Atmospheric Research 137 (2014) 176–182

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Variability of annual daily maximum rainfall of Dhaka, Bangladesh

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ARTICLE INFO

Article history:
Received 23 August 2013
Received in revised form 11 October 2013
Accepted 11 October 2013

Keywords:
Rainfall variability
Return periods
Annual daily maximum rainfall
Gumbel distribution
Normal distribution

ABSTRACT

This paper deals with a study on rainfall characterises of Dhaka, the capital city of Bangladesh for the period of 1953 to 2009. Data were collected from Bangladesh Meteorological Department in January 2011 and found 2.84% missing data. Descriptive statistical analysis was conducted on annual rainfall, annual daily and monthly maximum rainfall. We applied Gumbel distribution function to estimate return periods of extreme rainfall events and found that annual daily maximum rainfall equal or greater than 425 mm had a return period of 100 years. Normal distribution function was adopted to forecast rainfall variability due to global climate change and found that annual daily maximum rainfall equal or greater than 200 mm might occur in any 12 years during the period of 2010 to 2066. The outcomes of this paper can be used in better understanding rainfall patterns of Dhaka, Bangladesh.

1. Introduction

Rainfall pattern is one of the most important inputs and key issues for hydrological science and practices (Sangati and Borga, 2009). This information is widely required for flood forecasting, hydrological modelling and designing drainage structures (Lagouvardos et al., 2013). Rainfall pattern of Bangladesh is highly variable in time and space (Shahid et al., 2012) and hence, we got a motivation to study on rainfall characteristics of Dhaka, the capital city.

The delta of Bangladesh was formed by the three major rivers, the Ganges, the Brahmaputra and the Meghna and their tributaries and distributaries. Geographically, it is located between 20°34′ to 26°38′ north latitude and 88°01′ to 92°44′ east longitude. The country experiences heavy rainfall, generally between 1433 and 4338 mm (Bangladesh Bureau of Statistics, 2008) due to its geographical features including the presence of the Himalaya Mountains and the Bay of Bengal (Murata et al., 2008). Rainfall mainly occurs in summer and monsoon seasons (Yamane et al., 2010; Sikder et al., 2013), which accounts for 72% of the total annual rainfall (Ahasan et al., 2010). Climate change will increase around 5% of the country's rainfall by 2030 (Su et al., 2006) and small changes in mean and standard deviation will largely impact on rainfall intensity.

Only few researches have been carried out so far on rainfall characteristics of Dhaka and Bangladesh. Islam (2009) applied PRECIS model for forecasting rainfall of Bangladesh for the period of 2010 to 2020 using a baseline period of 1961 to 1990. He cross checked the estimated results with observed rainfall from 2000 to 2006 and found 4.47% over estimation. A study was carried out by Ahasan et al. (2011) on simulation of heavy rainfall event (341 mm) on September 14, 2004 in Dhaka using fifth generation PSU/NCAR Mesoscale model (MM5); analysis showed that this heavy rainfall event was the result of interaction of the monsoon land depression with southwest monsoon weather system. MM5 model also suggested that the depression was almost stationary and moisture required for heavy rainfall was supplied from the Bay of Bengal. Intra-seasonal Oscillation (ISO) of daily rainfall data from 25 gauge stations for 20 years (1981–2000) was examined by Fujinami et al. (2011) and the results showed that ISO was a dominant mode of summer rainfall fluctuation over Bangladesh. Ahasan et al. (2010) investigated rainfall variability of Bangladesh with respect to Nepal,

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http://dx.doi.org/10.1016/j.atmosres.2013.10.013

Bhutan and India. They found that Bangladesh rainfall had positive correlation with some of Indian regions, like, Naga–Manipur–Mizo–Tripura, Sub-Himalayan West Bengal, Sikkim and Bhutan; meanwhile, Orissa showed negative correlation with Bangladesh. Ahammed and Hewa (2012) studied on extreme rainfall events of Dhaka and developed rainfall intensity–frequency–duration (IFD) relationship required in the design process for hydraulic structures. Shahid (2011) applied Mann–Kendall Statistic and Sen's slope model for 50 years rainfall data (1958 to 2007) and observed significant changes to extreme rainfall indices in Northwest Bangladesh. Shahid (2010) also found a reasonable increase in the average rainfall and pre-monsoon rainfall in past years; the number of wet months was found to be increased and dry months to be decreased in most parts of Bangladesh. Karmakar and Alam (2011) developed simple and multiple linear regression equations for statistical prediction of 24 h maximum rainfall over Bangladesh and correlation co-efficient corresponding to equations were statistically significant. European Centre for Medium Range Weather Forecast (ECMRWF) modelling system and Tropical Rainfall Measuring System (TRMS) were applied by Rahman et al. (2011) to cross check Bangladesh Meteorological Department (BMD) rainfall data at three stations: Dinajpur, Rangpur and Sylhet. The continuous variables verification methods showed the better accuracy of TRMM data. The probability of occurrence TRMM rainfall was close to BMD observed data.

Papalexiou and Koutsoyiannis (2013) recognized the battle among Gumbel, Fréchet and Weibull distribution for analyzing extreme rainfall data; they analysed global rainfall data and identified that the Gumbel distribution function is better described than Fréchet. Allamano et al. (2011) and Evin et al. (2011) also revealed that the Gumbel distribution function is an acceptable choice to describe the annual maxima hydrological extremes.

This paper deals with statistical analysis of 57 years (1953 to 2009) rainfall data of Dhaka. We conducted descriptive statistical analysis to annual, annual daily maximum and annual monthly maximum rainfall data. We also applied Gumbel distribution and normal distribution function to estimate expected return periods of extreme rainfall events and to predict annual daily maximum rainfall variability due to the effect of global climate change respectively.

2. Materials and methods

2.1. Study area

Dhaka, the selected study area (Fig. 1), is the capital city of Bangladesh. It is situated almost in the central part of Bangladesh and located on the bank of the river Buriganga. It accommodates approximately 40% of the total urban population of the country (Jahan and Moniruzzaman, 2007). According to the Bangladesh Bureau of Statistics (2008), the total area of Dhaka is 1640 km^2 and total population is about 10.3 million with 4.2% annual growth rate. The annual average temperature of the city is 25 °C. The rainfall intensity for 10 years average recurrence interval and one hour duration is 98 mm/h (Ahammed and Hewa, 2012).

2.2. Rainfall data

Daily rainfall data of Dhaka for 57 years (1953 to 2009) were collected from Bangladesh Meteorological Department in January 2011. The amount of missing data was 2.84%. We did not find any single data for the year of 1974. Due to the independence war in 1971, meteorological station did not work properly and we found missing data for the month of March, April and December in this year. Other significant missing data were found during the periods of January to March, 1966 and July, 1973. The average of ten nearby data was replaced by each missing data.

We carried out number of checks to ensure quality control of data. We observed each data carefully; any suspicious data was cross-checked with rainfall data of nearby station. In some cases, suspicious data were correlated against records of other years, which were close to missing year.

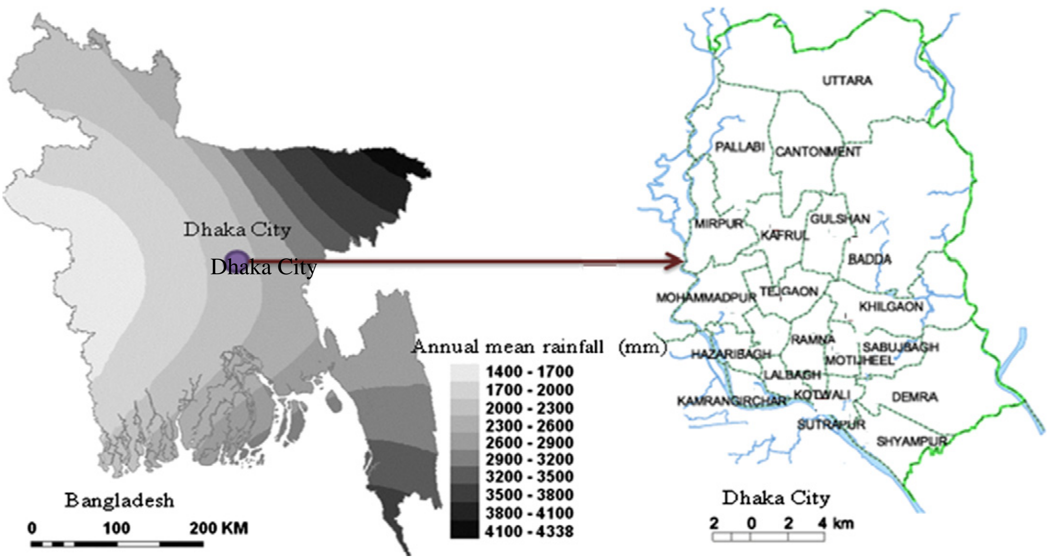

Fig. 1. Map of Dhaka, Bangladesh (Source: Ahammed et al., 2012).

2.3. Descriptive statistics

We conducted descriptive statistical analysis for three types of data: i) annual rainfall, ii) annual daily maximum rainfall and iii) annual monthly maximum rainfall. Descriptive statistics deals with organization and summary of large scale data. It includes tables, graphs and numbers to present raw data (Ott and Longnecker, 2010). We applied descriptive statistics to rainfall data to examine its central tendency (mean, median and mode), variability (standard deviation), symmetry (skewness) and peakedness (kurtosis). The various statistical moments used in this study are given below:

First moment (mean):

$$\bar{y} = \frac{\Sigma y_i}{n}$$

Second moment (variance):

$$s^2 = \frac{\Sigma(y_i\text{-}\bar{y})^2}{n\text{-}1}$$

Third moment (skewness):

$$g = \frac{n\Sigma(y_i\text{-}\bar{y})^3}{(n\text{-}1)(n\text{-}2)s^3}$$

Fourth moment (kurtosis)

$$\gamma_2 = \left[\frac{(\mu_4)}{(\mu_2)^2}\right]\text{-}3$$

2.4. Gumbel distribution function

The famous statistician Emil Julius Gumbel (1941) was probably, the first person who dealt extreme values of hydrological data in organized way for conducting flood frequency analysis. Traditionally three extreme value distributions: Fréchet, Weibull and Gumbel are commonly used for analysing return periods of annual daily maximum rainfall. Nadarajah and Choi (2007) and Carvalho et al. (2013) expressed the cumulative distribution function of the Generalized Extreme Value (GEV) distribution as:

$$F(x) = \exp\left\{-\left(1+\xi\cdot\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right\} \tag{1}$$

for $1 + \xi\,(x-\mu)/\sigma > 0$, where ξ, μ and σ are referred as shape, location and scale parameters respectively. The Eq. (1) is referred as Gumbel distribution for the cases of $\xi \rightarrow 0$; the GEV distribution can be expressed as Eq. (2). The probability and return periods of annual daily maximum rainfall were estimated using Eqs. (3) and (4) respectively.

$$F(x) = \exp\left[-\exp\left\{-\left(\frac{x-\mu}{\sigma}\right)\right\}\right] \tag{2}$$

$$P(x) = 1-F(x) \tag{3}$$

$$N = \frac{1}{P(x)} \tag{4}$$

Where,

x annual daily maximum rainfall,
μ mean of observed annual daily maximum rainfall,
σ standard deviation of observed annual daily maximum rainfall,
$F(x)$ cumulative probability distribution,
$P(x)$ probability distribution,
N return periods of expected annual daily maximum rainfall.

2.5. Normal distribution and rainfall variability

The normal distribution, sometimes called as Gaussian distribution is an important element of continuous probability distribution and is applied in many fields for conducting statistical analysis (Yerukala et al., 2011). We assumed the observed annual daily maximum rainfall data as normal distribution (Fig. 2) and considered single tailed test. We estimated cumulative probabilities of the normal probability distribution, F(z) from the appendix table available in the book of "Project management: a managerial approach" by Meredith and Mantel (2002). Similar tables and charts are usually found in many statistical books.

We applied normal distribution function using Eq. (5). Probability of annual daily maximum rainfall greater than a particular event was estimated using Eq. (6). Thereafter, we used Eq. (7) for the estimation of expected number of extreme rainfall events for specific return periods.

$$z = \frac{x-\mu}{\sigma} \tag{5}$$

$$P(z) = 1-F(z) \tag{6}$$

$$n = P(z) \times N' \tag{7}$$

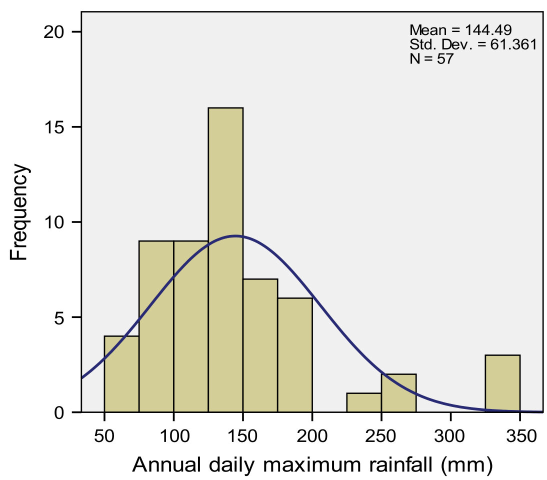

Fig. 2. Histogram of annual daily maximum rainfall data.

Where,

x	annual daily maximum rainfall,
μ	mean of observed annual daily maximum rainfall,
σ	standard deviation of observed annual daily maximum rainfall,
z	number of standard deviation of a normal distribution,
$F(z)$	cumulative probability of annual daily maximum rainfall equal or greater than x,
$P(z)$	probability of annual daily maximum rainfall greater than x,
N	frequency of expected extreme rainfall events for a return period,
N'	number of years.

The frequency, intensity, duration and pattern of rainfall events are changing due to the impact of climate change (Nielsen, 2012; Willems et al., 2012). Murshed et al. (2011) studied annual daily maximum rainfall of Dhaka City for predicting climate change impacts and trend analysis conducted by them for 30 years data series (1980 to 2009) showed an increasing rate of 2.7 mm. The changes of mean and standard deviation of annual daily maximum rainfall may transform the Eq. (5) as (8).

$$z = \frac{x - \mu'}{\sigma'} \tag{8}$$

Where,

$$\mu' = \mu \pm \Delta(\mu) \quad \text{and} \quad \sigma' = \sigma \pm \Delta(\sigma) \quad .$$

In this study, we observed the changed mean (μ') and standard deviation (σ') of annual daily maximum rainfall for the recent 30 years (1980 to 2009); linked these changes to 57 years (1953 to 2009) observed data and predicted the variability of annual daily maximum rainfall for the next 57 years (2010 to 2066).

3. Results and discussions

3.1. Extreme rainfall events

The highest amount of daily rainfall was recorded in Dhaka as 341 mm on September 14, 2004 followed by 333 mm on July 28, 2009. These were extreme rainfall events and more than two thirds of the city was inundated (Ahasan et al., 2011). Most of the streets were flooded and traffic system was collapsed on these days (Murshed et al., 2011). Another extreme event of rainfall (326 mm/day) also occurred in 1956. Table 1 shows the ranking of historical extreme rainfall events of Dhaka.

It is noticeable from Table 1 that out of ten, four extreme rainfall events occurred in recent years (2004, 2006, 2008 and

Table 1
Historical extreme rainfall events of Dhaka City, Bangladesh.

Rank	Date	Daily rainfall (mm)
1	September 14, 2004	341
2	July 28, 2009	333
3	July 14, 1956	326
4	September 16, 1966	257
5	July 22, 1971	251
6	May 25, 1972	231
7	June 05, 2008	190
8	June 19, 1963	189
9	June 21, 1961	185
10	September 12, 2006	185

Table 2
Number of rainy days of Dhaka City, Bangladesh.

Criteria	Number of rainy days		
	Rainfall ≤ 10 mm/day	Rainfall ≥ 100 mm/day	Number of annual rainy days
Mean	67	2	120
Mode	65	2	116
Maxima	85	6	144
Minima	54	0	95
Standard deviation	6.99	1.55	11.11
Skewness	0.59	0.30	−0.03
Kurtosis	0.14	−0.57	−0.22

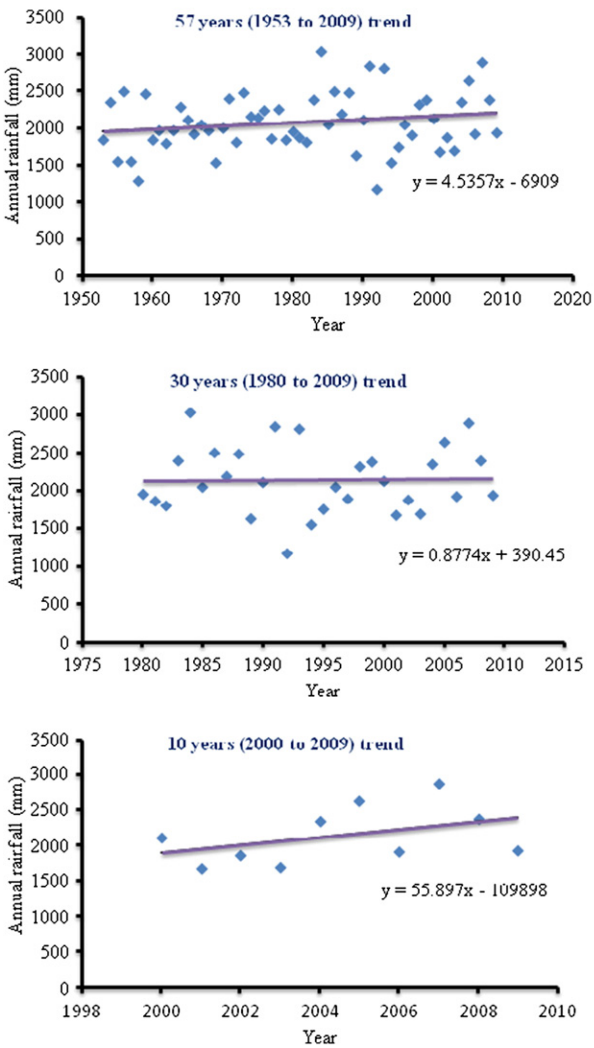

Fig. 3. Trend of annual rainfall of Dhaka City.

Table 3
Descriptive statistics of rainfall pattern of Dhaka City.

Criteria	Annual monthly maximum rainfall (mm)	Annual daily maximum rainfall (mm)	Annual rainfall (mm)
Mean	528.54	144.53	2076
Maxima	856	341	3028
Minima	266	61	1169
Standard deviation	134.64	61.31	388.92
Skewness	0.34	1.63	0.22
Kurtosis	−0.09	3.067	0.09

2009). This is clear evidence that climate change is altering the rainfall pattern of Bangladesh.

3.2. Rainfall characteristics

The number of annual rainy days of Dhaka City varies from 95 to 144. The mean value is 120 and standard deviation is 11.11. The distribution is slightly negative skewed (−0.03), i.e. the left tail is slightly longer than normal distribution. The kurtosis value is −0.22, means that comparing with normal distribution, the central peak is lower and boarder and the tails are shorter and thinner.

The number of days in a year with rainfall equal or less than 10 mm/day varies from 54 to 85; the mean value is 67 (standard deviation as 6.99), which is close to mode (65). The distribution is skewed right and leptokurtic, i.e. compared with normal distribution, the central peak is higher and sharper. Sometimes, the rainfall intensity of Dhaka City is extremely higher and the average number of rainy days in a year with rainfall equal and greater than 100 mm/day is 2 with standard deviation as 1.55. Table 2 shows the details of number of rainy days of the city.

Annual rainfall of Dhaka City varies from 1169 to 3028 mm; the mean value is 2076 mm with standard deviation as 388.92. The skewness and kurtosis values are 0.22 and 0.09 respectively. Trend analysis (simple regression method) for fifty seven years (1953 to 2009) rainfall data shows that there is increasing trend of 4.54 mm per year; however, the recent ten years (2000 to 2009) trend shows the increasing rate as 55.90 mm/year. Fig. 3 shows the trend analysis of annual rainfall of Dhaka City. The annual monthly maximum rainfall of the city varies from 266 to 856 mm; the mean value is 528.54 mm with standard deviation as 134.64. The maximum monthly rainfall usually occurs in the month of July (35%) followed by June (21%). Table 3 shows the descriptive statistics of rainfall characteristics of Dhaka City.

3.3. Return periods of annual daily maximum rainfall

The mean and standard deviation of annual daily maximum rainfall of Dhaka are 144.53 mm and 61.31 respectively. Putting these values in Eq. (2); we developed Eq. (9) for the estimation of return periods of extreme rainfall events as

$$N = \left[1 - \exp\left[-\exp\left\{-\left(\frac{x - 144.53}{61.31}\right)\right\}\right]\right]^{-1} \tag{9}$$

Eq. (9) estimates that daily rainfall equal or greater than 225 and 425 mm have return periods of 4 and 100 years respectively. Fig. 4 shows the workout results of return periods of expected annual daily maximum rainfall for Dhaka City.

3.4. Forecasting of annual daily maximum rainfall variability

57 years (1953 to 2009) annual daily maximum rainfall data can be expressed using Eq. (10), which will be invalid for future years due to the changing of rainfall pattern as an effect of climate change. The increasing rate of annual daily maximum rainfall for the recent 30 years (1980 to 2009) is 3 mm per day and the standard deviation is 64.30. We added these changes ($\mu' = 147.53$ mm and $\sigma' = 64.30$) to observed data and forecasted annual daily maximum rainfall (x) for the following 57 years (2010 to 2066) using Eq. (11). Considering x = 200 mm, the number of standard deviations of a normal distribution (z) is 0.82. The cumulative probability of annual daily maximum rainfall equal or less than 200 mm becomes 0.7939, which is derived from normal distribution table and chart available in most statistical books and hence, the probability of annual daily maximum rainfall greater than 200 mm becomes 0.2061 (See Fig. 5 for details). This analysis shows that over the next 57 years (2010 to 2066), probably in any 12 years ($0.2061 \times 57 = 12$) annual daily maximum rainfall will be equal or greater than 200 mm. Table 4 shows

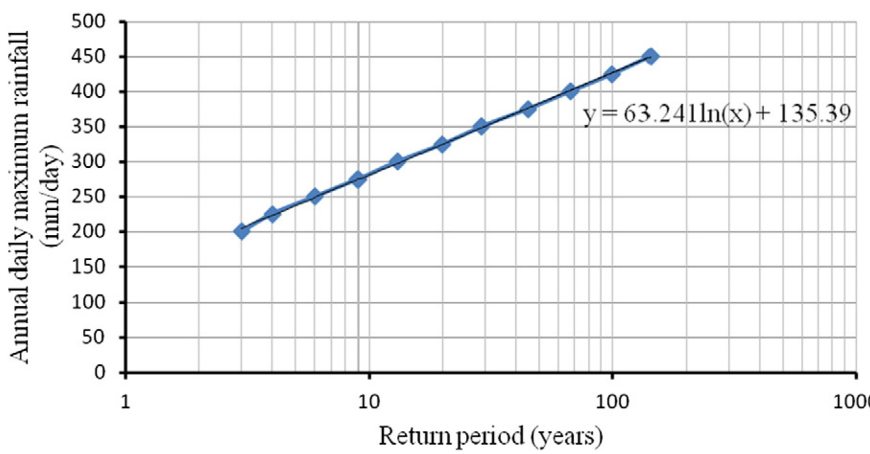

Fig. 4. Return periods of annual daily maximum rainfall of Dhaka City.

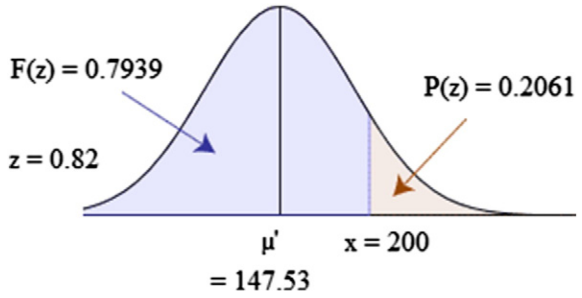

Fig. 5. Normal distribution calculation for annual daily maximum rainfall, x = 200 mm.

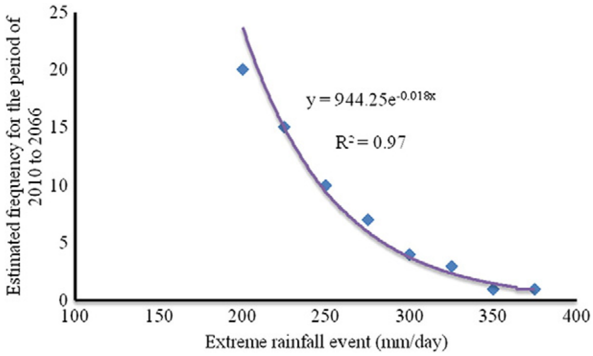

Fig. 6. Estimated frequencies of extreme rainfall events for Dhaka City under conditions of global climate change.

the forecasting of annual daily maximum rainfall for Dhaka City.

$$z = \frac{x - 144.53}{61.31} \tag{10}$$

$$z = \frac{x - 147.53}{64.30} \tag{11}$$

The estimation of variability of annual daily maximum rainfall for the period of 2010 to 2066 under conditions of global climate change provides likely frequencies of extreme rainfall events. This part of the study was carried out applying the normal distribution function leading to an outcome which can be used to develop measures for managing urban flooding to Dhaka to any standard up to and including ARI (Average Recurrence Interval), Y = 100 years taking account of global climate change. Fig. 6 shows estimated frequencies of extreme rainfall events for the period of 2010 to 2067 for Dhaka City under conditions of global climate change.

4. Conclusions

The statistical analysis was carried out based on daily rainfall data, which is the only source of precipitation in Bangladesh. The analysis shows the forecasting of extreme rainfall events for a particular return period. Any drainage structure to be designed and constructed in Dhaka should be resilient to extreme rainfall event. The existing system was designed based on historical rainfall data, but the capacity of the drainage network will not be sufficient enough with high intensive short duration rainfall which is expected due to global climate change. The proposed return periods of annual daily maximum rainfall of this study can be used for upgrading the capacities of hydraulic structures of Dhaka City.

Table 4
Forecasting of annual daily maximum rainfall for the period of 2010 to 2066.

Annual daily maximum rainfall (mm)	Z	F(z)	P(z)	Frequency (n)
200	0.816019	0.7939	0.2061	12
225	1.204821	0.8849	0.1151	7
250	1.593624	0.9452	0.0548	3
275	1.982426	0.9767	0.0233	1
300	2.371229	0.9911	0.0089	1

The forecasting of annual daily maximum rainfall variability for the period of 2010 to 2066 shows the likely frequency of extreme rainfall events. This part of the study was carried out through normal distribution function and the authors believe that such analysis and findings are the first kind of work in rainfall data of Bangladesh. This outcome can be used in many ways; it can help to understand future flash flooding risk and opportunity of stormwater harvesting. This paper also describes the overall rainfall pattern of Dhaka. Any high value infrastructure, like, industrial site, power station etc. should be constructed considering this rainfall pattern so that damages and maintenance cost can be minimised.

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