Debris Flow Sediment Discharge at the Volcanic Area of Mt. Merapi in Indonesia

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ABSTRACT: Of sediment related disasters, it is well known that debris flow has destructive energy and causes heavy casualties and asset losses. To prevent or mitigate debris flow disasters, it is necessary to take rational and effective measures for dealing with debris flows. For that purpose, it is important to accurately estimate sediment discharge by debris flows. According to Sabo Division (1988), possible sediment discharge to be transported by a debris flow is applied to sediment discharge for the plan, in case that a great volume of unstable sediment is deposited in the upper basin. The possible sediment discharge is calculated multiplying volumetric sediment concentration of a debris flow by total water volume that is calculated multiplying rainfall and basin area. When doing so, debris flow runoff correction rate is taken into account. The correction rate changes according to the scale of river basin. But it is supposed that the correction rate could change according also to the natural basin characteristics. In this paper, the debris flow runoff correction rate in an active volcanic area was estimated based on measured sediment discharge by debris/flood flow, and it is shown that the correction rate becomes more than two (2) times of that in normal areas. In addition, the paper shows that during one (1) to two (2) years just after a large-scale pyroclastic flow, sediment discharge becomes huge and the correction rate becomes more than five (5) times.

1 INTRODUCTION

Mt. Merapi is one of the most active volcanoes in the word. Frequent eruptions have induced pyroclastic flows due to collapse of a lava dome or a lava tip. They have been resulting in disasters in the downstream areas, and have been accumulating tremendous amount of volcanic loose deposit on the slope of Mt. Merapi. Once an intensive rainfall happens, the loose deposit flows downstream as a debris flow endangering the people's lives and assets in the downstream areas. The foothills of Mt. Merapi, such as Yogyakarta City, Sleman and Magelang, have been suffering from those volcanic disasters, and many sabo facilities and hydrological monitoring equipment have been installed.

Possible sediment discharge by a debris flow, which is defined as sediment discharge that river water originated by rainfall can transport with its energy, is calculated by using the following equations compiled by Sabo Division (1988):

$$V_{ec} = \frac{10^3 \cdot R_t \cdot A}{1-\lambda} \cdot \left[\frac{C_d}{1-C_d}\right] \cdot f_r \qquad (1)$$

$$f_r = 0.05 \cdot (\log A - 2.0)^2 + 0.05 \qquad (0.1 \le f_r \le 0.5) \qquad (2)$$

$$C_d = \frac{\rho \cdot \tan\theta}{(\sigma - \rho)\cdot(\tan\phi - \tan\theta)} \qquad (C_d = 0.9 \cdot C_* when\ \theta \le 20^\circ or C_d \ge 0.9 \cdot C_*\ ,\ C_d = 0.3 when C_d \le 0.3) \qquad (3)$$

Where, V_{ec}: Possible sediment discharge by debris flow (m^3), R_t: Daily rainfall (mm/day), A: Basin area (km^2), λ: Air porosity, C_d: Volumetric concentration of debris flow during flowing, f_r: Runoff correction rate, ρ: Water density (gr/cm^3), σ: Stone density (gr/cm^3), ϕ: Internal friction angle (degree), θ: Riverbed slope (degree)

The empirical formula of debris flow runoff correction rate f_r in Eq. (2) was developed based on observed debris flow discharges in various areas, but sediment discharges in volcanic areas, especially in active volcanic areas, are considered to be larger than that in ordinary mountainous areas. As is well known that Mt. Merapi is one of the most active volcanoes, debris flow runoff correction rate in the Mt. Merapi area was studied based on the observed debris flow sediment data in Bebeng River and Putih River.

2 DEBRIS FLOW SEDIMENT DISCHARGE IN THE VOLCANIC AREAS

2.1 Observed Sediment Discharges Estimated from Observed Water Level

Sutikno Hardjosuwaro and others (1998) compiled the water levels and discharges of 105 times debris/flood flows recorded from April 1988 to December 1996 by the ultra-sonic water level recorder at the sabo (sediment control) dam of BE-D1 in Bebeng River. The catchment area at the sabo dam is 7.74 km^2 and the river slope is 3.2 degrees (1/18). Refer to Figure 1. The basin condition from 1988 to 1996 in Bebeng River could be compared with active condition for sediment discharge in Mt. Merapi, according to the record of the volcanic activities and debris flows.

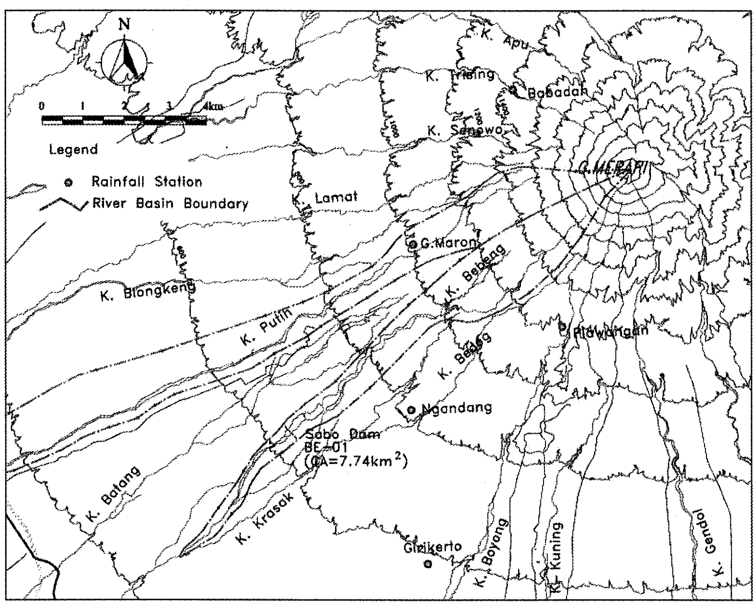


Figure 1. Location of Rainfall Stations and River Basins of Bebeng and Putih

Jitousono and others (1996) reported that sediment discharge is related to total discharge including sediment and water, and is shown as Eq. (4), based on the data of Saido River (C.A.=1.38 km^2) and Fukatani River (C.A.=0.38 km^2) in Mt. Sakurajima, Mizunashi River (C.A.=15.92 km^2) in Mt. Unzen, and Boyong River (C.A.=3.52 km^2) in Mt. Merapi. Applying this Eq. (4), the sediment discharges in Bebeng River are calculated from total discharges during debris/flood flows.

$$Q_S = 0.0161 \cdot Q_T^{\ 1.34} \qquad C_d = \frac{Q_S}{Q_T} = 0.0161 \cdot Q_T^{\ 0.34} \tag{4}$$

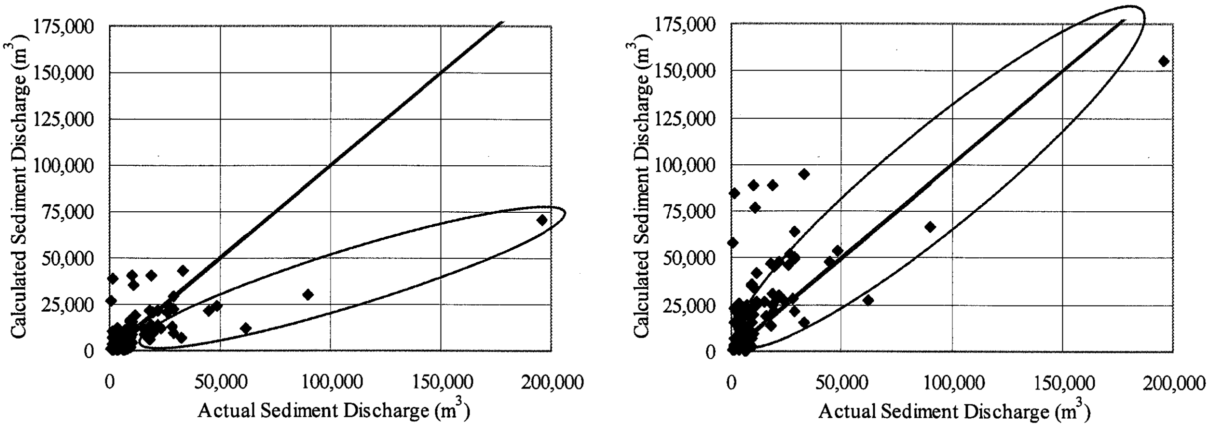
Where, Q_S: Sediment discharge (m^3), Q_T: Total discharge including sediment and water (m^3), C_d: Volumetric concentration of debris flow during flowing

2.2 Sediment Discharges at BE-D1 in Bebeng River Calculated by Eq. (1), (2) and (3)

On the other hand, sediment discharge can be estimated from rainfall, applying Eq. (1), (2) and (3). Rainfalls at the time of debris/flood flows were represented by daily rainfall closest to total runoff height of the observed flow, which is selected from the rainfall stations of Babadan, Plawangang, G. Maron and Ngandong. Because rainfall in the Mt. Merapi area is characterized by local, short and heavy rainfall, and because basin mean rainfall is difficult to be estimated, a station rainfall that would be closest to the runoff height was selected among the said four stations as the basin mean rainfall.

2.3 Comparison between the Observed and the Calculated Sediment Discharges at BE-D1

Comparing the observed and calculated sediment discharges, the calculated are smaller than the observed, especially in the range of large sediment discharges more than 20,000 m^3 as shown in Figure 2(a). And by enlarging debris flow runoff correction rate with 2.2 times, the calculated sediment discharges become as roughly same as the observed ones as shown in Figure 2(b). Thus, it is recognized that the debris flow runoff correction rate in the Mt. Merapi area seems to be larger than that by Eq. (2), especially for the debris flows with large sediment discharge.



(a) Applying Eq. (2) as it is. (f_r)   (b) Enlarging Eq. (2) with 2.2 times ($f_{r1} = 2.2 \cdot f_r$)

Figure 2. Observed and Calculated Sediment Discharges in Bebeng River from 1988 to 1996

3 DEBRIS FLOW SEDIMENT DISCHARGE JUST AFTER LARGE-SCALE PYROCLASTIC FLOWS

3.1 Observed Sediment Discharges in Bebeng and Putih Rivers from January 1969 to October 1970

As is well known, many times of recurring debris flows cause huge amount of sediment discharge after a large-scale volcanic eruption in Mt. Merapi and other volcanoes. JICA (1980) reported that Sediment discharge from January 1969 to October 1970, which is just after the large-scale pyroclastic flows on January 7, 1969, was surveyed in Bebeng River and Putih River, and is presented in Table 2.

3.2 Sediment Discharges in Bebeng and Putih Rivers Calculated by Eq. (1), (2) and (3)

Number of debris flows just after the past large-scale eruptions in 1931, 1969 and 1995 indicates that about 30 times of debris flows happened during a year just after the large-scale eruptions, and 10 times on average (4 to 20 times) happened during the second year. Thus, it can be assumed that the said times of debris flows happened in Bebeng and Putih Rivers just after the eruption in 1969. It is also assumed that the largest 30-days and 10-days rainfalls in the first and second years contribute to cause 30 times and 10 times debris flows in the first and second years respectively.

On the other hand, there are no old rainfall data on the slope of Mt. Merapi, but the rainfall data at Adjistipto Airport are available, where the largest 30-days rainfall in 1969 is 1,218 mm, and the largest 10-days rainfall in 1970 is 630 mm, totally 1,848 mm. Since the accumulative largest-30-days rainfall on average at Adjistipto Airport is 1,320 mm, accumulative daily rainfall to cause debris flows from January 1969 to October 1970 is estimated to be 1.4 times of the accumulative largest-30-days rainfall. Thus, accumulative rainfalls contributed to cause sediment discharges from January 1969 to October 1970 are estimated based on the accumulative largest-30-days rainfalls in Babadan and Girikerto, and are shown in Table 1. Sediment discharges during January 1969 to October 1970 are calculated applying the above rainfalls and basin characteristics to Eq. (1), (2) and (3), and are shown in Table 2.

Table 1. Accumulative Largest-30-days Daily Rainfall in a Year

River Basin	Rainfall Station	Accumulative Largest-30-days Rainfall (Average during 20 years: 1980-1999)	Accumulative rainfalls contributed to cause sediment discharges from January 1969 to October 1970
Putih River Basin	Babadan	1,380 mm (104 – 27 mm/day)	1,932 mm
Bebeng River Basin	Girikerto	1,600 mm (126 – 31 mm/day)	2,240 mm

3.3 Comparison between the Observed and the Calculated Sediment Discharges in Bebeng and Putih Rivers

The observed and calculated sediment discharges are compared at a several points in Bebeng and Putih Rivers as shown in Table 2.

Table 2. Observed and Calculated Sediment Discharges during 1969 to 1970

River	Distance from Crater	Basin Area (km^2)	Sediment Discharge during 1969-1970 ($1000m^3$)					Specific Sediment Discharge during 1969-1970 ($1000m^3/km^2$)		
			Observed	Calculated: Case-1		Calculated: Case-2		Observed	Calculated (CSD)	
			(OSD)	CSD	CSD/OSD	CSD	CSD/OSD	(OSD)	Case-1	Case-2
Putih	6 km	5.40	1,642	1,832	1.12	-	-	304	339	-
	8 km	6.31	2,437	2,003	0.82	-	-	386	317	-
	11 km	8.40	2,177	2,358	1.08	-	-	259	281	-
	15 km	10.17	1,613	2,627	1.63	-	-	159	258	-
Bebeng	6km	4.93	4,154	4,452	1.07	4,452	1.07	843	903	903
	7km	5.89	4,154	2,233	0.54	5,251	1.26	705	379	892
	9km	6.85	7,173	2,434	0.34	6,106	0.85	1,047	355	891
	12 km	7.74	9,311	2,610	0.28	6,785	0.73	1,203	337	877
	16 km	10.23	7,565	3,056	0.40	7,946	1.05	739	299	777

Note: OSD: Observed Sediment Discharge, CSD: Calculated Sediment Discharge, Case-1: $f_{r1} = 2.2 \cdot f_r$, Case-2: $f_{r2} = 2.6 \cdot f_{r1} = 5.72 \cdot f_r$, Air Porosity: λ=0.3, Water Density: ρ =1.2 gr/cm^3, Stone Density: σ=2.7 gr/cm^3, Internal Friction Angle: ϕ =25 degrees, Volumetric Concentration of Sediment: C_*=0.7

<Putih River Basin>

In the Putih River basin, the calculated sediment discharge at 15 km is 63 % larger than the observed, but the other calculated sediment discharges are within an error of less than ± 18 % of the observed ones. Thus, the assumption that debris flow runoff correction rate is 2.2 times of Eq. (2) is judged to be approximately adequate for the Putih River basin.

<Bebeng River Basin>

In the Bebeng River basin, the calculated sediment discharge at 6 km corresponds well to the observed, but the other calculated sediment discharges downstream from 7 km show only 28 to 54 % of the observed ones. The specific sediment discharges of the observed and the calculated give 250,000 – 350,000 m^3/km^2 in Putih River, whereas the calculated ones in Bebeng River give 300,000 – 380,000 m^3/km^2, which is as nearly same as that of Putih River. However, the observed sediment discharges in Bebeng River reach 700,000 – 1,200,000 m^3/km^2. It is considered as follows referring to Figure 3 why the calculated sediment discharges are smaller than the observed in Bebeng River although the calculated ones correspond to the observed in Putih River.

- According to the area of the pyroclastic flow sediment in 1969 eruption, the sediment deposited area in Putih River reached only EL. 950 m (6.5 km away from the summit), whereas that in Bebeng River reached EL. 650 m (10.5 km away from the summit).
- Those river sections between EL. 950 m and EL. 650 m in Bebeng River corresponds to the river course between 6.5 km and 10.5 km away from the summit, and huge amount of sediment was deposited in this river course.
- The large amount of the observed sediment discharge downstream of 7 km in Bebeng River could be

assumed to be the sediment discharge from the pyroclastic deposit in the river course of Bebeng River from 7 km to 10.5 km.
- The calculation could not assume such condition of sediment fulfillment in the river course.

To express such condition in Bebeng River after 1969 eruption, that is to say, to express the condition that large amount of pyroclastic sediment is deposited in a river course, sediment discharge was calculated assuming the debris flow runoff correction rate would be 2.6 times of the Putih River's case and would be less than 0.65. The result is shown also in Table 2. In this case, the calculated sediment discharges are within an error of –27 % to +26 % of the observed ones.

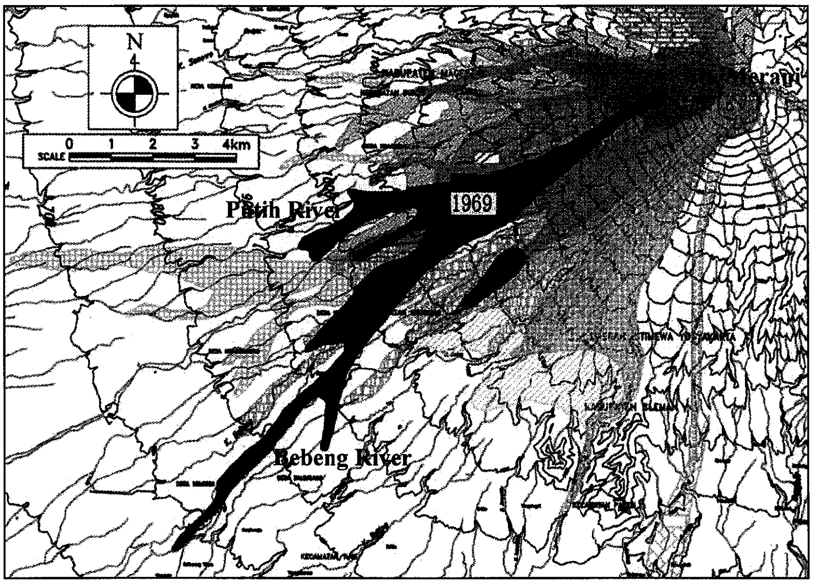


Figure 3. Distribution of Pyroclastic Flow Deposit in Mt. Merapi, especially Highlighted in the 1969 Pyroclastic Flow

4 CONCLUSION AND FURTHER ISSUES

4.1 Conclusion

It is understood that debris flow sediment discharge in the Mt. Merapi area is 2.2 times larger than sediment discharge in ordinary mountainous areas. The specific sediment discharge shows 250,000 to 350,000 m^3/year/km^2 in the Mt. Merapi area. Furthermore, when a large-scale pyroclastic flow happens with huge sediment deposit in a river course, during 1 to 2 years just after the large-scale pyroclastic flow, debris flow sediment discharge becomes 2.6 times larger than that in the normally active condition in Mt. Merapi. In other words, about 5.7 times larger than sediment discharge in ordinary mountainous areas could be expected. The specific sediment discharge gives 700,000 to 1,200,000 m^3/year/km^2 in such condition.

It is recognized that sediment discharge in active volcanic areas like the Mt. Merapi area is much larger than that in ordinary mountainous areas. As an example to estimate sediment discharge in an active volcanic area, debris flow runoff correction rate in Mt. Merapi is shown in Table 3 and Figure 4.

Table 3. Debris Flow Runoff Correction Rate in Mt. Merapi

Basin Condition	Sediment Deposit Condition	Debris Flow Runoff Correction Rate
Ordinary mountain area	-	$f_r = 0.05 \cdot (\log A - 2.0)^2 + 0.05$ $(0.1 \le f_r \le 0.5)$
Active volcanic mountain area	Pyroclastic flow sediment	$f_r = 2.2 \cdot (0.05 \cdot (\log A - 2.0)^2 + 0.05)$ $(0.11 \le f_r \le 0.5)$
	Pyroclastic flow sediment with huge sediment deposit in river course	$f_r = 5.72 \cdot (0.05 \cdot (\log A - 2.0)^2 + 0.05)$ $(0.29 \le f_r \le 0.65)$

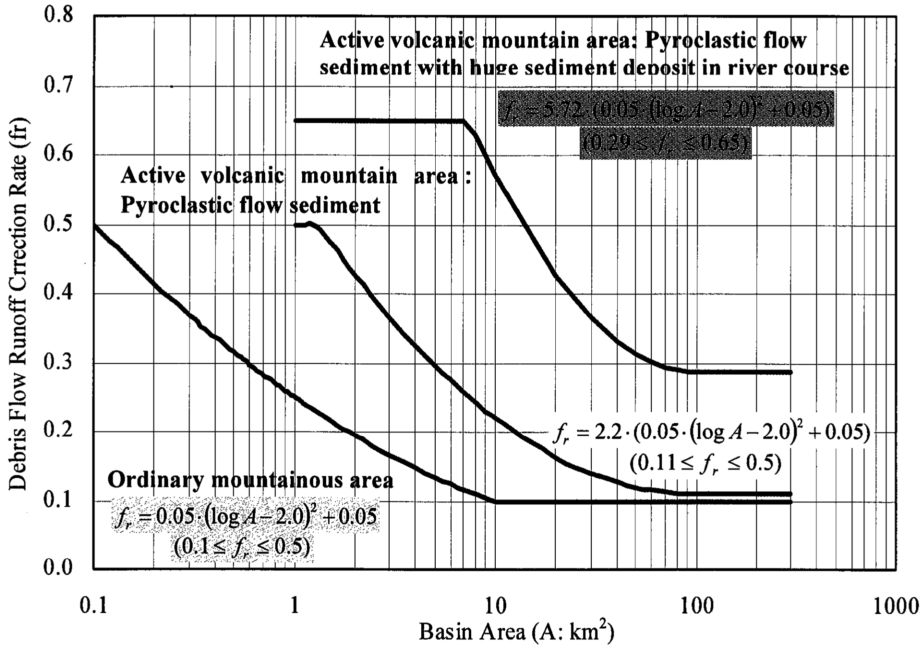


Figure 4. Debris Flow Runoff Correction Rate for Active Volcanic Area

4.2 Further Issues

It is supposed that the debris flow runoff correction rate (f_r) includes some unknown factors, and could be presented as the function of those factors such as basin area (A), rainfall runoff rate (f_e), sediment discharge rate (f_s), and basin characteristics (B_c).

$$f_r = f(A, f_e, f_s, B_c) \tag{5}$$

In this paper, the sediment discharge in the Mt. Merapi area is expressed (estimated) simply introducing enlargement ratio of 2.2 times or 5.7 times of debris flow runoff correction rate. It is one of the considerations in basin characteristics. In addition, the rainfall characteristics in the Mt. Merapi area show the short (a few hours), the heavy and the local (concentrated), and are understood to affect sediment discharge characteristics. Thus, the rainfall characteristics also have to be studied in parallel with the study of debris flow runoff correction rate.

In those ways, to accurately estimate debris flow sediment discharge, the above factors have to be studied respectively based on the mechanism of occurrence and flowing of a debris flow.

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