Characteristics of Rainfall in Peninsular Malaysia

Muhammad N S ¹, Abdullah J ² and Julien P Y ³

¹Senior Lecturer at the Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, 43600, Selangor, Malaysia
²Senior Lecturer at the Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, 40450, Selangor, Malaysia
³Professor, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO, 80523, USA

shazwani.muhammad@ukm.edu.my (Nur Shazwani Muhammad)

Abstract. This study presents the rainfall statistics, conditional probability structure and statistical dependence of rainfall amount of several gauging stations located around Peninsular Malaysia, namely Subang, Senai and Kota Bharu. Daily rainfall measurements for all stations were collected from the Department of Meteorology, Malaysia are long and reliable, with at least 40 years of data. The average annual rainfall estimated for Kota Bharu, Subang and Senai are 2,627 ± 574 mm, 2581 ± 399 mm and 2499 ± 340 mm, respectively. The effect of monsoon seasons on the monthly rainfall amount is evident in this study. The most significant variation in the average monthly rainfall is noticed for Kota Bharu. There was some variation in the average monthly rainfall for Subang and Senai. The conditional probability structure for t-consecutive wet and dry days show that the multi-day events are time-dependent. For example, the probability of occurrence for a single dry day is 0.458, 0.453 and 0.553 and increased significantly to 0.696, 0.780 and 0.817 for 8-consecutive dry days at Subang, Senai and Kota Bharu, respectively. The dependence of rainfall amount was analyzed using the auto correlation function (ACF). The range of ACFs estimated for all stations were very low, i.e. 0.0050 to 0.0209, 0.0093 to 0.0857 and 0.0633 to 0.3700 for Subang, Senai and Kota Bharu, respectively. This result shows that the rainfall amounts are independent of each other. Overall, the analysis shows that the east coast region received more annual rainfall with higher variability, as compared to the central and south parts of Peninsular Malaysia. Additionally, the total amount of rainfall observed for all stations varies spatially and temporarily.

Keywords: Multi-day rainfall; Monsoon rainfall precipitation; Conditional probability

1. Introduction
The nature of climate in Malaysia is hot and humid throughout the year. There is no distinctive difference between one season to another. However, the characteristics of rainfall are influenced by two monsoon seasons, i.e. North East (NE) and South West (SW). The months of November to March (May to September) marks the occurrence of NE (SW) monsoon; while inter-monsoon is expected in April and October. The country receives considerable amount of annual rainfall during these monsoon seasons, i.e. between 2000 to 4000 mm with 150 to 200 rainy days [1].

Although the country received significant amount of rainfall every year, previous studies on daily rainfall data mainly concentrate on the probability models of dry and wet spells [2, 3, 4, 5, 6, 7] and
distribution functions of daily rainfall amount [1]. These studies are common for countries affected by heavy rainfalls resulted from monsoon seasons, for example India [8, 9, 10, 11]. The advantages of probability models of dry and wet spells are it gives an empirical representation frequency distribution, to establish the relationship between the magnitude of extreme events to their frequency of occurrence and estimation of return periods, especially for areas where data is scarce and limited. However, these probability models do not provide detailed statistics on the magnitude of annual, monthly and daily rainfalls, the conditional probability of wet and dry days and also the dependency of rainfall amount for consecutive wet days. This information is important, especially for Malaysia which is prone to flood events, especially during the inter-monsoon and NE monsoon seasons.

Significant amount of rain was recorded as a result of multi-day rainfall events [12, 13, 14] and caused severe flooding in many areas of the country [15]. The most recent major flood occurred in Peninsular Malaysia was reported in 2014, which affected more than 200,000 people and economic loss of over RM1 billion [16]. In December 2006 and January 2007, Kota Tinggi received cumulative rainfalls of more than 350 mm in 4 consecutive days that caused devastating floods in the area [15, 17]. This natural disaster has forced more than 100,000 local residents to be evacuated and USD 0.5 billion of estimated economic loss [17, 18].

Given the severity of flood events in Malaysia, this study presents the characteristics of rainfall for several gauging stations located in Peninsular Malaysia, namely Subang, Senai and Kota Bharu. Additionally, a new discovery on the nature of multi-day rainfall events in Peninsular Malaysia is also presented here. The topics include rainfall statistics, conditional probability structure and statistical dependence of rainfall amount for daily and multi-day rainstorms.

2. Study Area

The daily rainfall measurements from three rainfall gauging stations located in Peninsular Malaysia, namely Subang, Senai and Kota Bharu were used in this study. Subang is located in the central region of Peninsular Malaysia and about 25 km from Kuala Lumpur (capital city of Malaysia); while Senai represents the second largest city in Peninsular Malaysia and Kota Bharu is a major city in the east coast part of Peninsular Malaysia, an area which is most affected by the NE monsoon. These stations also have a high-quality record of more than 40 years, supplied by the Malaysian Meteorological Department. The details of these rainfall gauging stations are given in Table 1 and the location of all rainfall gauging stations is shown in figure 1. The tipping bucket method is used at all locations, and the amount is recorded from 8 in the morning until 8 a.m the next day. Constant monitoring of rainfall is done at all stations because these stations are in an international airport, which is a high priority meteorological station. Hence, the dataset is complete with good quality, without any missing data.

Table 1. Details on Rainfall Gauging Stations

| Location   | Coordinate (Lat., Long.) | Altitude above mean sea level (m) | Period     | Duration (years) |
|------------|--------------------------|----------------------------------|------------|-----------------|
| Subang     | 03° 07’ N, 101° 33’ E    | 16.5                             | 1960-2014  | 55              |
| Senai      | 1° 38’ N, 103° 40’ E     | 37.8                             | 1975-2014  | 40              |
| Kota Bharu | 6° 10’ N, 102° 18’ E     | 4.4                              | 1960-2014  | 55              |
3. Methodology

The methodology of detailed rainfall statistics, conditional probability and statistical dependence of rainfall amount for daily and multi-day rainstorms are given in the following sub-sections.

3.1 Statistical Analysis of Rainfall Data

This study presents detailed statistical analysis of rainfall data gathered from Subang, Senai and Kota Bharu, such as the average total annual rainfall, standard deviation, maximum rain in a day, longest wet and dry runs in days, maximum total annual rainfall and year of occurrence and minimum total annual rainfall and year of occurrence.

The longest wet and dry runs (in days) were estimated using the concept of run length, as given in equations 1 and 2, respectively.

\[
\begin{align*}
(T_w = n) &= (X_0 = 0, X_1 = 1, \ldots, X_n = 1, X_{n+1} = 0 \text{ given that } X_0 = 0, X_1 = 1) \\
(T_d = n) &= (X_0 = 1, X_1 = 0, \ldots, X_n = 0, X_{n+1} = 1 \text{ given that } X_0 = 1, X_1 = 0)
\end{align*}
\]

where \(T_w\) is wet run, \(T_d\) is dry run, \(n\) is the number of days, 1 denotes a wet day, 0 is a dry day.
3.2 Conditional Probability of Multi-day Rainfall Events

Let W and D be the events in a probability space. W denoted a wet (rainy) day and D is a dry day on any random (t-th) day. The theoretical conditional probabilities are given in equations 3 to 6.

\[
P(X_t = W|X_{t-1} = D) = \frac{P(W \cap D)}{P(D)} \tag{3}
\]

\[
P(X_t = W|X_{t-1} = W) = \frac{P(W \cap W)}{P(W)} \tag{4}
\]

\[
P(X_t = D|X_{t-1} = W) = \frac{P(D \cap W)}{P(W)} \tag{5}
\]

\[
P(X_t = D|X_{t-1} = D) = \frac{P(D \cap D)}{P(D)} \tag{6}
\]

where \(X_t\) is any random day and \(t\) is time (days), \(P(W)\) is the probability of wet and \(P(D)\) is the probability of dry on any day.

The conditions given in equations 7 and 8 have to be fulfilled in order to prove that \(W\) and \(D\) are independent.

\[
P(X_t = W|X_{t-1} = D) = P(W) \text{ if } P(D) > 0 \tag{7}
\]

\[
P(X_t = D|X_{t-1} = W) = P(D) \text{ if } P(W) > 0 \tag{8}
\]

3.3 Dependence of Rainfall Amount

The dependency of rainfall amount for consecutive wet days is determined using two methods, i.e. Auto Correlation Function (ACF) and by plotting the scatter plots. Equations 9 and 10 give the formula to estimate ACF.

\[
\hat{r}_k = \frac{\sum_{t=1}^{N-k} (x_t - \bar{x})(x_{t+k} - \bar{x})}{\left(\sum_{t=1}^{N} (x_t - \bar{x})^2\right)^{-1}}, \quad k \geq 1 \tag{9}
\]

\[
\bar{x} = \frac{1}{N} \sum_{t=1}^{N} x_t \tag{10}
\]

where \(r_k\) is the ACF of lag \(k\)-th day, \(x_t\) is the amount of rainfall on \(t\)-th day and \(N\) is the number of samples.

4. Rainfall Characteristics of Peninsular Malaysia
4.1. Rainfall Statistics

Total annual rainfall statistics shows that on average, Kota Bharu received more rainfall annually as compared to Subang and Senai. The average annual rainfall estimated for Kota Bharu is 2,627 mm, with a standard deviation of 574 mm. Subang and Senai rainfall gauging stations recorded an annual average rainfall of 2581 ± 399 mm and 2499 ± 340 mm, respectively. This initial analysis shows that the east coast region received more rainfall with higher variability annually, as compared to the central and south parts of Peninsular Malaysia. Similar findings were reported by Muhammad et al. [19]. The maximum total annual rainfall for Senai, Subang and Kota Bharu are 3,402 (year 2007), 3,455 (year 2006) and 3,735 mm (year 1999), respectively. In addition, Kota Bharu received the highest rainfall amount in a day, i.e. 608 mm on 6th January, 1967, as compared to Senai (364 mm on 2nd December, 1978) and Subang (172 mm on 4th January, 1971). Interestingly, these events occur during NE monsoon.

Another significant outcome that should be noted here is that the longest wet run occurred during NE monsoon for Kota Bharu and Senai, with 36 and 24 continuous rainy day, respectively. The longest wet run for Subang occurred twice, i.e. in 1984 and 2003 during inter monsoon season and the duration is 31 days.

These stations also experience several dry periods. The minimum total annual rainfall for Senai, Subang and Kota Bharu are 1,860 (year 1990), 1,802 (year 1974) and 1,541 mm (year 1989), respectively. The longest dry run (in days) for these stations are 34 (9th February to 14th March, 2014), 22 (21st January to 11th February, 2014) and 41 (20th February to 29 April, 1983), for Senai, Subang and Kota Bharu, respectively.

The total annual rainfall for all stations is shown in figure 2, while the rainfall statistics are summarized in Table 2.

![Figure 2. Total annual rainfall at Subang, Senai and Kota Bharu from 1975 to 2014](image)

| Year | Subang | Senai | Kota Bharu |
|------|--------|-------|------------|
| 1975 |        |       |            |
| 1976 |        |       |            |
| 1977 |        |       |            |
| 1978 |        |       |            |
| 1979 |        |       |            |
| 1980 |        |       |            |
| 1981 |        |       |            |
| 1982 |        |       |            |
| 1983 |        |       |            |
| 1984 |        |       |            |
| 1985 |        |       |            |
| 1986 |        |       |            |
| 1987 |        |       |            |
| 1988 |        |       |            |
| 1989 |        |       |            |
| 1990 |        |       |            |
| 1991 |        |       |            |
| 1992 |        |       |            |
| 1993 |        |       |            |
| 1994 |        |       |            |
| 1995 |        |       |            |
| 1996 |        |       |            |
| 1997 |        |       |            |
| 1998 |        |       |            |
| 1999 |        |       |            |
| 2000 |        |       |            |
| 2001 |        |       |            |
| 2002 |        |       |            |
| 2003 |        |       |            |
| 2004 |        |       |            |
| 2005 |        |       |            |
| 2006 |        |       |            |
| 2007 |        |       |            |
| 2008 |        |       |            |
| 2009 |        |       |            |
| 2010 |        |       |            |
| 2011 |        |       |            |
| 2012 |        |       |            |
| 2013 |        |       |            |
| 2014 |        |       |            |

Table 2. Rainfall statistics for Senai, Subang and Kota Bharu
### Rainfall Station

|                      | Senai | Subang | Kota Bharu |
|----------------------|-------|--------|------------|
| Average total annual rainfall in mm | 2499  | 2581   | 2627       |
| Standard deviation in mm   | 340   | 399    | 574        |
| Maximum rain in a day in mm [date] | 364.4 [2nd December, 1978] | 171.5 [4th January, 1971] | 608.1 [6th January, 1967] |
| Longest wet run in days [date] | 24 [20th January, 1984 – 12th February, 1984] | 31 [14th March 1984 – 13th April 1984 and 27th October 2003 – 26th November, 2003] | 36 [25th November, 1965 – 30th December, 1965] |
| Maximum total annual rainfall in mm [year] | 3402 [2007] | 3455 [2006] | 3735 [1999] |
| Longest dry run in days [date] | 34 [9th February to 14th March, 2014] | 22 [21st January to 11th February, 2014] | 41 [20th February to 29 April, 1983] |
| Minimum total annual rainfall in mm [year] | 1860 [1990] | 1802 [1974] | 1541 [1989] |

The effect of monsoon seasons on the monthly rainfall amount can be seen clearly from figure 3. The most significant variation in the average monthly rainfall is noticed for Kota Bharu. For example, the highest average monthly rainfall in Kota Bharu was observed in the beginning of NE monsoon, i.e. November and December which represents about 47% of total average annual rainfall. However, the remaining 10 months show the lowest observed rainfall as compared to Subang and Senai. Other study areas, i.e. Subang and Senai do not show significant variation in average monthly rainfall. Subang (Senai) recorded the highest cumulative rainfall during NE monsoon and the total rainfall observed during this season is 47% (43%) of the total average annual rainfall. Additionally, significant values are also observed during inter monsoon seasons, i.e. in April and October, that represents 11% (10%) and 10% (9%), respectively. Most of the rainfall events in these months are convective rain, which usually occurs in the afternoon. The months of June and July are considered as dry periods for Subang, while February is the lowest average monthly rainfall for Senai. Although SW monsoon is considered as a dry season for these station, the average rainfalls during these months are 32%, 38% and 28% of total average annual rainfall for Subang, Senai and Kota Bharu, respectively.

Overall, the total amount of rainfall observed for all stations varies spatially and temporarily. The monsoon seasons represent the direction of the most prevailing wind and it has significant influence on the characteristics of rainfall for stations located around Peninsular Malaysia.
Figure 3. Average total monthly rainfall at Subang, Senai and Kota Bharu

4.2 Conditional Probability of Multi-day Rainfall Events

The discussion on the conditional probabilities of wet and dry days for Subang, Senai and Kota Bharu is given in this section. The analyses of conditional probabilities are important to demonstrate that the occurrence of rainfall is statistically independent or dependent.

For all locations, the probability structure increased significantly when the number of consecutive wet day increased, as shown in figure 4. For a single wet day, the conditional probability is 0.542, 0.547 and 0.447 and increased to 0.751, 0.695 and 0.786 for 8-consecutive days at Subang, Senai and Kota Bharu, respectively. This result also indicates that Subang and Senai have more wet days than Kota Bharu and similar trend is observed, up to 3-consecutive days. From 4- to 8-consecutive days, the conditional probabilities for Kota Bharu are slightly higher than Subang and Senai.

For t-consecutive dry days, the conditional probabilities are lower than the wet events for most stations, i.e. Subang and Senai. For a single dry day, the probability of occurrence is 0.458, 0.453 and 0.553 and increased significantly to 0.696, 0.780 and 0.817 for 8-consecutive dry days at Subang, Senai and Kota Bharu, respectively, as shown in figure 5. Interestingly, this analysis reveals that there are more dry days (55%) as compared to wet days (45%) in Kota Bharu, although this station recorded the highest amount of total annual rainfall, as discussed in previous section. Table 3 summarized the estimated conditional probability of t-consecutive wet and dry days.

Another important finding that should be noted from figure 4 (5) is that the conditional probabilities of t-consecutive wet (dry) days increased as the number of t-consecutive wet (dry) days increase. The estimated probability of a wet and dry day is not constant. These findings demonstrate that the multi-day wet and dry events are dependent. Today’s event, i.e. wet or dry determines the probability of occurrence the next day.
Figure 4. Conditional probability of t-consecutive wet days

Figure 5. Conditional probability of t-consecutive dry days
Table 3. Estimated conditional probability of t-consecutive wet and dry days

| t-consecutive wet days | Estimated probability | conditional dry days | Estimated probability | conditional dry days |
|------------------------|-----------------------|----------------------|-----------------------|----------------------|
|                        | Subang | Senai | Kota Bharu | Subang | Senai | Kota Bharu |
| 1                      | 0.542  | 0.547 | 0.447      | 1       | 0.458  | 0.453      |
| 2                      | 0.642  | 0.647 | 0.620      | 2       | 0.577  | 0.573      |
| 3                      | 0.675  | 0.667 | 0.663      | 3       | 0.625  | 0.641      |
| 4                      | 0.691  | 0.670 | 0.701      | 4       | 0.665  | 0.687      |
| 5                      | 0.714  | 0.677 | 0.729      | 5       | 0.678  | 0.720      |
| 6                      | 0.723  | 0.684 | 0.749      | 6       | 0.690  | 0.746      |
| 7                      | 0.743  | 0.685 | 0.762      | 7       | 0.697  | 0.771      |
| 8                      | 0.751  | 0.695 | 0.786      | 8       | 0.696  | 0.780      |

4.3 Dependence of Rainfall Amount
A comprehensive analysis was done and where three scenarios were tested, i.e. (1) all consecutive wet days; (2) rainfall on Day 1 and Day 2 (D1 & D2); and (3) rainfall on day 2 and day 3 (D2 & D3). The results are summarized in table 4. Figures 6 and 7 provide the validation of the results thru the plots of rainfall amounts on D1 & D2 and rainfall amounts of D2 & D3 for Kota Bharu.

Table 4. The ACFs for all consecutive rainy days, D1 & D2 and D2 & D3

| Scenario                       | Sample Size (days) | ACF       |
|--------------------------------|--------------------|-----------|
|                                | Subang | Senai | Kota Bharu | Subang | Senai | Kota Bharu |
| All consecutive rainy days     | 10,911 | 8,212 | 9,009       | 0.0209 | 0.0857 | 0.37       |
| D1 & D2                        | 6,185  | 4,669 | 5,305       | 0.005  | 0.0123 | 0.0457     |
| D2 & D3                        | 3,735  | 2,935 | 2,987       | 0.015  | 0.0093 | 0.0633     |
The ACFs estimated for all stations and scenarios are very low, which shows that the rainfall amounts are independent of each other. The range of ACFs are 0.0050 to 0.0209, 0.0093 to 0.0857 and 0.0633 to 0.3700 for Subang, Senai and Kota Bharu, respectively. Additionally, Figures 6 and 7 further prove that there is no dependency between the amounts of rainfall for consecutive rainy days because there are no structured appearances at any of the points and the plots are totally random.

**Figure 6.** Amounts of Rainfall on D1 and D2 for Kota Bharu

**Figure 7.** Amounts of Rainfall on D2 and D3 for Kota Bharu
5. Conclusions
The analysis of rainfall characteristics in 3 stations around Peninsular Malaysia, namely Subang, Senai and Kota Bharu establish the following:

1. The rainfall events in Kota Bharu (east coast) are more intense as compared to Subang (central region) and Senai (south), especially during NE monsoon
2. Kota Bharu is more prone of experiencing long and continuous rainfall events
3. The total amount of rainfall observed for all stations varies spatially and temporally
4. The wet and dry events at all stations are time-dependent because the conditional probabilities of increase with the duration.
5. During wet events, the amount of rainfall is independent from one rainy day to another.

Acknowledgement
This study was financially supported by the Ministry of Education, Malaysia (grant number FRGS/2/2014/TK02/UKM/03/2) and Universiti Kebangsaan Malaysia. The authors would like to thank the Malaysian Meteorological Department for supplying the rainfall data. The authors also appreciate the comments from anonymous reviewers that improve the quality of this article.

References
[1] Suhaila J and Jemain A A 2007 Fitting Daily Rainfall Amount in Malaysia Using the Normal Transform Distribution J. Appl. Sci. 7 pp1880-1886
[2] Mohd. Deni S, Jemain A A and Ibrahim K 2008 The spatial distribution of wet and dry spells over Peninsular Malaysia Theor. Appl. Climatol. 94 pp163-173
[3] Mohd. Deni S, Jemain A A and Ibrahim K 2009 Mixed probability models for dry and wet spells Statistical Methodology 6 pp290-303
[4] Mohd. Deni S and Jemain A A 2009 Fitting the distribution of dry and wet spells with alternative probability models Meteorol. Atmos. Phys 104 pp13-27
[5] Mohd. Deni S and Jemain A A 2009 Mixed log series geometric distribution for sequences of dry days Atmospheric Research 92 pp236-243
[6] Suhaila J and Jemain A A 2009 Investigating the impacts of adjoining wet days on the distribution of daily rainfall amounts in Peninsular Malaysia Journal of Hydrology 368 pp17-25
[7] Mohd. Deni S, Jemain A A and Ibrahim K 2010 The best probability models for dry and spells in Peninsular Malaysia during monsoon seasons Int. J. Climatol. 30 pp1194-1205
[8] Upadhyaya A and Singh S R 1998 Estimation of consecutive days maximum rainfall by various methods and their comparison Indian Journal of Soil Conservation 26(3) pp193-201
[9] Ali S, Patnaik U S and Prakash C 2002 Frequency analysis of one day and consecutive days maximum rainfall of Eastern Ghat High Land Zone of Orissa for Marshy watershed management planning Journal of the Institution of Engineers (India) 83 pp33-36
[10] Machiwal D, Jha M K and Mal B C 2006 Forecasting of Salient consecutive days’ maximum rainfalls of Kharagpur, India using probabilistic approach International Agricultural Engineering Journal 15(2-3) pp 65-77
[11] Bhakar S R, Bansal A K and Chhajed N 2008 Frequency analysis of consecutive days of maximum rainfall at Udaipur Journal of the Institution of Engineers (India) 89 pp14-16
[12] Muhammad N S 2013 Probability structure and return period calculations for multi-day monsoon rainfall events at Subang, Malaysia Ph.D thesis Department of Civil and Environmental Engineering Colorado State University CO
[13] Muhammad N S, Julien P Y, and Salas J D 2016 Probability structure and return period of multiday monsoon rainfall J. Hydro. Eng. 21(1) pp11
[14] Muhammad N S and Julien P Y 2015 Multiday Rainfall Simulations for Malaysian Monsoons In: Abu Bakar S., Tahir W., Wahid M., Mohd Nasir S., Hassan R. (eds) ISFRAM 2014. Springer, Singapore
[15] Abdullah J 2013 *Distributed runoff simulation of extreme monsoon rainstorms in Malaysia using TREQ* Ph.D thesis Department of Civil and Environmental Engineering Colorado State University CO

[16] Akasah Z A and Doraisamy S V 2015 2014 Malaysia flood: impacts and factors contributing towards the restoration of damages *J. Sci. Res. and Dev.* 2 pp53-59.

[17] Abdullah J, Muhammad N S, Julien P Y, Ariffin J and Shafie A 2018 Flood flow simulations and return period calculation for the Kota Tinggi watershed, Malaysia *J. Flood Risk Manag.* 11 ppS766-S782.

[18] Abdullah J, Muhammad N S, Muhammad S A and Julien P Y 2019 Envelope curves for the specific discharge of extreme floods in Malaysia *J Hydro-env. Res.* 25 pp 1-11

[19] Muhammad N S, Akashah A I and Abdullah J 2016 Analysis of extreme rainfall indices in Peninsular Malaysia *Jurnal Teknologi* 78(9-4) pp 15-20