Effects of Volcanic Ash on the Runoff Process in Sakurajima Volcano

Yukiyoshi Teramoto,[1)] Etsuro Shimokawa[2)] and Takashi Jitousono[3)]
1) Faculty of Agriculture, Kagoshima University, 1-21-24 Korimoto, Kagoshima 890-0065, JAPAN (sabot@agri.kagoshima-u.ac.jp)
2) Faculty of Agriculture, Kagoshima University, 1-21-24 Korimoto, Kagoshima 890-0065, JAPAN (sabos@agri.kagoshima-u.ac.jp)
3) Faculty of Agriculture, Kagoshima University, 1-21-24 Korimoto, Kagoshima 890-0065, JAPAN (saboj@agri.kagoshima-u.ac.jp)

Abstract

We investigated the effects of volcanic ash covering on the runoff process and the areas contributing to the occurrence of Hortonian overland flow on a bare land slope by spreading Sakurajima volcanic ash over the experimental catchment. Results of analyses by a runoff model and field investigation showed that the ash-covering caused a decrease of rainfall loss and Manning's coefficient of roughness and an increase of the area contributing to the occurrence of Hortonian overland flow, surface runoff, and sediment discharge. However, the rainfall loss and Manning's coefficient of roughness increased over time through the armoring of the surface volcanic ash layer, and as a result, the area contributing to the occurrence of Hortonian overland flow, surface runoff, and sediment discharge also decreased.
Keywords: Sakurajima Volcano, volcanic ash, runoff process

Introduction

Volcanic eruptions create a radical alteration of the hydrologic and erosion regime of the surrounding areas. The hydrologic and erosion phenomena caused by volcanic eruptions have been investigated at many volcanoes, including Mount Usu (Chinen, 1986), Sakurajima Volcano (Shimokawa & Jitousono, 1987a, 1987b), Mount St. Helens (Collins & Dunne, 1986; Pierson, 1986), Mount Merapi (Shimokawa et al., 1996; Jitousono et al., 1996) and Mount Yakedake (Okuda et al., 1980; Suwa et al., 1989). Sediment yield and sediment discharge have been found to decrease with time except for volcanoes with continued volcanic activity, such as Sakurajima Volcano.

Sakurajima Volcano, which is an active volcano, has been continuously in action with frequent and lively small scale ash eruptions since 1972. Through this long period of volcanic activity, the flanks of Sakurajima Volcano became thickly covered with volcanic ash. Moreover, the flanks have experienced accelerated erosion, and consequently debris and mud flows have often occurred in the rivers located around them.

To clarify the effects of volcanic ash covering on the runoff process of rain water and sediment discharge in addition to the area contributing to the occurrence of Hortonian overland flow, we established an experimental catchment on a bare land slope, whereupon we spread Sakurajima volcanic ash over the experimental catchment. The results of this investigation are presented and discussed in this paper.

ISTUDY AREA AND METHODS

The study area is a part of the upper reach of the Hachitani gully of the tributary of the Hikinohira River located on the western flank of Sakurajima Volcano, as shown in **Fig. 1**. To investigate the effects of volcanic ash on the runoff process, the area contributing to the occurrence of Hortonian overland flow, surface runoff, and sediment discharge by sheet erosion on Sakurajima Volcano, an experimental catchment was established at 418 m above sea level in the Hachitani gully (Fig. 1, **Photo 1**). The catchment area is 11 m^2, with an average slope inclination of 21 degree and slope length of 5 m. It is covered with volcanic ash resulting from successive eruptions of Sakurajima Volcano (Photo 1). Both the topography of the experimental catchment and the distributions of the median diameter of solid particles of the surface volcanic ash layer, measured in the experimental catchment on the 16th of May, 2003, are shown in **Fig. 2**. The median diameter of solid particles in the concave part was larger than those in the ridge part. The mean value of the median diameter of solid particles in the surface volcanic ash layer in the experimental catchment was 0.19 mm.

In the lowest part of the experimental catchment, a plastic box for measuring surface runoff and

pp. 303–310

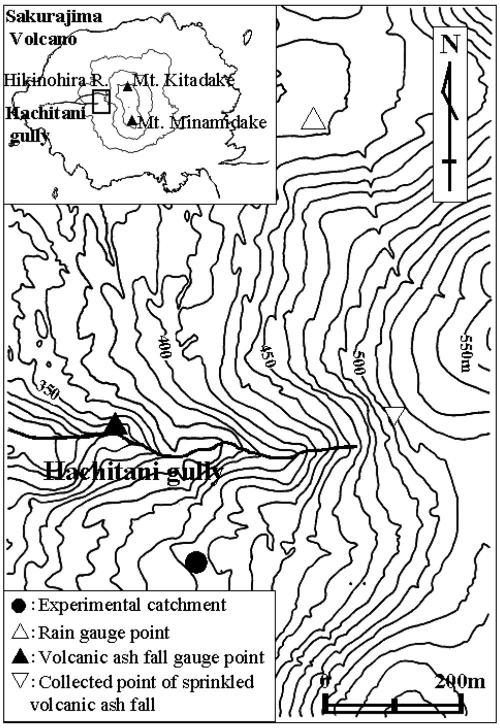

Fig. 1. Location and topography of the study area.

Photo. 1. State of the experimental catchment.

sediment discharge by sheet erosion was installed (Photo 1). Measurement began on the 16th of May, 2003. Surface runoff and sediment discharge by sheet erosion were measured during the 16th of May and the 17th of August, 2003, in their natural state in the experimental catchment. After the volcanic ash was spread on the whole of the ground surface of the experimental catchment on the 17th of August, 2003, the measurement of surface runoff and sediment discharge by sheet erosion was continued. The spread volcanic ash was collected at 510 m above sea level in the Hachitani gully (Fig. 1). The thickness of the volcanic ash spread on the whole of the ground surface of the experimental catchment was about 5 mm. **Fig. 3** shows the grain-size distribution of the volcanic ash spread on the surface ground of the experimental catchment. The median diameter of solid particles in the spread volcanic ash was 0.15 mm, and the coefficient of uniformity of the spread volcanic ash was 6.4. The measurement of surface runoff and sediment discharge by sheet erosion was repeatedly conducted for every runoff during the measured period. After sediment discharge by sheet erosion was collected, grain-size analysis was conducted. Moreover, the amounts of volcanic ash fall and rainfall were measured at a location nearby the experimental catchment (Fig. 1).

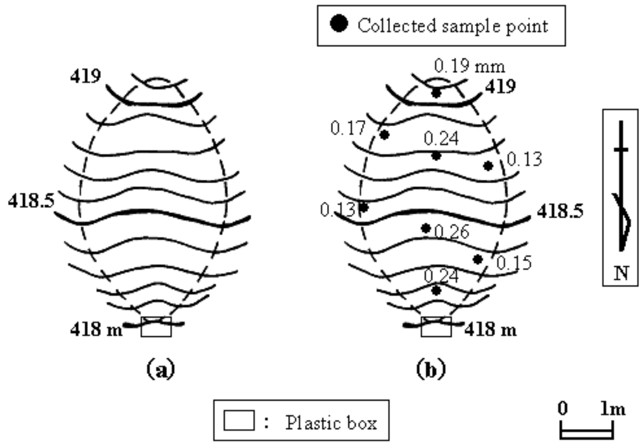

Fig. 2. Topography of the experimental catchment (a) and the distributions of the median diameter of solid particles of the surface volcanic ash layer in the experimental catchment (b).

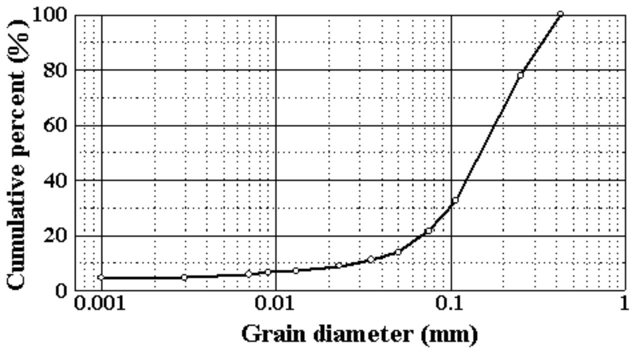

Fig. 3. Grain-size distribution of the spread volcanic ash.

RESULTS AND DISCUSSION

Surface runoff and sediment discharge by sheet erosion before and after the spreading volcanic ash

Figure 4 shows the relationship between the total amount of rainfall and surface runoff (a) and sediment discharge by sheet erosion (b) for each runoff before and after the spreading volcanic ash during the measured period. Surface runoff and sediment discharge became larger with increased rainfall. In cases where rainfall intensities were of the same degree, surface runoff and sediment discharge were greater on the slope spread with volcanic ash than on the slope before volcanic ash was spread.

Figure 5 shows the relationship between the maximum rainfall per 60 minutes and the median diameter of solid particles in the sediment discharge by sheet erosion for each runoff before and after the spreading volcanic ash during the measured period. The median diameter of solid particles in the sediment discharge became larger with increased maximum rainfall per 60 minutes. In cases where rainfall intensities were of the same degree, the median diameter of solid particles in the sediment discharge was greater on the slope with spread volcanic ash than on the slope before volcanic ash was spread.

Figure 6 shows changes in the value of sediment discharge by sheet erosion divided by surface runoff (in this paper, we refer to this value as SD/SR) and the total amount of rainfall for each runoff during the measured period. The SD/SR for the slope before volcanic ash was spread was between 0.006 and 0.114 (average 0.055), and for the slope spread with volcanic ash it was between 0.077 and 0.189 (average 0.126). The SD/SR was greater on the slope spread with volcanic ash than on the slope before volcanic ash was spread. After the 14th of September, 2003, the SD/SR tended to decrease with time by erosion of the surface volcanic ash layer. The volcanic activity of Sakurajima Volcano during the period between the 16th of May, 2003, and the14th of March, 2004, when surface runoff and sediment discharge by sheet erosion was measured, was very light. The accumulation thickness of the total amount of volcanic ash fall measured at a location nearby

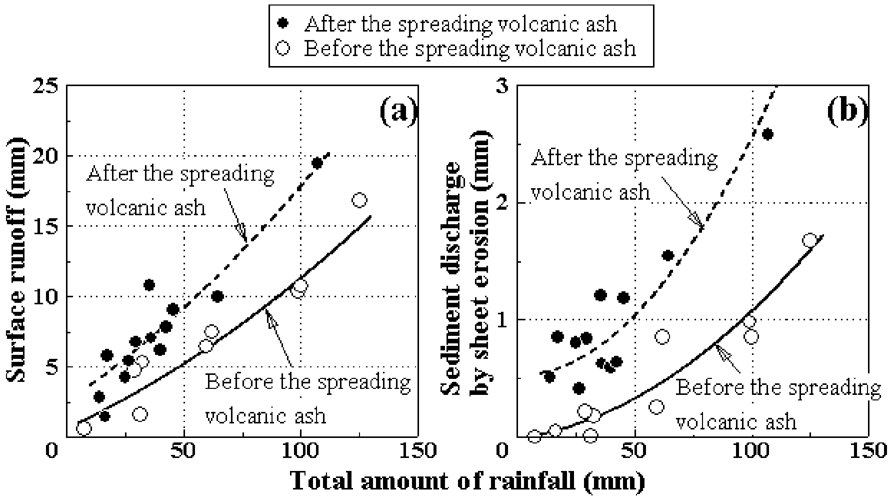

Fig. 4. elationship between the total amount of rainfall and surface runoff (a) and sediment discharge by sheet erosion (b) for each runoff during the measured period.

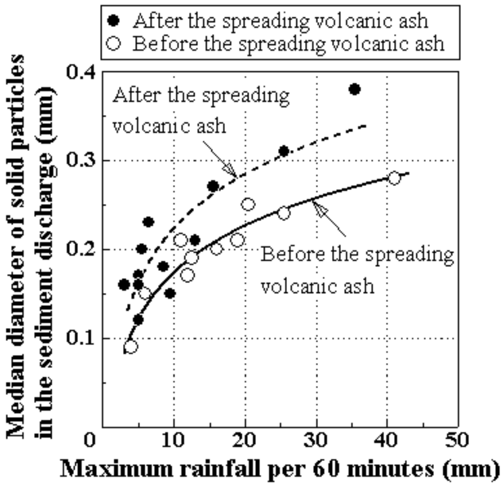

Fig. 5. Relationship between maximum rainfall per 60 minutes and the median diameter of solid particles in the sediment discharge by sheet erosion for each runoff during the measured period.

the experimental catchment during the measured period was 0.01 mm.

Ogawa et al. (2003) conducted a field experiment on the ash-covering of a slope made up of pyroclastic-flow deposits caused by volcanic activities on Unzen Volcano. Their results showed that the SD/SR was greater on the slope spread with volcanic ash than on the slope before volcanic ash was spread, and that the SD/SR decreased with erosion of the surface volcanic ash layer. These results are in harmony with the results of the current study.

Runoff process

The runoff process was investigated by using surface runoff measured during the period between the 16th of May, 2003, and the 14th of March, 2004, in the experimental catchment. The runoff process was modeled as follows. The rainfall that exceeds the sum of initial rainfall loss and final infiltration capacity generates Hortonian overland flow in the rainfall that reached the ground surface of the experimental catchment. Hortonian overland flow transports the eroded sediments of the surface volcanic ash layer. The kinematic-wave method was used as a runoff model. In this model, the runoff process was expressed using three parameters: rainfall loss, Manning's coefficient of roughness, and the area contributing to the occurrence of Hortonian overland flow. Surface runoff was also calculated using these three parameters.

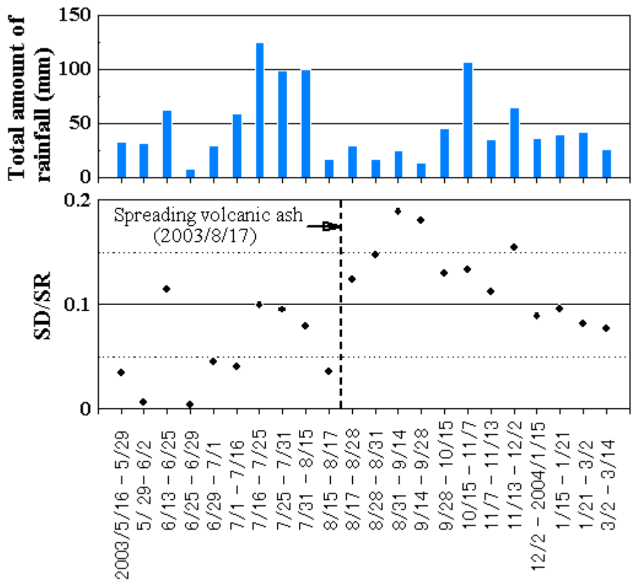

Fig. 6. Changes in the SD/SR (sediment discharge by sheet erosion divided by surface runoff) and the total amount of rainfall for each runoff during the measured period.

Effective rainfall (Re(i)) can be expressed as follows,

$$R_e(i) = 0 \qquad (\Sigma R < R_L) \tag{1}$$
$$R_e(i) = R(i) - I_r \qquad (\Sigma R > RL) \tag{2}$$

where $R(i)$ is rainfall, I_r is final infiltration capacity, ΣR is the total amount of rainfall during each measured period, and R_L is initial rainfall loss. When it is supposed that Hortonian overland flow follows Manning's formula, continuous and the equation of motion of the flow on the slope can be expressed as follows,

$$\partial A/\partial t + \partial Q/\partial x = R_e \tag{3}$$
$$A = n^{0.6}B^{0.4}I^{-0.3}Q^{0.6} \tag{4}$$

where A is the cross sectional area per unit width, Q is the water discharge per unit width, t is time, x is distance along the slope, R_e is effective rainfall, n is Manning's coefficient of roughness, B is the width of running water of Hortonian overland flow, and I is the average slope inclination in the experimental catchment. According to a field investigation, B was 0.2 m. The values of I and slope length were determined based on the result of a field survey, which indicated that I was 0.24 and slope length was 5 m. These calculations supposed that the continuous time of the occurrence of Hortonian overland flow was equal to the continuous time of the occurrence of effective rainfall. Rainfall loss is given by subtracting the measured surface runoff from the total amount of rainfall during each measured period. The optimum set of two parameters, Manning's coefficient of roughness and the area contributing to the occurrence of Hortonian overland flow, was decided after the calculation of all possible combinations of the parameters. The minimum value of the mean square deviation (E) in equation (5) was regarded as the optimum value of the two parameters.

$$E = (Q_m - Q_c)^2/Q_m^2 \tag{5}$$

where Q_m is the measured surface runoff, and Q_c is the calculated surface runoff. Manning's coefficient of roughness was varied between 0.001 sec/m1/3 and 0.5 sec/m$^{1/3}$. The area contributing to the occurrence of Hortonian overland flow was varied between 0 m^2 and the catchment area (11 m^2).

Figure 7 shows the relationship between 10-day antecedent rainfall and the rainfall loss both before and after the spreading volcanic ash for each runoff. The rainfall loss became smaller with increased antecedent rainfall. In cases where antecedent rainfall values were of the same degree, the rainfall loss values were smaller on the slope spread with volcanic ash than on the slope before volcanic ash was spread.

Figure 8 shows the changes of Manning's coefficient of roughness by runoff analysis and the total amount of rainfall for each runoff. Manning's coefficient of roughness for each runoff in the slope before volcanic ash was spread was between 0.02 sec/m$^{1/3}$ and 0.066 sec/m$^{1/3}$, and in the slope spread with volcanic

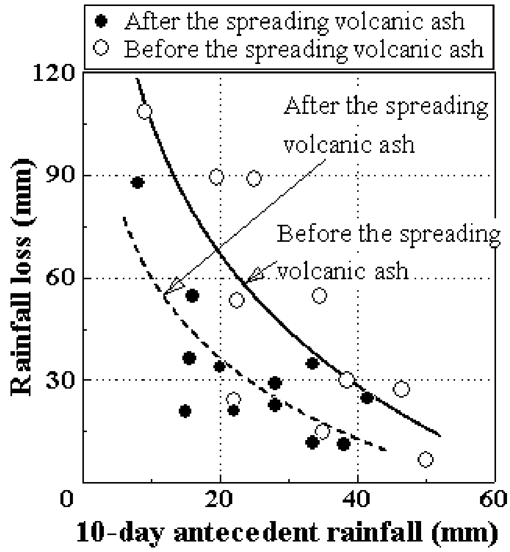

Fig. 7. Relationship between the 10-day antecedent rainfall and the rainfall loss for each runoff during the measured period.

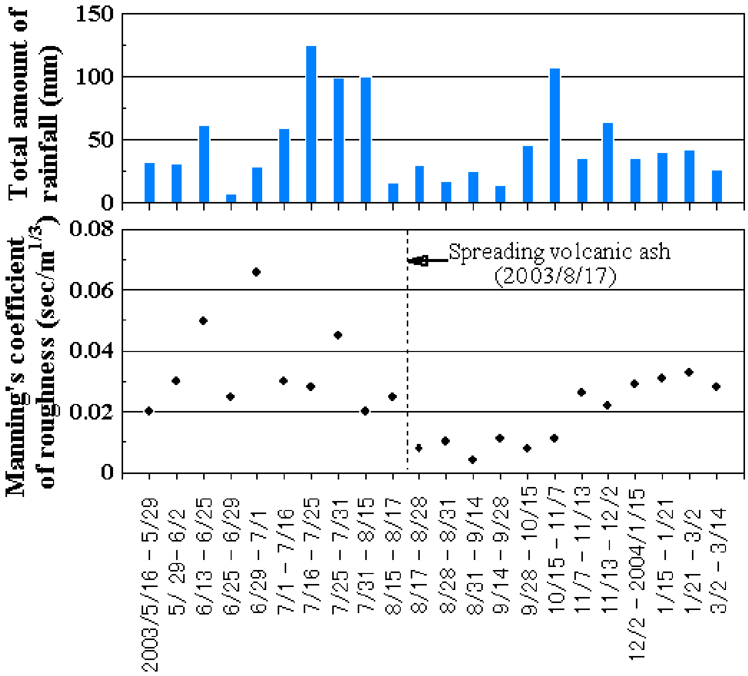

Fig. 8. Changes in Manning's coefficient of roughness by runoff analysis and the total amount of rainfall for each runoff during the measured period.

ash it was between 0.008 sec/m$^{1/3}$ and 0.033 sec/m$^{1/3}$. Manning's coefficient of roughness decreased greatly after the volcanic ash was spread, but it also tended to increase with time by erosion of the surface volcanic ash layer.

Figure 9 shows the relationship between the total amount of rainfall and the proportion of the area contributing to the occurrence of Hortonian overland flow by runoff analysis in the catchment area of the experimental catchment for each runoff before and after the spreading volcanic ash. This figure shows that the area contributing to the occurrence of Hortonian overland flow becomes larger with increased rainfall. Indeed, the proportion of the area contributing to the occurrence of Hortonian overland flow in the catchment area of the experimental catchment became larger with increased rainfall, and in cases where rainfall intensities were of the same degree, the proportion of the area contributing to the occurrence of Hortonian overland flow in the

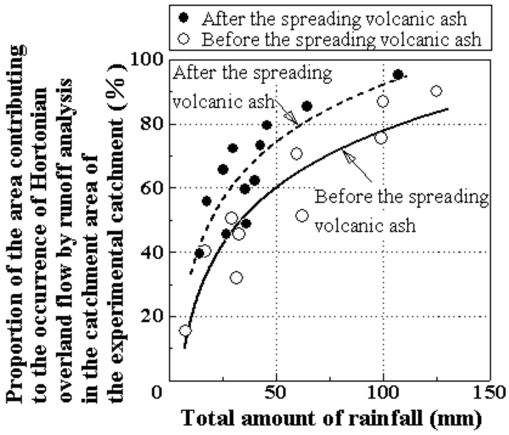

Fig. 9. Relationship between the total amount of rainfall and the proportion of the area contributing to the occurrence of Hortonian overland flow by runoff analysis in the catchment area of the experimental catchment for each runoff during the measured period.

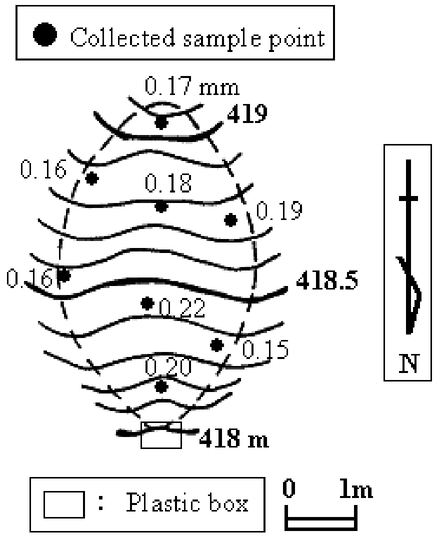

Fig. 10. Distributions of the median diameter of solid particles of the surface volcanic ash layer in the experimental catchment.

catchment area of the experimental catchment was greater on the slope spread with volcanic ash than on the slope before volcanic ash was spread.

Figure 10 shows the distributions of the median diameter of solid particles of the surface volcanic ash layer in the experimental catchment. Samples of the surface volcanic ash layer were collected on the 17th of March, 2004, after the end of the measurement. The collected sample points and method of collecting samples were the same, as shown in Fig. 2 (b). The mean value of the median diameter of solid particles in the surface volcanic ash layer of the volcanic ash that was spread on the 17th of August, 2003, in the experimental catchment was 0.15 mm, but the mean value of the median diameter of solid particles in the surface volcanic ash layer measured on the 17th of March, 2004, in the experimental catchment was 0.18 mm. This indicates that the surface volcanic ash layer became armored with time by erosion. This result is in harmony with the incremental tendency of Manning's coefficient of roughness by runoff analysis with erosion of the volcanic ash layer after the spreading volcanic ash, as shown in Fig. 8. The armoring of the surface volcanic ash layer occurred not only in the concave part but also in the ridge part of the experimental catchment, indicating that the ridge part of the experimental catchment became the area that contributed to the occurrence of Hortonian overland flow.

CONCLUSIONS

We investigated the effects of volcanic ash covering on the runoff processes of rain water and sediment discharge in addition to the areas contributing to the occurrence of Hortonian overland flow on a bare land slope by spreading Sakurajima volcanic ash over the experimental catchment. Results indicated that in cases where rainfall intensities were of the same degree, surface runoff, sediment discharge by sheet erosion, and the median diameter of solid particles in the sediment discharge were greater on the slope spread with volcanic ash than on the same slope before volcanic ash was spread. The SD/SR value, that is, the value of sediment discharge by sheet erosion divided by surface runoff, increased after the volcanic ash was spread. However, the SD/SR tended to decrease with time by erosion of the surface volcanic ash layer. Moreover, results of analyses by a runoff model and field investigation showed that the ash-covering caused a decrease of rainfall loss and Manning's coefficient of roughness and an increase of the area contributing to the occurrence of Hortonian overland flow, surface runoff, and sediment discharge. However, the rainfall loss and Manning's coefficient of roughness increased with time through the armoring of the surface volcanic ash layer, and as a result, the area contributing to the occurrence of Hortonian overland flow, surface runoff, and sediment discharge also decreased.

ACKNOWLEDGEMENTS

The authors thank the students of the Erosion Control Engineering and Forest Hydrology Laboratory of the Faculty of Agriculture at Kagoshima University, the Kagoshima Regional Forestry Management Office, and the Foundation of Ringyodoboku Consultants for their cooperation.

REFERENCES

Chinen, T. (1986) Surface erosion associated with tephra deposition on Mt. Usu and other volcanoes, *Environ. Sci. Hokkaido Univ.*, **9**(1),137–149.

Collins, B. D. and Dunne, T. (1986) Erosion of tephra from the 1980 eruption of Mount St. Helens, *Geol. Soc. Amer. Bull.*, **97**, 896–905.

Jitousono, T. and Shimokawa, E. (1989) Surface runoff on tephra-covered hillslope in Sakurajima volcano, *Jour. Jap. Soc. Erosion Control Engineering*, **42**(3), 18–23 (in Japanese).

Jitousono, T. and Shimokawa, E. (1991) Effects of volcanic activity on occurrence and runoff of debris flow in Sakurajima volcano, *Jour. Jap. Soc. Erosion Control Engineering*, **43**(6), 9–15 (in Japanese with English abstract).

Jitousono, T., Shimokawa, E. and Tsuchiya, S. (1996) Debris flow following the 1984 eruption with pyroclastic flows in Merapi volcano, *Jour. Jap. Soc. Erosion Control Engineering*, **48**, *Special Issue*, 109-116.

Ogawa, Y., Shimizu, A., Shimizu, T. and Miyabuchi, Y. (2003) An experimental study on surface runoff and sediment discharge on a slope covered with fine-grained volcanic ash, *Jour. Jap. Soc. Erosion Control Engineering*, **39**(6), 11–17 (in Japanese with English abstract).

Okuda, S., Suwa, H., Okunishi, K. Yokoyama, K. and Nakano, M. (1980) Observation on the motion of a debris flow and its geomorphological effects, *Zeit. Geomorph. N. F., Suppl., Bd.* **35**, 142–163.

Pierson, T. C. (1986) *Flow behavior of channelized debris flows, Mount St. Helens, Washington*, In Abrahams, A. D. ed., Hillslope Processes, Boston, Allen & Unwin, 269–296.

Shimokawa, E. and Jitousono, T. (1987a) Sediment yield by sheet erosion from hillslopes of Sakurajima volcano, *Jour. Jap. Soc. Erosion Control Engineering*, **39**(6), 11–17 (in Japanese).

Shimokawa, E. and Jitousono, T. (1987b) Rate of erosion on tephra-covered slopes of volcanoes, *Trans. Jap. Geomorph. Union*, **8**, 269–286 (in Japanese with English abstract).

Shimokawa, E., Jitousono, T. and Tsuchiya, S. (1996) Sediment yield from the 1984 pyroclastic flow deposits covered hillslopes in Merapi volcano, *Jour. Jap. Soc. Erosion Control Engineering*, **48**, *Special Issue*, 101-107.

Suwa, H., Manaka, T. and Inaniwa, A. (1989) Occurrence of debris flows and their scales in the Kamikamihori valley of Mount Yakedake, *Ann. Disast. Prev. Res. Inst. Kyoto Univ.*, **32B-1**, 229–247 (in Japanese with English abstract).