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The Estimation of Probable Maximum Precipitation (PMP) for 24 Hours Duration in the Upper Brantas River Basin, East Java

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Abstract: The probable maximum precipitation (PMP) is defined as the highest precipitation (measured by a rain gauge) for a given period that is meteorologically reliably recorded in the rainfall station. Estimation of the PMP is very important, especially for the safety design of dams and reservoirs, because precipitation data are available for a much longer period of time than those for river floods. Analysis of the daily rainfall, which was used to estimate the PMP values of the upstream Brantas River showed high consistency, so that the collected rainfall data were reliable. These facts were shown by a straight line produced by each rainfall station based on the double mass curve test. The PMP estimation for upstream Brantas River varied between 419 and 556 mm/day. The estimated PMP values were highest at the Birowo station and lowest at the Tangkil station. They were then not correlated to the maximum daily rainfall observed at a rainfall station. This means that there are other factors as described by the Hershfield equation that resulted in higher estimated PMP values. Therefore, the safety design of dam and reservoir construction in this area has to consider the estimated maximum PMP reaching 556 mm/day.

Key words: Hershfield equation, maximum rainfall, probable maximum flood, probable maximum precipitation, upper river, safety, dam design.

Introduction

Currently some regions in Indonesia are in a critical situation in terms of the availability of water resources, especially in areas that are densely populated as urban areas and those developed as industrial zones. In Java Island, the existing surface water availability is not sufficient compared with water demand. The water balance calculation found that in 1995 there was a water deficit of 32,357.8 million m^3/year, and in 2000 water deficit reached 52,809 million m^3/year. Moreover, for 2015 the water deficit was projected to increase to 134,102.8 million m^3/year (State Ministry of Environment, 1997; Nugroho, 2003). Therefore, the water resources in Indonesia are recently managed integratedly following an integrated water resources management (Helmi, 2002; Pasandaran, 2002). Integrated water resources management is a process that emphasizes the development and management of water resources, land and related resources in a coordinated manner to maximize the resultant of economic and social welfare in parallel with the ecosystem sustainability (GWP-TAC, 2000).

The one effort to increase the availability of surface water is the development of dams, reservoirs, weirs and other water infrastructures. Dam and reservoir construction requires strict technical regulations for the safety building construction. If not so, the dam can collapse by such an extreme flood or flash flood, endangering the river downstream properties such as

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infrastructures and human settlement. Usually, response times of flood warning due to dam collapse upstream is much shorter as compared to flood occurrence downstream. Dam collapse is generally caused by water overtopping due to insufficient capacity of the spillway during a major inflow into the reservoir from high rainfall intensity (Chan et al., 1996). In determining the safety flood design and spillway capacity, the dams and spill way constructions must consider the flood capacity by calculating the Probable Maximum Flood (PMF). Generally the approach of PMF calculation apply the concept of Probable Maximum Precipitation by assuming that the PMF is initially generated by the occurrence of PMP. This approach is used due to the difficulty of obtaining long-term flood event data to estimate the PMF. Where the long-term rainfall data are available, these could be used to calculate PMP (Hershfield, 1986; Desa et al., 2001). Therefore the requirements of safety flood design in building dams, spillway and reservoir should apply the PMP approach to minimize the risk of overtopping dam collapse.

PMP is a method to estimate the maximum rainfall events that occur in a river basin at a given time (Miller, 1973; WMO, 1986; Winarso, 1999). Therefore the PMP is a high requirement needed for safety design of dam, reservoir and other water infrastructures. Probable Maximum Precipitation analysis for a river basin can be estimated by two methods: (1) by the statistical method of frequency analysis and (2) physical methods that are based on the recorded transposition and the maximum of the rain storms (Desa et al., 2001). In the latter, to estimate PMP, the model inputs are humidity and winds at different altitudes in the atmosphere. Unfortunately, the lack of these data leads to a model which cannot be applied and, thus the statistical method is more often applied in the world.

In this study we used daily rainfall data of the upper Brantas River Basin to estimate the PMP. The PMP estimation in the upper Brantas river basin is very important because in this area many reservoirs, dams and weirs have been constructed to increase the amount of surface water availability; even in the future there will be some large-scale development plans of water reservoirs. The existing major water infrastructures in the Brantas River Basin are shown in Table 1.

Table 1: Dams/reservoirs capacity in the Brantas River basin

No	*Dams/ reservoirs*	*Year constructed*	*Purpose*	*Capacity (mcm)*	
				Initial	*2003*
1	Selorejo	1970	Wd, H	50.1	42.7
2	Sutami	1972	Wd, I, Wi, H, F, R	253.0	176.3
3	Lahor	1977	Wd, I, Wi, F	29.4	32.6
4	Bening	1982	I, H, F, R	32.9	24.2
5	Wonorejo	2001	Wd, H, F	121.5	121.5
6	Sengguruh	1988	Sc, H	21.5	3.5
7	Ledoyo	1980	H	5.8	2.0
8	Wlingi	1977	Sc, H	24.0	4.0

Source: Ramu (2004). Note: I = Irrigation, H = Hydropower, F = Flood control, Wd = Water supply for domestic, Wi = Water supply for industry, R = Recreation, Sc = Sediment control; (mcm) = million cubic metres.

Methods

This study used maximum daily rainfall data from eight rainfall stations for a period of 48 years (1955-2002) which are located in the upper Brantas River Basin. The data were collected from the water authority called Perum Jasa Tirta (Jasa Tirta Interprise) located in the city of Malang. The Brantas River System is shown in Figure 1, and the annual maximum rainfall data at each station are presented in Table 1. The quality of calculated PMP depends on the quality and reliability of rainfall data series. As some rainfall data in Indonesia are less reliable, the quality of available data was checked by a screening, either manually or statistically. Screening process based on available daily data were done statistically. After completing the screening process, the rainfall data were used to calculate the PMP. In doing screening process, firstly the rainfall data have to be tested for its consistency. The method used is the double mass curve analysis that is done by comparing the mean cumulative rainfall from the particular rainfall station (as the y-axis) with a cumulative mean of surrounding rainfall stations (as the x-axis) (Sosrodarsono and Takeda, 1987; Asdak, 1995; Harto, 1995). The data consistency can be identified based on the line of the double mass curve in the rainfall stations. If the comparison produces a straight line, data are supposed to be reliable. Conversely, if the line is not straight, it indicates that rainfall data from that particular rainfall station are distorted.

In order to estimate the PMP values we applied the method of Hershfield (1961, 1965) and Chow et al. (1988) to each rainfall station. The equation used is:

$$X_{PMP} = \bar{X}_n + K_m \sigma_n$$

where X_{PMP} is PMP value, $\bar{X}_n$ = mean of n annual maximum, σ_n = standard deviation of annual maximum rainfall data series and K_m is frequency factor (a function of the recurrence interval for a particular probability distribution).

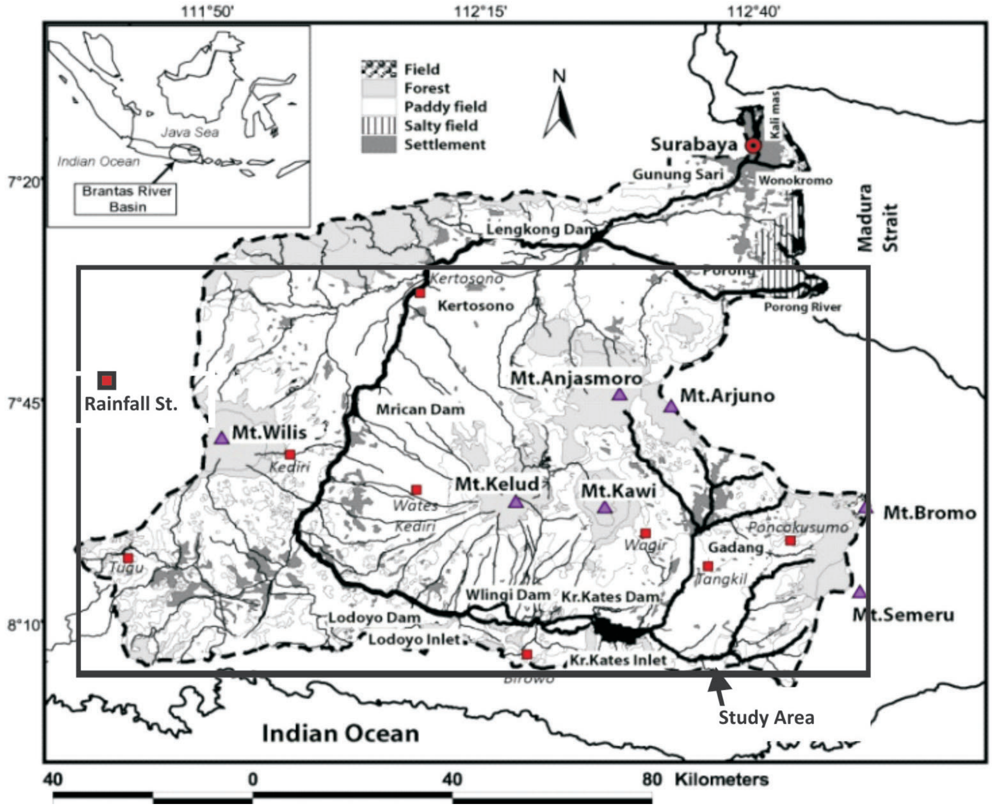

Figure 1: Brantas River Basin: inside the box is the study area.

For estimating the PMP, the Frequency factor (K_m) is calculated by using formula:

$$K_m = \frac{(X_1 - \bar{X}_{n-1})}{\sigma_{n-1}}$$

where X_1 is annual maximum rainfall, $\bar{X}_{n-1}$ = mean annual maximum rainfall, excluding the highest values from the data series and σ_{n-1} is standard deviation of annual maximum rainfall, excluding the maximum values from the data series.

Results and Discussion

The total daily rainfall data used for the analysis of Probable Maximum Precipitation in the upper Brantas River Basin comprised 140,264 daily rainfall data, where each station has 17,533 rainfall data from January 1, 1955 to December 31, 2002. Those rainfall data revealed that the maximum rainfall was recorded in Kertosono Station (433 mm on 1 January 1986). The maximum daily rainfall data and the date of occurrence are presented in Table 2. While the maximum yearly rainfall data that occurred every year at each station are presented in Table 3. The use of long-term rainfall data series for the estimation of PMP is valid when the long-term rainfall data indicates normal rainfall pattern (Desa et al., 2001). To determine the homogeneity of rainfall data, a consistency test was done by using a double mass curve analysis. The analysis revealed that the rainfall data at the eight rainfall stations have a fairly high consistency and were reliable. It was shown a straight line for each station. The straight line indicates that rainfall data from stations are not distorted. The result of the consistency test is presented in Figure 2. Thus the existing rainfall data can be used for estimating the PMP.

Table 2: Daily maximum rainfall (mm/day) and the date of occurrence

No	*Station*	*Daily maximum rainfall*	*Date of occurence*
1	Tugu	285	04-02-1983
2	Kertosono	433	01-01-1986
3	Kediri	240	15-02-1962
4	Wates Kediri	215	01-04-1994
5	Birowo	256	12-11-1955
6	Wagir	216	04-03-1990
7	Poncokusumo	217	16-01-1994
8	Tangkil	141	12-05-1978

Source: Perum Jasa Tirta (PJT) 1, Malang, 2003.

Table 3: Yearly maximum rainfall (mm/day) of eight rainfall stations in the upper Brantas River between 1955 and 2002

Year	*Tangkil*	*Poncokusumo*	*Wagir*	*Station Birowo*	*WatesKediri*	*Kediri*	*Kertosono*	*Tugu*
1955	125	89	81	256	88	141	85	84
1956	98	118	102	81	113	81	120	81
1957	128	116	90	97	105	94	79	94
1958	98	100	109	69	92	96	80	84
1959	91	60	76	91	135	90	144	117
1960	109	107	70	95	128	141	106	113
1961	121	86	100	110	115	129	89	116
1962	137	127	115	95	127	240	95	87
1963	91	89	104	85	58	153	87	74
1964	115	90	80	90	75	115	120	81
1965	105	74	116	84	71	75	73	83
1966	87	73	82	125	65	90	105	87
1967	100	136	85	75	85	101	87	49
1968	91	64	75	83	98	129	90	89
1969	73	141	59	41	53	0	227	93
1970	95	89	100	70	87	123	133	79
1971	78	122	95	75	108	90	97	45
1972	87	70	82	90	93	78	93	62
1973	78	90	143	75	91	67	136	89
1974	61	66	107	160	76	0	89	84
1975	114	106	118	85	89	138	145	144
1976	73	88	95	81	105	102	102	83
1977	74	66	92	99	34	92	89	66
1978	141	74	77	85	88	108	105	140
1979	108	112	69	132	91	139	157	65
1980	64	73	78	95	99	108	83	61
1981	83	91	135	98	80	155	92	200
1982	62	47	176	68	82	99	78	95
1983	80	78	110	116	125	91	100	285
1984	92	72	97	108	113	90	170	46
1985	59	42	45	85	64	151	80	84
1986	72	52	44	52	42	163	433	70
1987	86	119	121	91	58	90	70	64
1988	111	104	121	98	51	105	82	71
1989	64	88	53	34	82	109	108	122
1990	76	37	216	31	90	105	89	53
1991	90	110	108	90	141	79	78	88
1992	125	95	216	99	178	141	95	152
1993	63	128	134	116	110	94	82	179
1994	112	217	86	71	215	89	62	70
1995	101	198	137	47	104	88	105	70
1996	104	184	116	79	177	112	98	88
1997	114	75	100	80	92	78	186	58
1998	95	103	113	244	146	104	120	90
1999	91	91	76	185	87	147	71	57
2000	105	84	101	129	115	93	97	113
2001	114	66	208	102	166	121	113	107
2002	95	86	119	183	96	96	79	118

Source: Perum Jasa Tirta (PJT) 1, Malang, 2003.

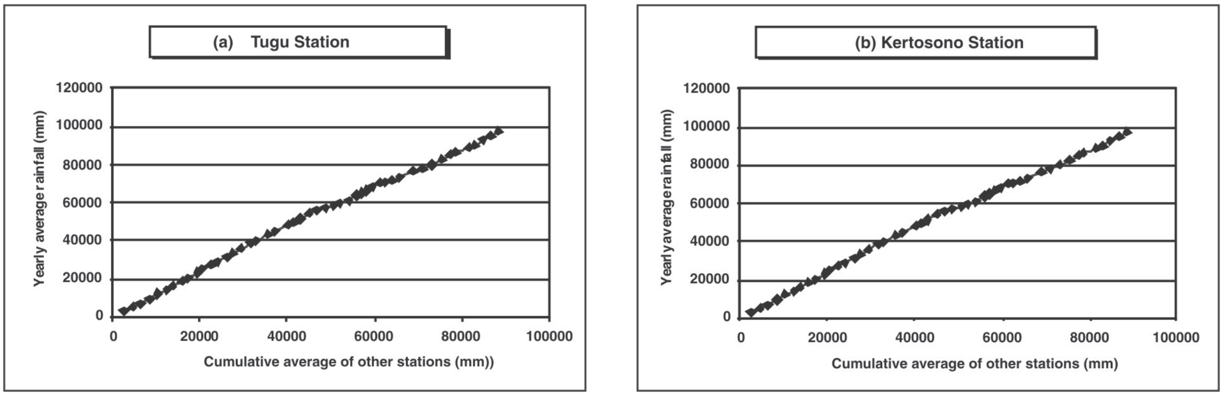

Figure 2: Result of consistency test of rainfall data for two rainfall stations—(a) Tugu station and (b) Kertosono station—by using double mass curve analysis. Other six rainfall stations at Kediri, Wates, Birowo, Wagir, Poncokusumo and Tangkil showed a similar pattern.

The PMP for the eight stations was calculated following the Hershfield equation (Table 4). The calculation of the frequency factor (K_m) showed that the distribution was dominated by K_m 10-12, and only one rainfall station with K_m 15 was Tangkil station. Frequency distribution plot of the K_m and the mean of daily maximum rainfall is presented in Figure 3. The calculated PMP for upper Brantas River ranges from 419 to 556 mm/day. The highest PMP values occurred in Birowo station and the lowest PMP values in Tangkil station (Table 4). These results reveal that the magnitude of PMP did not correlate with highest daily rainfall at the respective rainfall station. This means that there were other factors as those described by the Hersfield equation which cause the higher PMP values. In case of Kertosono station, daily rainfall maximum reached 433 mm/day which was the highest compared with other stations; however the estimated PMP value was 419 mm/day, that means low PMP values. This is due to frequency factor (K_m) 7 which was the lowest frequency factor, whereas other stations showed K_m > 10. The frequency factor of 11.1 then could be applicable to estimate the PMP values in this region. These values were higher compared with those of other studies which used a frequency factor of 8.7 as discussed by Desa et al. (2001).

The highest calculated PMP reached 556 mm/day, so that the design of (existing as well as future) dams and reservoirs in the upper Brantas River Basin should be at least equal to or >556 mm/day. The result of this PMP estimation indicated that rainfall at six stations (Tugu, Kediri, Wates Kediri, Birowo, Wagir and Poncokusumo) was in the same range as found in other studies on Java. Two rainfall stations (Kertosono and Tangkil), however, displayed lower values than other studies in Java which reported on 24h PMP between 500 mm and 1400 mm (Puslitbang Air, 1997), and 500 mm to 700 mm in the East Java region (Pawitan, 1999). Another study by Colonco gave a generalized 24h PMP estimate at 800

Table 4: Result of PMP parameters calculation of each rainfall station

No	*Station*	*Daily maximum rainfall (X_1) (mm)*	$\bar{X}_n$	σ_n	K_m	*CV*	*PMP 24 hours (mm)*	*PMP 24 hours/X_1*
1	Tugu	285	92,49	42,00	9,8	0,45	504	1,77
2	Kertosono	433	106,08	44,74	7,0	0,42	419	0,97
3	Kediri	240	105,60	38,10	10,6	0,36	509	2,12
4	Wates Kediri	215	99,65	37,44	11,1	0,38	515	2,40
5	Birowo	256	97,56	44,95	10,2	0,46	556	2,17
6	Wagir	216	104,83	38,41	11,1	0,37	531	2,46
7	Poncokusumo	217	94,63	37,43	11,0	0,40	506	2,33
8	Tangkil	141	95,92	22,66	15,0	0,24	436	3,09

Note: CV = coefficient of variance = $\left(\dfrac{\sigma_n}{\bar{X}_n}\right)$

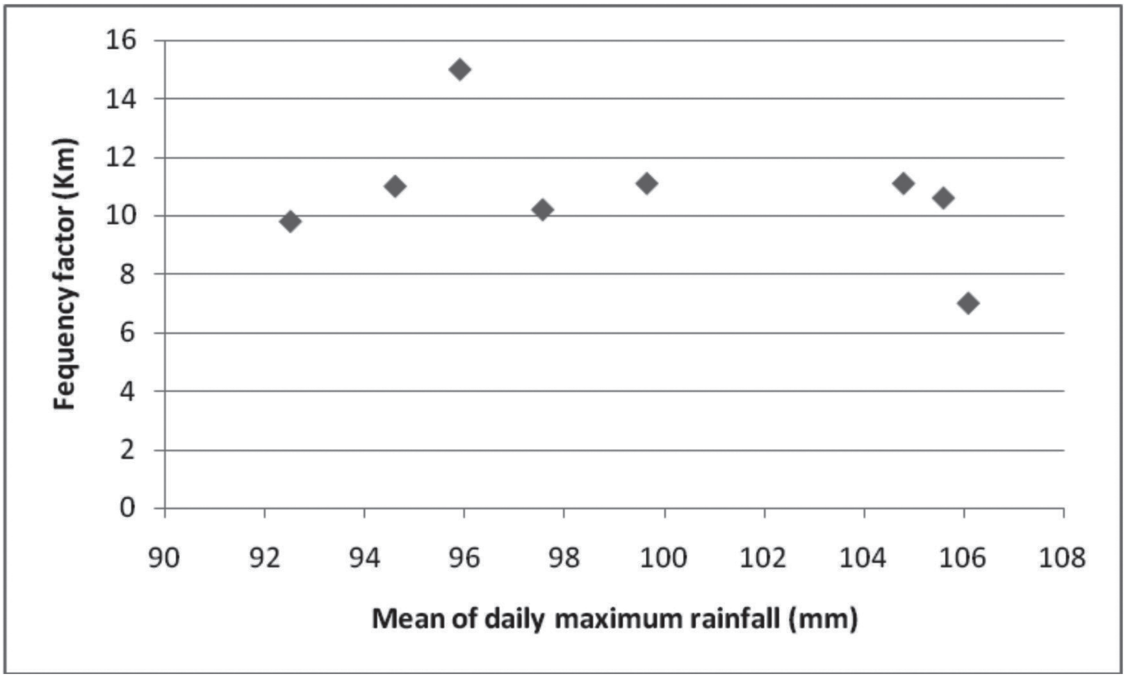

Figure 3: Frequency factor (K_m) and mean of daily maximum rainfall (mm).

mm (Supriyanto, 1999). The discrepancies between individual studies were caused by the use of different precipitation data series, especially the use of rainfall data with varying time cover. The study by Kaul (1976, in Supriyanto, 2001) reported 134 events of high daily rainfall >400 mm, 28 events >500 mm, and nine events >600 mm for Java. The highest rainfall record was 671 mm, so he concluded that the daily rainfall over 650 mm can occur in many rainfall stations on Java. That is why his PMP study resulted higher than this study. Therefore the evaluation of extremely high rainfall data are needed for PMP estimation. This study derived daily rainfall data from some stations which were measured manually and automatically for the years 1955 to 1990, while the year 1991 and 2002 measurements data were performed by telemetry system, which was more accurate and delivers highly consistent rainfall data.

Commonly, there are two types of rain gauge stations in Indonesia: observatory rain gauge type recording daily rain, and the Hilman type of rain gauge that records daily or a weekly rain depending on the recording resolution. The observatory rain gauge type has funnel rain gauge area of 100 cm^2. While the Hilman type of rain gauge has funnel rain gauge area of 200 cm^2 and the collected rainwater will be passed to a floating syphon system; then each time the syphon tube drains the collected water into the rain gauge tank. For both types tank capacity is 5 litres, which means it is only able to record a maximum amount of rainfall of 500 mm. Therefore the accuracy of any daily rainfall data over 500 mm/day should be reevaluated before using the data.

Thus, the use of daily rainfall data to estimate PMP values is crucial. The inaccurate rainfall data used to estimate PMP lead to misguiding PMP values, affecting the safety level of the dam/reservoir construction design. There are two active volcanos (Mt. Kelud and Mt. Semeru) that erupted large quantities of light and highly mobile volcanic ash which ran down to the river system as the major problem in this region (Toshikatsu and Musiake, 2003). This uncertain volume of the volcanic material from the eruption that goes to the river system may be one of the problems to have an appropriate design of some dams and reservoirs.

Summary and Conclusions

Homogeneity and consistency of rainfall data were tested by using a double mass curve analysis. The tests showed that the daily rainfall data recorded at eight rainfall stations in the upper Brantas River Basin were highly consistent and reliable. By using the Hershfield equation, the estimated Probable Maximum Precipitation (PMP) for upper Brantas River Basin ranged from 419 to 556 mm/day. The PMP was highest at the Birowo station and lowest at the Tangkil station. The result of these calculations indicated that the estimated PMP values did not show a positive correlation with the maximum daily rainfall in recorded rain gauge. It means that there were other factors than those described by the Hersfield equation which caused the deviation between estimated PMP and maximum rainfall. The highest estimated PMP reached 556 mm/day, which needs to be taken into account for the design of dam and reservoir construction in the upper Brantas river.

A comparison of the estimated PMP with other studies for East Java found that the results of the six rainfall stations of this study (Tugu, Kediri, Wates Kediri, Birowo, Wagir and Poncokusumo) were fairly consistent with previous results in the range between 500-600 mm; however two rain stations (Kertosono and Tangkil) were characterized by lower PMP values. The discrepancy between PMP studies was caused by differences in the availability of quality and quantity data. The quality of data was better when an automatic recorder was used and the use of longer time series rainfall data produced a better PMP estimate.

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