

HEAVY RAINFALL CHARACTERISTICS AT SOUTH-WEST OF MT. MERAPI- YOGYAKARTA AND CENTRAL JAVA PROVINCE, INDONESIA

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ABSTRACT: Heavy rainfall analysis is an important data for disaster management of flash floods and debris flows in mountainous areas. Those disasters may cause casualties and property damages. It is an urgent consideration to analyze the heavy rainfall characteristics in the area in order to gain well-planned disaster mitigation. Hourly rainfall data were analyzed over Mt. Merapi area especially those which are located in the Yogyakarta and Central Java Province. The rainfall data were collected from a number of automatic rainfall stations with 11 to 28 years of data length. Heavy rainfall is defined when the rainfall depth exceeds 50 mm per event. Heavy rainfall analysis at the study area indicates that heavy rainfall varies among the stations and it is likely occurred more often at the south-west of Mt. Merapi. Statistical analysis gives that maximum rainfall depth for an event varies from 99 mm at the south-east area to 282 mm at the south-west area of Mt. Merapi. Maximum rainfall intensity values show that at the south-west of Mt. Merapi have higher rainfall intensity than at the south-east area. The results indicate that orographic effects and west monsoon are important in determining the spatial distribution of heavy rainfall occurrences in Mt. Merapi area. Besides, heavy rainfall more frequent occurred from noon until late afternoon. The annual maximum heavy rainfall data at the south-west of Mt. Merapi was best fitted with the LN3 distribution.

Keywords: heavy rainfall, West monsoon, Debris flow, Flood warning, Heavy rainfall

1. INTRODUCTION

Heavy rainfall resulting frequent flood during rainy season over Mt. Merapi area. The flooding occurred following Mt. Merapi eruption in October-November 2010 had caused secondary disaster in the area especially in the south to west of Mt. Merapi. Recent eruption that equivalent to 100 years eruption [1] has released more than 100 million cubic meters of volcanic material [2]. Since the eruptions, the heavy rainfall events occurred during November 2010 to March 2011 had caused lahar (debris) flow, at all 12 rivers whose upper streams originated from Mt. Merapi, disruption of villages, infrastructure such as bridges, check dams and even loss of life. Lahar flows following the 2010 Mt. Merapi eruption were larger than any previously recorded ones [1].

A better understanding and knowledge of characteristics of heavy rainfall events will facilitate the flood warning of the rainfall events that may trigger lahar flow. In an attempt to understand the characteristics of heavy rainfall over Mt. Merapi, observed hourly data were analyzed for a period of 11 years length of data. The main objective of this paper is to investigate the characteristics of heavy rainfall events over Mt. Merapi. Understanding the spatial and temporal distribution of heavy rainfall events as well as the

frequency of occurrences is a key aspect of early flood warning system. Knowledge of the heavy rainfall characteristics could help in developing early flood or lahar flow warning system by providing rainfall characteristics on how likely heavy rainfall might be during a year. This warning system is an essential part of flood risk reduction.

2. DATA AND METHODS

2.1 The Study Area

Mt. Merapi is located in the north of Yogyakarta city about 25 km from the central city. It is located between two provinces namely Central Java and Yogyakarta province. This mount is the most active volcano in Indonesia even in the world. This volcano erupts frequently and the biggest eruption since 1930 occurred during October to November 2010 resulting in huge material deposit at the mountain that estimated more than 150 million m³ and even destroyed villages and loss of life. The secondary disaster also creates another disaster in the downstream of the mountain when heavy rainfall occurred. There is a number of rivers which originated from Mt. Merapi such as Pabelan river, Putih river in the Magelang District of the Central Java Province and Code river, Gendol river, Kuning

river in the Sleman district of Yogyakarta province got to suffer from disaster due to lahar flow.

There were 14 (fourteen) automatic rainfall stations mostly located at the south to the west slope of Mt. Merapi and were selected for the study as shown in Table 1 and Fig.1. Hourly rainfall data were obtained from Indonesian Sabo Research Centre, Yogyakarta, Indonesia from 1980 to 2010. All the available data were investigated for their suitability for the study. From the data obtained, it was found that some data were missing in several years. For further analysis, only the available data at all stations were used for further analysis. Data availability analysis shows that only 11 years data out of 30 years data which can be used for the study.

Table 1. Rainfall station used in the study

No	Station	Coordinate		Elevation (+msl)
		Latitude (S)	Longitude (E)	
1	Argomulyo	07°33'21.00"	110°21'49.93"	720
2	Babadan	07°31'35.70"	110°24'34.70"	1138
3	Batur	07°36'56.80"	110°27'08.50"	745
4	Deles	07°34'46.20"	110°28'15.00"	1098
5	Girikerto	07°37'36.50"	110°23'21.20"	550
6	Mt. Maron	07°33'56.80"	110°23'34.50"	960
7	Ngandong	07°35'43.80"	110°24'27.60"	840
8	Ngepos	07°34'06.46"	110°21'08.57"	631
9	Pakem	07°39'14.60"	110°24'57.80"	445
10	Plosokerep	07°38'11.35"	110°29'36.25"	530
11	Pucanganom	07°33'54.90"	110°18'49.74"	465
12	Randugunting	07°46'01.46"	110°29'02.33"	131
13	Sorasan	07°41'24.30"	110°28'00.80"	300
14	Sukorini	07°40'44.40"	110°30'49.70"	326



Fig.1 Rainfall stations at south-west of Mt. Merapi

2.2 Defining Heavy Rainfall

A heavy rainfall event is normally defined by using a daily amount exceeding a certain threshold [3]. For instance, Karl et al. [4] used a threshold of 2 inches (50.8mm) to define an extreme rainfall event for the United States. Dyson [5] in the study of heavy daily rainfall characteristics in South Africa applied a heavy rainfall event when the average rainfall exceeds 15 mm and a very heavy rainfall when the average rainfall exceeds 25 mm. In Indonesia, Sosrodarsono and Takeda [6] used 50 mm a day as a threshold for heavy/extreme rainfall or using rainfall intensity as a threshold i.e. 20 mm/hour.

2.3 Heavy Rainfall Characteristics

Heavy rainfall characteristics were analyzed based on rainfall events where rainfall amounts for each event are greater than 50 mm. Floris et al. [7] have studied the recent changes in rainfall characteristics in north-eastern Italian Alps. Results show that local climatic changes might produce an increasing frequency of rainfall events, potentially triggering debris flows in the study area. Jeng and Sue [8] developed a threshold value curves of heavy rainfall for predicting slope stability. This curve is important in slope disaster prevention. The frequency of heavy rainfall is likely to increase in some places such as Fukuoka [9] and the United State [10].

2.4 Statistical Analysis of Heavy Rainfall

Analysis of heavy rainfall characteristics was done based on statistical analysis of the rainfall data. Such approach has been applied by Chen et al. [11] for investigating heavy rainfall characteristics in Taiwan. Results show that orographic effects and typhoon track are important in determining the spatial distribution of heavy rainfall occurrences. The statistical analysis used in the study includes the maximum rainfall event for the area, maximum rainfall intensity, a number of extreme rainfall events, spatial and temporal as well as the frequency of occurrences of heavy rainfall.

Sujono [12] used circular approach for determining dominant heavy rainfall. This approach is analogous to wind rose analysis whereas rainfall is assumed as a vector that consists of direction (rainfall duration) and magnitude (rainfall depth). Using the circular approach, frequency for a given rainfall depth and dominant rainfall duration can be easily determined.

The frequency of occurrences of heavy rainfall could be analyzed using L-moments approach. The approach and associated goodness-of-fit procedures as introduced by Hosking [13]-[14], have been recommended for selecting the most appropriate rainfall distribution in a region [15]-[16]. Based on the L-moment diagrams, three-parameter distributions including Log Pearson type 3 (LP3), Generalized Extreme Value (GEV), Generalized Pareto (GPA), Generalized Logistic (GLO) show more flexible distributions for regional purposes rather than two-parameter distributions such as Gumbel, Normal. Malekinezhad and Zare-Garizi [17] applied L-moments and an index rainfall approach for regional frequency analysis of daily rainfall extremes in Iran. Results show that GEV and GLO probability distributions are more appropriate at a number regions in Iran.

L-moment parameters can be estimated based on unbiased PWM estimators using the following equations [15]-[16], [18]-[19]:

$$\begin{aligned} b_0 &= \frac{1}{n} \sum_{j=1}^n X_{(j)} \\ b_1 &= \sum_{j=1}^{n-1} \frac{(n-j)}{n(n-1)} X_{(j)} \\ b_2 &= \sum_{j=1}^{n-2} \frac{(n-j)(n-j-1)}{n(n-1)(n-2)} X_{(j)} \\ b_3 &= \sum_{j=1}^{n-3} \frac{(n-j)(n-j-1)(n-j-2)}{n(n-1)(n-2)(n-3)} X_{(j)} \end{aligned} \quad (1)$$

where $X_{(j)}$ represents the ordered rainfall data with $X_{(1)}$ and $X_{(n)}$ being the largest and the smallest data, respectively. For any distribution, the first four L-moments are computed from the PWM using [13]:

$$\begin{aligned} \lambda_1 &= \beta_0 \\ \lambda_2 &= 2\beta_1 - \beta_0 \\ \lambda_3 &= 6\beta_2 - 6\beta_1 + \beta_0 \\ \lambda_4 &= 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \end{aligned} \quad (2)$$

Analogous to product moment ratios, the coefficient of variation, skewness, and kurtosis, Hosking [13] defined the L-moment ratios as:

$$\begin{aligned} \tau_2 &= \frac{\lambda_2}{\lambda_1} \\ \tau_3 &= \frac{\lambda_3}{\lambda_2} \\ \tau_4 &= \frac{\lambda_4}{\lambda_2} \end{aligned} \quad (3)$$

where τ_2 , τ_3 , and τ_4 are L-coefficient of variation, L-skewness, and L-kurtosis, respectively. The first L-moment λ_1 is equal to mean value [18].

3. RESULTS AND DISCUSSION

3.1 Heavy Rainfall Characteristics

Heavy rainfall characteristics at the study area are presented in Table 2. The table shows clearly that the heavy rainfall varies among the station in the study area. In the west, southwest slopes of Mt. Merapi for instance at Babadan and Mt. Maron stations have higher maximum rainfall compare with southeast areas such as at Deles and Sukorini stations. Maximum rainfall depth for an event varies from 99 mm in the southeast area to 282 mm in the southwest area of Mt. Merapi. In addition, maximum rainfall intensity values indicate that in west, southwest of Mt. Merapi have higher rainfall intensity than in southeast area. The maximum rainfall intensity varies greatly from 65mm/h in southeast area to 109 mm/h in southwest area of Mt. Merapi. Those characteristics indicate that orographic type of rainfall due to west monsoon give more effect on rainfall magnitude rather than altitude or station elevation. Moreover, average rainfall duration for a heavy rainfall is quite similar in the range of 4.8 hours to 7.1 hours. It means that in the southeast area, rainfall hyetograph is flatter than in the south-west area.

Table 2 Heavy rainfall characteristics

Station	average duration (hour)	maximum depth (mm)	maximum intensity (mm/h)
Argomulyo	4.9	188	108
Babadan	7.1	282	103
Batur	7	196	96
Deles	6.2	129	71
Girikerto	4.8	191	94
Mt. Maron	5.3	273	109
Ngandong	5.9	184	89
Ngepos	5	199	94
Pakem	6.3	202	85
Plosokerep	5.8	157	95
Pucanganom	4.9	157	91
Randugunting	6.4	160	65
Sorasan	6.1	180	66
Sukorini	4.8	99	68

3.2 Frequencies of Heavy Rainfall Events

The frequency of heavy rainfall events in 2003 for example in the study area was presented in Table

3. The table shows that a number of heavy rainfall occurrences vary among the stations. The heavy rainfall mostly occurred during rainfall season from October to April. Heavy rainfall events are more common in the south-west of Mt. Merapi, while in the south-east area are relatively rare. This phenomenon could be the result of the west monsoon season. However, time occurrence of heavy rainfall in the area is relatively similar as depicted in Fig. 2. The figure shows that more than 80% of heavy rainfall events occurred after 12 noon until 06.00 pm. The highest frequency lies between 03:00 pm until 05:00 pm. It is very rare that heavy rainfall occurs in the morning or in the late night.

Heavy rainfall characteristics are also indicated by the debris flood/lahar flow events that occurred after the eruption of Mt. Merapi. The lahar flow are more common in the rivers that flow to southwest of Mt. Merapi such as Pabelan River, Putih River in the Central Java Province compared to rivers in the

southward likes Code river at the Yogyakarta Province, as well as the river that flows southeastward such as Gendol river at the Central Java province as shown in Fig.3.

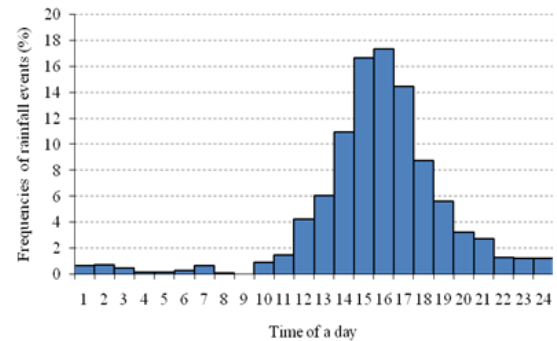


Fig.2 Frequencies of heavy rainfall events

Table 3 Number of heavy rainfall in 2003 at each station

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Argomulyo	12	14	9	0	0	0	0	0	0	6	17	9	67
Babadan	9	12	16	7	2	0	0	0	1	2	12	14	75
Batur	15	13	15	5	3	3	0	1	3	8	8	10	84
Deles	15	9	7	4	2	0	0	0	0	3	8	6	54
Girikerto	26	23	16	20	11	8	0	2	0	12	19	23	160
Mt. Maron	24	18	19	13	1	3	0	1	2	6	23	8	118
Ngandong	23	28	20	7	6	3	4	0	2	15	25	17	150
Ngepos	24	9	15	10	3	0	3	2	2	24	23	22	137
Pakem	7	11	1	3	1	0	0	0	0	6	5	9	43
Plosokerep	6	11	4	3	3	1	0	0	1	0	2	4	35
Pucanganom	11	4	2	0	8	0	1	0	1	2	5	11	45
Randugunting	11	9	2	4	0	0	0	0	0	1	2	10	39
Sorasan	8	4	2	2	1	0	0	0	0	1	3	6	27
Sukorini	4	4	1	2	0	0	0	0	0	0	2	1	14



Fig.3 Potential lahar flows from Mt. Merapi

3.3 Temporal and Spatial of Heavy Rainfall Events

Fig. 4(a) shows an example of rainfall variability on November 30, 2004, in the study area. It appears that the variability of rainfall in the study area is very high, although their coverage area is not too large. Heavy rainfall mostly occurred in the west and southwest of Mt. Merapi compared to the south and southeast area as shown in Figure 4(b). In addition, circular data analysis using WR PLOT [20] showed that the characteristics of heavy rainfall both rainfall depth and duration between south-west and south area is quite different as depicted in Figure 5. This figure shows that the heavy rainfall >50mm occurs more frequently at

Mt. Maron station (southwest area) rather than at Deles station (southeast area). At Mt. Maron station, most heavy rainfall occurred for 3 hours only, whereas at Deles station, the heavy rainfall occurred for more than 6 hours. This phenomenon may occur due to the rainfall type is influenced by west monsoon and orographic effect. These conditions correspond to debris flood events that occurred during 2010-2011 following Mt. Merapi eruption where debris/lahar flow occurred in a river that flows to the southwest-west direction of Mt. Merapi. It means that flood warning system based on rainfall occurrence should be installed in the area which has heavy rainfall potential both depth and frequency.

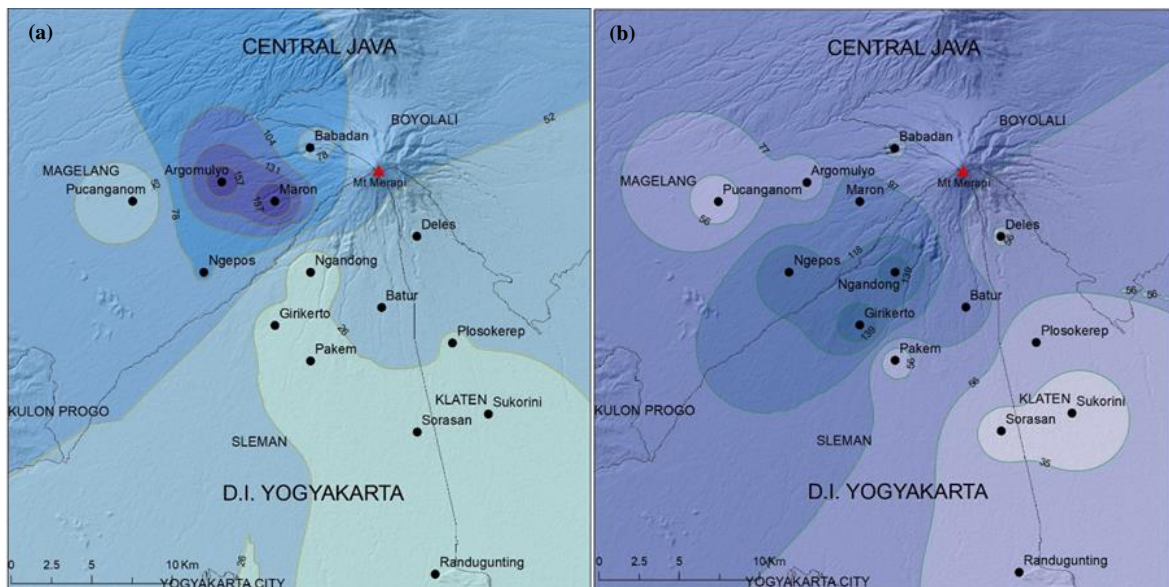


Figure 4. (a) Rainfall variability on November 30, 2004. (b) number of heavy rainfall events in the study area

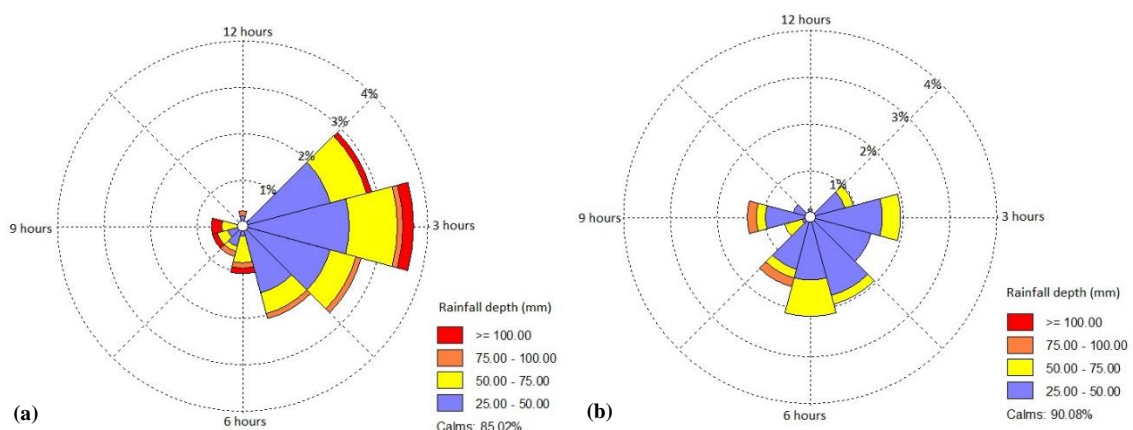


Figure 5. Rainfall depth and duration characteristics at (a) Mt. Maron station and (b) Deles station

3.4 Heavy rainfall Frequency Analysis Using L-Moments

Based on the L-moments method of Eq. (1) through Eq. (3), L-moments and L-moment ratios of annual maximum rainfall data such as L-coefficient of variation (τ_2), L-skewness (τ_3), L-kurtosis (τ_4) are presented in Table 4 and Table 5. Table 5 shows that the values of L-moment ratios lie between -1 and +1, L-coefficient of variation satisfies $0 < \tau_2 < 1$, and the L-kurtosis fulfills $-1 < \tau_4 < 1$ [19].

L-moment diagrams comparing L-moment ratio of the data and theoretical relationships between L-skewness and L-kurtosis used to select the most appropriate distribution is depicted in Fig. 6. The figure shows that LN3 distribution provides the best approximation to regional weighted average L-moments ratios in the study area [15], [18] followed by GEV. Other three parameter distributions such as GPA and GLO and two-parameter distributions including Normal, Gumbel and Exponential perform poorly.

Given the most appropriate distribution for the region, the index-rainfall method is then applied for estimating design rainfall depth for any return period or average recurrence interval. Analogous to the index-flood method, the index-rainfall method is used for regional frequency analysis by using the following expression [17]-[19], [21]:

$$Q_i(F) = \bar{P} q(F) \quad (4)$$

where $Q_i(F)$ is the quantile estimate with non-exceedance probability F at site i , \bar{P}_i is the at-site sample mean for site i called index rainfall and $q(F)$ is the normalized regional LN3 distribution called regional growth curve.

The regional LN3 parameters i.e. shape (k), scale (α), and location (ξ) can be estimated using [19], [21]:

$$\begin{aligned} k &\approx -\tau_3 \frac{E_0 + E_1\tau_3^2 + E_2\tau_3^4 + E_3\tau_3^6}{1 + F_1\tau_3^2 + F_2\tau_3^4 + F_3\tau_3^6} \\ \alpha &= \frac{\lambda_2 k e^{-k^2/2}}{1 - 2\Phi(-k/\sqrt{2})} \\ \xi &= \lambda_1 - \frac{\alpha}{k} (1 - e^{k^2/2}) \end{aligned} \quad (5)$$

The E_i and F_i coefficients can be found in [19]. By using Eq. (5), regional LN3 parameters could be computed as follows: $\xi = 0.9431$, $\alpha = 0.2699$, and $k = -0.4046$.

Table 4 L-moments of annual maximum rainfall

Station	L-moments			
	λ_1	λ_2	λ_3	λ_4
Argomulyo	96.58	20.21	3.28	2.20
Babadan	108.09	24.95	8.44	7.53
Batur	96.36	23.11	6.75	2.46
Deles	78.65	11.43	-0.80	3.14
Girikerto	110.65	15.67	3.28	3.57
Maron	142.57	33.91	4.78	2.02
Ngandong	123.44	22.11	-2.13	1.16
Ngepos	119.10	22.55	3.86	2.20
Pakem	84.24	18.18	6.84	4.09
Plosokerep	86.66	18.14	4.35	0.54
Pucanganom	84.28	17.99	3.85	2.68
Randugunting	76.45	13.60	4.74	3.07
Sorasan	80.39	16.94	8.77	5.95
Sukorini	74.39	9.30	1.19	-0.60

Table 5 L-moment ratios of annual maximum rainfall

Station	L-moments ratios		
	τ_2	τ_3	τ_4
Argomulyo	0.21	0.16	0.11
Babadan	0.23	0.34	0.30
Batur	0.24	0.29	0.11
Deles	0.15	-0.07	0.27
Girikerto	0.14	0.21	0.23
Maron	0.24	0.14	0.06
Ngandong	0.18	-0.10	0.05
Ngepos	0.19	0.17	0.10
Pakem	0.22	0.38	0.22
Plosokerep	0.21	0.24	0.03
Pucanganom	0.21	0.21	0.15
Randugunting	0.18	0.35	0.23
Sorasan	0.21	0.52	0.35
Sukorini	0.12	0.13	-0.06
Regional weighted average	0.20	0.22	0.16

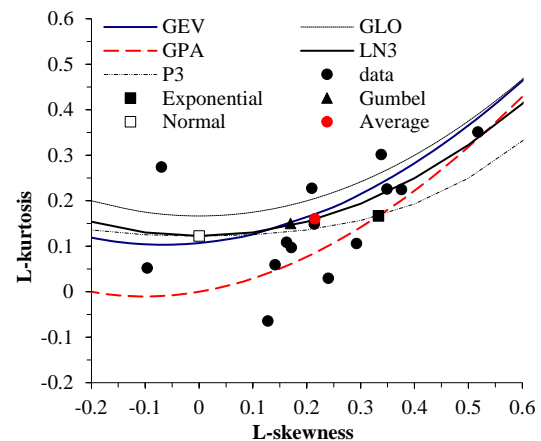


Fig.6 L-moment ratios diagram for annual maximum rainfall

Based on the regional parameter values, the normalized regional LN3 distribution may be obtained from [17], [19]:

$$q(F) = \xi + \alpha k^{-1} \left(1 - e^{-k \Phi^{-1}(F)} \right) \quad \text{if } k \neq 0$$

$$= \xi + \alpha \Phi^{-1}(F) \quad \text{if } k = 0 \quad (6)$$

where Φ^{-1} denotes the inverse of the standard normal distribution function. Substituting the regional LN3 parameters i.e. ξ , α and k into Eq. (6) gives:

$$q(F) = 0.9431 - 0.6671 \left(1 - e^{-0.4046 \Phi^{-1}(F)} \right) \quad (7)$$

3.5 Design Rainfall Depth for Ungauged Sites

Design rainfall depth for any return period at gauged sites can be estimated by using an index rainfall method. However, for ungauged sites where there is no data, the at-site mean maximum rainfall, \bar{P} is unknown. Regional regression method is then used to estimate this value [21]. Analysis of \bar{P} at the study area shown that there is a strong relationship between \bar{P} and mean annual rainfall ($R^2=0.73$) as depicted in Fig. 7. An additional parameter of station elevation does not improve accuracy ($R^2 = 0.71$), because heavy rainfall is mainly caused by the west monsoon and orographic effects.

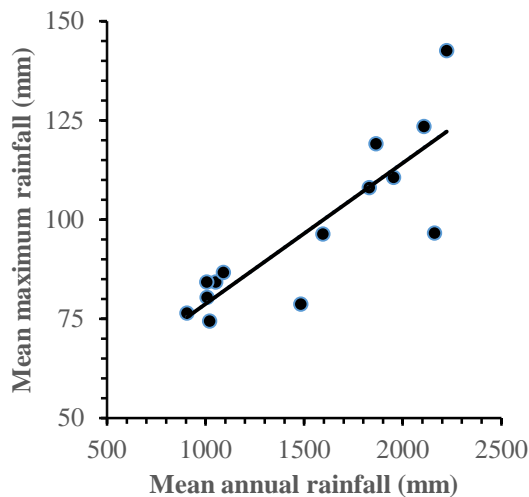


Fig. 7 Relationship between mean maximum rainfall and mean annual rainfall

The following equation can be used to estimate \bar{P} at ungauged-site:

$$\bar{P} = 0.0355 MAP + 43.212$$

where \bar{P} is the mean annual maximum rainfall (mm) and MAP is the mean annual rainfall (mm). Design rainfall at any ungauged-site thus can be estimated using the estimated \bar{P} and the regional growth curve of Eq. (7).

4. CONCLUSION

Characteristics of heavy rainfall in the area of Mt. Merapi study showed that both the frequency of heavy rainfall events and the rainfall intensity in the south-west of Mt. Merapi more dominant than in other areas. These heavy rainfall characteristics indicate that orographic effects and west monsoon are important in determining the spatial distribution of heavy rainfall occurrences in Mt. Merapi area. Beside, heavy rainfall more frequent occurred from noon until late afternoon. The annual maximum rainfall data in south-west part of Mt. Merapi was best fitted with the LN3 distribution. For applying index-rainfall method at ungauged sites, mean maximum rainfall at any site, \bar{P} could be estimated based on mean annual rainfall only. These results need to be followed by debris/lahar flood disaster mitigation. Lahar flow or flood warning systems need to be developed based on the spatial and temporal occurrence of heavy rainfall.

5. ACKNOWLEDGEMENTS

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