azli and Rao (2010) used hourly rainfall data from 13 gauge stations in Peninsular Malaysia to derive Huff's curves and observed that there was no clear difference in the Huff's curve for the rain gauge stations. Trang *et al*. (2018) applied the Chicago method and alternating block method to investigate the scaling behaviour of statistical moments over various rainfall durations for monsoon climate areas in Vietnam. Generally, these studies were limited in representing the rainfall patterns of actual rainstorm events as they purely relied on the direct application of existing methods such as the Huff, Chicago, and alternating block methods.

In recent years, the storm-event-based approach has been increasingly used to determine the depth, intensity, and duration of actual rainstorm events in studies of the analysis of the frequency of extreme rainfalls and rainfall-runoff modelling, the determination of the critical duration of rainfall for flood estimation, the determination of independent rainstorm events, the estimation of peak discharge, the determination of the quantiles of maximum annual flows and the quantification of the temporal rainfall pattern (Jun and Yoo 2012; Yoo and Park 2012; Park *et al*. 2013; Grimaldi and Petroselli 2015; Jun *et al*. 2017; Mlynski *et al*. 2020; Petroselli 2020). These approaches retrieved independent rainstorm events from rainfall time series without fixing on pre-selected time intervals in an attempt to improve the accuracy of conventional methods for generating synthetic hyetographs and evaluating urban flooding risks in a more realistic way. Technical details about the storm-event-based approach are given in Jun *et al*. (2018). However, there have been limited studies that have produced design storm hyetographs using the storm-event-based approach in a tropical region. One recent attempt to analyse the temporal characteristics of the rainstorm events was made by Jun *et al*. (2019), who presented a preliminary analysis of the temporal distribution of tropical storms based on the concept of inter-event time definition (IETD) in order to determine percentage frequencies and representative quartiles of storm events in two sites in Singapore; however, their study was short of detailed analysis of the temporal pattern of design rainfall. Hence, as an extension to the work of Jun *et al*. (2019), this study aims to carry out a more holistic study of the determination of design storm hyetographs using the storm-event-based approach. First, individual events are extracted from rainfall time series considering the IETD and storm depth/duration/intensity thresholds. By pinpointing the locations of heaviest rainfall during each storm, the representative quartile of the design storm is obtained. A hyetograph of design rainfall is then derived based on the relative rainfall rate of consecutive peak rainfalls for the quartiles of each rainstorm event corresponding to different intervals of storm duration. The analysis is based on 5-min rainfall data collected from three gauge stations in Singapore.

METHODOLOGY

Figure 1 shows the overall framework for determining the temporal pattern of design rainfall. This framework consists of three major parts: (1) the determination of individual rainstorm events; (2) the selection of representative design groups; and (3) the determination of temporal patterns for design rainfall. Firstly, each rainstorm event is extracted to examine the temporal variation of rainfall intensity. Here, we consider storm depth and duration thresholds to reduce the error in establishing each representative quartile of the rainstorm events based on the location where the peak rainfall rate occurred during the storm. Secondly, the threshold value is identified based on the regional rainfall characteristics. The final step is to determine a distribution of rainfall depth ratios of consecutive peak rainfalls to total rainfalls for each rainstorm event in a sequential order, corresponding to a representative quartile group. Here, consecutive peak rainfalls represent the 5-min rainfall intensity values in each rainstorm event that follow each other continuously in the order from the largest to the smallest.

Place Figure 1 here

Data

Singapore is a highly urbanized nation with a high population density and a land area of 712.4 km^2 (PUB 2011). Although the country′s weather conditions are heavily influenced by northeast and southwest monsoons each year, there is no distinct seasonality in rainfall, with an average annual rainfall depth of about 2400 mm (Selvalingam *et al*. 1987). The rainfall in the region is generally characterized by heavy rainfall, mainly consisting of rainstorm events with high storm intensities and short durations (Mandapaka and Qin 2013). This study utilized 5-min rainfall data collected over three years from July 2010 to June 2013 at three rain gauge stations for analysis. Station #1 is located in the central part of Singapore (1.3415°N, 103.8334°E), Station #2 is located in the east (1.3678°N, 103.9826°E), and Station #3 is located in the west (1.31985°N, 103.66162˚E) (Jun *et al*., 2019). The relevant map was shown in the Supplementary Material (see Figure S1).

Rainstorm Event Definition

In this study, the rainfall events of interest were pre-screened by using the following criteria: (i) the intensity is larger than 0.3 mm per 5 min; and (ii) the duration is longer than 5 min from the observed 5-min rainfall data. The IETD is used to describe the minimum no-rain periods between consecutive rainstorm events (Jun *et al*. 2017) and in this study, it was set to 20 min to extract individual rainstorm events. A final sequence of rainstorm events is determined from each event with a total rainfall depth larger than 3 mm and duration equal to or longer than 30 min. Here, the IETD and threshold values were selected under the condition that the coefficient of variation (CV) is close to one (Restrepo-Posada and Eagleson 1982). The independence of rainstorm events can be evaluated statistically from the goodness-of-fit test for the exponential distribution (Hassini and Guo 2016). The total numbers of events satisfying the above criteria were 308 for Station #1, 248 for Station #2, and 284 for Station #3. Of these events, only 6 to 8% had storm durations longer than 2 hours and about 66 to 76% of events lasted less than 1 hour. The mean depths of the rainstorm events are 20.88 mm for Station #1, 22.46 mm for Station #2, and 19.57 mm for Station #3, with the respective standard deviations being 19.02, 21.37, and 16.50 mm. The mean durations are 1.03 hours for Station #1, 0.96 hours for Station #2, and 1.01 hours for Station #3, with respective standard deviations of 0.66, 0.61, and 0.53 hours. Generally, the three stations show only small differences between the mean and standard deviation of rainfall. The mean value of storm durations is found to be close to one hour and this reflects the importance of identifying correctly the temporal patterns of storms with relatively short durations in urban drainage designs.

To analyse the temporal distribution of extreme storms, hyetographs of the rainstorm events with the largest storm depth for different intervals of storm duration for the three individual study years were produced. These are provided in the Supplementary Material (see Figures S2 to S7). It should be noted that there are large differences in the peak rainfall locations and the ratios of peak rainfall to total storm depth between the rainstorm events. It gives an idea of how to reflect the temporal rainfall patterns of actual storms when deriving the synthetic hyetographs from randomly generated rainfall series.

RESULTS AND DISCUSSION

Representative Quartile Storms

The rainstorm events of interest are divided into four quartile groups. By identifying the location where the heaviest rainfall intensity occurred during each storm (i.e. the first, second, third or fourth quartile), the frequency of rainstorm events in each quartile (expressed as a percentage) corresponding to different intervals of storm duration is obtained. The results are summarized in Figure 2. The hyetographs of the rainstorm events with the largest storm depth for storms in quartiles 1, 2, 3 and 4 for different intervals of storm duration are given in the Supplementary Material. For all rainstorm events (i.e., regardless of storm duration), it is found that the highest rainstorm frequency belongs to the second quartile, with 38.64% of rainstorm events for Station #1, 38.31% for Station #2, and 36.97% for Station #3. However, the number of first-quartile storms generally increases with increasing storm durations, and its percentage becomes larger than that of the second quartile storms when the storm duration is longer than 1.5 hours. For hydraulic design applications to tropical regions such as Singapore, this result implies that hyetographs for the first quartile storms could be used to determine the temporal characteristics of design rainfall with durations longer than 1.5 hrs and those for the second quartile storms with durations shorter than 1.5 hrs.

Place Figure 2 here

Temporal Patterns for Design Rainfall

The distribution of the rainfall depth ratios of consecutive peak rainfalls to total rainfalls for the first or second quartile storms is considered for the development of design storm hyetographs, which can describe representative temporal patterns of actual rainstorm events in Singapore. To allow a comparison of these distributions across different levels of peak rainfall, basic statistics of relative rainfall rates for each level of peak rainfall are summarized in the Supplementary Material (see Tables S1 to S3). In this study, the median values of relative rainfall rates are used to determine temporal patterns of consecutive peak rainfall for different intervals of storm duration of 0.5, 1.0, 1.5, and 2.0 hrs. Here, relative rainfall rates mean rainfall depths ratios of consecutive peak rainfalls to total rainfalls of each rainstorm event corresponding to specific quartile storms. From relative rainfall rates of entire rainstorm events, their median values can be determined for each level of peak rainfall. The results are summarized in Tables 1, 2, and 3. It is found that rainstorm events with a storm duration of 30 min correspond to the interval of storm duration between 0.0 and 0.5 hrs. Thus, the total number of rainstorm events in this interval is relatively small compared to that in different intervals because it considers a sequence of rainstorm events with duration equal to or longer than 30 min. The total amount of each relative rainfall rate is not exactly equal to 1, with median values ranging from 0.91005 to 1.02928. This is because the relative rainfall rates for each level of peak rainfall are different from each rainstorm event and also dependent on the rainstorm selection. However, it should be noted that this result can give useful information about the relative rainfall rate of consecutive peak rainfalls including the characteristics of individual rainstorm events. This bias can be adjusted by increasing or decreasing a certain value of relative rainfall rates evenly throughout consecutive peak rainfall for different intervals of storm duration, which makes the sum of individual ratios equal to 1.

Place Tables 1, 2 and 3 here

Additionally, a distribution of relative locations for time to peak over each storm duration was determined for the first or second quartile storms for different intervals of storm duration. Based on the occurrence time to the first peak rainfall with the selected quartile group, a final distribution of relative peak rainfalls is determined by locating consecutive relative rainfall rates over time to the left or right side of the first peak rainfall in sequential order. Here, we consider the median values of relative locations for time to peak as the occurrence time to the first peak rainfall in order to determine the temporal patterns for design rainfall. The basic statistics of relative locations for time to the first peak rainfall are summarized in the Supplementary Material (see Table S4), followed by representative quartile storms and storm durations.

For the first or second quartile storms with durations of 0.5, 1.0, 1.5, and 2.0 hrs, synthetic rainfall distributions of 5-min temporal patterns are summarized in Figures 3 and 4.

Temporal patterns for design rainfall are obtained from the rainfall characteristics of each rainstorm event at specific rain gauge stations. A final distribution of temporal patterns for design rainfall can be determined based on different intervals of storm duration, representative quartile storms, statistics of rainfall depth ratios of consecutive peak rainfalls to total rainfalls, and statistics of relative locations for time to the first peak rainfall. To establish synthetic hyetographs, it is helpful to consider the design rainfall corresponding to pre-determined storm durations and return periods. Temporal patterns for design rainfall are differently determined from the selected statistics of relative rainfall rates and locations among five numbers including minimum, first quartile, median, third quartile and maximum values, which can be dependent upon extreme rainfall conditions, types of hydraulic structure, degree of risk, etc.

Place Figures 3 and 4 here

Synthetic hyetographs for design rainfall need to properly reflect temporal patterns of randomly observed rainfall data for flood estimation and an appropriate design of stormwater management facilities. For tropical regions such as Singapore, the temporal variability in the rainfall patterns of design rainfall can be determined based on synthetic hyetographs produced using conventional Huff's curves (PUB, 2012). The Huff's type-II distribution is summarized in the Supplementary Material (see Figure S8), with a fixed interval of 5-min and durations of 0.5, 1.0, 1.5 and 2.0 hrs for the whole Singapore island. Compared to the representative temporal patterns for design rainfall in Figure 4 (i.e., event-based result), the conventional fixed interval method represents only a 5-min delay on time to peak rainfall but normally describes smaller ratios of peak rainfall to total storm depth, which may lead to the underestimation of peak flow and flood volume. The differences between two approaches ranged from -9.95% to 7.97%, from -49.46% to -36.52%, from -50.05% to -32.58%, and from -63.91% to -23.81% for storm durations of 0.5, 1.0, 1.5, and 2.0 hrs, respectively. Even though this finding depends on the selected storm duration and rain gauge station, it is consistent with the results of Choi *et al*. (2014) and Na and Yoo (2018), who showed that determining the rainfall temporal distribution based on Huff's curves could obtain lower values of peak rainfall and further runoff characteristics such as peak flow.

CONCLUSIONS

This study adopted a storm-event-based approach to analyse the temporal pattern of design rainfall. Both IETD and rainfall depth/duration/intensity thresholds were used to extract individual rainstorm events from a minutes-level observational record in a tropical region. The collected events were divided into four groups according to the location where the peak rainfall occurred. The results indicate that the highest percentage of rainfall events occurred in the first and second quartiles. This gives a good reference to better describe temporal patterns of actual rainstorm events in design rainfall. One main advantage of the storm-event-based approach is that it is helpful, particularly from the perspective of synthetic hyetographs, in determining the magnitude and shape of design storm hyetographs that are dependent on the location of peak rainfall rates during a storm. It was found that the proposed approach could obtain a distribution of rainfall depth ratios of consecutive peak rainfalls to total rainfalls, which well describes the characteristics of various individual storm events based on the observed record. The proposed approach can be used to consider temporal patterns for design rainfall depending on different intervals of storm duration and representative quartile groups. Overall, it can be recommended as one of the possible alternatives to the use of conventional methods such as the Huff's distribution or the Chicago approach to determine synthetic rainfall data based on DDF or IDF curves.

For the development of design storm hyetographs for first or second quartile storms corresponding to different intervals of storm duration, this study considered the distribution of rainfall depth ratios of consecutive peak rainfalls to total rainfalls and the distribution of relative locations for the time to peak rainfall during each storm. These distributions are affected by the selection of statistics of relative rainfall rates and rainfall locations for the five critical values (i.e., minimum, first quartile, median, third quartile, and maximum). It should be noted that the proposed approach can be generalized to consider the temporal patterns of design rainfall on various time scales, design conditions (e.g., extreme rainfall conditions, types of hydraulic structure, degree of risk, etc.), and geological locations with regional rainfall characteristics, although it was only applied to a tropical region in this study. Nevertheless, this method also has some limitations, such as the time interval of observational data, the focus on the time to the first peak rainfall, the selection of IETD and rainfall depth/duration/intensity thresholds, and the consideration of statistics for relative rainfall rates and locations. These should be addressed in further studies. Furthermore, the use of continuous modelling can be considered for the rain input to investigate a more realistic estimation of hydrograph with a design simulation (Grimaldi *et al*. 2012; Grimaldi *et al*. 2021).

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Table 1. Median values of rainfall depth ratios of consecutive peak rainfalls to total rainfalls of each rainstorm event for the first or second quartile storms at Station #1.

# of Peaks	Relative Rainfalls for Consecutive Peak Rainfalls over Total Rainfalls							
	First-Quartile Storms				Second-Quartile Storms			
	0.0 < Duration ≤ 0.5 hrs	**0.5 < Duration ≤ 1.0 hrs**	**1.0 < Duration ≤ 1.5 hrs**	**1.5 < Duration ≤ 2.0 hrs**	**0.0 < Duration ≤ 0.5 hrs**	**0.5 < Duration ≤ 1.0 hrs**	**1.0 < Duration ≤ 1.5 hrs**	**1.5 < Duration ≤ 2.0 hrs**
1	0.32143	0.26667	0.20476	0.17000	0.30536	0.25000	0.17793	0.14582
2	0.22222	0.18868	0.17391	0.11364	0.23629	0.19780	0.15172	0.10677
3	0.14815	0.14493	0.13043	0.10280	0.17426	0.15044	0.12433	0.09488
4	0.11111	0.11475	0.09677	0.08367	0.12599	0.12150	0.10394	0.08252
5	0.10714	0.09677	0.07500	0.07955	0.08387	0.09333	0.08856	0.07170
6	0.00000	0.07527	0.05128	0.06542	0.04060	0.07595	0.06728	0.06041
7		0.05556	0.05000	0.05919		0.04808	0.06250	0.05632
8		0.02532	0.03846	0.05000		0.02941	0.05207	0.05487
9		0.00000	0.03226	0.04425		0.02830	0.03747	0.04654
10		0.00000	0.02985	0.03540		0.01802	0.03137	0.04417
11		0.00000	0.02564	0.03540		0.01406	0.02502	0.04191
12		0.00000	0.02299	0.03097		0.00000	0.02151	0.04191
13			0.01724	0.02841			0.01340	0.03758
14			0.01724	0.02273			0.00863	0.02826
15			0.00000	0.01837			0.00617	0.02210
16			0.01064	0.01485			0.00832	0.01526
17			0.00000	0.01136			0.00797	0.01189
18			0.00000	0.00990			0.00000	0.01189
19				0.00816				0.01017
20				0.00618				0.00449
21				0.00408				0.00000
22				0.00000				0.00000
23				0.00000				0.00000
24				0.00000				0.00000
Sum	0.91005	0.96794	0.97649	0.99433	0.96637	1.02689	0.98820	0.98945

Table 2. Median values of rainfall depth ratios of consecutive peak rainfalls to total rainfalls of each rainstorm event for the first or second quartile storms at Station #2.

# of Peaks	Relative Rainfalls for Consecutive Peak Rainfalls over Total Rainfalls							
	First-Quartile Storms				Second-Quartile Storms			
	0.0 < Duration ≤ 0.5 hrs	0.5 < Duration ≤ 1.0 hrs	1.0 < Duration ≤ 1.5 hrs	1.5 < Duration ≤ 2.0 hrs	0.0 < Duration ≤ 0.5 hrs	0.5 < Duration ≤ 1.0 hrs	1.0 < Duration ≤ 1.5 hrs	1.5 < Duration ≤ 2.0 hrs
1	0.35897	0.25551	0.21642	0.14939	0.34447	0.25789	0.16849	0.14757
2	0.26667	0.17647	0.14286	0.13132	0.27449	0.19643	0.15565	0.13079
3	0.17647	0.14035	0.09917	0.11396	0.16382	0.13793	0.12208	0.09184
4	0.10526	0.11013	0.08197	0.09054	0.11702	0.11111	0.11712	0.08642
5	0.05641	0.09386	0.07184	0.07879	0.06550	0.08943	0.09750	0.07316
6	0.03077	0.07639	0.05970	0.06681	0.02393	0.06923	0.07630	0.06887
7		0.05054	0.05785	0.05185		0.05000	0.06979	0.05391
8		0.03280	0.05785	0.04673		0.04368	0.05321	0.04786
9		0.02198	0.03727	0.03914		0.03061	0.04261	0.04028
10		0.02353	0.03106	0.03340		0.01331	0.03271	0.03793
11		0.00000	0.02795	0.03058		0.00466	0.02353	0.03423
12		0.00889	0.01553	0.02946		0.00960	0.01743	0.03034
13			0.01081	0.02532			0.01341	0.02607
14			0.01553	0.02016			0.00897	0.01710
15			0.00000	0.01786			0.00000	0.01438
16			0.00000	0.01515			0.00567	0.01361
17			0.00000	0.01515			0.00000	0.01283
18			0.00359	0.01389			0.00000	0.01129
19				0.01136				0.01051
20				0.00506				0.01051
21				0.00000				0.00641
22				0.00886				0.00387
23				0.02239				0.00000
24				0.01213				0.00000
Sum	0.99455	0.99045	0.92939	1.02928	0.98923	1.01389	1.00447	0.96981

Table 3. Median values of rainfall depth ratios of consecutive peak rainfalls to total rainfalls of each rainstorm event for the first or second quartile storms at Station #3.

# of Peaks	Relative Rainfalls for Consecutive Peak Rainfalls over Total Rainfalls							
	First-Quartile Storms				Second-Quartile Storms			
	0.0 < Duration ≤ 0.5 hrs	0.5 < Duration ≤ 1.0 hrs	1.0 < Duration ≤ 1.5 hrs	1.5 < Duration ≤ 2.0 hrs	0.0 < Duration ≤ 0.5 hrs	0.5 < Duration ≤ 1.0 hrs	1.0 < Duration ≤ 1.5 hrs	1.5 < Duration ≤ 2.0 hrs
1	0.37681	0.28235	0.21042	0.15361	0.37750	0.26654	0.15909	0.11494
2	0.27778	0.19048	0.15724	0.12796	0.21232	0.20412	0.14773	0.10000
3	0.18750	0.13334	0.11865	0.10769	0.15639	0.15662	0.11935	0.09766
4	0.11111	0.10959	0.10034	0.09091	0.11263	0.11270	0.10345	0.08333
5	0.07246	0.08182	0.08013	0.08205	0.06696	0.08713	0.08501	0.08333
6	0.00000	0.06364	0.07670	0.07576	0.04500	0.06897	0.07692	0.06667
7		0.05357	0.06294	0.06383		0.04412	0.06294	0.06667
8		0.02655	0.04533	0.04545		0.02800	0.05639	0.06422
9		0.02829	0.03900	0.04265		0.02273	0.04167	0.05505
10		0.02619	0.03501	0.03318		0.01860	0.0375	0.04587
11		0.00913	0.02532	0.03135		0.01527	0.03077	0.03830
12		0.00000	0.02331	0.02712		0.02174	0.01961	0.03404
13			0.01343	0.02381			0.01307	0.03333
14			0.01626	0.02128			0.01396	0.02752
15			0.00772	0.01702			0.01198	0.02128
16			0.00000	0.01026			0.01203	0.01702
17			0.00000	0.00948			0.00655	0.00966
18			0.00000	0.00000			0.00319	0.00966
19				0.00000				0.00000
20				0.00313				0.00000
21				0.00000				0.00000
22				0.00000				0.00000
23				0.00000				0.00000
24				0.00000				0.00000
Sum	1.02566	1.00494	1.01178	0.96653	0.97080	1.04654	1.00121	0.96856

Figure Captions:

Figure 1: Flow chart of a storm-event-based approach to develop temporal patterns for design storm hyetographs of a tropical city. IETD: inter-event time definition.

Figure 2: Percentage frequencies of each quartile's rainstorm events corresponding to different intervals of storm duration: (a) Station #1; (b) Station #2; (c) Station #3.

Figure 3: Representative temporal patterns for design rainfall in Singapore for the first quartile storms with durations (hrs) of (a) 0.5; (b) 1.0; (c) 1.5; and (d) 2.0. Left: Station #1; middle: Station #2; right: Station #3.

Figure 4: Representative temporal patterns for design rainfall in Singapore for the second quartile storms with durations (hrs) of (a) 0.5; (b) 1.0; (c) 1.5; (d) 2.0. Left: Station #1; middle: Station #2; right: Station #3.

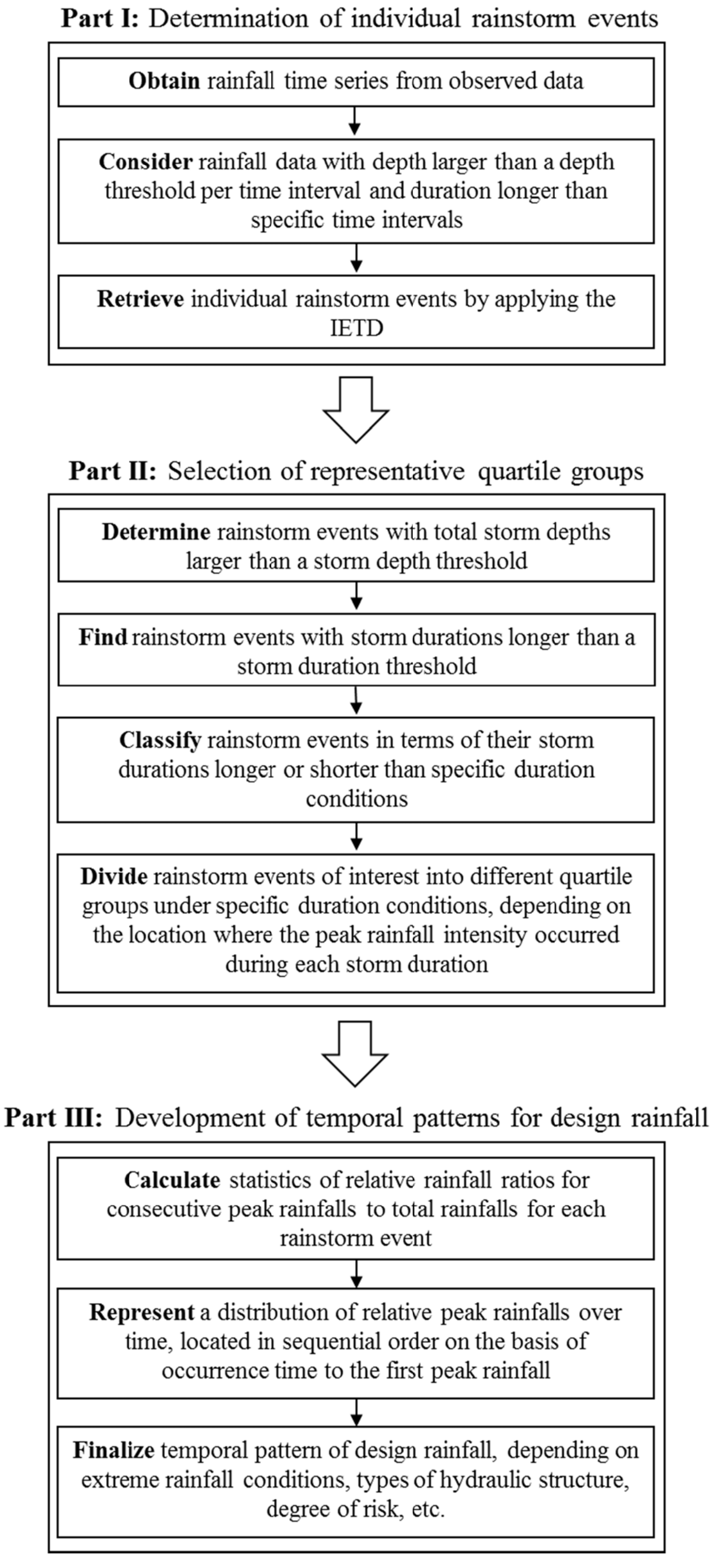
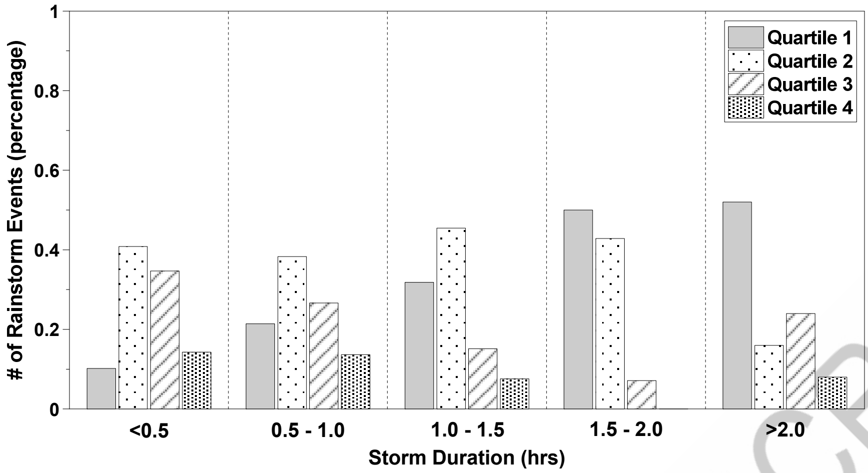
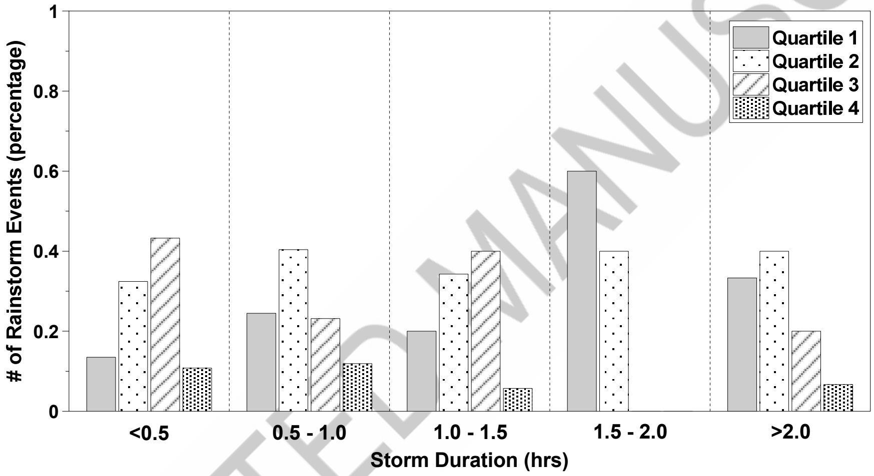


Fig. 1: Flow chart of a storm-event-based approach to develop temporal patterns for design

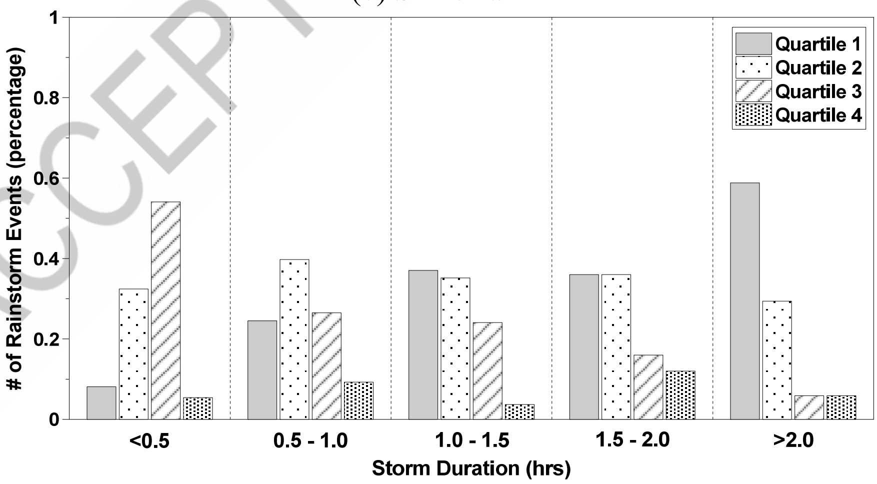
storm hyetographs of a tropical city. IETD: inter-event time definition.



(a) Station #1



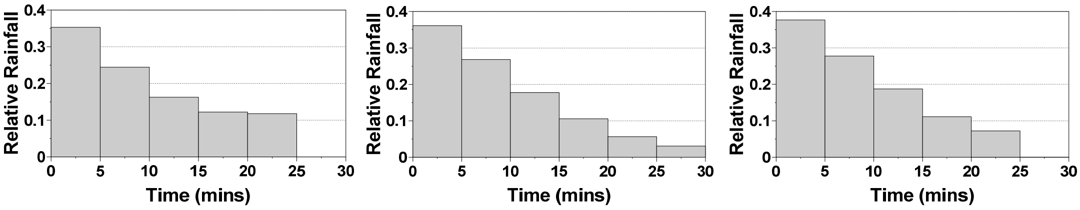
(b) Station #2



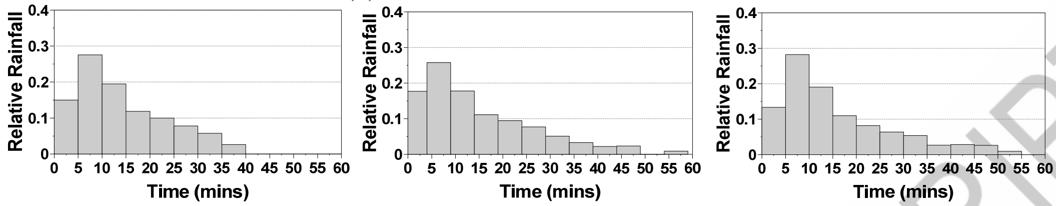
(c) Station #3

Fig. 2: Percentage frequencies of each quartile's rainstorm events corresponding to different

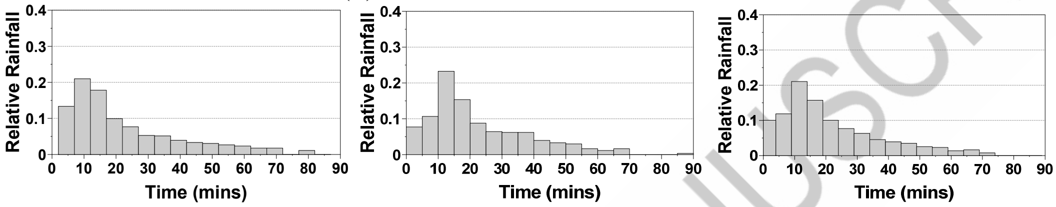
intervals of storm duration: (a) Station #1; (b) Station #2; (c) Station #3.



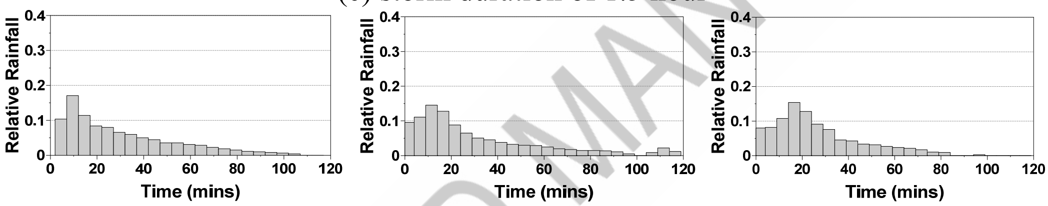
(a) storm duration of 0.5 hour



(b) storm duration of 1.0 hour



(c) storm duration of 1.5 hour



(d) storm duration of 2.0 hour

Fig. 3: Representative temporal patterns for design rainfall in Singapore for the first quartile storms with durations (hrs) of (a) 0.5; (b) 1.0; (c) 1.5; and (d) 2.0. Left: Station #1; middle: Station #2; right: Station #3.

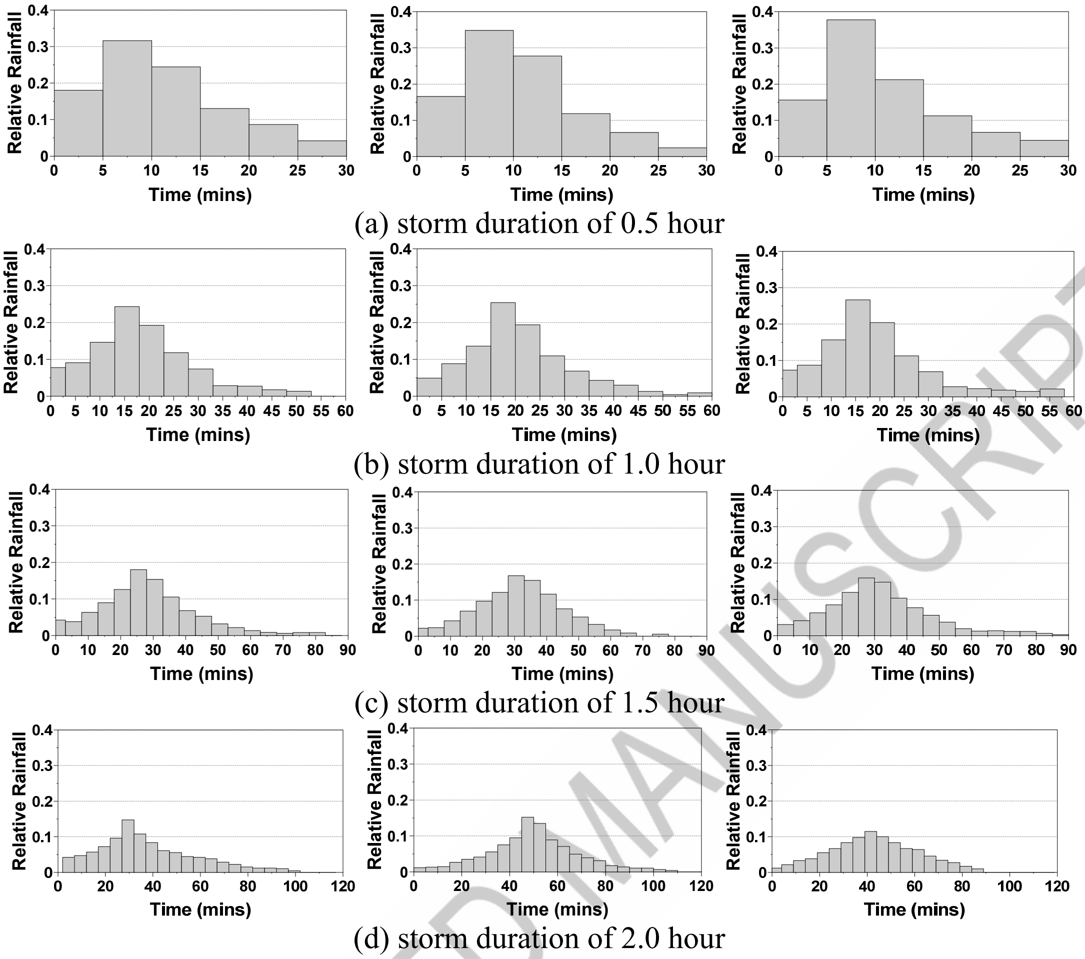


Fig. 4: Representative temporal patterns for design rainfall in Singapore for the second quartile storms with durations (hrs) of (a) 0.5; (b) 1.0; (c) 1.5; (d) 2.0. Left: Station #1; middle: Station #2; right: Station #3.