

Spatial Variation in Specific Sediment Discharge Volume from First-Order Catchment due to Heavy Rainfall and its Factors

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Abstract. In this study, we evaluated the variations in sediment discharge between basins from the first-order catchment of the Akatani River watershed, where sediment discharges as a result of heavy rainfall. We tested the correlation between sediment discharge, topography, and rainfall magnitude using LiDAR datasets. The results showed that the specific eroded sediment volume in the first-order catchment was sufficiently greater than the specific deposited sediment volume, and the variation of the specific discharge sediment volume from the first-order catchment was determined by the variation of the specific eroded sediment volume. The spatial variations of specific discharged sediment volumes could not be evaluated solely by topography and rainfall indices; even in the catchment, where the topographic condition and rainfall magnitude were almost the same, the specific sediment discharge varied by more than one magnitude.

1 Introduction

Debris flow and sediment-filled floods cause serious damage to properties and human lives. The magnitude of damage caused by the debris flow and sediment-filled floods is influenced by various factors, among which the amount of sediment deposited during the flood is one of the most important factors in determining the extent of the damage.

Numerous methods have been used to study sediment yield data, including *in situ* observations, LiDAR data analysis, measurements of sediment volumes deposited in sediment control dams, debris basins, and sediment traps, and assessments based on sediment lobes volume [1-3]. These studies have shown that a single rainfall can cause differences in sediment discharged from one watershed to another, and even within the same watershed, differences in sediment discharged can occur depending on the amount of rainfall [1,4].

It might be possible to evaluate the extent to which factors other than geology, vegetation, and rainfall conditions contribute to differences in sediment discharged when we focus on the spatial variation of sediment discharge caused by a single heavy rainfall event. However, studies evaluating the spatial variation

in sediment discharge and its factors in a single rainfall event in the same area are limited. Therefore, the objective of this study was to quantitatively evaluate inter-basin differences in sediment discharge in the first-order catchment in an area where intensive sediment runoff has occurred. Additionally, the relationship between the topographic indices and discharged sediment volume, which had been correlated with discharged sediment volume by previous studies [1], and the relationship between rainfall and discharged sediment volume were examined to analyze the factors that produce spatial variation in sediment volume.

2 Methods

2.1 Study site

The Akatani River watershed is located in Asakura City, Fukuoka Prefecture, and is a tributary of the middle reaches of the Chikugo River. The watershed area is approximately 20 km², and the elevation difference from the confluence with the mainstream of the Chikugo River to the highest point (Mt. Hirokura) in the Akatani River watershed is approximately 560 m. The Otoishi River feeds the Akatani River from the west side, the Ogouchi River from the east side, and the

Table 1. Specs of Data

Data	LiDAR		Rainfall data (R/A)
	Before the disaster	After the disaster	
Measuring institution	Kyushu Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism		Japan Meteorological Agency
Date	2017/1	2017/7	2017/6/5 0:00~8/6 0:00
Resolution	1m	1m	1km

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Ooyama River from downstream of the east side. There is a valley bottom plain along the main channel with sediment supplied by the tributary rivers.

The west side of the Akatani River is mainly composed of granodiorite (plutonic rocks) of the Late Mesozoic-Cretaceous age, whereas the east side is mainly composed of muddy schist (metamorphic rocks) of the Late Mesozoic-Triassic age [5].

2.2 Phenomenon

Heavy rain continued to fall from July 5 to 6, 2017, mainly due to warm and humid air flowing toward the rainy season, resulting in record heavy rainfall in the Akatani River watershed area. This disaster recorded the highest rainfall ever observed at many stations from Asakura City, Fukuoka Prefecture, to the northern part of the Hita City, Oita Prefecture. For example, the 12-hour rainfall observed at the JMA Asakura observatory was 511.5 mm. Human casualties were significant, with 41 people dead or missing, 197 houses destroyed, and 102 houses half destroyed, mainly in Asakura City.

2.3 Data collection and analysis

2.3.1 Data preparation

In this study, LiDAR data (10 m grid DEM, created from 1 m grid DEM) measured before and after the disaster was used for topographic data (Table 1). The Radar/Raingauge-Analyzer was used to analyze rainfall data. This product is an estimate of precipitation in areas without rain gauges based on radar rainfall intensity measurements. The spatial resolution of the data is a 1 km grid.

First, to divide the Akatani River watershed into sub-watersheds, the gradient and catchment area at each point within the watershed were calculated using GIS. The starting point of the channel was determined as the catchment area of 10,000 m² [6]. The channel network was created by searching for the steepest gradient direction from each channel initiation point. However, in cases where the steepest gradient could not be represented by searching toward the steepest gradient because of gentle slopes, topographic maps were used to compensate for this. As a result, 259 first-order catchments were classified.

Next, an elevation difference analysis was conducted using LiDAR data from two periods before and after the disaster to evaluate the volume of erosion, deposition, and discharge sediment in each first-order catchment. Using the orthophotographs, and a slope map created from the post-disaster DEM, the extent of the change in elevation due to sediment transport was deciphered, and polygons were mapped for the sediment transport area. Then, for each first-order catchment, the amount of eroded sediment (the integral value of the negative result of the elevation difference analysis), deposited sediment (the integral value of the positive result of the elevation

difference analysis), and discharged sediment (the difference between the amount of eroded and deposited sediment) within the polygon of the sediment transport

area were calculated.

2.3.2 Rainfall and topographic indices

Previous studies have shown that the amount of sediment discharged from a watershed is influenced by rainfall and topography [1-4,7]. Therefore, this study also tested the correlation between rainfall or topographic indices and each sediment amount, such as eroded, deposited, and discharged sediments, per unit area.

Seven rainfall indicators were tested at maximum conditions of 0.5, 1, 3, 6, 12, and 24 h. Thirteen topographic indicators were used based on the previous research [1], namely: perimeter (km), area (km²), relief (m), length (m), relief ratio, number of zero-order valleys, mean drainage area (m²), mean slope (%), mean topographic wetness index (TWI) (m²), Melton ratio, form factor, elongation ratio, circularity index. Perimeter and area are calculated using GIS, and relief is the difference between the highest and lowest elevation of the main channel, length (m) is the length of the main channel, and relief ratio is the relief of the main channel divided by its length. Several zero-order valleys are the number of valleys with a catchment area of less than 10,000 m² connected to the channel. Mean drainage area (m²), mean slope (%), and mean TWI are calculated as the averaged value of the 10-m-grid in the first-order watersheds.

3 Results

3.1 Cumulative frequency of sediment volume

The cumulative frequency distribution of eroded, deposited and discharged per unit was shown in Fig. 1. The specific eroded, discharged, and deposited sediment volume varied greatly among the watersheds, although the study area is around 20 km². The specific eroded sediment volume ranged from 10^{3.2} to 10^{6.1} m³/km² (excluding 24 watersheds with no erosion), and the specific discharged sediment volume ranged from 10^{3.2}

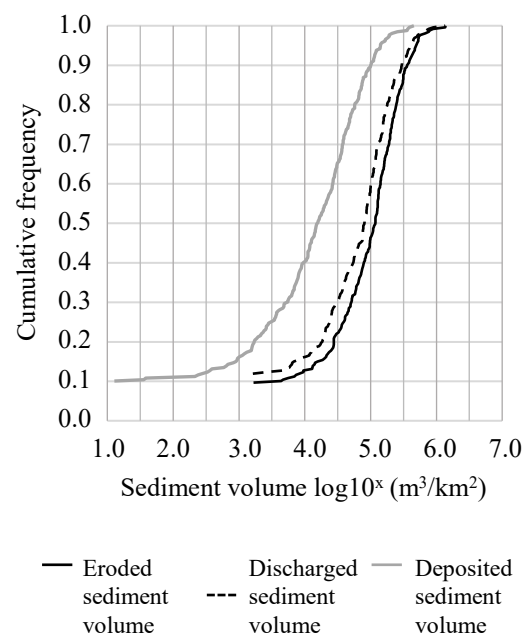


Fig. 1 Cumulative frequency of sediment volume

Table 2. Average volume of each sediment and standard deviation ($\log_{10} \times \text{m}^3/\text{km}^2$)

	Average	SD
Eroded volume	$10^{5.0}$	$10^{0.5}$
Discharged volume	$10^{5.0}$	$10^{0.5}$
Deposited volume	$10^{4.2}$	$10^{0.8}$

to $10^{6.1} \text{ m}^3/\text{km}^2$ (excluding 30 watersheds with no sediment discharge outside the watershed). The specific deposited sediment volume was distributed between $10^{1.1}$ to $10^{5.7} \text{ m}^3/\text{km}^2$ (excluding 25 watersheds with no sediment transport), which were about one order of magnitude smaller than the erosion/discharged sediment loads. The mean and standard deviation for these sediment volumes per unit area are shown in Table 2. Watersheds in which sediment volume was less than $0 \text{ m}^3/\text{km}^2$ were excluded from the calculation. These indicate that erosion dominates in sediment production in first-order valley watersheds.

3.2 Correlation between rainfall and topographic indicators and each sediment volume

The correlations between the thirteen topographic indicators and seven rainfall indicators and eroded, deposited, and discharged sediment amounts are shown in Table 3 and Table 4, respectively.

No indicators with $r \geq 0.5$ were found for either rainfall or topography indices. For rainfall indices, specific eroded and discharged sediment volume had the highest correlation coefficients with maximum 0.5 h rainfall, $r = 0.33$ and $r = 0.36$ (both $p < 0.01$). For specific deposited sediment volume, total rainfall had the largest correlation coefficient with $r = 0.29$ ($p < 0.01$). In terms of topographic indices, mean slope (%) had the largest correlation coefficient with specific eroded discharged sediment volume, with $r = 0.37$ and 0.38 , respectively. For specific deposited sediment volume, the Melton ratio had the highest absolute correlation coefficient, $r = -0.29$ ($p < 0.01$).

4 Discussion

4.1 Variation in specific produced sediment volume

The result showed large variations in the specific discharged, eroded, and deposited sediment (Fig. 1). This will help us examine how much this variation is affected by topography and rainfall magnitude. The magnitude of the variation that occurs is evaluated even when only the basins with similar topography and rainfall conditions are focused. Here, the catchments were classified using the indicators shown to be highly correlated with sediment volumes in Section 3.2 (Fig. 2).

The standard deviations for each class are generally distributed between $10^{0.2}$ and $10^{0.6} \text{ m}^3/\text{km}^2$ for specific eroded and discharged sediment volume, and between $10^{0.5}$ and $10^{1.3} \text{ m}^3/\text{km}^2$ for specific deposited sediment volume at (a) maximum 30-minute rainfall and (b) total rainfall. (c) The mean slope (%) shows that the specific erosion and discharge sediments are distributed between 100.2 and 100.9, and the specific deposition sediment is distributed between $10^{0.2}$ and $10^{0.9} \text{ m}^3/\text{km}^2$. The standard deviations for each layer ranged from 0.4 to 1.8 times the values calculated from watershed-wide data for erosion and sediment discharged and from 0.3 to 1.2 times for deposited sediment.

These indicate that even if the three indicators that are relatively highly correlated with each sediment volume are compared in watersheds with somewhat similar conditions for each indicator, the variability in the magnitude of each sediment volume is not significantly reduced.

5 Conclusions

In this study, we quantitatively evaluated the differences in the amount of sediment produced from first-order valley watersheds using LiDAR data in the Akatani River watershed, Japan, which experienced intensive debris flow due to heavy rainfall, and analyzed the effects of topographic and rainfall indicators on the spatial variation in the amount of sediment discharged to determine the following.

- The volume of eroded sediment was sufficiently large compared to the deposited sediment volume, and the variation in discharged sediment volume in the first-order valleys was determined by the variation in eroded sediment volume.
- Spatial changes in specific eroded sediment volume, specific discharged sediment volume, and specific deposited sediment volume from primary catchments are not determined by rainfall or topographic indices alone but must also include factors other than rainfall and topography, such as geology and vegetation.

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Table 3. Correlation between topographic indicators and sediment volume ($\log_{10} \times \text{m}^3/\text{km}^2$)

	Perimeter (km)	Area (km ²)	Relief (m)	Length (m)	Relief ratio	Number of 0th valleys	Mean drainage area (m ²)	Mean slope (%)	Mean TWI (m ²)	Melton ratio	Form factor	Elongation ratio	Circularity index
Eroded	-0.15 ⁺	-0.06	-0.08	-0.12 ⁺	0.12	-0.04	-0.11	0.37 ⁺	-0.08	-0.02	0.14 ⁺	0.15 ⁺	0.26 ⁺
Discharged	-0.15 ⁺	-0.07	0	-0.12	0.22 ⁺	-0.05	-0.11	0.38 ⁺	-0.14 ⁺	0.11	0.11	0.13 ⁺	0.21 ⁺
Deposited	-0.01	0.08	-0.14 ⁺	0	-0.19 ⁺	0.06	0.02	0.19 ⁺	0.16 ⁺	-0.29 ⁺	0.1	0.11	0.23 ⁺

⁺ $p < 0.01$, ⁺ $0.01 < p < 0.05$

Table 4. Correlation between rainfall indicators and sediment volume ($\log_{10} \times \text{m}^3/\text{km}^2$)

	Maximum rainfall						Total rainfall
	0.5 hours	1 hour	3 hours	6 hours	12 hours	24 hours	
Eroded	0.33 ⁺	0.23 ⁺	0.1	0.2 ⁺	0.25 ⁺	0.28 ⁺	0.29 ⁺
Discharged	0.36 ⁺	0.27 ⁺	0.12	0.21 ⁺	0.21 ⁺	0.23 ⁺	0.25 ⁺
Deposited	0.25 ⁺	0.19 ⁺	0.1	0.19 ⁺	0.25 ⁺	0.28 ⁺	0.29 ⁺

⁺ $p < 0.01$, ⁺ $0.01 < p < 0.05$

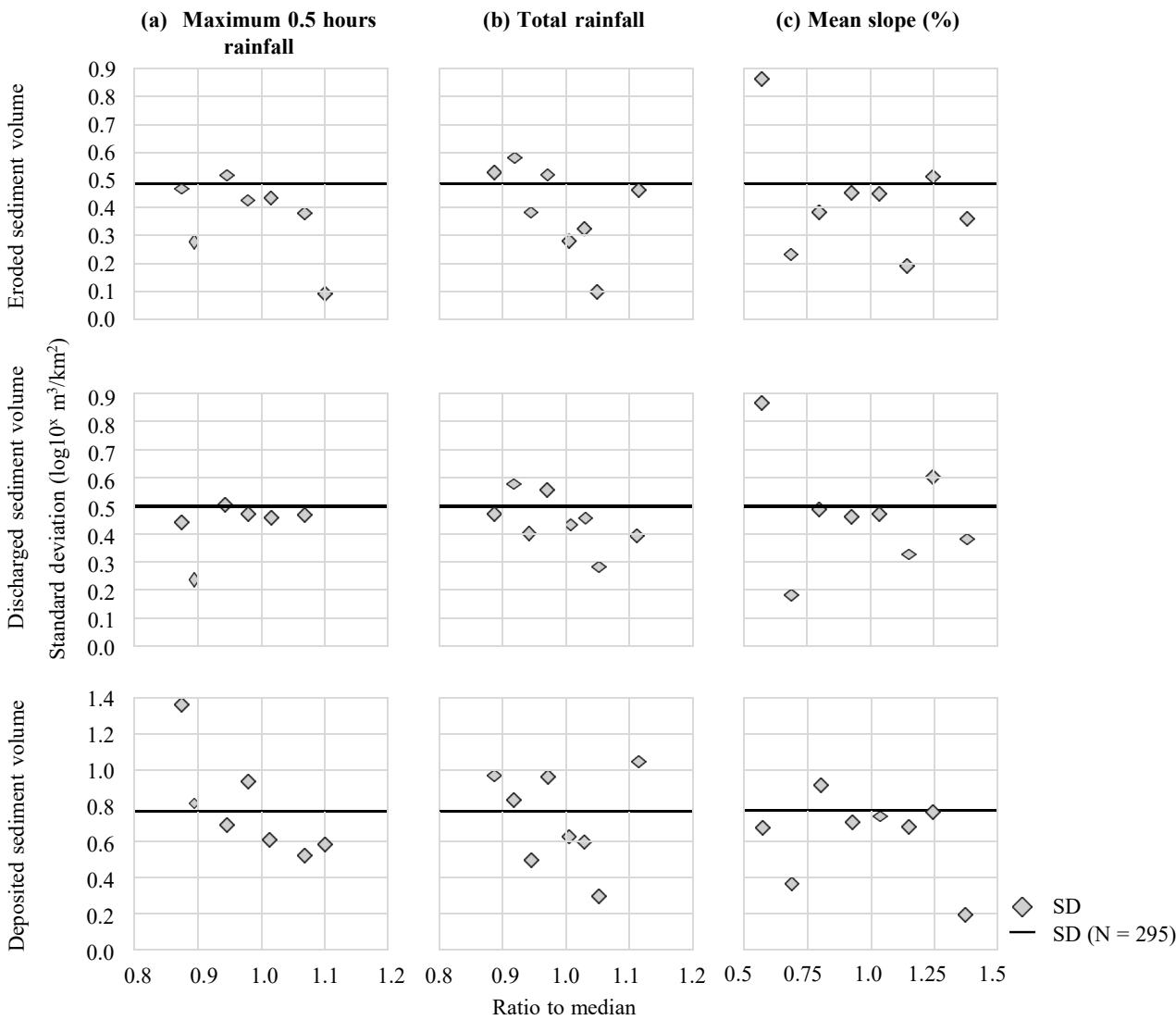


Fig. 2 Relationship between median ratio of (a) maximum 0.5 hours rainfall, (b) total rainfall, and (c) mean slope (%) and sediment dispersion