Effects of Scale on Interpretation and Management of Sediment and Water Quality (Proceedings of a Boulder Symposium, July 1995). IAHS Publ. no. 226, 1995.

Sediment transport by volcanic torrents of different scale

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Abstract Observation of debris flows and floods clarified the differences in sediment transport by three volcanic torrents of different scale. Catchment area and elapsed time after the last eruption were major controlling factors for surface runoff. Runoff was rarely found except just after debris flow at the small torrent on Mount Yakedake, Japan, whereas runoff was continuous at the torrents on Mount Merapi, Indonesia. A large flux of suspended sediment by floods was observed in the torrents from larger catchments on Mount Merapi and Mount Unzen, Japan. Following an eruption, a decrease in runoff coefficient by winnowing of fine particles and an increase in slope stability due to processes of erosion and dissection seemed to decrease the flux of sediment, including debris flows.

INTRODUCTION

Sediment transport on the slopes of a volcano is large and the change in topography is great. Transport rate is strongly affected by the eruptive activity of the volcano and is closely related to the scale of the catchment, which might change by stream piracy (Furuya, 1989). A large catchment is expected to have a high capacity of sediment transport. These relations in the torrents of similar volcanoes, whose factors in activity and topography are different, are discussed.

OBSERVATIONS OF DEBRIS FLOWS AND FLOODS

Observations of debris flows and floods have been collected at the Kamikamihori-zawa gully on Mount Yakedake, Japan, since 1970, and at the Bebeng River on Mount Merapi, Indonesia, and at the Mizunashi-gawa River on Mount Unzen, Japan, since 1991 (Fig. 1). After the last phreatic eruption of Mount Yakedake from a fissure at the headwaters of Kamikamihori gully in 1962, debris flows occurred frequently, being triggered by heavy rainfall; recently the scale and frequency of the flows have decreased year by year. Mount Merapi repeats eruptions of pyroclastic flows every several years, causing successive phenomena of debris flows. Major pyroclastic flows ran down onto the southwestern slope in 1969 and 1984, and small, ineffective, activity was observed in 1992. After 198 years of inactivity, Mount Unzen erupted in 1990. From May 1991, intermittent collapses of the lava dome have initiated frequent pyroclastic flows and successive debris flows, thereby devastating lower parts of the fan.

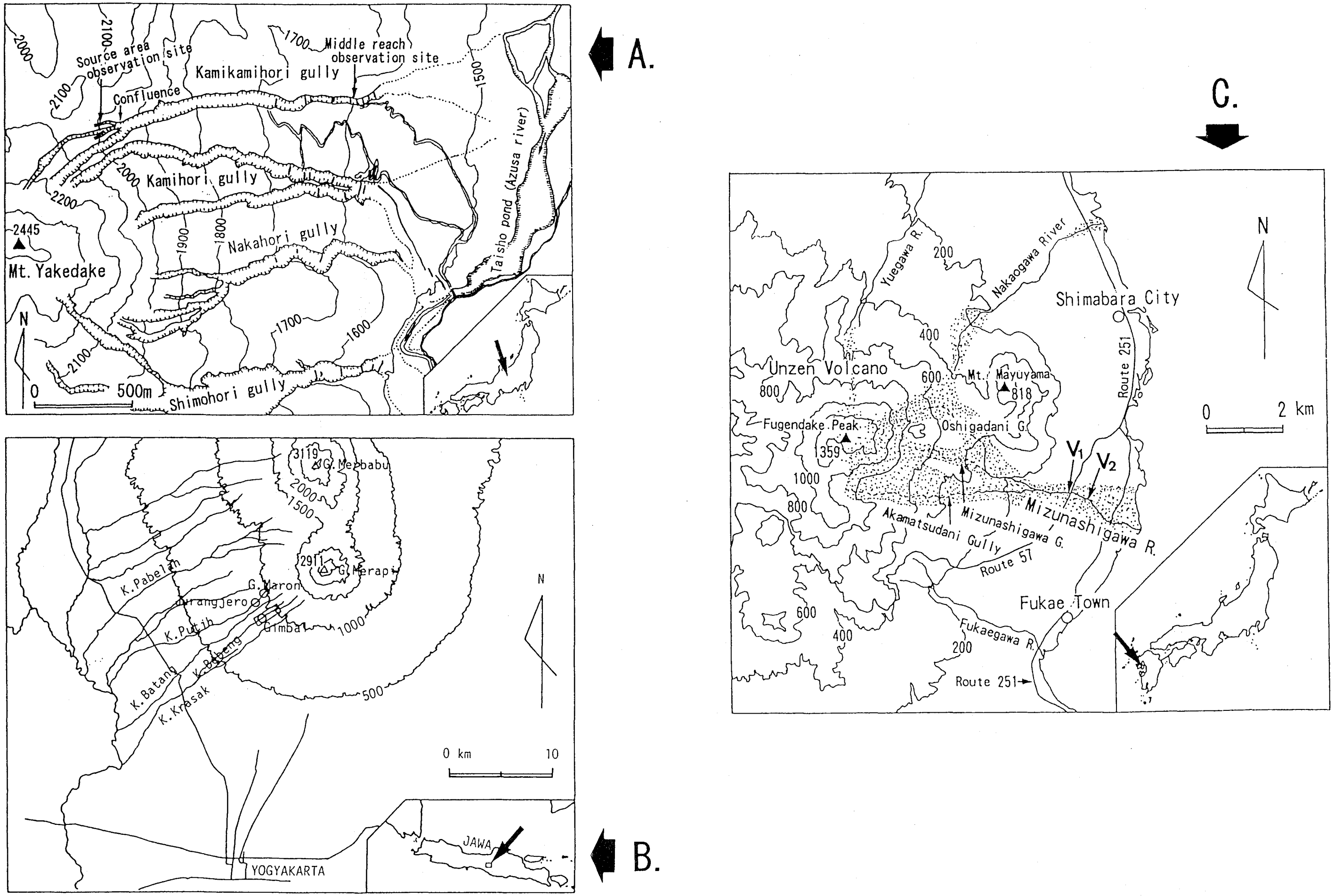

Fig. 1 Maps showing: (A) observation site at Kamikamihori gully on Mount Yakedake; (B) Bebeng River on Mount Merapi; and (C) Mizunashi River on Unzen Volcano: V_1 and V_2 show locations of video cameras.

SEDIMENT TRANSPORT BY DEBRIS FLOW

At the Mizunashi River, there were no debris flows for many years before 1991. Starting in 1991, more than 190 million m^3 of lava were ejected; about half of this collapsed, forming pyroclastic flows that killed 44 persons and destroyed 651 buildings. Successively, the Mizunashi River generated stony types of debris flows due to intense rainfall throughout the year after mid-May 1991. About 95 debris flows transported huge amounts of debris and deposited about 6.3 million m^3 over the fan, destroying 1004 buildings. Fig. 2(A) shows the time series of 10-min rainfall and peak flow rates of debris flow surges that were calculated from visual data of video cameras. It was difficult to document the full hydrographs of the debris flow surges because a dense fog of steam from the hot flow obstructed the visual recording of each flow except its front. The maximum peak flow rate was 1850 $m^3\ s^{-1}$ on 2 May 1993; the frontal velocity was 11 $m\ s^{-1}$ on a slope of 2.7°. Figure 2(A) shows that most debris flows coincide with intense rainfall. This coincidence indicates that debris flow occurrence is similar to that on Mount Yakedake, where rapid runoff entrains debris and converts a muddy and boulder-laden water flow into a debris flow (Suwa, 1989).

At the observation point of the Bebeng River, sloppy, stony debris flows are often observed after heavy squalls of October into April. Most debris flows coincide with intense rainfall, whereas some are delayed tens of minutes from the peak rainfall. The delays may be caused by spatial difference between the rain gage and the debris flow or by breaching of landslide dams. Low sediment concentrations of small debris flows may be due to transformation from debris flow to hyper-concentrated flow, in which only the lower layer has traction flow due to insufficient dispersion of solids as it runs down slope.

Motion and deposition were observed at Kamikamihori gully for 49 of 65 debris flows since 1970, all of which occurred in the rainy season, June through September. The frequency and scale of debris flows were very large after the 1962 eruption, and the frequency was still about 20 $year^{-1}$ in 1969. Recently, scale and frequency (0.7 $year^{-1}$ for the last 10 years) have decreased. The last eruption deposited ash that remarkably reduced infiltration capacity and increased the runoff coefficient of the catchment so that the debris flow frequency and scale also greatly increased. With time, decrease in the runoff coefficient due to washing out of fine particles and increase in slope stability have decreased the frequency and scale (Suwa, 1993).

Figure 2(B) shows the temporal change in flow materials and hydraulic factors of the 14 July 1993 debris flow at Kamikamihori gully, for which two striking characteristics are common to stony debris flows. One is the concentration of large boulders at the flow front, which mainly results from the force balance against each boulder in the flow (Suwa, 1988). The other is the appearance of hydraulic values from flow depth through flow rate to surface velocity, which results from the change in flow composition from front to tail (Suwa *et al.*, 1993).

HYDROLOGIC CONDITION OF DEBRIS FLOW OCCURRENCE

Most debris flow processes on the three volcanoes are similar. The incorporation of debris by a sudden muddy water flow causes conversion to typical debris flow in which

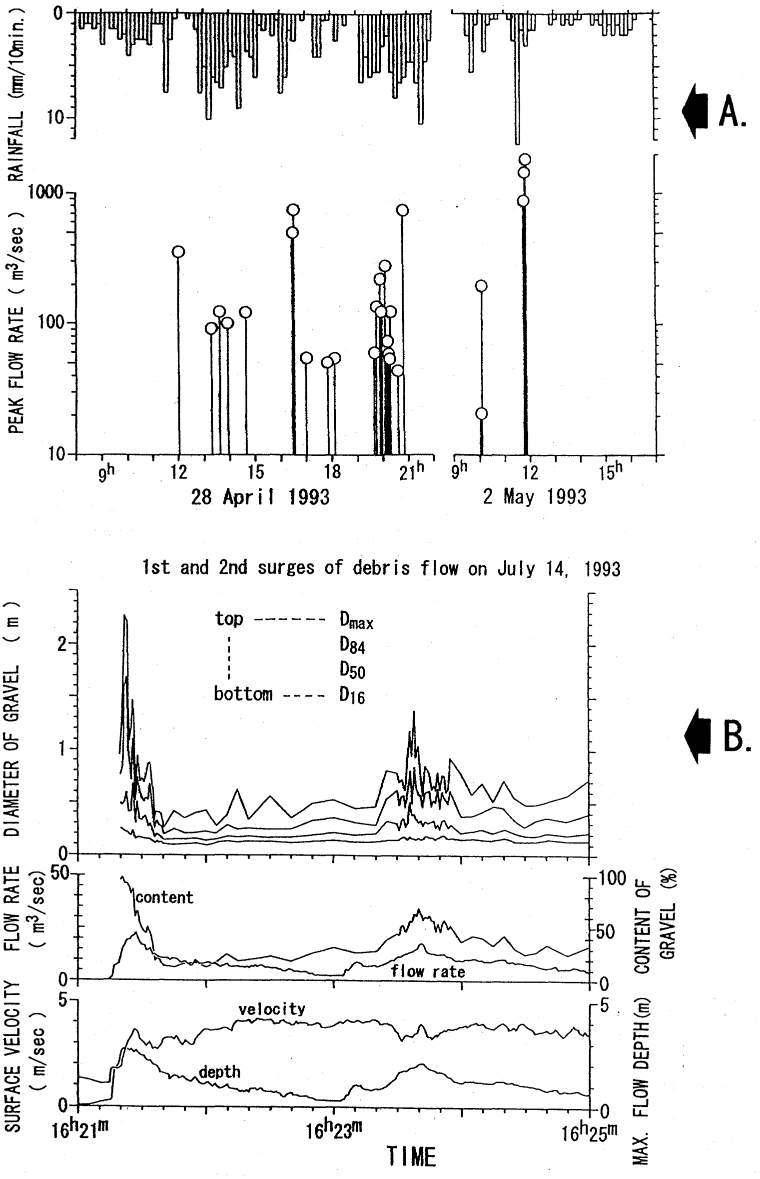

Fig. 2 Graphs showing: (A) the time series of 10-min rainfall and peak debris flow rates, 29 April and 2 May 1993, at Mizunashi River; and (B) temporal change in composition and hydraulic factors of the first and second surges of the 14 July 1993 debris flow at Kamikamihori gully: analyses of size and content of gravel are for particles larger than 10 cm.

debris clasts are fully dispersed at high concentration. Different rainfall conditions for three debris flows are shown in Fig. 3. Debris flows occur most readily on Mount Unzen, where eruptive activity continues. Comparison between Mount Yakedake and Mount Merapi indicates that debris flows at Merapi are less likely to reach the observa-

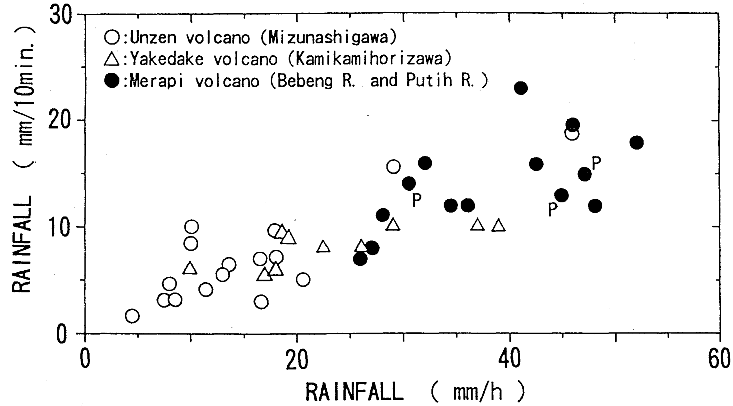

Fig. 3 Comparison of rainfall intensities for debris flow occurrences at three volcanic torrents.

tion site than are flows at Kamikamihori gully because of lower slope and greater distance on Merapi.

SURFACE RUNOFF AND SUSPENDED SEDIMENT

The back part of a stony debris flow may convert to hyper-concentrated flow. Whereas surface runoff hardly occurs at Kamikamihori gully, runoff due to intense rain transports suspended sediment and bed load at Mizunashi River. Bebeng River is a gaining stream below an altitude of 920 m and flow is always muddy. At high stages during and after a squall, sediment flux is large (Suwa & Sumaryono, 1994). Examples of runoff and suspended sediment (Table 1) show that values of direct runoff ratio vary from 10 to 40% and mean volumetric concentrations of suspended sediment are high, 1-2.6%.

MASS WASTING IN THE GULLY

Rock fall induced by freeze—thaw sequences in spring and by stream erosion in summer supplies much debris from side walls to the bottom of Kamikamihori gully. In the rainy season, some material is removed by debris flow, depending on transport capacity. Mean annual volume of debris removed is nearly balanced by volume from side walls (Suwa & Okuda, 1988; Okunishi *et al.*, 1988).

The upper Bebeng River slope was covered by the 1969 and 1984 pyroclastic flows. Gully side walls are steep due to cohesion in the tephra and various scales of side wall toppling and slide occur on the undercut slope. Toppled debris sometimes dams the stream and is removed by later floods. The source of the sediment for debris flows is considered to be side walls at altitudes of 800-1400 m (Suwa & Sumaryono, 1994).

Deposition of large pyroclastic flows on Mount Unzen slopes buried the former stream networks. Because the frequency of pyroclastic flow is high, development of new stream networks is difficult. New rills and gulleys are generated following shifts of flow direction and deposition to other parts of the mountain slope. These processes of alternating deposition and dissection continue to the present.

DISCUSSION AND CONCLUSIONS

Conditions of sediment transport at three volcanic torrents are summarized in Table 2. At Kamikamihori gully, the channel is short and steep. Thus, an observation site was selected at the fan head, whereas observation sites on the other two torrents were selected on the fan. Consequently, channel gradients at the latter sites are too low to sustain typical debris flows and many transform to hyper-concentrated flow before reaching the observation site. The larger the catchment area, the larger is the sediment transport capacity. The catchment area of Mizunashi River is large due to irregularity of the slope configuration (Fig. 2). With elapsed time following eruption, the runoff coefficient declines, reducing the sediment transport capacity. Considering the above factors and following rough relations of conceptual functions for frequency of debris flow, F, bulk volume of sediment transport, V, and permeability of the surface layer of the slope, K, in addition to other statistical and accidental factors:

$$F = \mathrm{func}_1\,(I, P, A, T, K, \ldots) \tag{1}$$

$$V = \mathrm{func}_2\,(H, I, P, A, T, K, \ldots) \tag{2}$$

$$K = \mathrm{func}_3\,(P, T, \ldots) \tag{3}$$

Table 1 Rainfall condition, runoff ratio and transportation of suspended sediments by five examples of flood at the Bebeng river.

Year	1992				1993
Date	Dec. 1	Dec. 2	Dec. 3	Dec. 31	Jan. 19
Beginning of rainfall	14:10	14:00	11:30	13:00	13:40
End of rainfall	16:00	16:00	17:50	18:00	17:30
Total depth of rainfall (mm)	33	47	73	66	59
Peak of hourly rainfall (mm/h)	27	44	39	59	41
Peak of 10 min. rainfall(mm/10min.)	7	16	20	39	11
Total volume of runoff (m^3)	33,900	30,300	38,400	105,700	35,500
Depth of direct runoff (mm)	5.1	4.1	3.4	18.5	5.4
Direct runoff ratio	0.156	0.088	0.047	0.27	0.092
Peak of runoff ratio	0.51	0.106	0.074	0.51	0.21
Peak flow rate (m^3/sec)	19.8	8.3	2.3	54	9.8
Peak concentration of suspended sediment(m^3/m^3)	0.027	0.0194	0.0118	0.040	0.020
Mean concentration of suspended sediment(m^3/m^3)	0.0166	0.0123	0.0094	0.026	0.0127
Total volume of suspended sediment (m^3)	560	370	360	2,700	450

(Observation of rainfall : G. Maron,
Observation of runoff and suspended sediments: 800 m, a.s.l. at the Bebeng river)

Table 2 Comparison of sediment transport at three volcanic torrents.

		Mt. Yakedake Kamikamihori gully	Mt. Merapi Bebeng river	Mt. Unzen Mizunashi river
Lava		Andesite	Basaltic andesite	Dacite
Altitude of mountaintop	(m, a. s. l.)	2445	2911	1473
H: Relative height between the top and the observation site	(m)	865	2100	1392
Full length of the stream	(m)	2500	14000	7600
Stream length to the observation site	(m)	1500	6000	5000
Mean inclination of the stream	(°)	20.7	9.9	10.9
I: Mean inclination of the stream to the observation site	(°)	29.9	19.3	15.5
Inclination of the stream at the observation site	(°)	7	2.8	2.7
A: Catchment area for the observation site	(km^2)	0.83	6	12
P: Mean of annual precipitation	(mm)	2600	4500	3100
Year of the last activity of effective eruption		1962	1984	1990-1994-
T: Time after the last effective eruption	(years)	33	11	0
K: Permeability in the surface layer of the slope	(cm/sec)	$10^{-2} \sim 10^{-3}$	$10^{-2} \sim 10^{-3}$	$10^{-3} \sim 10^{-5}$
F: Frequency of debris flow	(/Year)	0.7	5	23
V: Bulk volume of sediment transportation	($\times 10^4\ m^3$/year)	0.5	30	210

Among the variables above, catchment area, A, for an observation site, and time, T, after an eruption are the most effective controls of sediment transport. The larger the area, A, the larger are frequency and bulk volume of debris flow. There are many examples of change in F and V due to change in A by stream piracy (Furuya, 1988). As time increases, frequency and bulk volume decrease exponentially and permeability of the surface layer increases. Such functional relations to time may be common to sediment transport at any volcanic torrent.

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