Characteristics of pyroclastic flows and debris flows accompanying the Mt Unzen-Fugendake eruption

HIROSHI IKEYA
Sediment Control Department, Ministry of Construction, 2-1-3, Kasumigaseki, Chiyoda-ku 100, Japan
YOSHIHARU ISHIKAWA
Public Works Research Institute, Ministry of Construction, 1, Asahi, Tsukuba-shi, Ibaraki-ken 305, Japan

Abstract Mt Unzen-Fugendake erupted on November 17, 1990. An investigation of the pyroclastic flows and debris flows occurring in the Mizunashi River during the period from May 1991 to August 1992 indicates the pyroclastic flows and debris flows had the following characteristics. The larger the amount of material flowing in a pyroclastic flow material ejected from the volcano, the further downstream the front edge of the pyroclastic flow will reach. The main body materials of a pyroclastic flow moves downward, to some degree, along a valley configuration, but the hot ash cloud moves straight down, without being much influenced by the topography. The temperatures of the hot ash clouds accompanying the pyroclastic flows were over 450°C and their wind velocity was more than 50 m/s. Debris flows are likely to occur even when rainfall is low. The larger the total volume of water runoff, the larger is the sediment concentration of the debris flow.

INTRODUCTION

Mt Unzen-Fugen (1359 m) (Fig. 1), located near the center of the Shimabara Peninsula, awoke in 1990 from its 198 years of inactivity and began to erupt. Following this eruption, debris flows and pyroclastic flows have been occurring continuously from May 1991 until the present time (August 1992) at the Mizunashi River, which lies at the eastern foot of Mt Unzen-Fugen. These debris flows and pyroclastic flows have caused much damage to people and buildings. This study describes characteristics of the pyroclastic flows and the debris flows produced by the Mt Unzen-Fugen eruptions.

COMMENCEMENT OF ERUPTION AND OCCURRENCE OF PYROCLASTIC FLOWS

Starting around July 1990, the frequency of earthquakes and tremors began to increase in the Shimabara Peninsula and in the area to the west. The eruptions started on November 17, 1990, at the Jigokuato crater and Kujukushima crater. After that initial activity, eruptions abated, then started again on February 12, 1991, at Byobuiwa crater,

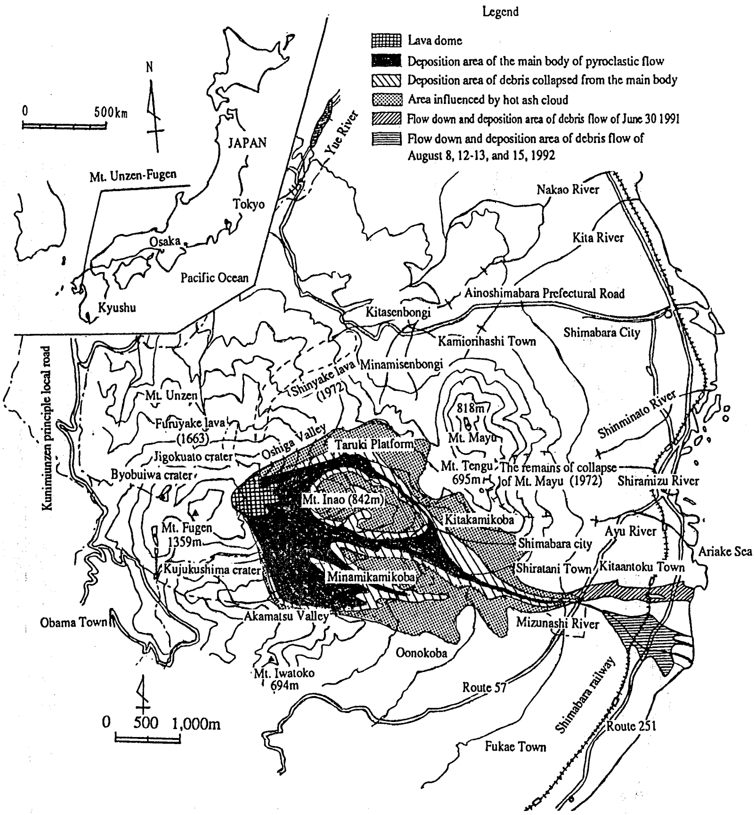

Fig. 1 Map of the peripheral area of Mt Unzen Fugen (as of August 27, 1992).

near the peak of Mt Fugen, and a large amount of volcanic ash was erupted. Accumulated volcanic ash reached a maximum thickness of about 1.5 m near the peak of the mountain. A pyroclastic flow (the first dome) was extruded out of the Jigokuato crater on May 20. This pyroclastic flow grew in height every day, and on the 24th some of the lava began to flow down to the source of the Mizunashi River. This was the beginning of the pyroclastic flows, and since that time very small pyroclastic flows have been occurring frequently.

PYROCLASTIC FLOWS OF JUNE 3, JUNE 8, AND OCTOBER 15

A pyroclastic flow larger than all the earlier flows occurred at about 3:50 a.m. on June 3, and it swept over some parts of Kitakamikoba-machi and Minamikamikoba-machi, causing a disaster with 43 fatalities, 10 injuries, with 49 residential buildings burned down or collapsed completely (Figs 2 and 3, Table 1).

Later, a second dome emerged at the same location where the first dome had collapsed, and continued to grow. Most of this second dome collapsed, and a pyroclastic flow larger than all the previous flows occurred at around 7:50 p.m. on June 8. The main body of the new pyroclastic flow ran down along the Mizunashi River, filling up the river course with volcanic debris, and nearly reached Route 57,

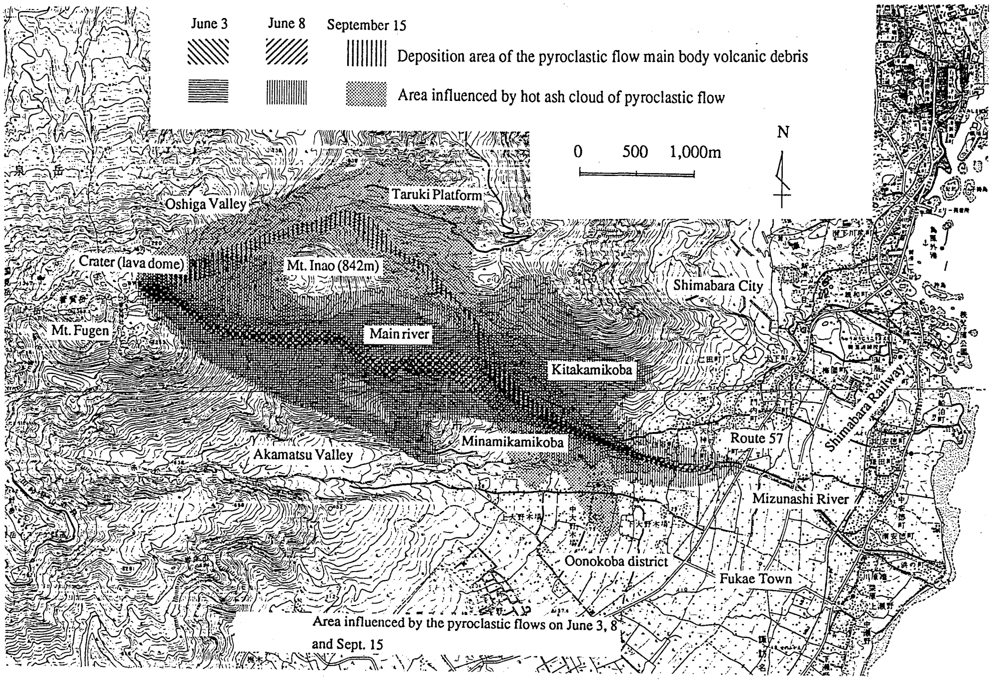

Fig. 2 Area influenced by the pyroclastic flows on June 3, 8 and September 15.

which lies 5.5 km downstream from the crater (Fig. 2). Due to the breaking of a lava lump accompanying the growth of the third dome, very small pyroclastic flows started to occur on the northeastern slope (Oshiga Valley, which is the left branch of the

Fig. 3 Overview of route and deposition area of the pyroclastic flow of June 3 (Mt Unzen-Fugen in the front and Mt Mayu to the right).

Table 1 Casualties and damage to houses caused by the pyroclastic flows and debris flows.

Type	Date of occurrence		River name	Casualties (persons)		Damage to building (ridges)	
				Fatalities	The injured	Residential buildings	Non-residential
Pyro-clastic flow	1991	May 29th	Mizunashi Riv.	0	1	0	0
		June 3rd	Mizunashi Riv.	43	10	49	130
		June 8th	Mizunashi Riv.	0	0	72	135
		Sept. 15th	Mizunashi Riv.	0	0	53	165
	1992	Aug. 8th	Mizunashi Riv.	0	0	6	12
Puroclastic Flow			Total	43	11	180	442
Debris flow	1991	May 15th	Mizunashi Riv.	0	0	0	1
		June 30th	Mizunashi Riv.	0	0	64	87
			Yue Riv.	0	1	34	17
	1992	Aug. 8th	Mizunashi Riv.	0	0	35	7
		Aug. 12th	Mizunashi Riv.	0	0	84	4
		Aug. 15th	Mizunashi Riv.	0	0	56	11
Debris Flow			Total	0	1	273	127
Total				43	12	453	569

Note: The number of fatalities includes those listed as missing (as of August 18, 1992).

Mizunashi River). At 9:21 p.m. on September 6, a small pyroclastic flow occurred in Oshiga Valley. At this time the front part of the hot ash cloud moved down along the Oshiga Valley and reached a point about 3.1 km from the crater. At 6:45 p.m., September 15, the largest pyroclastic flow up to that time occurred in Oshiga Valley. This pyroclastic flow struck against Taruki Platform, turned to the right, and flowed downhill. When it met the main stream of the Mizunashi River the main body (bottom part) changed its direction, veering left, and flowed down along the Mizunashi River main stream, reaching a point near Shiratani Bridge, located about 5.8 km downstream from the crater (Fig. 2).

CHARACTERISTICS OF THE PYROCLASTIC FLOWS

Using aerial photographs taken at different times, aerial cross section photogrammetry was conducted on the pyroclastic flow deposition area in the drainage basin of the Mizunashi River. Cross sections were set at intervals of 100 m along the river. Based on these cross sections, the amount of soil deposited by each pyroclastic position area in the drainage basin of the Mizunashi River. Cross sections were set at intervals of 100 m along the river. Based on these cross sections, the amount of soil deposited by each pyroclastic flow was determined for each photogrammetry interval (Fig. 4). Considering the amount of deposited soil produced by the very small pyroclastic flows that occurred in these three periods, it is estimated that the volumes of deposited sediment (volume of flow sediment) caused by the pyroclastic flows occurring on May 26, June 3, and June 8 should be approximately 300 000 m^3, 2 500 000 m^3, and 3 500 000 m^3, respectively.

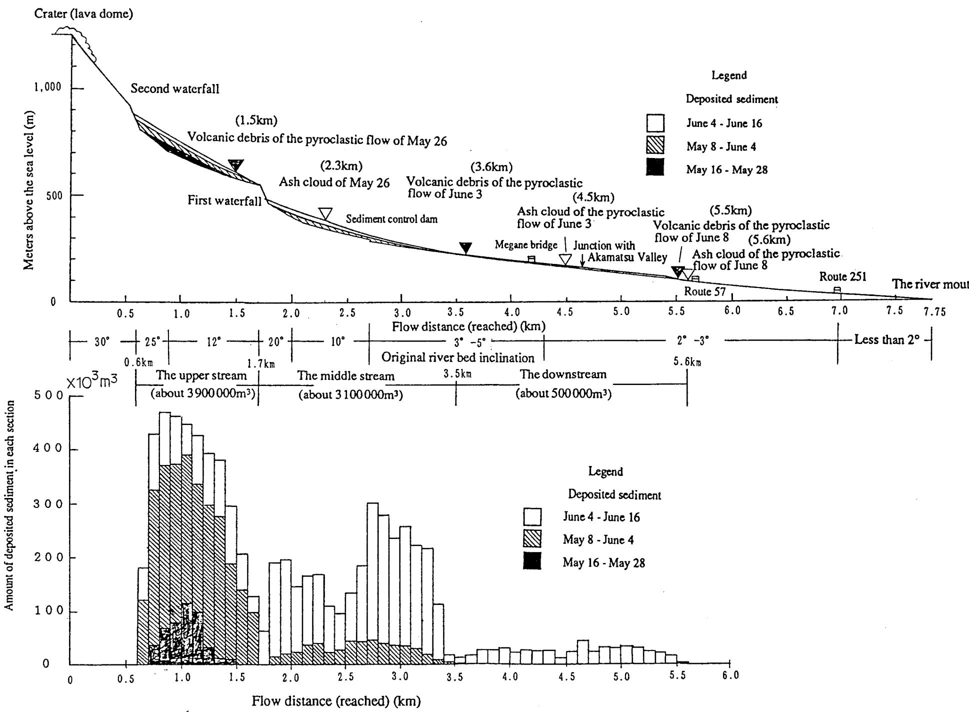

Fig. 4 Flow down and deposition of volcanic debris of pyroclastic flows at the Mizunashi River main channel.

Also, the amounts of soil deposited by the pyroclastic flows of August 26, September 6, and September 15 are estimated to be approximately 800 000 m^3, 1 000 000 m^3, and 4 000 000 m^3, respectively.

Figure 5 shows the relationship between the amount of deposited flow down sediment produced by pyroclastic flows occurring in the Mizunashi River basin since

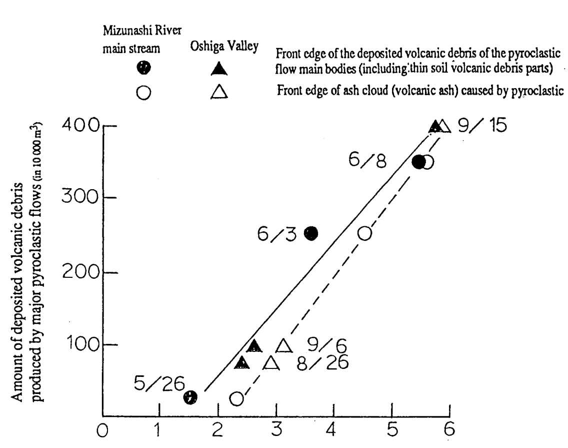

Fig. 5 Amount of deposited volcanic debris produced by major pyroclastic flows and their reaching distance.

the last third of June, and the travel distance of the pyroclastic flow. As seen in Fig. 5, a tendency can be observed, whereby the pyroclastic flows carrying more material (more material ejected by the volcano) are seen to reach a greater distance from the crater. Using this relationship, the distance reached by the front edge of a pyroclastic flow can be estimated to some extent from the amount of material in the pyroclastic flow (amount ejected from the crater).

DAMAGE CAUSED BY THE PYROCLASTIC FLOWS HOT ASH CLOUDS

The areas damaged by the hot ash clouds of the pyroclastic flows of June 3 and June 8 in the drainage basin of the Mizunashi River covered about 3.0 km^2 and 4.1 km^2 respectively. This was more than twice the area of the deposits of the main bodies which were about 1.0 km^2 and 1.9 km^2 for June 3 and June 8 respectively.

In the areas affected by the hot ash clouds, wooden buildings were burned down and vehicle tires melted. Judging from the temperatures at which wood catches fire and at which tires melt, it is estimated that the temperature of the hot ash cloud near the exit from the valley was over 450°C. Considering the way in which trees and concrete utility poles were felled and vehicles up-ended in the path of the hot ash cloud, it is estimated that wind pressures equivalent to a maximum instantaneous wind velocity of 40-50 m per second occurred near the valley exit during the pyroclastic flow of June 3. Since there was a forest of coniferous trees and broad-leaved trees spreading along the Mizunashi River, many trees were blown down by the wind pressure from the hot ash cloud. From Fig. 2, it can be said that although the main body sediments of a pyroclastic flow move downwards, following to some degree along the valley configuration, there is a tendency for the hot ash cloud to move straight down, without being influenced by the terrain of small valleys. This suggests that, even if the flow direction of the main body debris is changed by a training dike, the flow direction of the hot ash cloud does not necessarily follow it. This is an important point to be taken into a consideration when planning and designing facilities to counter pyroclastic flows.

DEBRIS FLOW AND INFLUENCE OF RAINFALL AND VOLCANIC ASHFALL

On May 15th, 1991, debris flows were caused by rainfall and as much as 70 000 m^3 of debris flowed down from the upper stream of the Mizunashi River main stream. After the 15th, debris flows again occurred on the 19th, 20th, 21st, and 26th. However, no injuries or damage to buildings occurred, except for damage to two bridges, one hut and three utility poles.

On June 30, 1991, a large debris flow was triggered by a heavy rainfall (64 mm/hr) at the Mizunashi River. As of June 30, the river channel of the Mizunashi River was filled up to a point near route 57, with material produced by the pyroclastic flow of June 8. Therefore, after the two debris flows met, one from the Akamatsu Valley and the other from the left branch of the Mizunashi River, the confluent debris flow ran down onto the alluvial fan, concentrating on the relatively lower left bank of the Mizunashi River channel (Fig. 1). Based on aerial photography interpretation, the new area covered by the sediment from the debris flow was about 350 000 m^2 and the volume of deposited soil was about 380 000 m^3. At the same time, it is estimated that some of the debris flow changed into a hyper-concentrated flow and flowed downstream to the Mizunashi River main stream river channel, further down from Route 57, resulting in the deposition of as much as 80 000 m^3 in the river channel near Route 251.

Figure 6 shows the relationship between changes in the amount of rainfall per day, maximum rainfall per hour measured at Mt Unzen meteorological station, and occurrence of debris flows after February 12, when a lot of ash fell. On May 15, the rainfall per day and the maximum rainfall per hour was the greatest since February 12. Therefore, it is considered that this heavy rain(fall) directly caused the debris flow in the Mizunashi River. There seems to be a tendency for debris flows to repeat, after the first one occurs after an ashfall, even with low rainfall. On May 26 and 29, a small pyroclastic flow occurred, and a large amount of pyroclastic flow material was accumulated, which created a condition whereby a debris flow could occur even with small amount of rainfall. However, after June 3 and 8, when relatively large pyroclastic flows occurred, there was no debris flow occurrence.

It is considered that this was because of the following: The temperature of the

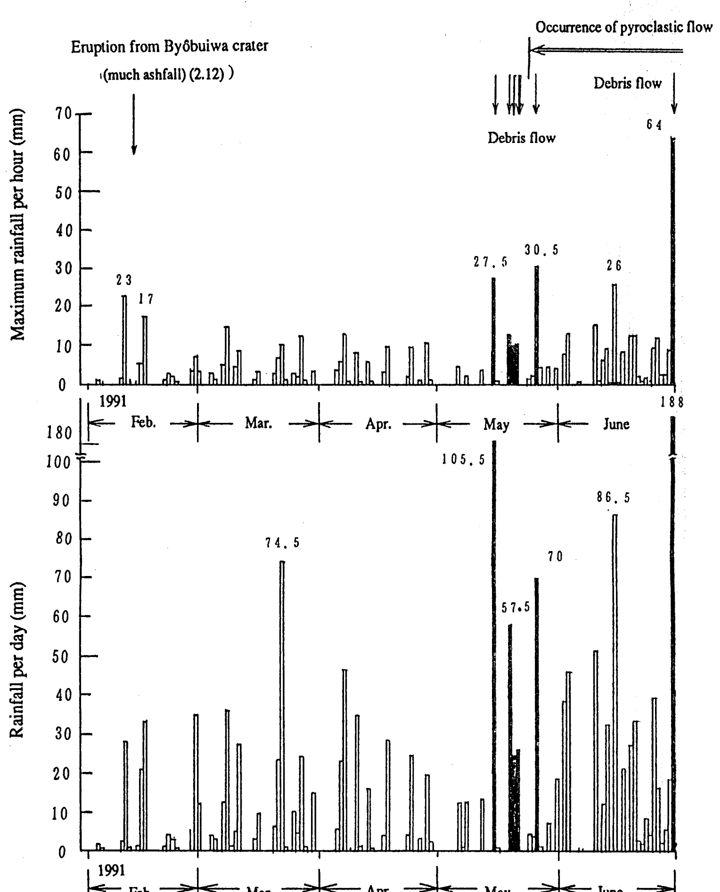

Fig. 6 Changes in rainfall per day and the maximum rainfall per hour and occurrence of debris flow (rainfall observation station: Mt Unzen meteorological station).

deposits from the pyroclastic flow was still high, therefore, rain was evaporated and precluded surface water runoff, therefore, deposits accumulated at the upper and middle reaches of the Mizunashi River main stream did not become a debris flow source. Since the 64 mm maximum rainfall per hour rate, recorded on June 30, occurs only once in every four years, it can be said that the ashfall produced by the eruption became a major factor which supplied the conditions where a debris flow could easily occur. Rainfall per hour was about 10 mm, and continuous rainfall of 20-100 mm had occurred at the time when debris flows (including those similar to hyper-concentrated flows) occurred on May 15-26. These rainfalls were less than those usually experienced when a torrential debris flow occurs. Therefore, it is evident that there was an influence from the great amount of ashfall on the upper stream basin of the Mizunashi River.

At 1:28 a.m. on March 1, 1992, there was a debris flow from the Mizunashi River, caused by heavy rainfall from a weather front activity. The Oshiga Valley, along the left branch of the Mizunashi River, supplied a lot of material of the debris flow. Gullies have formed directly below the lava dome along the Oshiga Valley, because the pyroclastic flows had hardly occurred in the Oshiga Valley since January, 1992. Conversely, significant gullies have not formed, and there was little flooding in the main stream of the Mizunashi River. In the Akamatsu Valley, no significant erosion was noted in the pyroclastic deposits. The debris flow of March 1 did not cause fatalities or serious damage to houses, but the Shimabara Railway, Route 251, were blocked by flood water and deposits, which disrupted transportation. On March 15, 1992, there was a debris flow similar in size to the one occurring on March 1.

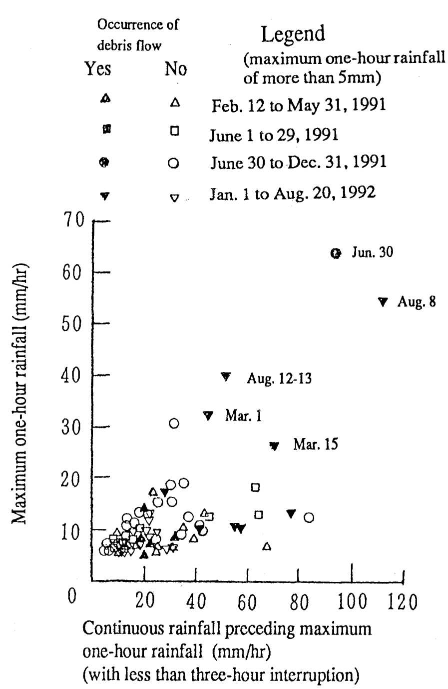

Fig. 7 Relationship between occurrence of debris flows and debris and precipitation (measured by the Unzen meteorological station).

On August 8, 12-13, and 15, 1992, relatively large debris flows were triggered by heavy rainfall along the Mizunashi River. At that time the river channel of the Mizunashi River was opened to the middle reaches with the erosion of the right river bank after March 1992. Therefore, in August the debris flows flowed down along the original channel of the Mizunashi River, resulting in deposits totaling about 470,000 m^3 in the river channel. As a result, the river bed was raised up to the top of the bank protection levee, and the hyper-concentrated flow flooded onto the fan and caused great damage to buildings.

Figure 7 shows the maximum one-hour rainfall and the continuous rainfall (amount falling with interruptions of three hours or less) measured by the Unzen Meteorological Station since February 12, 1991 when a large quantity of ash fell during a volcanic eruption and the relationship between these rainfall data and the debris (and hyper-concentrated) flow occurring during the same period. Rainfall on June 30, 1991 and August 8, 1992 significantly exceeded that on other days, and the volume of debris flow transported and the area flooded were also larger. Maximum one-hour rainfall was approximately 10 mm and continuous rainfall about 20-100 mm at the time when debris flow (including that similar to hyper-concentrated flow) occurred in May of 1991. The rainfall that triggered debris flow in 1992 was within the above range.

The volume of sediment (V) which deposited in the downstream area (down Route 57) of the Mizunashi River by debris flows since May, 1991 was measured by surveys, and the total volume of water runoff (Q) of each rainfall was calculated as: the catchment area of the Mizunashi River (up Route 57) times continuous rainfall, times runoff rate (0.9). Figure 8 shows the relationship between the average sediment concentration [$100V/(V + Q)$] and the total volume of water runoff for each debris flow. Figure 8 indicates more of the debris flows occurring on the Mizunashi River were low sediment concentration flows, containing only several percent sediment. Figure 8 also indicates that the higher volumes of runoff tend to have the higher concentrations of sediment.

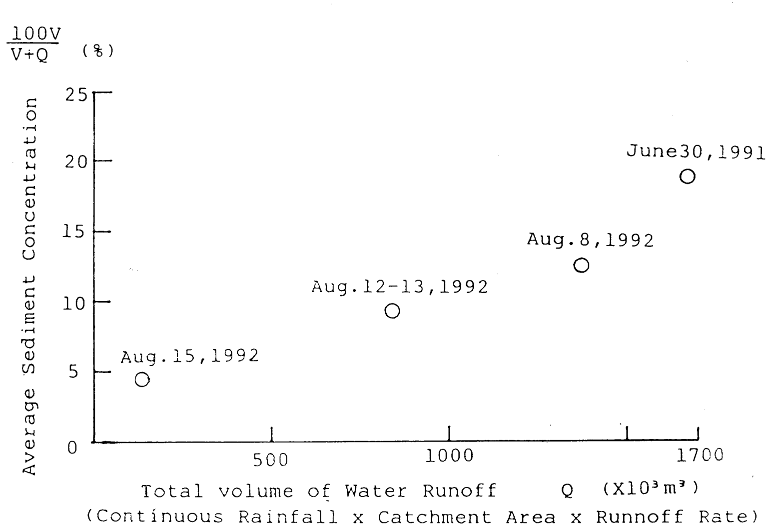

Fig. 8 Average sediment concentration of debris flows in the Mizunashi river.

CONCLUSIONS

The larger the amount of sediment flowing down in a pyroclastic flow (amount ejected from the crater), the further downstream the front edge of the pyroclastic flow reaches. The main body sediments of pyroclastic flows move downwards, to some degree, along a valley configuration, but the hot ash cloud moves straight down without being much influenced by the topography. The temperature of the hot ash clouds of pyroclastic flows can be over 450°C, and their wind velocity can exceed 50 m/s. These features caused the loss of lives and the heavy damage to houses and forests in the Mizunashi River basin.

When volcanic ash from an eruption accumulates on a mountain slope, and it absorbs water from rainfall, its permeability is lowered, and the surface runoff rate increases. Since deposited volcanic ash itself becomes liquefied by absorbing water, and will flow down as a debris flow, debris flows or hyper-concentrated flows are likely to occur, even with low rainfall. When the temperature of the pyroclastic flow deposit is still high, rain is evaporated and there is no surface water runoff. Therefore, when deposit temperatures are high, debris flow does not occur with low rainfall. After the temperature of the pyroclastic flow deposits cool, debris flow is likely to occur, even with low rainfall. The debris flows which occurred at the Mizunashi River were low sediment concentration flows, containing several percent sediment. In addition, it was found that the greater volume of water runoff, the higher the concentration of sediment in the debris flow.

Acknowledgments We would like to express our deep appreciation to the Erosion Control Division, Erosion Control Department, Ministry of Construction, the Shimabara District Promotion Bureau, Nagasaki Prefecture, for extending their valuable time and assistance to us for our investigation during continuous pyroclastic flows and debris flows.

REFERENCES

Ikeya, H. & Ishikawa, Y. (1991a) Disaster caused by pyroclastic flows and debris flows occurring at Mt Unzen in 1991. *J. Japan Society of Erosion Control Engineering* **44**(2), 46-56.

Ikeya, H. & Ishikawa, Y. (1991b) Disaster caused by pyroclastic flow and debris flow occurring at Mt Unzen in 1991 (the second report). *J. Japan Society of Erosion Control Engineering* **44**(5), 35-46.

Ikeya, H. & Ishikawa, Y. (1992a) Disasters caused by debris flows at Unzen-Fugen Volcano in March, 1992, and Countermeasures. *J. Japan Society of Erosion Control Engineering* **45**(1), 56-60.

Ikeya, H. & Ishikawa, Y. (1992b) Disasters caused by debris flows at Unzen-Fugen Volcano in August, 1992. *J. Japan Society of Erosion Control Engineering* **45**(3).