Post-Eruption Characteristics of Rainfall Runoff and Sediment Discharge at the Miyakejima Volcano, Japan

Satoshi Tagata,[1)] Takao Yamakoshi,[1)] Yasuhiro Doi,[2)] Jun'ichi Kurihara,[1)] Hideki Terada[1)] and Naoki Sakai[1)]
1) Public Works Research Institute, 1-6 Minamihara, Tsukuba Ibaraki 305-8516, Japan (tagata44@pwri.go.jp)
2) C. S. J. Co., Ltd

Abstract

The Miyakejima Volcano, which is located to the south of Tokyo, erupted voluminous tephra in 2000. Deposition of tephra changed the hydrologic properties of the river basins around the volcano and intensified erosion processes and storm runoffs have occurred even at the time of low-intensity rainfall in the rivers that had hardly ever generated runoff before the eruption. In this study, post-eruption hydrology and erosion properties at the Miyakejima volcano are studied through field hydrologic measurements.

The results indicate that runoff rates of the study slopes were different from each other depending on the conditions and properties of the deposited tephra and that the runoff rates have declined in the 4 year study period. Fine sediments still run off from the upper slopes, while gullies developed rapidly for a few months and subsequently their development has decelerated. Runoff rates of all the river basins were also different from each other depending on the conditions and properties of the deposited tephra in the upper slopes. Almost no sediment discharge is observed in the rivers where the solidified lava has been exposed on the riverbeds. On the other hand, the significant sediment discharge continues in the rivers whose riverbeds are composed of the erodible sediment such as scoria.

Keywords: rainfall runoff, sediment discharge, Miyakejima volcano

Introduction

In river basins where tephra has been deposited by a volcanic eruption, the permeability of the ground surface is sharply reduced, causing frequent mud flows during rain events (e.g. Collins and Dunne, 1986). Miyakejima volcano erupted voluminous fine ash in 2000. After this eruption, storm runoff and sediment runoff were caused by only light rainfall in river basins where runoffs almost never occurred before the eruption. We started surveys and observations of rainfall runoff, erosion, and vegetation in 2002 to clarify rainfall and sediment runoff properties, and changes over time (e.g. Yamakoshi et al., 2005). And we surveyed changes of vegetation between 2002 and 2005 that were 2 and 5 years respectively after the eruption. This report discusses the post-eruption storm runoff properties, sediment runoff properties, and the conditions of the vegetation according to the results of these surveys and observations.

Eruptive activity of Miyakejima Volcano in 2000

Miyakejima Island is a round volcanic island, located approximately 180km south of Tokyo. Its area is 55km^2 and its diameter is 8km. The volcano consists of basaltic rocks. A crater is located in the center of the island, and valleys radiate from the crater.

While past eruptions on Miyakejima have belched lava, scoria etc. from cracks in the mountain slope of the volcano, the 2000 eruption discharged voluminous volcanic ash from its mountaintop. The 2000 eruptions discharged a total of 32,000,000m^3 of volcanic ejecta during a total of 7 eruptions from July 8 until August 29, 2000 (E.R.I., 2001). Figure 1 shows the thickness of the volcanic ash deposited by these eruptions. This figure indicates that it was deposited in thicker layers in the east–west direction. After ash deposition, mudflows occurred in almost all the streams on Miyakejima.

Method

Hydrological observation points were established at a total of 7 locations on the slopes of Kaniga-sawa River on the eastern side, Tatsune-sawa River on the southern side, and on Enoki-sawa River on the west side of the island, and water level gauges were established at the bottom ends of the streams on the island to observe storm runoffs and sediment runoffs from the ash-deposited slopes and drainage basins (Fig. 2). On the

pp. 291–301

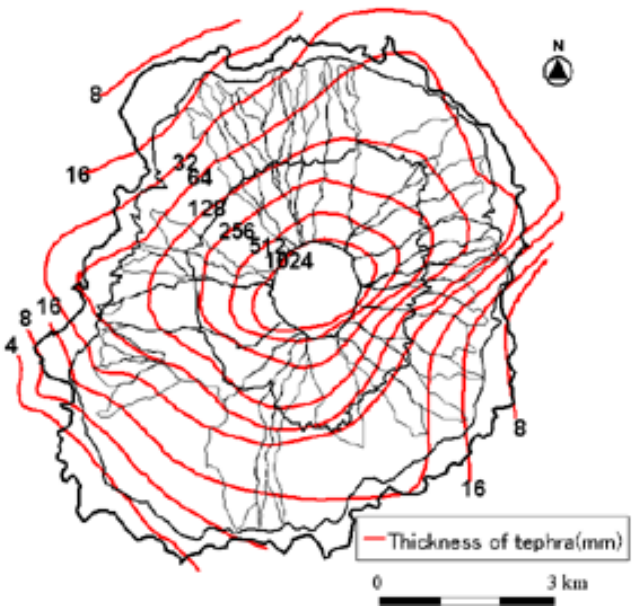

Fig. 1. Thickness of volcanic ash of the eruptions of the 2000 eruption of Miyakejima volcano (E.R.I., 2001)

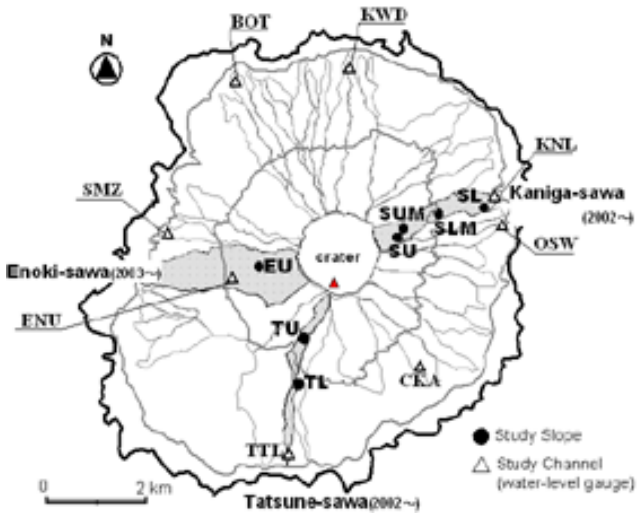

Fig. 2. Location map of the survey site

observation slopes, flow gauging weirs were established, and the rainfall and soil water content were measured. The quantity of sediment yield from the observation slopes was periodically measured by using buckets to sample sediment deposited in sediment settlement ponds. Table 1 shows the specifications of each study slope. The study slopes indicated by the codes SU, SUM, SLM, TU, and EU are bare slopes, while those indicated by SL and TL are vegetated. And the grain size on SU, SUM, SLM, SL, and on TU and on TL were fine grains of D_{50} = 0.05mm, while on EU they were D_{50} = 2.9mm, that is coarser grain diameter than on the other study slopes.

Runoff and Sediment Discharge on the Study slopes

(1) Storm runoff properties on the study slopes

Figure 3 shows the hydrograph for November 20, 2003 as an example of storm runoff on the 7 study slopes. Percentages in the figure show the runoff ratios defined as the total Runoff per total Rainfall. This total Rainfall indicates the continuous rainfall that is no rainfall in the last 6 hours. The response to rain on SU, SUM, and SLM on Kaniga-sawa and at TU on Tatsune-sawa, and at EU on Enoki-sawa were extremely

Table 1. Characteristics of study sites

Drainage Basin	Study sites	Alutitude (m)	Drainage area (m^2)	Mean slope angle (degree)	Thickness of tephra deposit (cm)	Average particle diameter (mm)
Kaniga-sawa	SU	480	82	28	60	0.05
	SUM	440	35	21	46	0.08
	SLM	280	475	14	26	0.07
	SL	130	138	19	11	0.04
Tatsune-sawa	TU	480	204	20	15	0.03
	TL	350	455	10	5	0.08
Enoki-sawa	EU	480	163	26	60	2.9

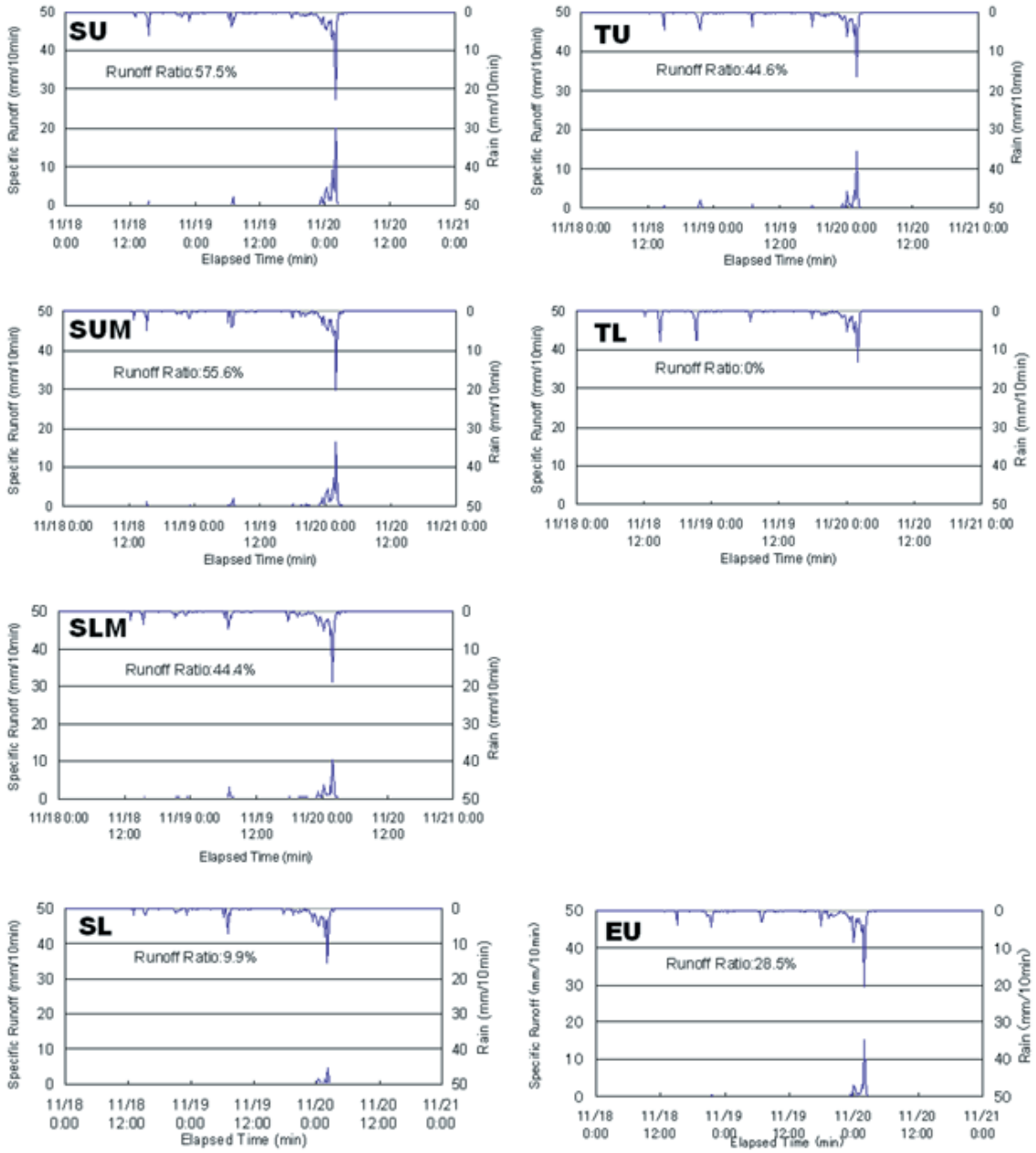

Fig. 3. Hydrographs at the study sites on November 20, 2003

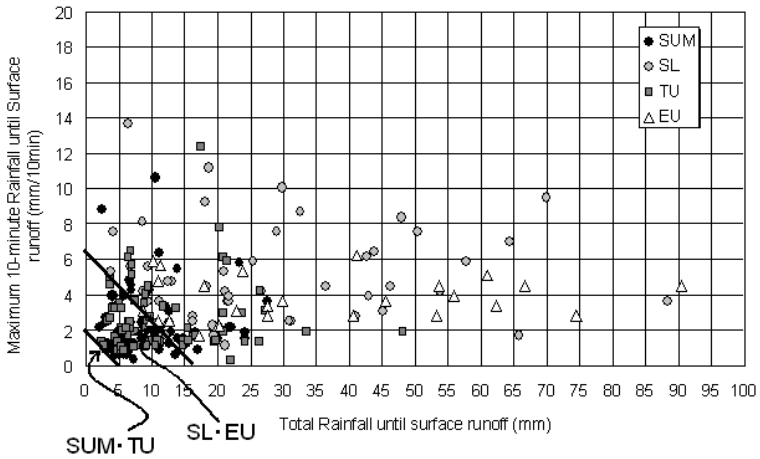

Fig. 4. Rainfall Conditions Until Surface Runoff on the Study Slopes

quick, with the runoff peak appearing at almost the same time as the peak of the rain, revealing high runoff ratio. The runoff ratio was next highest on EU, while, on SL and at TL there was almost no response to the rain, and the runoff ratio were extremely low.

Next, Figure 4 shows the relationship of the total rainfall with the maximum 10 minute rainfall until surface flow occurred. The figure shows the results for SUM and SL at Kaniga-sawa, for TU at Tatsune-sawa, and for EU at Enoki-sawa. At SUM and TU where the annual average runoff ratio is high, surface runoff occurs at total rainfall of 5mm and at 10-minute rainfall of 2mm, while at SL and EU where the runoff ratio is low, surface runoff occurs at total rainfall of 15mm and at 10-minute rainfall that exceeds 6mm.

Figure 5 shows the relationship between the rain and runoff from 2002 to 2004. This figure plots the total rainfall and the total runoff caused by each rain event, and the inclination shows the runoff ratio. This figure shows large inclinations on SU, SUM, and SLM and on TU, revealing high runoff ratio. While, the inclination on SL and TL is extremely low. As shown by Figure 3 and Figure 5, runoff properties differ according to the study slopes. The following are considered to be the causes of this difference. On SU, SUM, SLM, and TU, the high runoff ratios are considered to have been caused by the thick covering of fine-grained volcanic ash deposited on their surfaces in bare condition. On SL and on TL on the other hand, the runoff ratios are low because the surfaces were covered with fallen leaves and with vegetation. The runoff ratio on EU where volcanic ash is deposited to the same thickness as it is on SU and SUM is lower than the runoff rate on SU and SUM, presumably because the grain size of the volcanic ash deposited on EU is coarser and has higher permeability than in the other study slopes.

Next, runoff ratio on SU and SUM and on TU located upstream tended to fall over time. And even on SL, slight runoffs occurred in 2002 and 2003, but almost none was seen in 2004. Previous studies show that the runoff ratio falls because of the impact of vegetation on the slopes (e.g. Nishida et al., 1998). However, on SU, SUM, and TU, little change of the vegetation on the surface was seen from 2002 to 2004. On SU, SUM, and TU, rills with depth from 30cm to 50cm formed, and the original ground surface was partly exposed in the bottoms of these rills (Fig. 6). The original ground layer was formed mainly by scoria and other highly pervious materials, and it is hypothesized that when surface runoff flowed inside the rill, a part of it might permeate into small patches where the original ground surface was exposed. Although we have never found the quantitative evidence on the increase in the exposed areas in the study slopes, SU, SUM and TU, it seems to be most likely because no vegetation increase had been observed. Furthermore, we have measured the saturated hydraulic conductivity of the original soil and found that it is 2-order larger than that of the tephra. It means that the slight and undetectable increase in the exposed area could reduce considerable amount of water discharge from the rill. It is also consistent with the previous studies (e.g. Collins and Dunne, 1986; Yamamoto, 1984) that have shown that the exposure of the original soil by the progressive erosion of the covering tephra can play a major role in the temporal decrease in surface runoff from tephra-mantle slopes.

On SL, on the other hand, the vegetation recovered remarkably in 2004, and the recovery of the vegetation lowered the runoff ratio. There was almost no change of the runoff rate on SLM under the influence of the fact that rills had not developed to the degree they had on SU and SUM, the insides of the rills were still covered by volcanic ash, and the vegetation had not recovered.

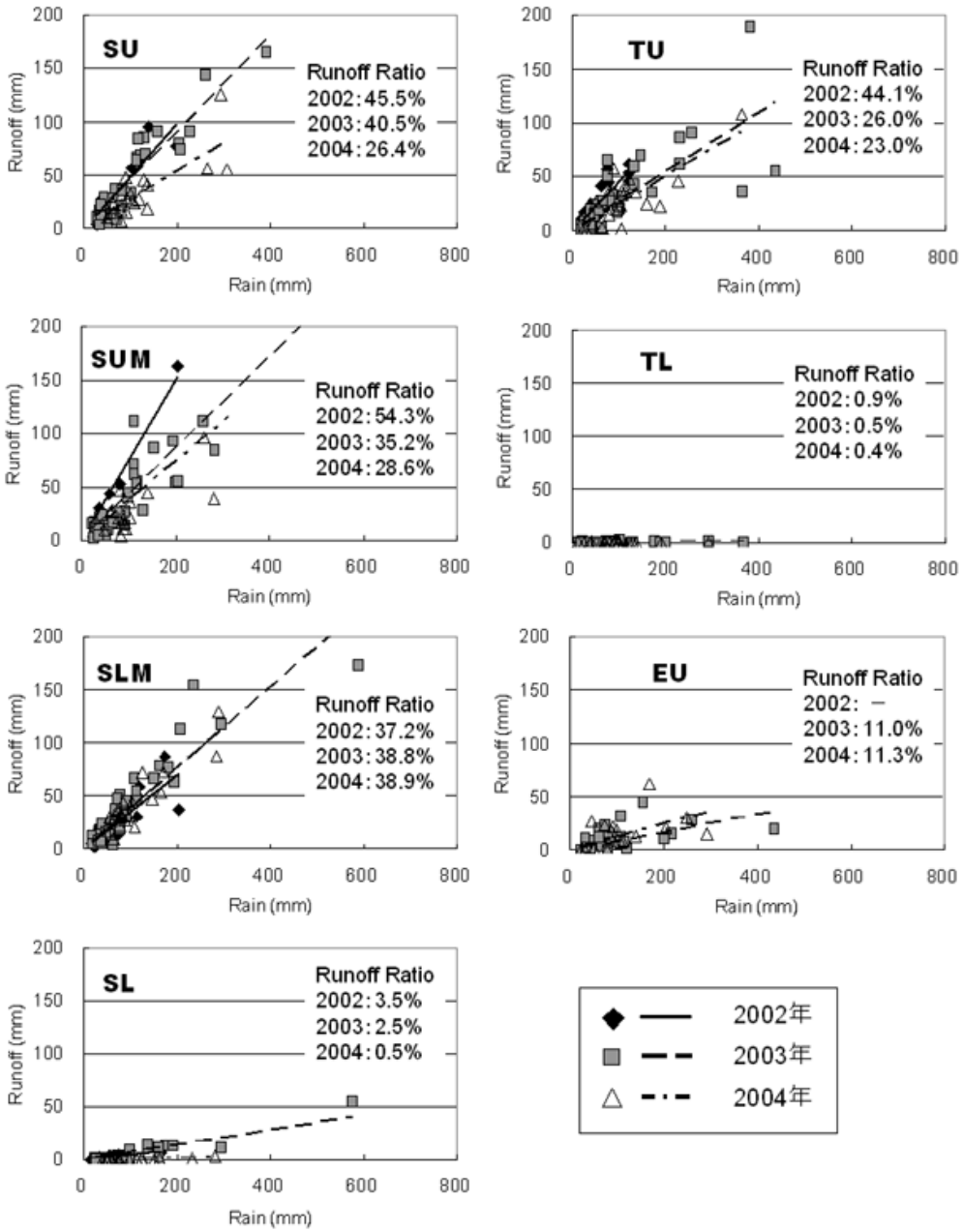

Fig. 5. Rainfall-runoff relationship at the study sites

(2) Properties of sediment runoff from the study slopes

The sediment deposited in the settling basins installed at the ends of the study slopes was periodically measured. The sediment was measured using buckets to take samples of sediment deposited in the settling basin to record the number of buckets of sediment obtained and its weight. The sediment that was deposited is assumed to be runoff by rill erosion and by surface erosion. But because assuming that it is run off as suspended load and as wash load, it is believed that the suspended load and wash load in the discharged water are partly discharged without settling in the settling basin, consequently the fine-grained sediment was not all trapped.

Figure 7 shows changes in the sediment yield from the study slopes between 2002 and 2004. It reveals that the sediment yield from SU and SUM, from TU and from EU located on upstream areas were high. Next, it was 1 order lower on SLM and almost no sediment was run off on SL and TL. As the years passed, it tended to fall a little at SU, but remained on almost all the study slopes and the sediment yield hardly changed with time. This is assumed to be a result of no change in erodibility, because the erosion depth has remained on the newly deposited volcanic ash layer. On the other hand the fall of sediment yield as years passed on SU is

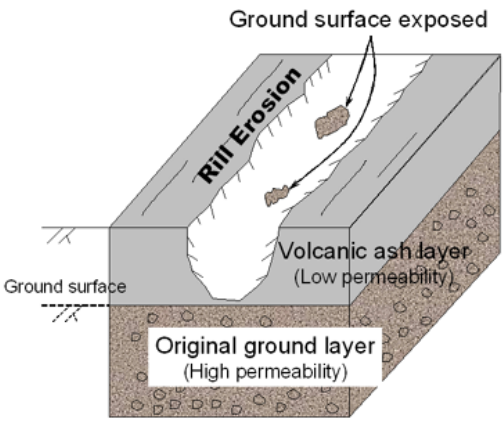

Fig. 6. Exposure of Original Ground surface in a Rill erosion

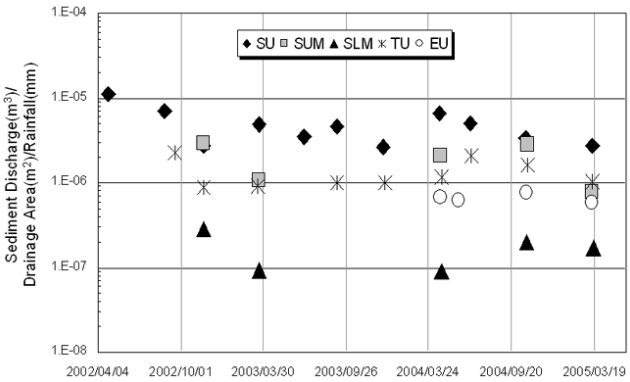

Fig. 7. Sediment yield from the Study Slopes between 2002 and 2004

assumed to be an effect of the fall of the runoff ratio. But on SUM and on TU where the runoff ratio of surface runoff fell with the years, no clear falling trend was seen in the quantity of sediment run off. It is necessary to conduct a study of the relationship of this factor with erosion resistance.

Runoff and Sediment discharge on the Study Streams

(1) Storm runoff properties in the streams

Water level gauges were established in each stream on Miyakejima to measure the rainfall runoff. Figure 9 shows the September 20, 2003 hyeto-hydrographs for the 8 streams shown in Figure 8. The island was divided into eastern, western, southern, and northern sectors and two streams in each direction were studied. The hydrographs for the streams in the north, east, south and west parts of the island are shown from the top. A comparison of the graphs for the four directions reveals differences between the streams, with streams on the east side showing the highest response to the rain particularly clearly. This suggests the same tendency seen in the other rains. As shown here, in each stream, the storm runoff characteristics differ. There are presumed to be a number of causes of these differences, but of these, the following are the major causes (see Table 2). In Kaniga-sawa and in Osawa on the east side, in addition to thick layers of deposited fine-grained volcanic ash on upstream slopes that reduce permeability, the exposure of lava throughout the stream bed is assumed to be a factor causing the high runoff ratio. While in Enoki-sawa located on the west side, the volcanic ash deposited in the upstream has coarser grain size and higher permeability than volcanic ash deposited on slopes in other river basins, presumably contributing to the low runoff ratio. In Tatsune-sawa on the south side, it is assumed that in addition to the small area impacted by the volcanic ash in the upstream region, the highly pervious scoria deposited on the stream bed from the midstream to the downstream also contributes to the low runoff ratio.

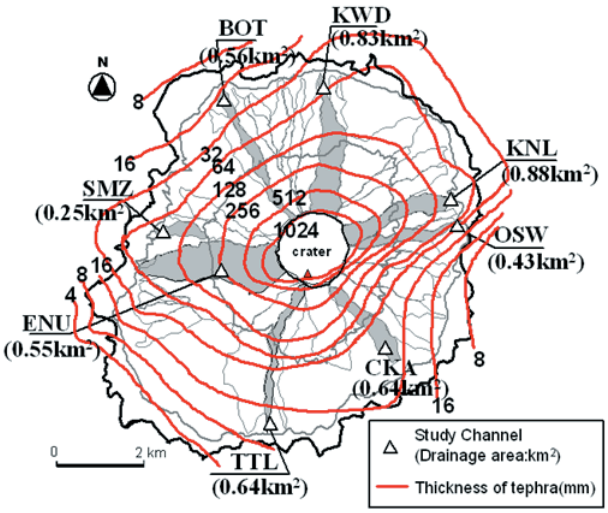

Fig. 8. Locations of the Study Streams

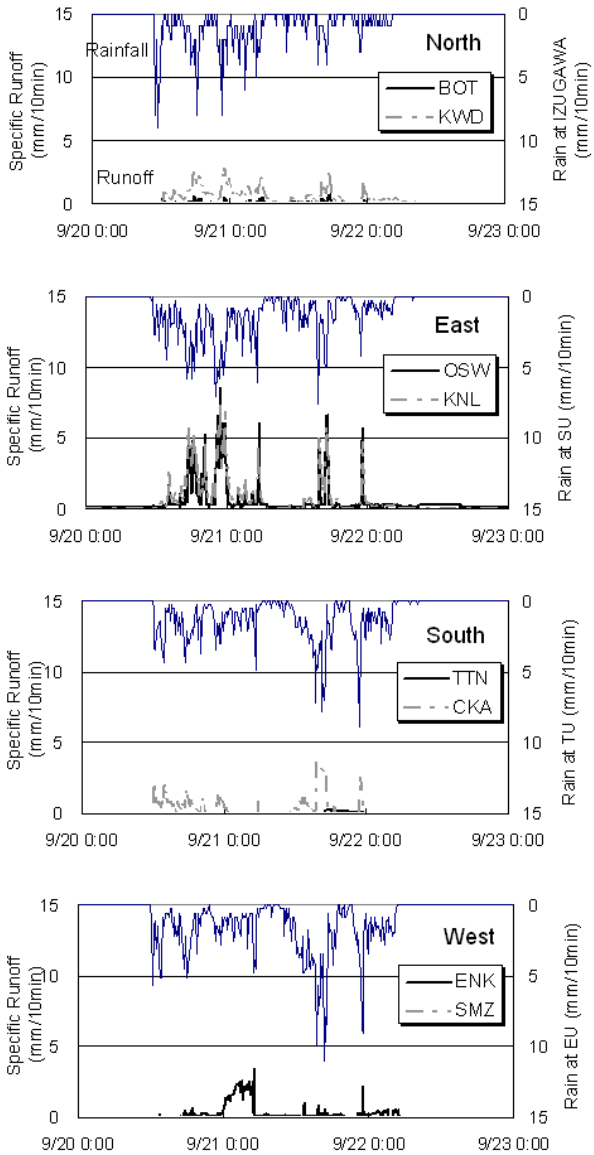

Fig. 9. Hydrograph of the Streams (Sep. 20, 2003)

Table 2. Factors Causing Differences between Runoff Ratio by Stream

	North	East	South	West
Runoff Ratio*	Low	High	Low	Low
Causes	・Narrow range of impact of volcanic ash ・Little damage to vegetation	・Wide range of impact of volcanic ash ・Lava exposure in streambed	・Large quantity of scoria deposited in streambed	・Coarse-grained volcanic ash

*: Relative evaluations

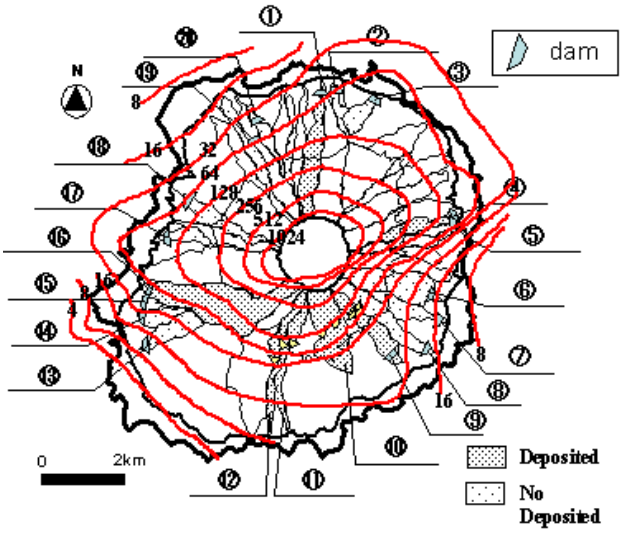

Fig. 10. Map of Locations of the Studied Torrents with Volcanic Ash Etc. Layer Thickness Contour Lines and Existance/non-existance of Deposited Ash Added

(2) Sediment runoff from each stream

The sediment deposition in the furthest upstream check dams that were established after the eruption was surveyed from August to September 2004 to study the state of sediment yield from each stream. Check dams were surveyed at the 20 locations shown in Figure 10. The map also shows 8 contour lines ranging from 1,024mm to 8mm representing the depth of the volcanic ash deposits, with coloring indicating whether or not sediment was run off in each stream.

According to whether or not deposition of sediment in dams during the one month period from August to September 2004 was confirmed, the streams are classified into two categories in Table 3. In this table, the area inside each stream covered by volcanic ash layers with thickness of 256mm or more is shown for descriptive purposes because it seems that it depends on the area covered by thick tehpra. This table shows that in streams with a range where volcanic ash was deeply deposited, sediment was deposited in the dams, but of the 13 streams where deposition was not found, in 9 streams with the area with deep volcanic ash deposition was zero. This means that in streams with a small area affected by volcanic ash, surface flow does not occur considerably, so little sediment is run off, while in streams with a large area affected by volcanic ash, surface flow occurs considerably when rain falls, thus sediment is discharged, suggesting a correlation of the deposition of volcanic ash with sediment runoff.

State of vegetation on the study slopes

Vegetation was surveyed two years after the eruption in 2002 and again in 2005, clarifying its recovery. The survey was conducted on SU, SUM, SLM, and SL in Kaniga-sawa and on TU and TL in Tatsune-sawa. The survey was conducted on EU in Enoki-sawa only in 2005.

First, the number of living trees per 10m × 10m on the surveyed slopes are shown in Figure 11. At both Kaniga-sawa and Tatsune-sawa, there is a tendency for the tree density to be low on high elevation surveyed

Table 3. Study Streams and Percentage of Area with Deposited Volcanic Ash

Deposition of dam	Stream	Drainage area(km²)	Stream length (km)	Stream gradient (%)	Percentage of area with volcanic ash deposit of 256mm or more(%)	Connection to crater ○ : Connected × : Not connected	Remarks
No deposited	②	0.17	1.23	19.3	0	×	
	③	0.29	0.85	24.3	0	×	
	⑤	0.14	0.90	23.1	0	×	
	⑥	1.13	2.00	29.2	7.8	○	Scoria on the alluvial cone
	⑦	0.42	1.75	26.3	0	×	
	⑧	0.86	2.55	25.0	8.6	○	
	⑬	0.49	1.27	22.4	0	×	
	⑭	0.29	1.18	21.2	0	×	
	⑮	0.11	0.80	25.0	0	×	
	⑰	0.25	1.20	18.3	0	×	
	⑱	0.53	2.45	22.9	34.6	○	
	⑲	0.58	2.30	25.3	20.4	○	
	⑳	0.27	0.50	15.1	0	×	
Deposited	①	0.82	2.55	25.1	38.3	○	Fine-grained sediment
	④	0.37	2.05	22.0	35.4	×	Fine-grained sediment, driftwood
	⑨	0.72	2.20	27.8	2.5	○	Fine-grained sediment, Scoria
	⑩	1.26	1.90	34.8	17.7	○	Fine-grained sediment
	⑪	0.65	3.10	18.9	6.3	○	Fine-grained sediment
	⑫	0.54	3.50	18.5	18.0	○	Scoria
	⑯	2.29	2.90	20.1	11.5	○	

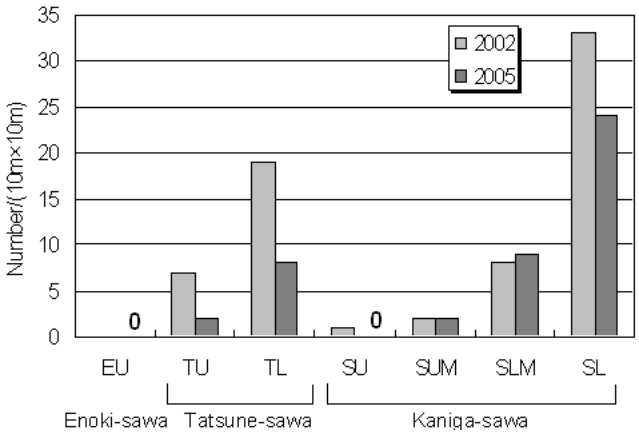

Fig. 11. Change over Time of Tree Density (Living Trees)

slopes. It is assumed that the further upstream and nearer the crater, the greater the impact of the volcanic gas and ash, obstructing the growth of live trees. A comparison between 2002 and 2005 reveals that on almost all the slopes, the tree density fell. Next, Figure 12 shows the percentage of land coverage areas of the surveyed slopes. We set a 2m-square quadrate at each slopes in 2002, and took a vertical photograph from above about 4m high, then analyzed the image data of this photograph. In 2005, another photograph was taken at the same point. On Kaniga-sawa and Tatsune-sawa, as in the case of the tree density, the coverage area is low on SU, SUM and TU that are in upstream districts, with high values observed on SL and TL that are downstream. Regardless of the fall of the tree density on SL and TL, the coverage rate increased as a result of the luxuriant growth of vegetation covering the ground: bats-wing ferns (*Histiopteris incisa*) at SL and a species of Evergold (*Carex oshimensis Nakai*) at TL. The ground surface on SU, SUM, and TU on the other hand was almost completely covered with fallen branches and no new plants were found. The formation of litter was not found, and it is assumed that it will take a long time for new plants to invade the area. A study of the results of these vegetation surveys shows that almost all the trees died in the upstream areas where the impacts of volcanic gas

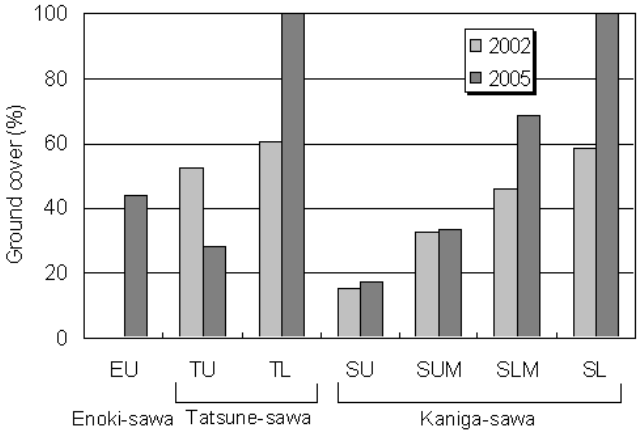

Fig. 12. Change over Time of Ground Cover

and volcanic ash are strong. And while no new growth has appeared even five years after the eruption, in the downstream areas where their impacts are weak, new plants were growing remarkably in 2005 although new tree growth is poor, and in the future, it is expected that the vegetation will gradually recover as the volcanic gas declines.

Conclusions

The results of surveys and observations performed since 2002 on Miyakejima where the volcano erupted in 2000 were summarized to study the characteristics of storm runoff and sediment runoff on slopes and in streams on the island. The following knowledge was gained from the results.

1) The storm runoff on the slopes is greatly influenced by the state of deposition of fine-grained volcanic ash and the grain diameter of the volcanic ash. At Kaniga-sawa and Tatsune-sawa, although the runoff ratio ranged from 50% to 30% in their upstream areas, almost no runoff was observed in their downstream areas. The total rainfall until the surface runoff was about 5mm in the upstream parts of Kaniga-sawa and Tatsune-sawa, and it was about 15mm in the downstream part of Kaniga-sawa and the upstream part of Enoki-sawa. An examination of change over time shows that generally the runoff rate has declined.

2) A comparison of sediment yield on the slopes shows that the further upstream, the heavier the quantity of sediment that is run off. Sediment runoff from slopes is assumed to be caused by surface erosion and rill erosion, and the differences between the quantities that are run off is a result of the effects of the runoff ratio of the surface flow and the slope gradient, etc.

3) Dividing the streams on the island into east, west, south, and north sectors and examining the storm runoff properties reveals differences between the four directions, and in particular, an extremely quick response to rain in the east sector. This is presumably a result of the fact that the percentages of the areas of the streams on the east side covered with fine-grain volcanic ash are high, that lava is exposed on the riverbeds, and that the permeability not only of the slopes, but of the riverbeds is low. The runoff ratios are low in the north, west, and south sectors because the percentages of the areas covered with a layer of fine-grained volcanic ash above a certain thickness is small, the grain size of the deposited volcanic ash is large, and the material deposited on riverbeds includes highly pervious scoria.

4) The results of a survey of the state of deposition in the furthest upstream check dams in each stream on the island from August to September 2004 that was 4 years after the eruption have shown that the larger the area of a river basin impacted by volcanic ash deposition, the greater the sediment discharge.

5) The vegetation was surveyed in 2002 and again in 2005 to study the state of recovery of vegetation. The results revealed that almost all the trees died in the upstream areas where the impacts of volcanic gas and volcanic ash are strong, and while no new growth has appeared even five years after the eruption, and in the downstream areas where their impacts are weak, the growth of trees has been poor, but in 2005, new vegetation was growing remarkably and the vegetation is expected to recover as it passes through a series of transitions, if the environmental conditions are adequate.

References

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

Earthquake Research Institute (2001) Volume of ejecta by eruptions of Miyakejima Volcano in 2000. *Data sheet assembly, 90th Coordinating Committee for Prediction of Volcanic Eruption, October 22*, 30

Nishida K., Kobashi S and Mizuyama T. (1998) How has revegetation changed surface runoff and sediment discharge on pyroclastic sediments in Unzen Volcano?, *J. Jap. Soc. Reveget. Tech.* 23(4), p.249–255.

Yamakoshi T., Doi Y. and Osanai N. (2005) Post-eruption hydrology and sediment discharge at the Miyakejima volcano, Japan. *Z. Geomorph. N. F.*, 40, p.55–72.

Yamamoto H. (1984) Erosion of the 1977–1978 Tephra Layers on a Slope of Usu Volcano, Hokkaido., *Transactions, Japanese Geomorphological Union.*, 5–2, p.111–124.