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Erosion of deposits from the pyroclastic flow that occurred on Mt Merapi, Indonesia in July 1998

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Abstract A pyroclastic flow occurred on the southwest flank of Mt Merapi in Indonesia on 19 July 1998. As a result, a large mass of pyroclastic flow deposits filled the valley of the Sat River. In order to understand the gully erosion processes acting on the deposits, we conducted a cross-section survey and took photographs at fixed points within the site. The data obtained from the cross-section survey were used to calculate the sediment yield from gully erosion. The key findings are: (a) Rainfall occurring after the occurrence of the pyroclastic flow caused gully erosion on the deposits. Networks of gullies developed and their cross-sectional size increased rapidly during the first rainy season. (b) The total sediment yield from the gully erosion was estimated to be 680 000 m^3 for the period extending from the occurrence of the pyroclastic flow until February 2000. Most of the sediment yield associated with the gully erosion occurred during the first half of the rainy season. There was no sediment yield from gully erosion during the dry season. (c) the annual specific sediment yield from the pyroclastic flow deposit during the first year was estimated as 1.4×10^6 m^3 km^{-2} $year^{-1}$. This value is almost equal to that for the pyroclastic flow deposit on Mt Pinatubo, and is one to two orders of magnitude greater than that of several examples studied on other volcanoes.

Key words annual specific sediment yield; cross-section survey; gully erosion; Mt Merapi, Indonesia; pyroclastic flow deposit

INTRODUCTION

When pyroclastic materials that accompany volcanic eruptions are deposited on slopes and in valleys in the surrounding area, subsequent storm rainfall events can cause severe erosion and greatly increased sediment transport, resulting in debris flows and mudflows (hereinafter referred to as "lahars") which cause disasters in the downstream region. However, as shown by many reported case studies (Pierson *et al.*, 1992; Collins & Dunne, 1986; Shimokawa *et al.*, 1996), the erosion of the pyroclastic materials and the increased sediment transport do not continue for many years; rather they tend to peak immediately after an eruption, and then decrease gradually until after a certain period has elapsed, they are of very minor importance.

The eruption of Mt Merapi (Fig. 1) in July 1998 caused a pyroclastic flow that deposited sediment around the mountain. In order to investigate the erosion and

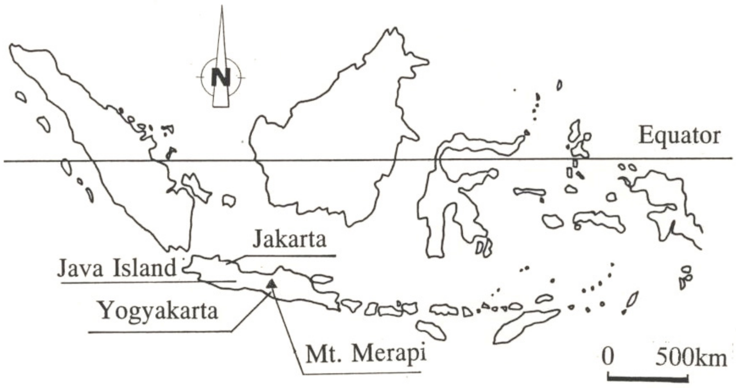

Fig. 1 The location of Mt Merapi.

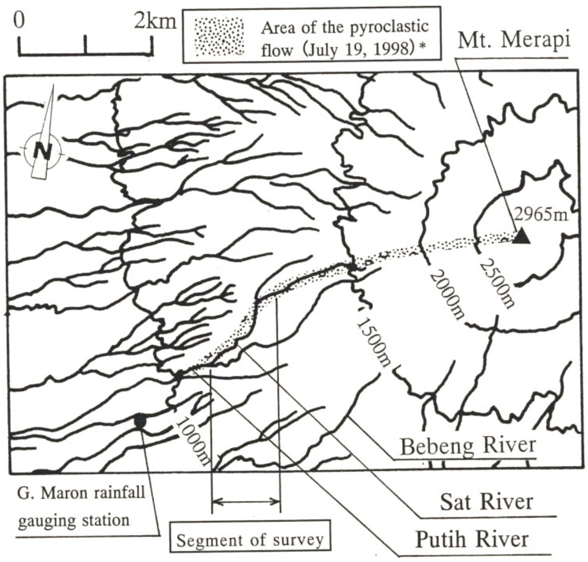

Fig. 2 The location of the study area.

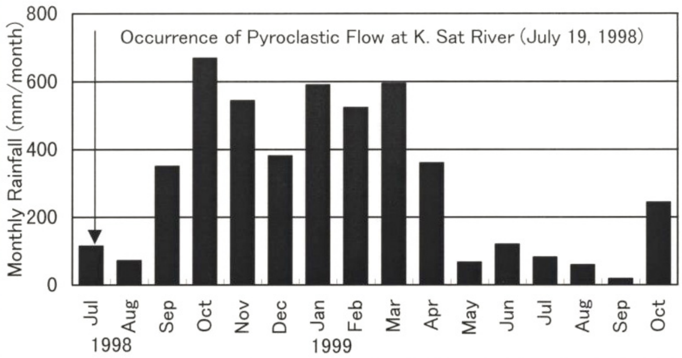

Fig. 3 Monthly rainfall at the G. Maron Rainfall Measuring Station for the period July 1998–October 1999.

sediment transport occurring on the pyroclastic flow deposits, the temporal changes in the erosion of the sediment deposited in the valley of the Sat River, which is a tributary of the Putih River (Fig. 2), were observed and recorded by the authors. Rainfall data from the G. Maron Rainfall Observation Station (Fig. 2), that is located about 2 km from the confluence of the Sat and Putih Rivers, was used for the analysis (Fig. 3). The results are presented in this paper.

OBSERVATION METHODS

In order to characterize the erosion of the pyroclastic flow deposits deposited in the valley of the Sat River, cross-section surveys and photographs taken from fixed points on the site were conducted at 20 cross-sections. The lengths of the cross-sections ranged from 150 to 300 m and these were located on the pyroclastic flow deposits around the Sat River at intervals of between 50 m and 100 m from the confluence with the Putih River to a point about 1.5 km upstream from the confluence. The surveys were undertaken primarily in the rainy season, when erosion of the deposited sediment was expected to be increased by the rainfall. Table 1 lists the dates of the surveys.

Table 1 The number and timing of the cross-section surveys.

	Number of times	Date
First rainy season after the pyroclastic flow of 19 July 1998 (1998–1999)	1st	6–7 January1999
	2nd	24–25 February 1999
	3rd	23–25 March 1999
	4th	10–15 May 1999
Second rainy season after the pyroclastic flow of 19 July 1998 (1999 2000)	1st	25–27 October 1999
	2nd	17–20 January 2000
	3rd	14–17 February 2000

EROSION OF THE PYROCLASTIC FLOW DEPOSITS

The results of the observations and measurements of the erosion occurring on the pyroclastic flow deposits are presented below.

Observation of the erosion by fixed-point photographs

Photographs 1 to 4 represent photographs taken on 6 August, 8 September, and 15 October 1998, and on 28 April 1999, respectively. These photographs show that gully erosion started to develop from September to October 1998, and increased greatly from October 1998 to April 1999. The results from another field survey showed that the depth and width of the gully cross-sections of were about 10 m on 10 December 1998, and that both increased to between 25 and 30 m by mid May 1999. These findings show that the sediment deposited around the Sat River in July 1998 was rapidly eroded by the subsequent rainfall, forming large gullies during a short period of only a few months after the pyroclastic flow.

Photo 1 Fixed-point photograph taken on 6 August 1998. The gully is not yet visible.

Photo 2 Fixed-point photograph taken on 8 September 1998. The gully is not yet visible.

Photo 3 Fixed-point photograph taken on 15 October 1998. The gully is now clearly visible.

Photo 4 Fixed-point photograph taken on 28 April 1999. The gully is clearly visible.

The development of the gullies as shown by the cross-section surveys

Gully network development Maps showing the spatial distribution of the gully network, based on the cross-section surveys, are presented in Figs 4(a) and (b). These show that there were more gullies and that the gully network was more developed in May after the rainy season than in January during the rainy season.

Calculation of the quantity of sediment eroded from the gullies

Based on the results of the cross-section surveys, the volume of the gully network over the survey range, which is equivalent the "total sediment yield by gully erosion", was calculated by integrating the products of the cross-sectional areas of the gullies on the measurement lines and the distance between the measurement lines. The result of this calculation is shown in Fig. 5. The total sediment yield from gully erosion between July 1998 and February 2000 was approximately 680 000 m^3. Approximately 430 000 m^3 of gully erosion occurred by May 1999 during the first rainy season, while approximately 250 000 m^3 occurred during the second rainy season from May 1999 to February 2000.

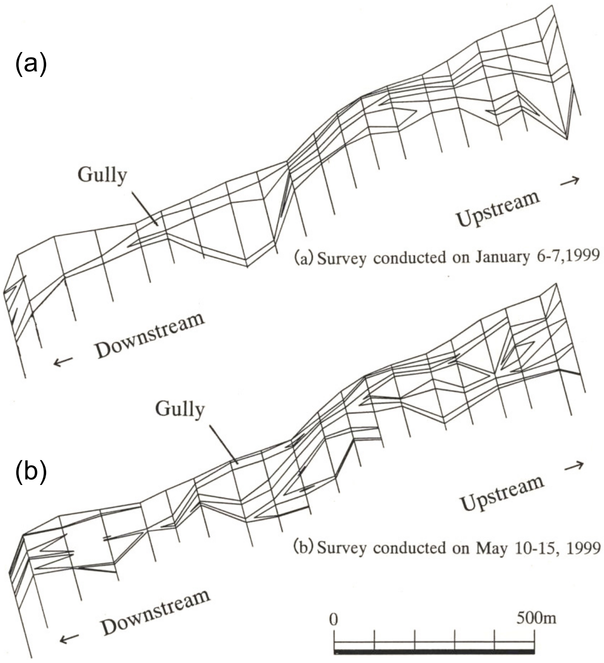

Fig. 4 A distribution map of the gullies developing on the pyroclastic deposit.

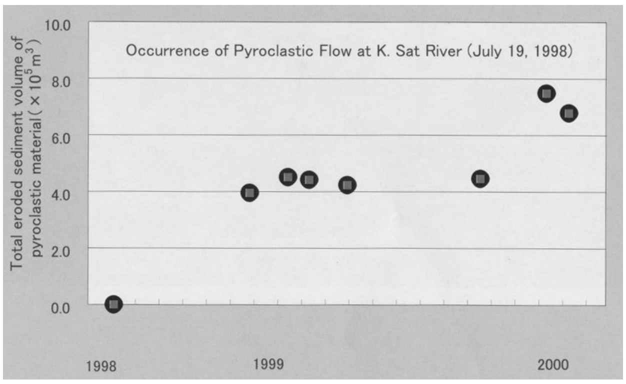

Fig. 5 Temporal variation of the volume of pyroclastic material eroded.

Figure 5 and the fixed-point photographs confirm that the total sediment yield from gully erosion increased from October to January for the first half of the rainy season, while it was almost constant during the second half of the rainy season and the dry season from May to October.

Comparison of the annual specific sediment yield

In order to place the quantitative scale of sediment erosion by rain from the pyroclastic flow deposits around the Sat River on Mt Merapi in July 1998 into a wider context, it was compared with equivalent information from other erosion surveys of pyroclastic materials. The comparison was based on the quantity of sediment eroded per unit area during a single year, referred to below as the "annual specific sediment yield".

Table 2 Comparison of the annual specific sediment yield documented by this study with those reported for several other volcanoes.

Site of observation	Type of eroded sediment	Surface condition	Type of erosion in estimation	Annual specific sediment yield ($m^3 km^{-2} year^{-1}$)	Duration of estimation of sediment yield	Method of measuring sediment yield	Precipitation	Reference
Mt Merapi (Indonesia)	Pyroclastic flow deposit of 19 July 1998	Bare	Gully	1.4×10^6	July 1988–July 1999	Measuring erosion *in situ*	4385 mm $year^{-1}$ [(b)]	Our study
	Pyroclastic flow deposit of June1984	Bare	Sheet, rill, gully	$4.6–7.3 \times 10^5$	November 1984–October 1985	Measuring erosion *in situ* and with aerial photographs	4218 mm $year^{-1}$ [(b)]	Shimokawa *et al.*(1996)
Mt Pinatubo (Philippines)	Pyroclastic flow deposit of 15 June 1991	Bare	Gully	3.9×10^6	1991–1992	Measuring erosion with topographical maps	2000 mm $year^{-1}$ [(c)]	Hirose & Inoue (1999)
Mt Unzen (Japan)	Pyroclastic flow deposit and lava dome collapse deposit after February 1994	Bare	Gully	(5.6×10^4) [(a)]	September 1996–October 1997	Measuring erosion with aerial photographs	3820 mm[(b)]	Teramoto *et al.* (2000)
Mt Sakurajima (Japan)	Air-fall deposit and colluvium	Vegetation	Sheet, rill, gully	9.3×10^4	1983–1986	Measuring erosion *in situ*	2350 mm $year^{-1}$ [(d)]	Shimokawa & Jitousono (1987)
Mt Usu (Japan)	Air-fall deposit of eruption from 1977 to 1978	Bare	Sheet, rill, gully	5.4×10^4	September 1978–December 1979	Measuring erosion *in situ*	1400 mm $year^{-1}$ [(e)]	Yamamoto (1984)
Mt St Helens (USA)	Pyroclastic surge deposit and air-fall deposit of eruption of May 1980 and colluvium	Bare	Sheet, rill	2.6×10^4	1980–1981	Measuring erosion *in situ*	1140–3200 mm $year^{-1}$ [(f)]	Collins & Dunne (1986)

[a] This value is estimated for about 13 months, from September 1996 to October 1997.
[b] Amount during the period of estimating annual specific sediment yield.
[c] Amount from January to December of 1991.
[d] Average annual amount (Oosumi Work Office, Kyusyu Regional Bureau, Ministry of Construction, 1988).
[e] Average annual amount (Minami & Shida, 1980).
[f] Average annual amount from the lower slope to the upper slope of the mountain (Janda *et al*., 1984).

According to Table 2, the annual specific sediment yield from the Mt Merapi pyroclastic flow deposits in 1998 was similar to that for the pyroclastic flow deposits on Mt Merapi in 1984 (Shimokawa *et al.*, 1996) and the pyroclastic flow deposits on Mt Pinatubo in 1991 (Hirose & Inoue, 1999), although it is one to two orders of magnitude greater than that documented by the other three studies of erosion of pyroclastic surge deposits or tephra deposits. These comparisons emphasise the severity of the erosion of the pyroclastic flow deposits on Mt Merapi and Mt Pinatubo. From this it can be concluded that the annual specific sediment yield associated with erosion of the pyroclastic flow deposits is higher than that associated with pyroclastic surge deposits and other pyroclastic deposits.

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