Post-eruption sediment budget of a small catchment on the Miyakejima volcano, Japan

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Abstract The Miyakejima volcano erupted in 2000, emitting a massive quantity of fine tephra. The deposition of the tephra encouraged erosion processes. Gullies rapidly developed in the upper slope close to the peak, including the slope of interest in this study. To understand post-eruption erosion processes, an aerial photograph survey and airborne laser scanning survey were conducted. The complementary analysis of the survey data revealed the following: (a) The total volume of the eroded sediment exceeds that of the tephra deposited by the 2000 eruption. The amount eroded in the four years since the eruption was estimated at 470 000 m^3 while the deposition of tephra is estimated at about 370 000 m^3. (b) Gully erosion was the dominant process on the study slope. It accounted for at least 87% of the total erosion, while rill and sheet erosion represented 5 and 8%, respectively. (c) Gully erosion almost stopped several months after the eruption. (d) The gullies eroded to considerable depths through the new tephra mantle. Almost 80% of the gully-eroded sediment was original soil. (e) The post-eruption erosion rate observed on the upper slope of the Miyakejima volcano was almost the largest of the rates reported in previous studies. This occurs not only because the mountain of the Miyakejima volcano consists of erodible sediment, but also because few studies have documented the erosion rate of the uppermost slope of a volcano in the very early stages of erosion.

Key words erosion rate; gully erosion; laser scanning survey; Miyakejima volcano, Japan

INTRODUCTION

In July 2000, the Miyakejima volcano (Japan) erupted, emitting fine-grained volcanic ash. The eruptions continued until the end of August of that year, covering the slopes of the mountain with a thick layer of volcanic ash. Because the surface of the fine tephra reduced permeability, surface runoff occurred readily during rainfall events, and the resulting increase in surface flow caused sheet erosion, rill erosion and gully erosion (see Yamakoshi *et al*., 2003). Whenever rain fell, mudflows flowed downstream.

It is important to clarify the state of erosion after an ash fall in order to study the sediment budget after a volcanic eruption. Past research has shown that gully erosion is a particularly important source of sediment on the slopes of a volcano after it has erupted (e.g. Chinen & Kadomura, 1986). We analysed the erosional response of a small catchment on Miyakejma by interpreting aerial photographs and using an aerial laser scanner data, and performed field surveys to study the quantity of erosion after the ash fall. We also compared the calculated erosion rates with examples from other volcanoes.

Table 1 Amount of tephra emitted by the major eruptions of the 2000 eruption of Miyakejima.

Date of eruption	Volcanic product (10^4 m^3)
8 July 2000	99
14–15 July 2000	1100
10 August 2000	150
13 August 2000	31
14 August 2000	1.8
18 August 2000	1500
29 August 2000	530
Total	3300

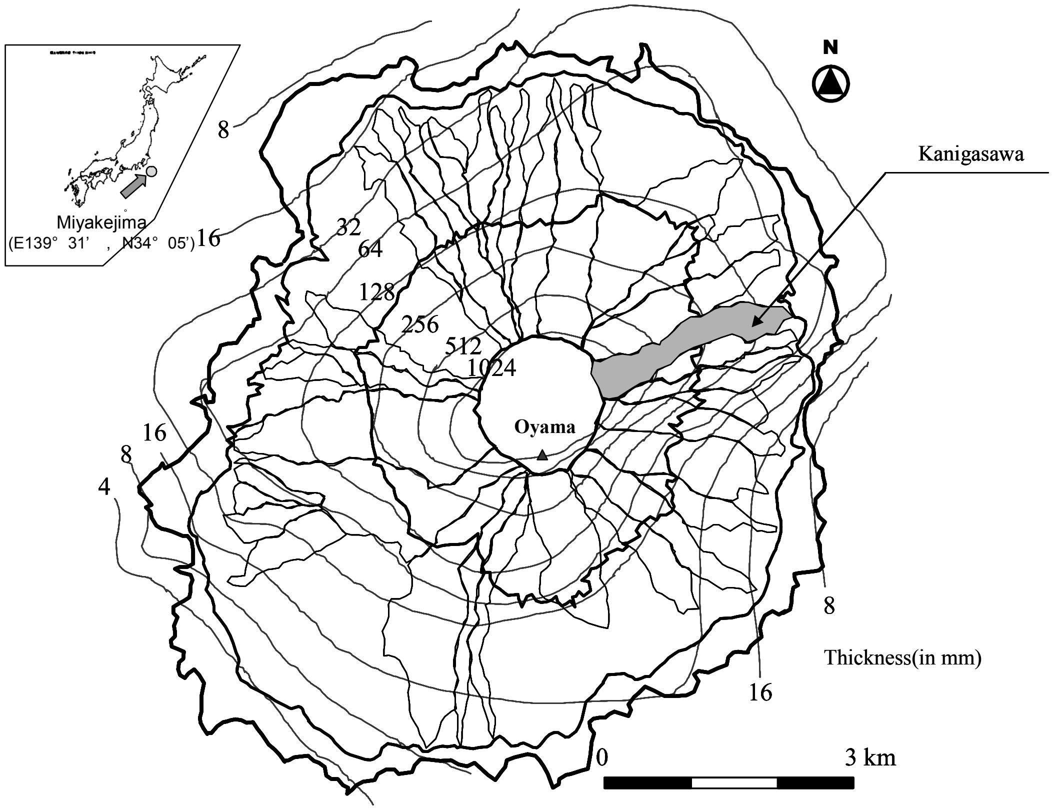

Fig. 1 Isopach of tephra thickness deposited from 8 July to 20 August 2000.

OUTLINE OF THE MIYAKEJIMA ERUPTION OF 2000

Miyakejima Island is a circular volcanic island with diameter of about 8 km located approximately 180 km south of Tokyo (34°05′N, 139°31′E). It is a stratovolcano consisting of basalt to andesite. During the past 10 000 years, large eruptions (volcanic product of 0.1 km^3 or more) occurred on Miyakejima Island, approximately 2500 years ago and between 7000 and 8000 years ago (see Tsukui & Suzuki, 1998). While eruptions that occurred before the 2000 eruption emitted scoria from cracks in the mountainside, and discharged magma, the eruption in 2000 emitted a large quantity of volcanic ash.

The eruption of 2000 began as volcanic activity increased, beginning in late June and continued with repeated eruptions emitting large quantities of volcanic ash in July and August, depositing a thick layer of volcanic ash on the ground surface. Table 1 and Fig. 1 show the distribution of volcanic ash produced by the major eruptions in 2000 and their quantities based on the survey conducted in August 2001 (Earthquake Research Institute, University of Tokyo). Volcanic ash fell over almost the whole area of Miyakejima Island, depositing over 1 m around the mountain top. The total quantity of material emitted was 3300×10^4 m^3. The deposited volcanic ash was thickly distributed to the east and west by the winds.

THE STUDY CATCHMENT

The area of interest in this study is the upper stream of the Kanigasawa catchment on the east side of Miyakejima Island. During the eruption of 2000, volcanic ash fell in this catchment on five occasions: 8 July, 14–15 July, 10 August, 18 August and 29 August. In this catchment, the thickness of the ash deposits increased upstream, ranging in thickness from 250 to 1000 mm (Fig. 2). The area studied was 0.39 km^2 and the mass of deposited tephra was 3.7×10^5 m^3. Vegetation in the catchment was almost entirely killed by the volcanic gas and the volcanic ash and even now, four years after the eruption, the ground is still covered with fine-grained volcanic ash. The annual rainfall over a 10-year period on Miyakejima is 2759 mm year^{-1} (average 1993–2003, excepting 2001).

The amount of erosion in the study catchment was calculated by performing an analysis based on laser scanner data and by interpreting aerial photographs. An airborne laser scanning survey performs digital measurement of the local topography to obtain detailed ground elevation data. The laser scanner data were obtained in July 2000 immediately after the eruption, and 11 months later in June 2001. The specifications of the laser scanner data that were used are presented in Table 2.

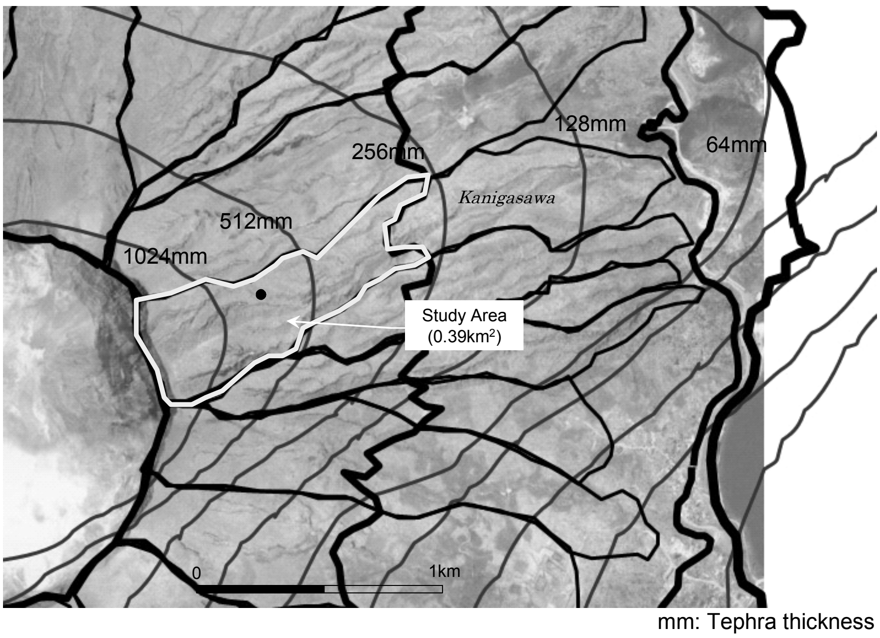

Fig. 2 Location of the study area.

Table 2 Table of the laser scanner data used (data array with orthogonal mesh).

Measurement period	Data array	Scanning angle	Distance measurement precision	Flight altitude	Flying speed	Wave length
17–22 August 2000	1.0 m	22.6°	Horiz. ±0.30 m Vert. ±0.15	65–1000 m	30–150 km h^{-1}	1064 µm
1–12 June 2001	1.5 m	18°	Horiz. ±0.30 m Vert. ±0.15	2500 m	203.7 km h^{-1}	1064 µm

Table 3 Aerial photographs interpreted in this study.

Date of photo	Scale
22 July 2000	1/8000
2 August 2000	1/8000
6 October 2000	1/10 000
8 November 2000	1/20 000
4 June 2001	1/10 000

The topographic change between two periods is commonly calculated by investigating the difference between the elevation data for the two periods. Generally speaking, however, when measurements are performed at different times with an airborne laser scanner, the systems of coordinates measured differ. In this study, it is assumed that the coordinate systems differ, because data collected for two different periods were used. Consequently the amount of topographic change was established by correcting the difference between the systems of coordinates for the July 2000 and the June 2001 data.

The differences between the coordinate systems are usually corrected using man-made structures as a reference point, but because there is no man-made structure in this study area, the difference was evaluated mainly by comparing the topography.

The results showed that there was almost no differences between the coordinates on the X axis (east–west direction) and Z axis, and that the difference between the Y axis (north–south direction) is particularly large, at 4.5 m. The following are the results of the evaluation of the differences.

After correction of the coordinate systems, the differences between the two data sets were obtained to prepare a difference distribution diagram. The corrected elevation difference is considered to include residual minor difference. Gully erosion can be evaluated by analysing laser scanner data, because the depth of gully erosion is 10 m or more, but it is difficult to calculate sheet erosion and rill erosion, quantities that are assumed to be less than 1 m, because of the limited precision of the data. To obtain the volume of sediment mobilized by gully erosion alone, the difference only along the gullies was also calculated.

Aerial photographs taken at different times were used to interpret the gully distribution, in order to clarify the detailed process of gully erosion from July 2000 to June 2001. Table 3 shows the aerial photographs that were used to interpret the gully distribution. Gullies are ditch-shaped forms, but their size varies. The study looked at gullies that can be interpreted using 1/8000 to 1/10 000 aerial photographs, and their area was calculated by drawing the boundary line of the gullies on a base map.

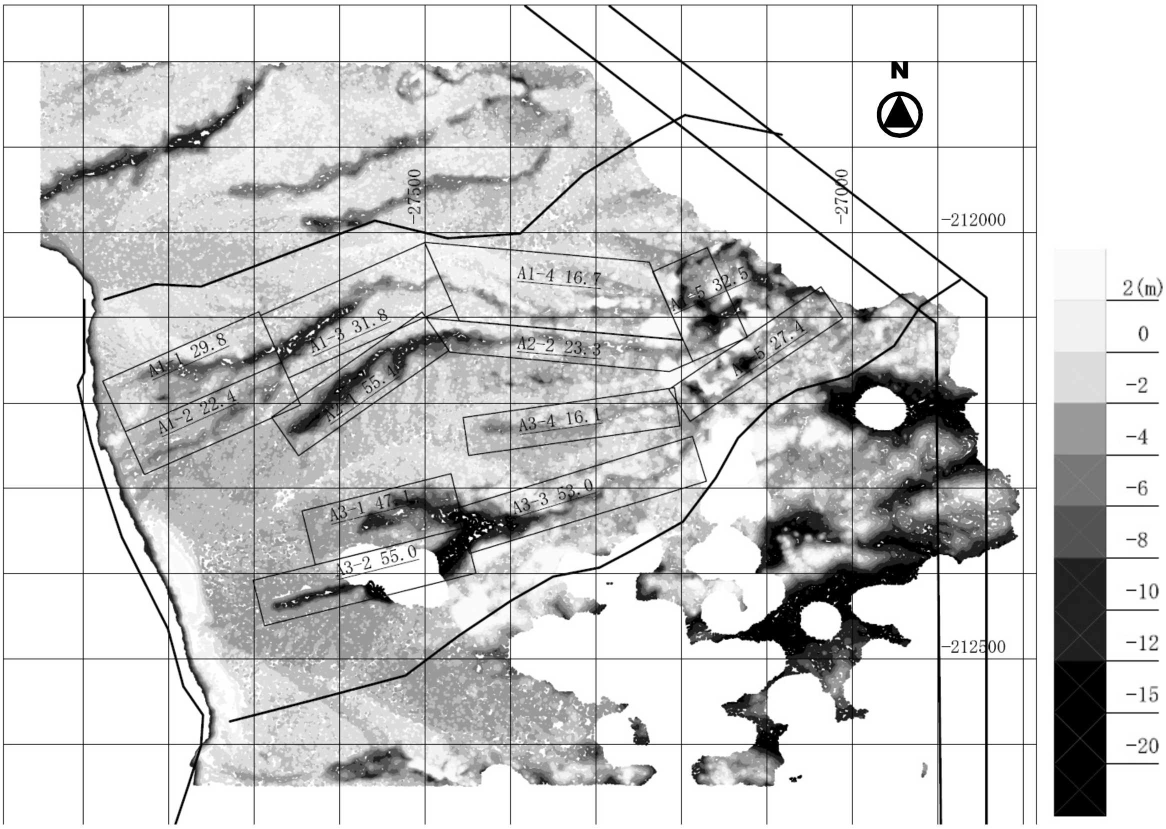

Fig. 3 State of gully erosion based on the analysis of laser profiler data.

RESULTS AND CONSIDERATIONS

Estimation of the quantity of erosion for each erosion type

Estimation of the quantity of gully erosion Figure 3 shows the results obtained from the analysis of the laser scanner data. The quantity of gully erosion from July 2000 to June 2001 in the study area was estimated to be 4.1×10^5 m^3. The erosion depth ranged from 2 to 15 m and the erosion width from 10 to 30 m.

Estimation of sheet erosion and rill erosion Sheet erosion was quantified by directly measuring the depth of the volcanic ash deposited by the eruption of 2000. At the site, volcanic ash deposits were manually excavated vertically from the surface and the thickness of the deposited ash was measured. Assuming that none would be eroded at locations where the slope gradient was 0°, the difference between the deposit thickness at such a location and that at the measurement location was assumed to be the erosion depth. This is assumed to represent the depth of erosion from July 2000, immediately after the ash fall, until April 2004. The quantity of erosion is the value obtained by multiplying the erosion depth by the areal extent of the sheet erosion. The slope gradient at the measurement location was about 25°.

The average sheet erosion depth obtained from the survey results is approximately 165 mm, and multiplying this by the area of sheet erosion provides an estimate of the quantity of sheet erosion of 3.6×10^4 m^3. The average erosion rate during the period from July 2000, immediately after the ash fall, until April 2001 when the field survey was done was calculated to be 43 mm year^{-1}.

Rill erosion was studied by calculating the quantity of sediment mobilized by rill erosion per unit area, by measuring the cross-section shape and length of the rills and the number of rills per unit area. The total quantity of rill erosion was obtained by multiplying this value by the area. The cross-section shape was obtained by measuring the width and depth of typical rills at intervals of 4 m in the slope direction. The gradient of the slope ranged from 25° to 30°. Based on the survey, rills that developed between July 2000 and April 2004 had an average length of 30 m, an average width of 1.0 m, and an average depth of 0.5 m. Rills in the study area were distributed at a density of about 1 rill per 2.5 m, and their incidence appears to have been determined by the micro-topography, including standing and fallen trees, of the study area. The quantity of erosion per rill was estimated to be about 30 m^3, and the quantity of rill erosion in the study area was calculated as 2.5×10^4 m^3 and the average erosion rate as 74 mm year^{-1}.

Sediment budget

Table 4 shows the quantities associated with each form of erosion and the percentage of the total erosion represented by each quantity. The different quantities of erosion that were calculated represent different periods. The gully erosion data relate to a period of about one year, but that for sheet and rill erosion cover a period of approximately four years after the eruption. According to Collins & Dunne (1986), a survey of the annual quantity of sediment eroded by sheet erosion and by rill erosion at Mount St Helens, USA, showed that these quantities peaked during the first year, and then reduced rapidly during the next two years. Assuming that the sheet erosion and rill erosion effectively occurred during the first year, this study compared the percentage of total erosion that they represented during the first year after the eruption. Although sheet erosion and rill erosion are estimated to be extremely high, gully erosion accounted for most (87%) of the erosion. This shows that erosion following an ash fall is dominated by gully erosion.

Considering the amount of sediment mobilized by gully erosion and the erosion depths that were calculated, it is considered that not only volcanic ash deposited during the eruption of 2000, but also the underlying original soil was eroded. Consequently, the percentages of the gully eroded sediment consisting of newly-deposited volcanic ash and underlying soil were estimated as follows. Assuming that the sediment eroded by sheet erosion and rill erosion is newly deposited volcanic ash, because the observations in the field confirmed that the sheet erosion and rill erosion depths do not extend to the original ground surface, the total volume of ash deposits mobilized by

Table 4 Quantities of erosion of each form of erosion.

Erosion type	Volume (m^3)	Ratio (%)
Sheet erosion	3.6×10^4	8
Rill erosion	2.4×10^4	5
Gully erosion	4.1×10^5	87
Total	4.7×10^5	

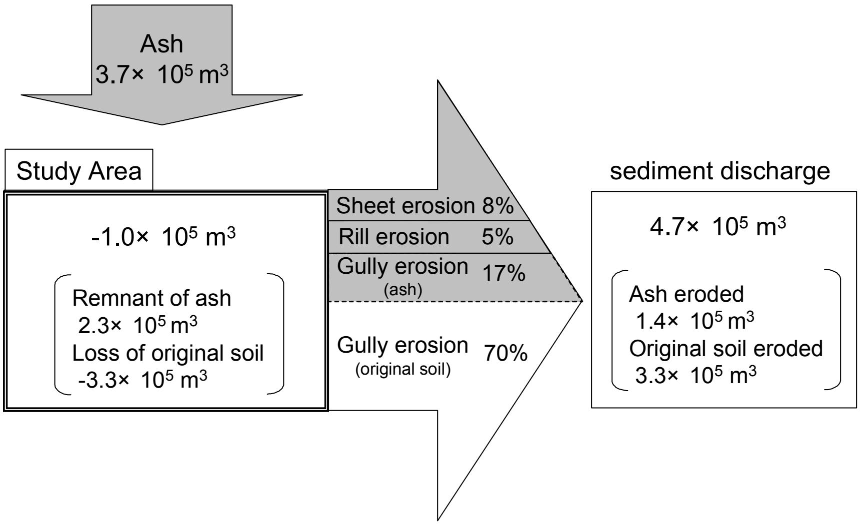

Fig. 4 A provisional sediment budget for the few years after a volcanic eruption.

gully erosion can be estimated by spatial integration of the ash deposit thickness in the gully-eroded area. All the values measured and calculated are summarized in Fig. 4.

About 30% of the mobilized sediment was volcanic ash deposited by the eruption of 2000, and about 70% of it was original soil. This reveals that after an eruption on Miyakejima, the deposited ash changes the form of the runoff, eroding large quantities of the original soil, almost none of which was eroded before the ash fall. In particular, more than 80% of the material mobilized by gully erosion was original soil. At the site, it was observed that gullies eroded deeply into the original soil. From this result, it can be concluded that the major source of sediment on Miyakejima after the eruption of 2000 was original soil eroded by gully erosion.

Comparison of erosion rates on Miyakejima with those on other volcanoes

Aerial photographs taken at different times were used to interpret the gully distribution and to calculate the area of gully formation. The gully distribution before the eruption was confirmed by interpreting aerial photographs taken on 22 July 2000. On 22 July 2000 no rain had fallen on Miyakejima since the start of the eruption emitting volcanic ash, so that no new gullies had formed. On 2 August 2000, channels formed by gullies could be seen extending close to the crater wall in the upper left part of the photograph. It can be confirmed that on 6 October 2000, a clear wide gully had formed in the lower left part of the photograph. A comparison of photographs taken on 4 June 2001 and 6 October 2000 shows that although the gullies widened a little, no remarkable change occurred.

Figure 5 shows time-series changes in the ratio of gully area, which represents the percentage of the overall area occupied by gullies. It shows that the gullies grew rapidly during the first four months after the eruption, and that the erosion rate subsequently declined.

Next, in order to clarify the significance of the quantity of sediment discharged after the volcanic eruption on Miyakejima, the results obtained were compared with those reported in the literature for other volcanoes, including a survey of Mt Merapi undertaken by Kaneko *et al.* (2001). Table 5 is based on a table produced by Kaneko *et*

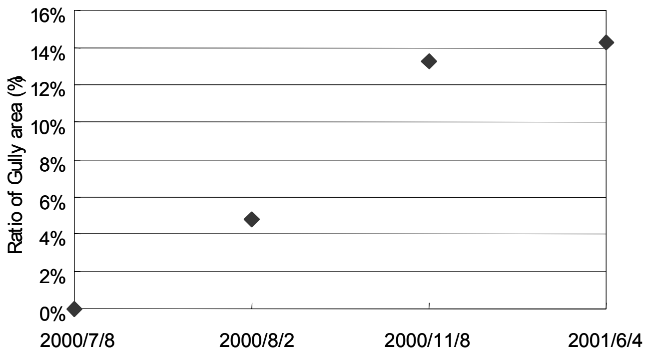

Fig. 5 Time-series of the change in gully coverage after the eruption in the catchment.

Table 5 Comparison with past surveys at other volcanoes.

Site	Surface condition	Type of erosion in estimation	Specific sediment yield (m^3 km^{-2} $year^{-1}$)	Erosion rate (mm $year^{-1}$)	Specific sediment yield/precipitation (m^3 $km^{-2}year^{-1}mm^{-1}$)	Duration of estimate	Precipi-tation (mm)	Reference
Mt Miyakejima	Bare	Gully	1.1×10^6	1100	573	July 200–June 2001	2270[a]	This study
Mt Merapi, Indonesia	Bare	Gully	1.4×10^6	1400	319	July 1988–July 1999	4385[a]	Kaneko *et al.*(2001)
Mt Pinatubo, Philippines	Bare	Gully	3.9×10^6	3900	1773	1991–1992	2200[b]	Hirose & Inoue (1999)
Mt Unzen, Japan	Bare	Gully	5.6×10^6	56	15	Sept. 1996–Oct. 1997	3820[a]	Teramoto *et al.* (2004)

[a] Amount January –December 1991 inclusive.
[b] Amount during period of sediment estimate.

al. (2001), but new values derived from this study were added. It includes estimates of the annual specific sediment yield. Conversion of this value to an estimate of the rate of surface lowering (mm $year^{-1}$) provides an estimate of the erosion rate. The specific sediment yield associated with gully erosion was estimated to be approximately 1.1×10^6 m^{-3} km^{-2} $year^{-1}$, which is equivalent to an erosion rate of 1100 mm $year^{-1}$. Since the form of erosion was not uniform, the results could not be compared uniformly with results of past surveys at other volcanoes, but the values are as high as those from Mt Merapi and Mt Pinatubo, and when compared with other volcanoes in Japan, are two orders of magnitude higher. As indicated previously, the gully erosion progressed rapidly during the four months after the eruption. The specific sediment yield for the four months after the eruption is estimated to be 3.0×10^6 m^{-3} km^{-2} $year^{-1}$, and the equivalent erosion rate is 3000 mm $year^{-1}$. Results of past research include values for Mt Pinatubo, where the erosion rate was extremely high. When the specific sediment yield per unit rainfall quantity is calculated, it is equivalent to 573 m^{-3} km^{-2} $year^{-1}$ mm^{-1} for the period from July 2000 to June 2001, and 3659 m^{-3} km^{-2} $year^{-1}$ mm^{-1} for the four months after the eruption. This latter value must be seen as extremely high, exceeding those for Mt Merapi and Mt Pinatubo. From these results, it can be concluded that the erosion rate on Miyakejima Island after the eruption of 2000 was extremely high. The causes of this high rate are, in addition to the high erodibility of the deposits in the catchment on Miyakejima Island, the fact that the study area is close to the crater in an upstream part of the catchment were erosion begins.

CONCLUSION AND FUTURE CHALLENGES

This study documents the quantities of sheet erosion, rill erosion, and gully erosion following the eruption of 2000 on Miyakejima Island by means of a field survey and by analysis based on data obtained by a laser profiler. It obtained the following results:

(a) The overall quantity of erosion exceeded the quantity of volcanic ash deposited by the eruption of 2000. While it is estimated that a total of approximately 370 000 m^3 of volcanic ash was deposited, the quantity of erosion during the four years after the eruption was 470 000 m^3.
(b) Gully erosion was the dominant form of erosion after the ash fell in the catchment.
(c) Gully erosion accounted for 87% of all erosion, while sheet and rill erosion accounted for 8 and 5%, respectively.
(d) Gully erosion penetrated to the bottom of the new volcanic ash deposit to erode a large quantity of the original soil. Of the soil eroded by gullies, about 20% was newly deposited volcanic ash and about 80% was original soil; i.e. the major source of sediment was original soil eroded by gullies.
(e) Gully erosion almost completely stopped four months after the eruption.

The post-eruption erosion rate observed on the upper slope of the Miyakejima volcano was higher than almost all the rates reported in previous studies. This occurs not only because the mountain of the Miyakejima volcano consists of highly erodible sediment but also because few studies have documented erosion rates for the uppermost slope of a volcano during the early stage of erosion.

It is extremely important to clarify the amount of deposited ash mobilized by erosion in order to study the sediment discharge following a volcanic eruption. Gullies are a particularly important source of sediment after an ash fall. Surveys of erosion quantities will be continued to clarify change over time and study of the erosion development process will be undertaken according to results of flow volume observations and surveys of soil water content and erodibility.

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