EASR

Engineering and Applied Science Research

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Published by the Faculty of Engineering, Khon Kaen University, Thailand

Modification of a design storm pattern for urban drainage systems considering the impact of climate change

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Received June 2017
Accepted July 2017

Abstract

Inundation of urban areas due to heavy rainfall more frequently occurs in many large cities all over the world. This is more evident now due to the impacts of climate change. The design rainfall storm pattern, an input used to design urban drainage systems, plays an important role for developing sufficient drainage capacity for big cities. There are few studies in Thailand focusing on the accuracy of the Chicago Design Storm, which has been widely used for decades, in estimation of the peak intensity of rainfall for drainage systems. This study aims to first examine the accuracy of the Chicago Design Storm using observed data. Second, the impacts of climate change on rainfall intensity and on the Chicago Design Storm were investigated. Bangkok and its vicinity were selected as study area. Rainfall storm data with 1-5 minutes records and 15 minute records were collected from the meteorological station at AIT over the past 21 years and from the rainfall station in Sukhumvit area of Bangkok for 15 years. The Gumbel distribution was used in a Frequency Analysis to establish IDF Curves. The CDS, Yen & Chow and Sifalda methods were used to synthesize a Design Storm Pattern. Comparison of results of these methods with the observed data revealed that the CDS has good agreement in shape, i.e. peak intensity and time to peak. The CDS is still recommended for use in practice. However, MAPE was also used to evaluate accuracy of the synthesized CDS in comparison with the observed data. It was found that the CDS should be modified to reduce its peak intensity. Moreover, the impact of climate was also investigated. The Equidistance Quantile-Matching Method was adopted to compute IDF curves to include the climate change impact. The Global Climate Model (GCM), and HasGEM2-ES with RCP4.5 were used to generate rainfall data for the next 25 years. The changes in IDF curves due to climate change were compared. With the changed IDF curves, the peak intensity of design storms increased by up to 25%. It is therefore recommended to account for the impacts of climate change on design storms.

Keywords: The Chicago design storm, Climate change, Urban drainage design

1. Introduction

Inundation of urban areas due to heavy rainfall occurs more frequently in many large cities, especially in the last decades owing to climate change. Thailand is influenced by tropical monsoon rainfall. Flood damage in the large cities results from climate change as well as inaccurate design of storm patterns. Generally, appropriate design of urban drainage systems should alleviate damage due to inundation in the big cities. Most probable design storm patterns provide suitable urban drainage system design which will consequently be used to mitigate flood damages.

The shapes of design storm patterns are unique for each region, depending on the local climate and rainfall characteristics. There are several methods to determine design rainfall patterns. Amongst these methods, the Chicago Design Storm (CDS) is used worldwide in practice [1].

A Chicago Design Storm (CDS) can be practically developed from the total intensity-duration-frequency (IDF) curves. This methodology has been adopted and applied in different parts of the world. For example, Bandyopadhyay [2] used the Chicago Design Storm in Gauhahi, India.

Sifalda [3] used a complex triangular design storm shape in Czechoslovakia, and also proposed an S-type shape with a long peak relative to total duration at the middle.

Desbordes [4] developed s D-type shaped design storm, with a complex triangular shape with a bi-linear line for rising and receding parts.

Yen et al. [5] developed a simple triangular hyetograph to represent the approximate geometry of local rain storm hyetographs for the design of small storm drainage systems. The design storm pattern was derived from analysis of hyetographs 2, 3, 4 and 5 using hourly rainfall at three stations in the USA.

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doi: 10.14456/easr.2017.24

Figure 1 Location of Meteorological Station at Asian Institute of Technology (AIT)

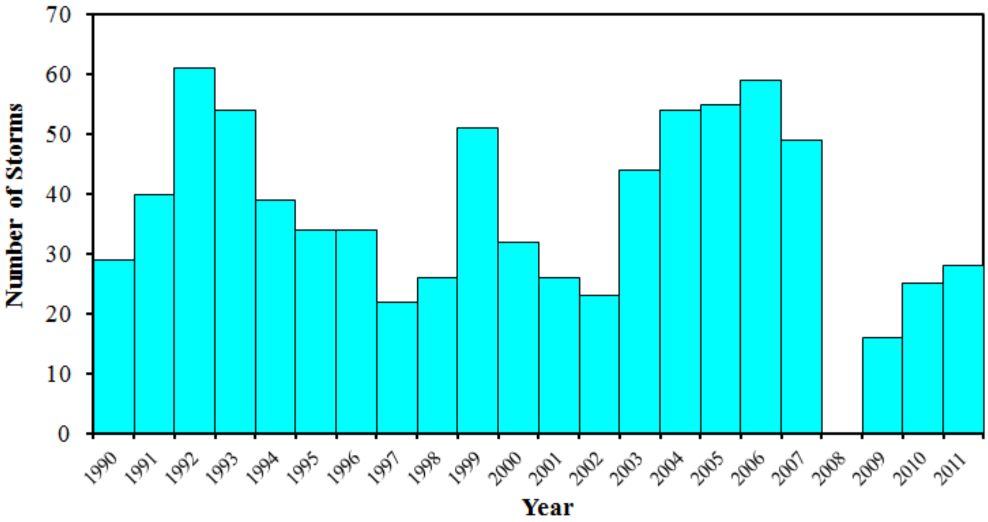


Figure 2 Number of rainfall events per year from 1990 to 2007 and 2009 to 2011

Another hourly urban design storm pattern was developed by Watt et al. [6], for a Canadian Urban design storm. This design storm has two parts, a rising portion where rainfall is linear and receding part that is exponential. Comparison between the simulated and the observed 1-hour storms, in both the temporal and frequency domains, revealed that a temporal design storm can simulate individual rainfall events as well as an average or design event for any particular site. This design storm model has been extended to a regional level in Canada by including two parameters in the model.

The Chicago Design Storm was used in southern Quebec, Canada, to identify the most suitable temporal rainfall patterns for an urban drainage design [7]. Seven popular design storm models were assessed based on the accuracy of their estimations of runoff peak flow and volume as compared to those values for a set of 199 significant historical storm events during the period of 1943-1994. Comparison between the simulated and observed values revealed that the Chicago design storm had unrealistically high peak intensity. Modified Chicago design storms were then developed using the peak intensity directly taken from the IDF relationships for five minute time intervals.

The Chicago design storm was widely used in the design of urban drainage systems in Thailand. For example, the Department of Drainage and Sewerage of the Bangkok Metropolitan Administration used the Chicago Design storms to design urban drainage systems in Bangkok as part of a project to investigate and design drainage systems in the Sukhumvit sub-catchments areas in Bangkok [8]. However, there have been few studies in Thailand focusing on the accuracy of the Chicago design storm in estimation of peak runoff for drainage systems.

Therefore, the objective of this study is to examine the accuracy of the Chicago Design Storms. Bangkok and its vicinity were selected as a case study due to its high land value as well as the availability of data appropriate for analysis of design storms, i.e., data with at least five years of records.

2. Data collection

To synthesize design storm patterns for urban drainage systems, records with at least five years of rainfall data were required with sufficient record lengths and numbers of storms. These need to reflect the rainfall characteristic of the

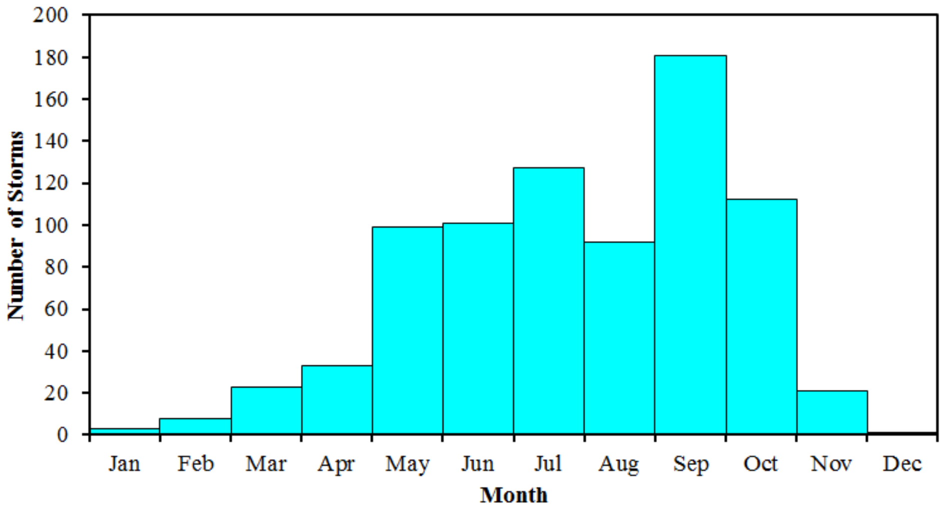


Figure 3 Number of storms from 1990 to 2011

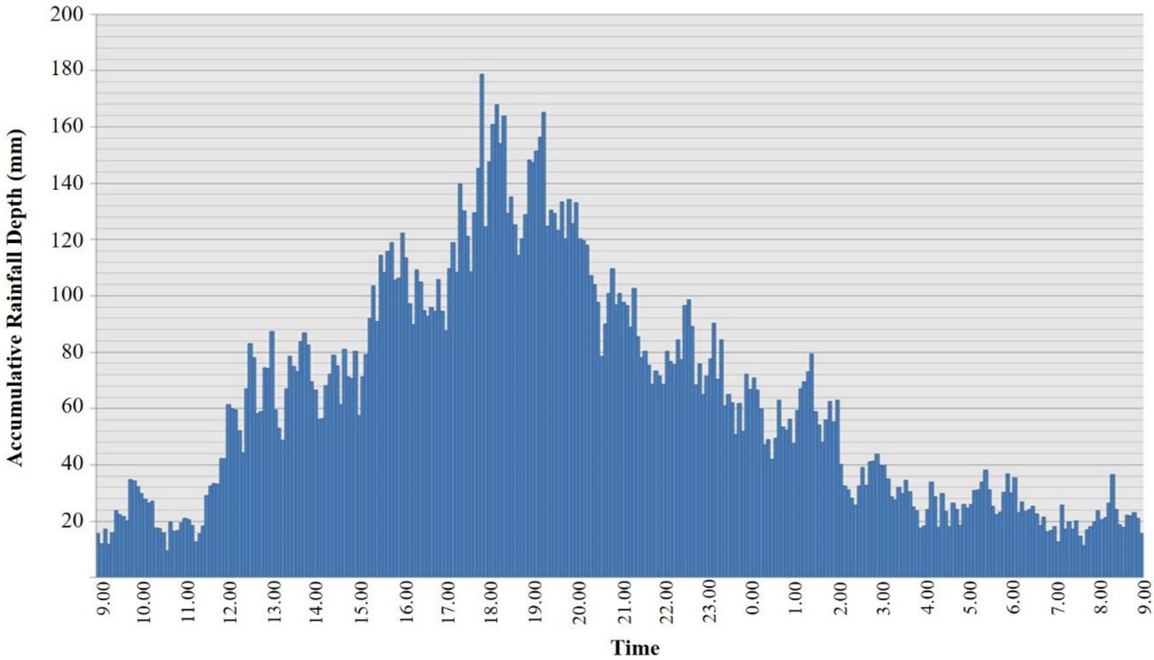


Figure 4 Distribution of Accumulative Rainfall Depth

area. Bangkok and its vicinity were selected as a study area due to its highly frequent inundation problems as well as their high land values. Based on such conditions, only two rainfall stations were selected for this study. The first is an experimental meteorological station located at the Asian Institute of Technology in Pathumthani, as shown in Figure 1. It has 21 years of records of five minute rainfall data from the years of 1990 to 2007 and from 2009 to 2011.

To simplify the analysis of design storm patterns, the most representative storm pattern should be obtained. Criteria should be set to select rainfall data as storm data. First, rainfall of less than 2 mm is not included in the analysis. There were totally 801 rainfall events during the 21 year period (1990-2011) as seen in Figure 2. The average annual rainfall is comprised of 36 rainfall events. Figure 3 shows the distribution of rainfall events over a year. It is a plot of accumulated numbers of rainfall events from 1990 to 2011. Its shape confirms that rainfall in Thailand is influenced by the monsoon beginning in May and ending in October, with the highest number of storms in September. Amongst these 801 rainfall events, some criteria were set to select rainfall storm data for future analysis. This type of data should have a rainfall duration of greater than 30 minutes. Storms selected should have accumulated rainfall equal to or greater than two years. Storms selected for further analysis should have a representative shape, i.e., a regular shape. With these criteria, data from only 41 rain storms data were selected for further analysis.

Another rainfall station, selected for this study is located in Bangkok with 15 years of records, from 1990 to 2004. This data was used to investigate the impact of climate change on rainfall intensity in the city core and consequently was considered in the calculation procedure for design of urban drainage systems.

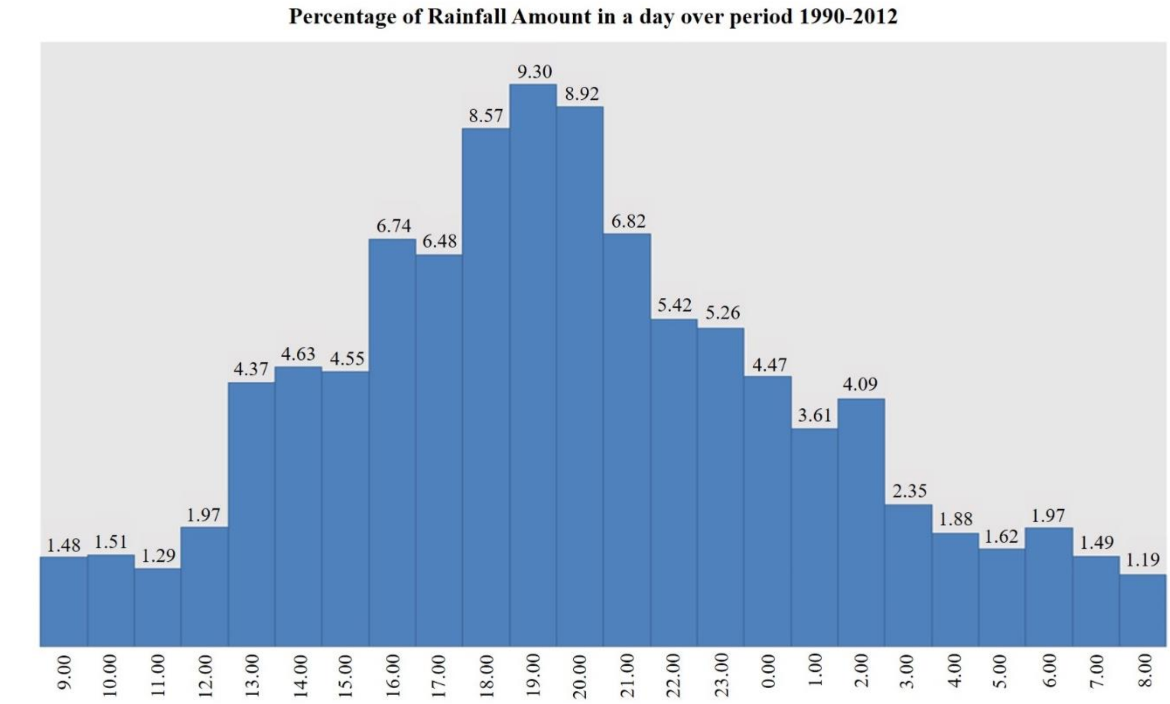


Figure 5 Percentage of rainfall in a day over period 1990 – 2012

Table 1 Intensity duration and frequency curves for AIT

Duration / Return Period (years)	Intensity (mm/hr)								
	5 min	10 min	15 min	30 min	1 hrs	2 hrs	6 hrs	12 hrs	24 hrs
2	130	117	105	81	53	30	11	6	3
5	148	133	123	100	67	41	15	8	5
10	160	143	135	113	75	47	18	10	5
25	175	156	150	129	87	56	21	12	7
50	186	166	161	141	95	63	24	13	7
100	198	175	172	152	103	69	26	15	8

3. Synthesis of design storm pattern

First, the accumulated temporal distribution of rainfall in one day was investigated using five minute intervals of rainfall data collected at the AIT station. Figures 4 and 5, reveal that highest likelihood of rainfall in Bangkok is from 18.00 to 20.00 hr and that about 30% of amount of the rainfall occurred in this period.

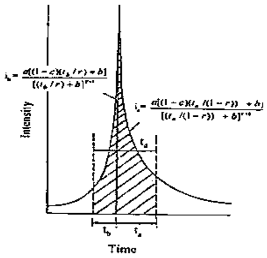
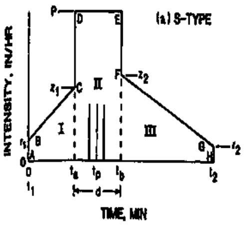
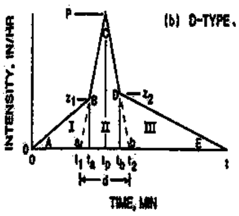
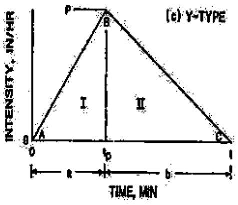
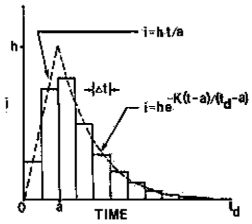
The Gumbel distribution was used to fit rainfall data to represent an Intensity Duration Frequency (IDF) curve. This used the results of frequency analysis of rainfall with durations of 5, 10, 15, 30 minutes and 1, 2, 6, 12 and 24 hr for return periods of 2, 5, 10, 25, 50, 100 years as shown in Table 1.

There are various types of design storm patterns. Examples of generally used design storm patterns are shown in Table 2 In the current study, three storm patterns were selected for comparison of their similarity. The first one, from Yen & Chow, has a triangular shape. It has a simple and practical pattern. The second is from Sifalda and it has a complex trapezoidal shape that is used to investigate the similarity of the peak intensity durations of rainfall. The third is the Chicago Design Storm (CDS), which is commonly used in Thailand.

The Chicago Design Storm was developed from a total intensity-duration-frequency-curve. The location of the peak intensity (r) is found in one of two ways. The first is to study the location of the peak intensity within the duration t_d, and the other way is to evaluate the antecedent rain volume before the period t_d with the maximum average intensity. Equations for designed storm patterns can be derived into two parts. The first part is the curve before the peak, which can be written as:

$$i_b = \frac{a\left[(1-b)\left[\frac{t_a}{r}\right]^b + c\right]}{\left[\left(\frac{t_a}{r}\right)^b + c\right]^2} \quad (1)$$

Table 2 Types of design storm patterns [9]

Location	Shape	Type of Design Storms
Chicago		Chicago Design Storm (CDS) [1]
Czechoslovakia		Sifalda [3]
France		Desbordes [4]
Massachusetts, Illinois, and New Jersey		Triangular Yen et al. [5]
Canada		Design storm pattern from Watt et al. [6]

The curve after the peak, which can be written as:

$$i_a = \frac{a\left[(1-b)\left[\frac{t_a}{1-r}\right]^b + c\right]}{\left[\left(\frac{t_a}{1-r}\right)^b + c\right]^2} \quad (2)$$

where:

$$t_d = t_a + t_b \quad (3)$$

$$r = \frac{t_a}{t_d} \quad (4)$$

$$i = \frac{a}{t_d^b + c} \quad (5)$$

where i_b and i_a are the intensities before and after the peak, t_b is the time before the peak in minutes, t_a is the time after the peak in minutes and a, b and c are constants. t_d is rainfall duration. “r” is storm advanced coefficient derived as a function of rainfall duration [9]. In the Chicago area,

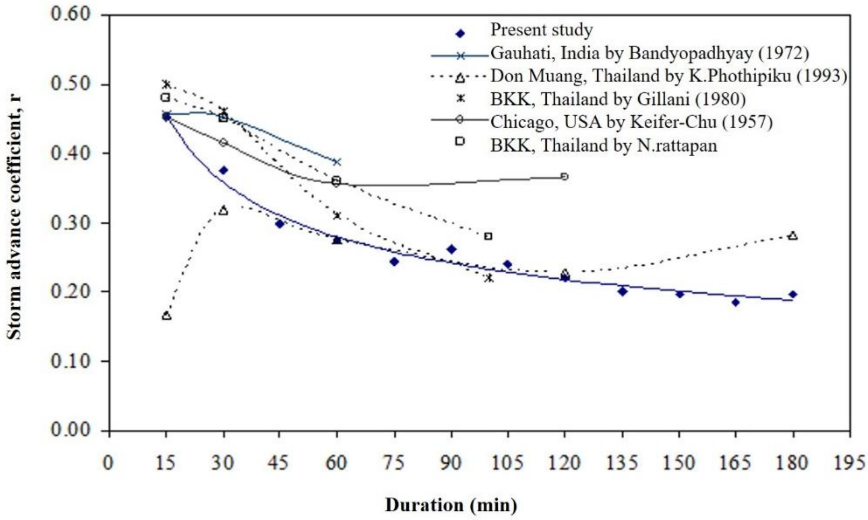


Figure 6 Relationship between the duration and storm advance coefficient [9]

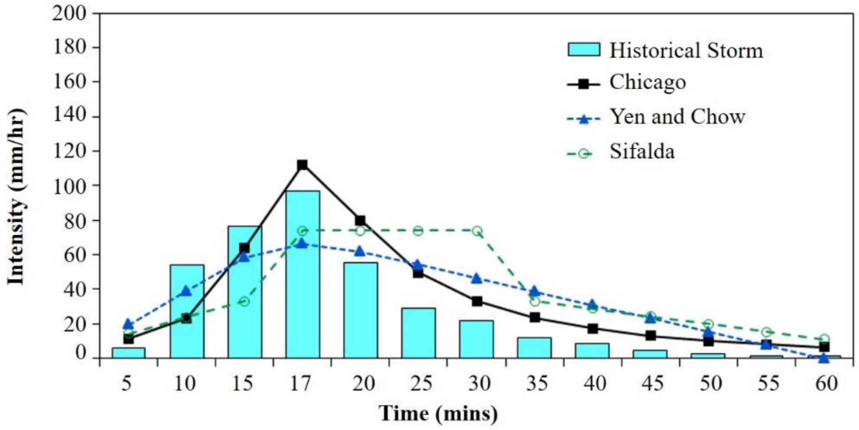


Figure 7 Comparison of three design storms with measured rainfall for a 1 hour duration with a five year return period: Date 3/8/2000 Time 17.20 to 18.20

Table 3 Summary of the Mean Absolute Percentage Error (MAPE) of Peak CDS and Modified CDS

Tr (years)	Number of storms	MAPE (%) of CDS			MAPE (%) of Modified CDS		
		Peak	5 min	10 min	Peak	5 min	10 min
2	36	56.0	27.3	12.7	54.1	27.1	12.6
5	3	57.4	31.3	7.5	53.4	30.4	7.5
10	2	71.7	44.9	12.6	66.8	43.6	12.6
Average	41	61.7	34.5	11.0	58.1	33.7	10.9

the synthetic storm pattern with r = 0.375 was found to be acceptable. Figure 6 shows value of r for Bangkok ranging from 0.20 to 0.49. This indicates that a design storm is almost symmetric for short duration. For longer durations, the timing of peak intensity will occur easier not less than 20% of rainfall duration. Recorded from data was used for a two year return period for 36 storms. There were three and two selected storms corresponded to five and ten year return periods, respectively.

The Chicago Design Storm, Yen & Chow and Sifalda methods were used to synthesize Design Storm Patterns from data on 41 storms. Comparison of results obtained from these three methods was done to identify the one with the best fit to the observed storm data for further use in engineering practice. In this study, the criteria for good fit of the shape of rainfall pattern to observed data were peak intensity and peak time.

Comparison of design storm patterns obtained from CDS, Yen & Chow and Sifalda with observed data from 41 storms revealed that the CDS better fits observed storm data with good agreement of the observed and computed peak rainfall intensities. There was also good agreement between the observed and computed time to peak. Figure 7 shows an example of a storm on 3/8/2000 where the CDS had a better agreement with observed peak rainfall intensities than the other two methods.

However, it has been noted that the design storm obtained from CDS method still had a higher peak intensity than the observed data. This results in an over-designed urban drainage system. The Mean Absolute Percentage Error (MAPE) was adopted to evaluate this over-design. It was found that MAPE at peak had an error ranging from 56%-72% for two to ten years return periods, as shown in Table 3.

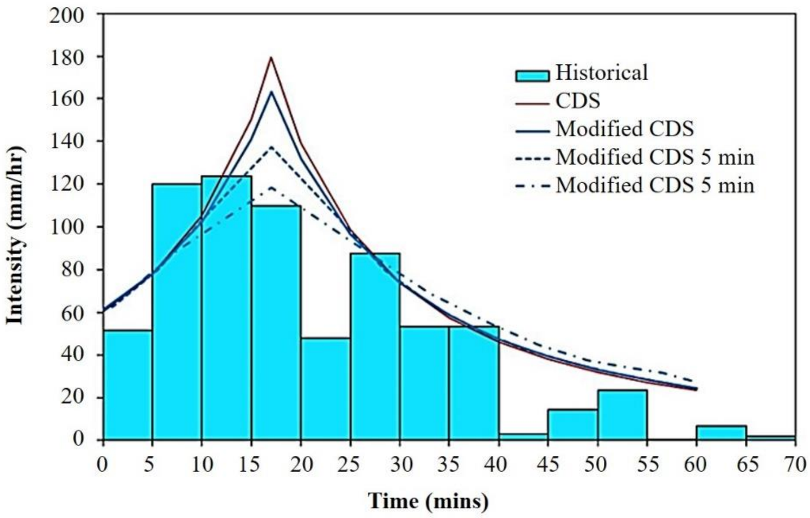


Figure 8 Comparison of CDS, Modified CDS and Historical storm dated 14-10-1998 (two year return period)

However, the error of over-design was reduced for a five minute rainfall duration, with values of the MAPE equal to 27%, 31% and 45% for two, five and ten year return periods, respectively, as shown in Table 3. It is notable that in Table 3, that minimum error (MAPE) occurred for 10 minute rainfall intensities with 13%, 8% and 13% for two, five and ten year return periods of storms.

To have an optimal and economically feasible design, it is good to modify and reduce peak intensity, using the following equation:

$$i = \frac{a}{[t_d + b]^c} \tag{6}$$

Comparison of the error (MAPE) from design storms obtained from CDS and the modified CDS using equation (6), revealed that MAPE at peak is reduced from 62% to 58% and errors for rainfalls of five minutes duration were reduced from 35%-34%, as shown in Table 3. Figure 8 presents an example of observed storm data 14/10/1998, compared with design storms obtained from the CDS and modified CDS. It is therefore recommended that the modified CDS should be used in engineering practice for designing urban drainage systems.

4. Analysis of impact of climate change on design storm pattern

Several research studies revealed that climate change has influenced rainfall in Thailand in various aspects.

Recorded climate data have been analyzed for their extreme indices by Rehan [10] using RClimDex software, specifically developed by Zhang and Yang in 2004. Results showed significant increases using Kendal's test score for PRCPTOT (annual total wet-day precipitation). It increased from approximately 1,300 to 1,600 mm and CDD (consecutive dry days) decreased by 26 days in 30 years at the Bangna meteorological station from 1985 to 2014. Additionally, the sub-daily rainfall is important for use in design of urban drainage systems. The time of concentration in Sukumvit covering 24 square kilometers was tested using a mathematical model, Mike Urban by Shrestha [11]. It was found to be 3 hours. Sub-daily annual maximum rainfalls from 5 minutes to 24 hours at the Asian Institute of Technology (AIT) were analyzed. A significant increase of 6 hours was found. Additionally, Asayama [12] showed an increased number of events having rainfall intensity greater than 50 mm/hr from 145 to 237 events using long term records from 1976 to 2016 in Japan. The frequency of events having rainfall intensity greater than 80 mm/hr increased from 10 to 19 events. This results show a climate change and their effects on a small time scale in sub-daily rainfall for both magnitude and frequency. The design of urban drainage should be revisited to cope with such changes.

In this study, frequency analysis of rainfall of several time intervals was conducted to establish IDF curves including impact of rainfall variability due to climate change. An Equidistance Quantile-Matching Method (EQM) was adopted in this study to compute IDF curves showing climate change impact. Peak intensity obtained from this modified IDF was then used to determine new Design Storm Patterns using the CDS method.

To obtain rainfall data with impact of climate change, the Global Climate Model (GCM) uses the GEM 2-ES from the Meteorological Office at Hadley Center with Representative Concentration Pathways (RCP) 4.5 were adopted to predict rainfall data from year 2015 to 2039 [13]. The Bangkok rainfall station at Sirikit Convention Center, Sukhumvit Area, with record length of 15 years ranging from 1990-2004 at 15 minute time intervals with 78 storm events available, was used as representative rainfall in Bangkok. Fifteen storms, representing rainfall characteristics in Bangkok area, were selected for analysis in this study.

Comparison of changes in IDF curves due to impact of climate change was done and shown in Figure 9 as an example of IDF curves for two and five year period. Table 4 summarizes changes in the IDF curves due to climate change in term of increased parameters values (a, b, c) for various return periods from 2 year to 100 years.

Changes in the IDF curves showed that the peak intensity of design storms also changed with increased peaks ranging from 13% to 25%. Comparison of peak intensity of a 1 hour storm of a modified present CDS and future CDS done and summarized in Table 5 for various return periods.

Table 4 Comparison of constants of IDF curves now and in the future with climate change

T_r (years)	Present Situation			Future Situation		
	a	b	c	a	b	c
2	3931	25	0.955	5,612	28	0.970
5	5593	28	0.970	7,400	30	0.980
10	6723	29	0.976	8,582	30	0.985
25	8267	30	0.985	10,161	31	0.991
50	9395	31	0.989	11,267	32	0.994
100	10515	32	0.992	12,427	32	0.991

Table 5 Comparison of Peak Intensity & One Hour Rainfall for Present and Future (Ensemble mean)

Tr (years)	Peak Intensity (mm/hrs)			Rainfall (mm)		
	Present	Future	Difference (%)	Present	Future	Difference (%)
2	179	224	25	51	64	25
5	223	267	20	63	76	20
10	252	297	18	71	84	18
25	288	334	16	82	95	15
50	315	361	15	89	102	15
100	341	388	14	97	110	13

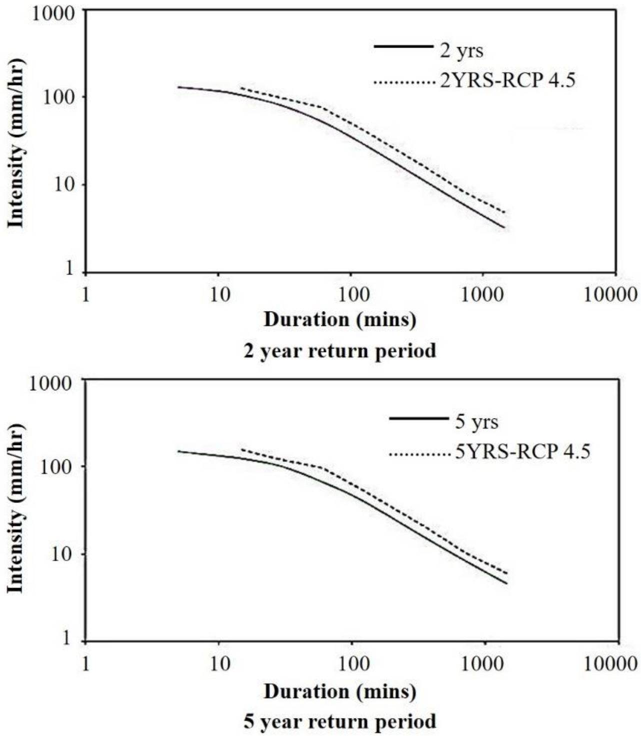


Figure 9 Comparison of IDF curves for 2015-2039 under Representative Concentration Pathways 4.5

For an average storm with a two year return period, the peak intensity of rainfall increased by 25%, while for with a 100 year return period, the peak intensity increased by 14%. Therefore it should be noted that the design of urban drainage systems should take this change into consideration to adapt to future climate change.

5. Conclusions

There are few studies in Thailand, focusing on evaluation of the accuracy of the Chicago Design Storm Method. This has been widely used in Thailand for decades, to estimate of peak rainfall intensity. This study examined the accuracy of the Chicago Design Storms by comparing the synthesized design storms with observed ones. A meteorological station, located at the Asian Institute Technology, Pathumthani Province, was selected due to the availability of one to five minute rainfall data for 21 years with 801 observed storms between 1990 and 2011. Amongst these rainfall data, 41 representative storms were selected for analysis in this study. The Gumbel distribution was used to establish Intensity Duration Intensity Curves for various return periods. Three method of synthesizing design storm patterns were examined in the current study. They were the Chicago Design Storm, Yen & Chow and Sifalda methods. Comparison of design storms obtained from these three methods with the observed data, using criteria of good agreement in peak intensity and time to peak, revealed that the Chicago Design Storm is the most appropriate of the three. However, it was found that the CDS method overestimated peak intensity. The Modified Chicago Design Storm was introduced and tested with the observed storms and it was found that the modified CDS can reduce the Mean Absolute Percentage Error (MAPE) from 35% to 34% at peak intensity. MAPE was reduced from 62% to 58% at five minutes.

Moreover, impact of climate change on design storms was also investigated using rainfall data from the weather station at the Sirikit Convention Center. This revealed the rainfall characteristics at the center of Bangkok. Data was available for rainfall periods of 15 minutes for the 15 year period from 1990-2004. This was selected in the study to examine the impact of climate change. An Equidistance Quantile-Matching Method was adopted to compute IDF curves with climate change impacts. The Global Climate Model (GCM), including GEM 2-ES with RCP 4.5 was used to generate rainfall data for the next 25 years. Comparison of the changes in IDF curves due to the impact of climate change was made. It was found from the changes in the IDF curves, the peak intensity of design storms increased 13% and 25% for a 100 and 2 year return periods, respectively. It is therefore recommended to account for the impacts of climate change on design storms so that design of urban drainage systems will be capable of discharging peak runoffs in the future.

6. Acknowledgements

The authors would like to acknowledge the World Bank for a financial scholarship to the Asian Institute of Technology (AIT) through the Punjab Irrigation Department, Pakistan. This work was done under the project “Climate Change Adaptation through Optimal Storm water Capture Measures: Towards a New Paradigm for Urban Water Security”. The authors would like to acknowledge the United Nations University, Japan, for their financial support through Asia Pacific Network for Global Change research (APN).

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