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The effect of rainfall intensity on sediment transport in a scoria-rich river on Miyakejima Island, Japan

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Abstract The volcanic eruptions on Miyakejima Island in 2000 triggered serious mudflows in most basins. Since then, the magnitude of sediment transport has decreased over time, as it has after other volcanic eruptions. However, some rivers on the island still discharge considerable volumes of sediment. In order to study the sediment transport dynamics, the authors installed a surveillance camera and a raingauge in the Tatsunesawa River, a typical river where high sediment transport persists. A comparison of the occurrence of sediment transport at the exit of the river basin with total rainfall and rainfall intensity revealed that sediment transport was primarily controlled by rainfall intensity rather than rainfall amount and occurred when the rainfall intensity exceeded a maximum 10-min rainfall of 4–5 mm. On 16 July 2002, despite the comparatively low total rainfall of 13 mm, the maximum 10-min rainfall was 5 mm and sediment transport occurred at the basin outlet. The transported sediment is composed primarily of scoria, comprising porous cinder-like fragments of dark lava with a mean diameter of 12 mm and a coefficient of permeability of 1.25 cm s^{-1}. Low rainfall intensities are easily absorbed by the scoria layer on the river bed and surface runoff only occurs under high rainfall intensities when inflow exceeds outflow. The volume of scoria deposited on the river bed and its permeability exert an important influence on sediment transport.

Key words Miyakejima Island, Japan; permeability; rainfall; rainfall intensity; scoria; sediment transport; total rainfall

INTRODUCTION

According to several research reports, the volume of sediment transport increases considerably after a volcanic eruption releases fine tephra into a river basin (e.g. Kadomura *et al.*, 1983; Jitousono *et al.*, 1996). Like other volcanoes, after its 2000 eruption, Mount Oyama on Miyakejima Island in Japan generated debris flows (hereinafter referred to as "lahars") destroying houses, roads and other infrastructure (Yamakoshi *et al.*, 2003). These disasters were obviously caused by rainstorms. In order to predict sediment related disasters, it is important to know the characteristics of the rainfall that triggers sediment transport.

The authors have investigated the hydrological response to rainfall on the island since 2002. The results have shown that the responses to rainfall at the exit of each watershed can be divided into three types: (a) no sediment transport and no surface water flow can be observed, (b) flash floods with muddy water can be observed, and (c) sediment transport can be observed. The Tatsunesawa River is a typical river where sediment transport still continues to occur after rainfall. We assembled data for the period July 2002–February 2004, in order to clarify the relationship between rainfall and sediment transport in the Tatsunesawa River. The sediment transported by the river is primarily scoria, i.e. porous cinder-like fragments of dark lava.

THE 2000 ERUPTION OF MIYAKEJIMA VOLCANO AND THE RESPONSE OF THE TATSUNESAWA RIVER

Miyakejima Island, located 180 km south of the Tokyo Metropolitan Region, is part of the Izu-Bonin volcanic chain. This volcanic island is circular, 55 km^2 in area and 8 km in diameter. In the last century, the volcano erupted in 1940, in 1962, and in 1983, i.e. approximately every 20 years. These eruptions were similar; the flank erupted, spewing scoria and ejecting lava, then it ceased. However, the 2000 eruption was different. Mount Oyama emitted fine volcanic ash from the mountain top, covering the entire area of the island. As a result, hydrological conditions changed drastically. Few sediment disasters were reported initially. However, rain started to generate sediment transport, causing serious disasters. During 26–27 July 2000, the first sediment movement after the onset of the 2000 eruption occurred due to a rainfall of 48 mm in total, with a maximum intensity of 26 mm h^{-1}. From 5–7 September 2000, relatively intense rainfall occurred with a total of 178 mm and maximum rate of 31 mm h^{-1}. This rainfall triggered lahars on almost all the major rivers on Miyakejima Island. Roads, houses and bridges were damaged, but without loss of human life, because all the residents had already been evacuated except for a few people involved in disaster management activities.

Thereafter, information on the sediment discharge in each river was limited because almost all efforts were focused on maintaining public facilities until May 2002. On 19 August 2002 Typhoon Phanfone struck the island and brought heavy rainfall of 257 mm day^{-1}, which was the heaviest rainfall recorded in the two-year post-eruption period. After a survey, we found that a much smaller number of lahars occurred than in the first post-eruption year, despite the unprecedented torrential rain.

Most rivers contain muddy water after intense rainfall, but some rivers have no discharge and there is no evidence of surface water. The Tatsunesawa River is one of the few rivers where lahars and related sediment transport persist.

The Tatsunesawa River is located in the southern part of the island, a part that is long and narrow. Its drainage area is 0.64 km^2, and the length of its main channel is 3.7 km. Sediment transport events after the 2000 eruption eroded a metropolitan loop road at the exit. There was a retaining wall to protect the road, but no drainage system. This indicates that there has been not only limited sediment transport but also that less drainage water has been generated in the Tatsunesawa River for many years. A smooth lava bed is exposed in its upper reaches, although there are thick scoria deposits in its lower reaches, extending 2.3 km upstream, from the basin exit.

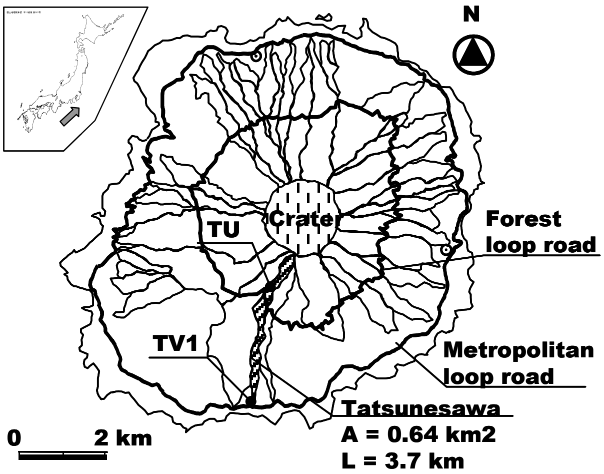

Fig. 1 Map of Miyakejima Island.

OBSERVATION METHODS

Observation apparatus

We installed a surveillance video camera and raingauge to identify the relationship between sediment transport and rainfall. A raingauge, with 0.1 inch (2.54 mm) set as its minimum reading, was installed at the TU station 2.7 km from the river exit and at an elevation of 470 m (see Fig. 1). The video camera was installed at the river exit (TV1) to observe sediment transport. It consisted of a camera, control unit, solar panel, battery and main stand. Its shooting interval can be controlled and it repeats at a designated interval until the videotape is finished. We filmed the site for 1 second per 3 minutes, or 1 s per 5 min, during the observation period, which extended from July 2002 to February 2004. Maintenance of the video camera was undertaken periodically to remove the used videotape and install a new tape. No lighting was provided, so sediment transport during the night could not be observed.

Data analysis

We discriminated between sediment transport occurrences and non-occurrences by viewing the videotapes that were recorded, by undertaking field research and by interviewing witnesses who had been working on a groundsill construction project at the river exit. The construction period of this project extended from July 2002 to June 2003. The recorded videotapes can be classified into three types: (a) sediment transport was recorded, (b) the riverbed profile was found to be disturbed the following morning, and (c) no sediment transport and no evidence of riverbed changes were recorded. In case (b), it can be assumed that sediment transport occurred during the night. Cases (a) and (b) are, therefore, classified as “sediment transport occurred”, and case (c) is classified as “no sediment transport occurred”.

The Ministry of Construction of Japan has prepared guidelines to plan and implement warning and evacuation systems (MOC, 1984). These methods use rainfall indices based on rainfall intensity and the total rainfall, because, based on the technical knowledge at the time, they focused on the fact that sediment disasters tend to occur as the rainfall intensity becomes greater, even though the total rainfall is small, and that they also occur as the total rainfall becomes greater, even though the rainfall intensity is low. In our research, we followed this approach and grouped the data that we obtained.

We defined the total rainfall as the accumulated rainfall between 6-hour no-rain periods. When we found sediment transport, we accumulated the rainfall until the time that sediment transport was observed, as the total rainfall. We identified events with no sediment transport, where the total rainfall was higher than approximately 15 mm or the maximum 10-min rainfall was higher than 5 mm, while the video camera was shooting. In addition, we had an opportunity to observe sediment transport at the site on 16 July 2002. This opportunity enabled us to construct a hyeto-hydrograph and to derive useful data.

OBSERVATION RESULTS

Rainfall and sediment transport

The recorded videotapes and the interviews with witnesses who observed sediment transport at the site proved that sediment transport occurs whenever surface flow occurs at the basin exit. Figure 2 shows the daily rainfall for the surveillance video camera operating period. The arrows in Fig. 2 show the events for which sediment transport was confirmed. The video camera frequently failed due to mechanical problems. However, the camera recorded 17 sediment runoff events, including four occasions when the riverbed was seen to be disturbed the following morning. By adding the data provided by interviews with witnesses, a total of 26 sediment runoff events were confirmed.

Figures 3 and 4 present the results of organizing the data to explore the relationship between the occurrence and non-occurrence of sediment runoff and the rainfall data. The horizontal axes show total rainfall and the vertical axes show maximum 10-min rainfall in Fig. 3 and hourly rainfall in Fig. 4, respectively.

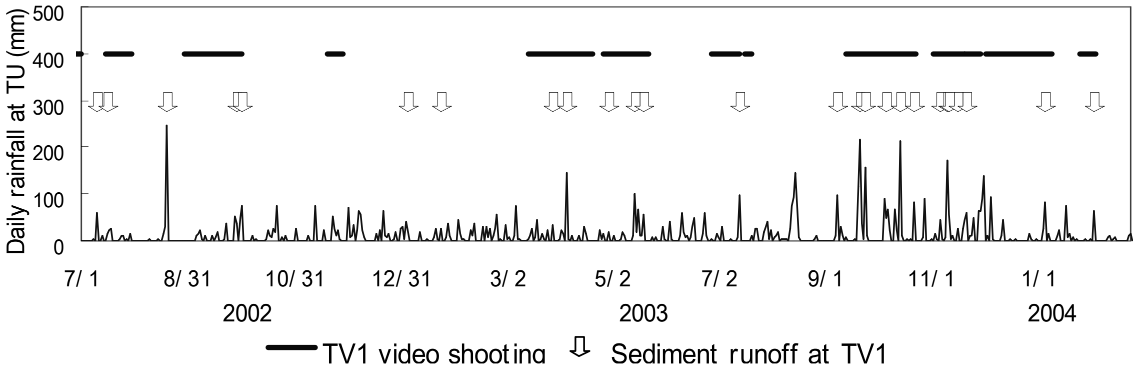

Fig. 2 Daily rainfall and video shooting period from 1 July 2002 to 29 February 2004.

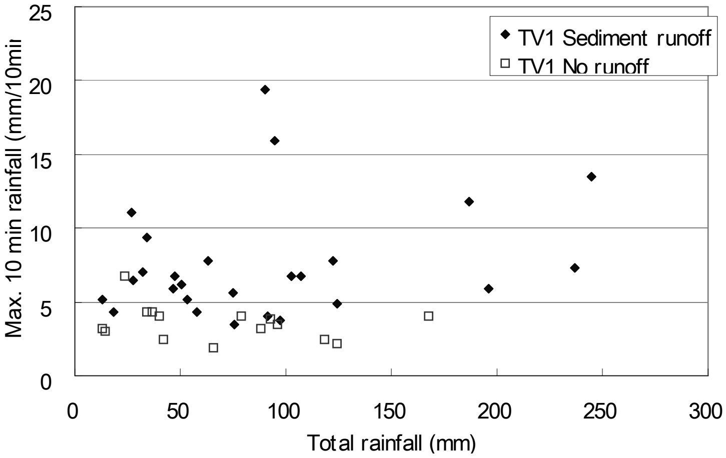

Fig. 3 Total rainfall and maximum 10-min rainfall with sediment transport occurrence and non-occurrence.

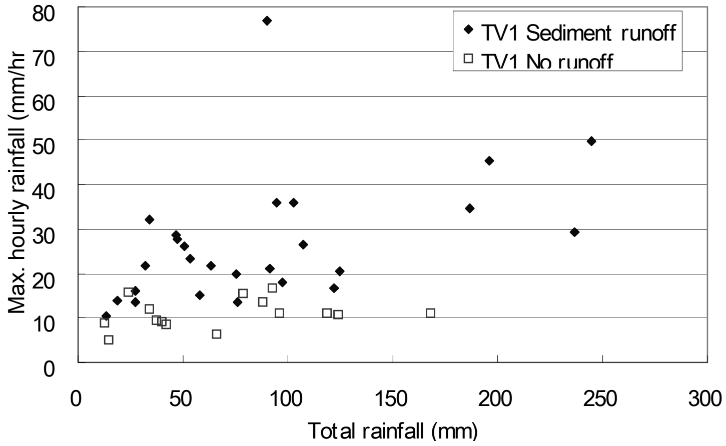

Fig. 4 Total rainfall and hourly rainfall with sediment transport occurrence and non-occurrence.

According to these figures, sediment transport events occurred when the maximum 10-min rainfall was greater than 4 mm or the hourly rainfall was higher than 10 mm. On the other hand, even a total rainfall of 170 mm, that must be considered to be heavy rainfall, did not generate sediment runoff.

Sediment runoff on 16 July 2002

We had an opportunity to directly observe a sediment transport event at the basin outlet on 16 July 2002. The total rainfall was 13.2 mm at the TU raingauge station and the peak rainfall was recorded at 08:30 in the morning. Sediment transport started at 12:10, four hours later than the peak rainfall. Figure 5 shows the hyeto-hydrograph representing the rain record at TU, the discharge measurement at the basin outlet and the recorded videotape. Both the rainfall and discharge values represent 10-min records. The measured discharge was divided by the watershed area to convert it to the

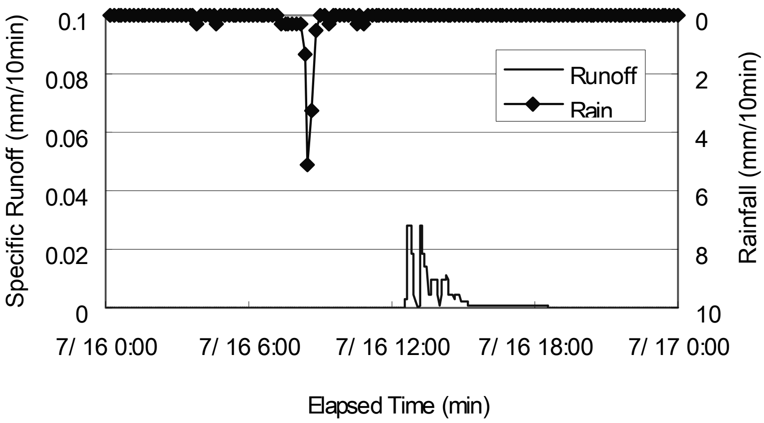

Fig. 5 Hyeto-hydrograph for the mouth of the Tatsunesawa River on 16 July 2002.

specific runoff. The peak discharge of the surface flow was 30 l s^{-1} at the surveillance camera site. At the same time, we confirmed higher discharge downstream from the camera location, because surface water and groundwater passed through the scoria deposit and converged downstream.

In Fig. 5, the specific runoff peaked and fell to zero, and then peaked again 30 min later. After that, it fluctuated, because the scoria carried by the surface water formed a dike so storing water. Then, the scoria dike collapsed and the discharge increased again. Repeated scoria dike formation and collapse is evidenced by this hydrograph. Surface flow was observed until darkness fell at 19:00, but it had stopped by the following morning.

DISCUSSION

The major constituent material of the transported sediment is scoria: porous cinder-like fragments of dark lava. Although neither surface flow nor sediment transport were observed at the surveillance camera site, water flow at the end of a scoria deposit was often seen 20 m downstream from the video camera. On 22 November 2002, we measured a water discharge of 15 l s^{-1} at 14:55 at the lower end of a scoria deposit. The rain started at 05:10 in the morning and persisted till 24 November and its total rainfall reached 92.8 mm. However, the maximum 10-min rainfall was only 3.8 mm, recorded at 09:40, and the maximum hourly rainfall was 16.7 mm recorded at 10:00, making this a relatively low intensity rainfall event compared with other events for which rainfall data had been collected.

To establish its physical properties, we conducted density testing, permeability testing and grain size analysis on the scoria. The results revealed that its apparent density was 1.7 g cm^{-3}, its coefficient of permeability was 1.25 cm s^{-1}, and the 60 percentile of the mass particle size distribution was 12 mm. The result of the grain size analysis classified the scoria as “GW”, well-graded gravel, according to the unified soil classification chart (Bowles, 1984).

In order to confirm the permeability of the scoria, we conducted a simple channel test. We prepared an experimental channel with a gradient of 10°, a length of 5 m, and

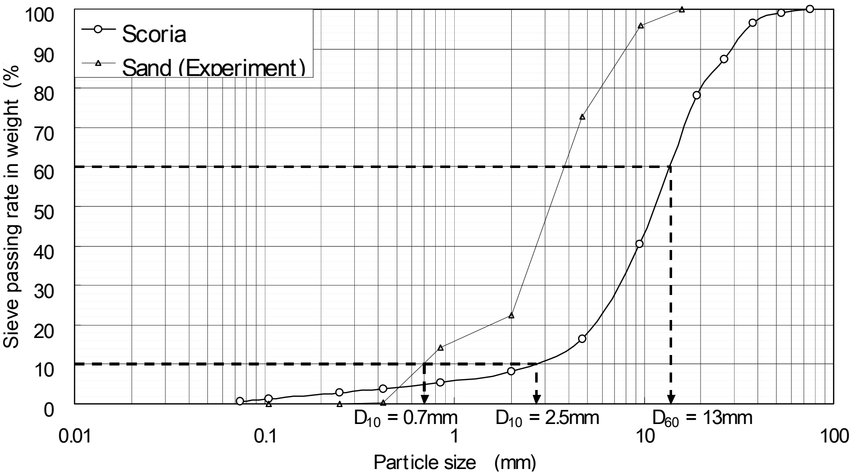

Fig. 6 Results of grain size analysis of the scoria and the sand.

a width of 20 cm. We introduced scoria to a depth of 10 cm over a length of 4 m, and then supplied water from the upper end starting with a discharge of 0.3 l s^{-1} and gradually increasing this. No scoria runoff was observed until the discharge reached 1.1 l s^{-1}. Until then, the water just passed through the scoria placed in the channel and no surface water could be observed. Under the same experimental conditions, we replaced the scoria with sand and conducted the same test. The sand started to be eroded at a discharge of 0.3 l s^{-1}. Permeability testing was not undertaken on the sand, although Hasen suggests an equation to predict the coefficient of permeability of sand from its grain size (see Taylor, 1961). The equation takes the form:

$$k = 100D_{10}^{2} \tag{1}$$

where k is the coefficient of permeability in cm s^{-1}, and D_{10} is the grain size of 10% passing rate by weight.

Figure 6 shows the results of the particle size analysis of the scoria and the sand. The D_{10} of the sand is 0.7 mm, so the coefficient of permeability can be estimated as 0.5 cm s^{-1}. The permeability of the scoria is 2.5 times greater than that of the sand. Because the scoria has a high coefficient of permeability, rainwater easily infiltrates into a scoria layer and all the water drains as groundwater if the rainfall intensity is low. Surface flow can only be observed when the inflow is higher than the outflow. Assuming that the physical character of the scoria and the riverbed gradient do not change, it is possible that future sediment transport in the Tatsunesawa River will be controlled by the rainfall intensity and by the thickness and volume of the scoria deposit in the river.

Our research is based on the period from July 2002 to February 2004, two to four years after the eruption. We could not find any clear change in the sediment transport regime during this period. This suggests that the properties of the scoria have not been drastically changed. Observations of this kind will be continued to clarify the relationship between the volume of sediment transported and other changes over a period of many decades.

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