Sediment Yield and Vegetation Recovery in a Mountainous Region with Repeated Heavy Precipitation
— A Case Study in the Omaru River Basin, Miyazaki, Japan —

Takashi Koi,[1)] Norifumi Hotta[2)] and Masakazu Suzuki[3)]
1) Graduate School of Agricultural and Life Science, the University of Tokyo, 1-1-1 Yayoi Bunkyo-ku Tokyo 113-8657, Japan (koit@fr.a.u-tokyo.ac.jp)
2) ditto (hotta@fr.a.u-tokyo.ac.jp)
3) ditto (suzuki@fr.a.u-tokyo.ac.jp)

Abstract

Geomorphological and meteorological factors affect landslide conditions in mountainous regions. Because of the hazards landsides present, detecting trigger factors is important; however, few studies have examined the periodicity of landslide occurrence using landslide history and long-term rainfall data. This study examined the history of landslides and vegetation recovery processes and the relationship between landslide occurrence and heavy rainfall events in mountainous areas of the upper Omaru River basin, which are prone to heavy frequent rainfall, using 12 sets of aerial photographs taken from 1948 to 2005, data for a 1954 landslide event, and 45 years of hourly rainfall data. Typhoons caused most of the heavy rainfall events in this region. These heavy rainfall events were divided into two types: those caused by one typhoon over a short duration and those caused by two or three typhoons over a long duration. Large landslides occurred in 1954, 2004, and 2005, and small landslides occurred in 1968 and 1997. These landslides were caused by heavy rainfall events. Vegetation had begun to recover at the 1954 landslide site by 1974. There was no correlation between rainfall at each scale and the landslide area, indicating that the landslide scale is not necessarily determined by differences in rainfall characteristics. Heavy rainfall events caused all the landslide events, except for the 1968 landslide, which had high maximum 1-h rainfall. Two heavy rainfall events in 1971 did not trigger landslides, even though these events were similar to the rainfall associated with the 1954, 1997, and 2004 events, because almost all unstable sediment in the basin failed in 1954. This suggests that there is a periodicity to landslides; after such a landslide has occurred, landslide recurrence at the same site is unlikely for several decades.

Keywords: aerial photograph, heavy precipitation, landslide, recovery, sediment yield

Introduction

Large-scale landslides can greatly affect the sediment yield characteristics of a basin (Oliver, 2004; Oliver *et al.*, 2005) and threaten human life and property; therefore, it is important to determine the history of large-scale landslide occurrences both to understand basin sediment yields and to detect factors that trigger landslide hazards. Geomorphological and meteorological factors affect landslide conditions in mountainous regions (José *et al.*, 1998). Meteorological factors, especially episodic rainfall, can trigger landslides. Several studies have examined the relationship between landslide occurrences and rainfall thresholds (Hiura *et al.*, 1979; Gerald, 1987; Thomas, 1998; Matthias, 2003; Fausto *et al.*, 2004; Jonathan *et al.*, 2006). Researchers have also suggested that once a landslide occurs because of a heavy rainfall event, the periodicity of landslide occurrence may become longer and the rainfall threshold may increase (Oishi, 1968; Araki *et al.*, 1997; Iida, 2000); however, few studies have examined the periodicity of landslide occurrence using landslide history with long-term rainfall data.

Some mountainous regions in Japan have repeatedly experienced heavy precipitation in the past several decades. Landslide occurrence in such regions has not been adequately described. In September 2005, the Mikado Automated Meteorological Data Acquisition station (AMeDAS), located approximately 3.5 km north of the Dogawa Dam, in the upper Omaru River basin of Miyazaki Prefecture, recorded 1238 mm of precipitation during a 48-h period. This is the largest precipitation, which the Japan Meteorological Agency has recorded in Japan during a 48-h period since its operations began in 1979. In 1954, this area suffered heavily from landslides that accompanied the passage of a typhoon. Given the high precipitation and history of landslides, it is important to assess landslide characteristics in this area.

This study investigated the history of landslides and vegetation recovery in mountainous areas of the upper Omaru River basin and the relationship between landslide occurrence and heavy rainfall events using

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12 sets of aerial photographs taken from 1948 to 2006 and hourly rainfall data from the 1954 event and over a period of 45 years (1961–2005).

Study site

The upper Omaru River basin (Dogawa River basin) lies upstream of Dogawa Dam in Nango Village, Miyazaki Prefecture, Kyushu, Japan (31°21′ N, 131°15′ E; Fig. 1). The catchment area was 81 km^2; the elevation ranged from 1400 m above sea level at the highest point to approximately 1100 m near the Dogawa Dam. The average annual rainfall was approximately 3270 mm (measured at the Dogawa Dam rain gauge station, 1961–2004), and typhoons brought heavy rainfalls from July to September. Geologically, the area was characterized by chaotic beds (melange and mixed-rock facies), sandstone, and basaltic volcanics of the Eocene-Early Miocene. Forest occupied 92.5% of the entire village area (Taniguchi *et al.*, 1998). We analyzed four creeks of the Dogawa River basin: Kashiba-dani watershed, Kamiyama-dani watershed, Kiura-dani watershed, and Araki-dani watershed (Fig. 2).

In 1954, a disastrous landslide triggered by heavy precipitation created a huge amount of sediment outflow and killed three people in the upper Dogawa River basin (Maruyama, 1956; Shidei, 1956). In September 2005, typhoon No. 14 brought an extraordinary amount of rain to the Kyushu region; thirteen people were killed or declared missing in Miyazaki Prefecture (Ushiyama *et al.*, 2006). Although no lives were lost in Nango Village, landslides occurred in the same area as in the 1954 event.

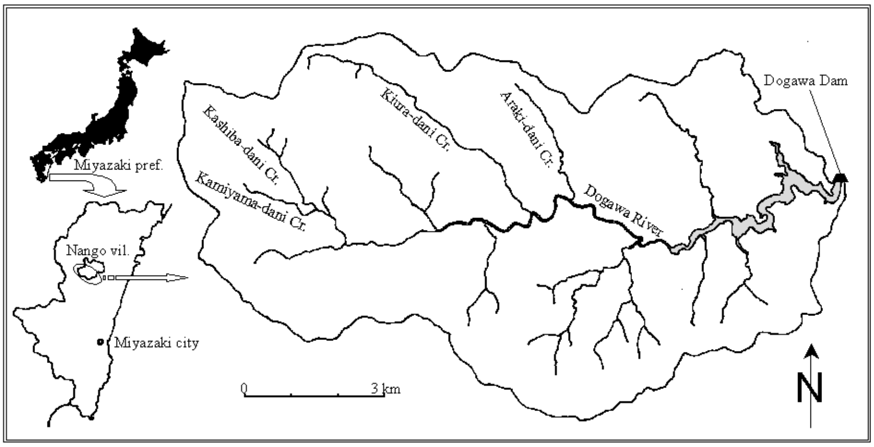

Fig. 1. Map of region and study site

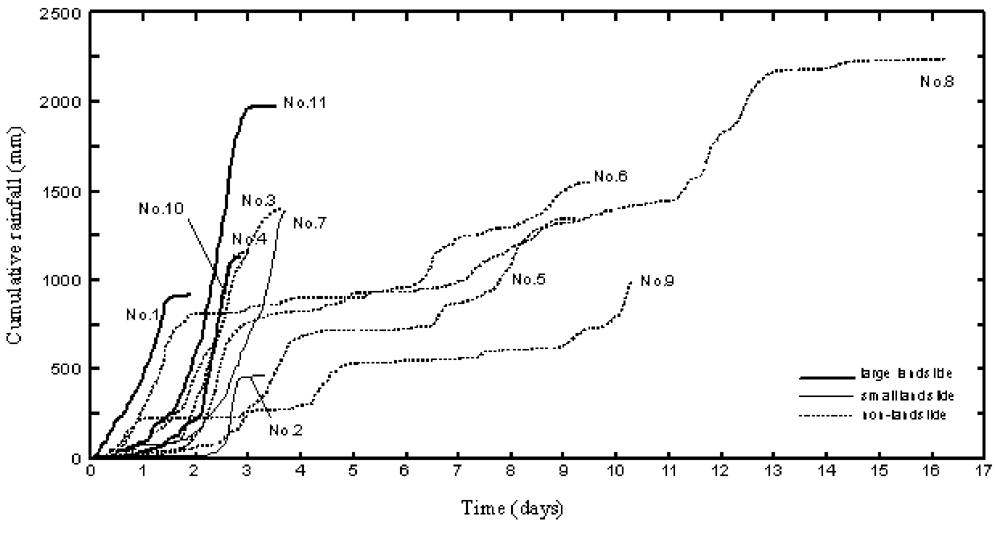

Fig. 2. Cumulative rainfall of the events

Table 1. Aerial photograph coverage

Month Year	Scale	Source
February 1948	1:30,000	U.S. forces
March 1961	1:21,400	Forestry Agency
May 1964	1:22,000	Miyazaki Prefecture
October 1969	1:20,000	Miyazaki Prefecture
May 1974	1:20,000	Miyazaki Prefecture
May 1979	1:16,000	Miyazaki Prefecture
October 1984	1:16,000	Miyazaki Prefecture
October 1989	1:16,000	Miyazaki Prefecture
June 1994	1:16,000	Miyazaki Prefecture
May 1999	1:20,000	Miyazaki Prefecture
September, October 2004	1:16,000	Miyazaki Prefecture
March 2006	1:20,000	Lab. of SABO, UT[a)]

a) Laboratory of Forest Hydrology and Erosion Control Engineering, the University of Tokyo

Materials and methods

Data acquisition

Hourly rainfall data recorded from 1961 to 2005 at the Dogawa Dam rain gauge station were used because sufficient data were unavailable from the AMeDAS observation point Mikado before 1979. Rainfall data for the 1954 disaster were obtained from a previous study (Tani, 1976). Hourly rainfall data for the 1954 event and from 1961 to 2005 were used to determine the rainfall characteristics of this area.

Aerial photographs were analyzed to determine landslide history and vegetation recovery. Generally, aerial photographic coverage of the area was available for every 3–13 years from 1948 to 2004. Because aerial photographs were not taken around the study site just after typhoon No. 14 in 2005, an aerial photograph was taken in March 2006 by the University of Tokyo's Laboratory of Forest Hydrology and Erosion Control Engineering. Consequently, 12 sets of aerial photographs were available for studying landslides at the site (Table 1).

Analysis

First, rainfall characteristics at the study site were investigated. Short-term rainfall characteristics were evaluated using maximum accumulation data for 1-h and 24-h periods. Long-term rainfall characteristics were evaluated using the total amount of continuous rainfall for the higher rainfall events. The total amount of continuous rainfall is defined as the cumulative rainfall during a period bounded both before and after by at least 24 h of no rainfall. Rain events were also categorized based on whether or not they were associated with a typhoon.

Second, the year of landslide occurrence was determined using time-series aerial photographs. The year of landslide occurrence was identified from correspondence between the photograph year and the latest rainfall event. Episodic heavy rainfall events were regarded as landslide-triggering events. Landslide-triggering events were identified by comparing the photograph date with the closest episodic rainfall event. The subsequent recovery process was examined to clarify the landslide history.

Next, the landslide area was measured for landslides that were large enough for measurement on aerial photographs. The relationship between landslide scale and rainfall intensity was also compared. Finally, the relationship between landslide occurrence and rainfall characteristics was assessed for the study region.

Results and discussion

Rainfall characteristics

The probable rainfall of exceedance, corresponding to a return period, was calculated using cumulative 24-h and 1-h rainfall between 1961 and 2005 (Table 2). Heavy rainfall events having cumulative 24-h and 1-h rainfall amounts exceeding 1000 mm and 100 mm, respectively, occurred at an approximate rate of once every 50 years.

Table 2. Return period and corresponding rainfall accumulated 24-h and 1-h from 1091 to 2005

Return period	24-hour rainfall (mm)	1-hour rainfall (mm)
2	357.3	45.0
5	562.7	63.9
10	713.5	76.8
20	868.0	89.3
50	1082.2	105.9
100	1253.7	118.7
200	1434.3	131.7
500	1685.8	149.1

Table 3. General information of top nine total amount of continuous rainfall events

Total amount of continuous rainfall (mm)	Date	Rainfall duration (h)	Maximam 24-hour rainfall (mm)	Maximam 1-hour rainfall (mm)	Induced by typhoon
2,244	25 July-10 August 1999	391	625	59	yes (No.5,7,8)
1,973	3-7 September 2005	84	1,421	96	yes (No.14)
1,547	25 July-4 August 1989	228	664	62	yes (No.12.13)
1,400	2-5 August 1971	87	1,023	71	yes (No.19)
1,387	12-16 October 1997	89	955	88	no
1,343	17-27 July 1972	222	490	38	yes (No.7,9)
1,160	27-30 August 1971	72	768	59	yes (No.23)
1,125	27-30 August 2004	68	962	81	yes (No.16)
1,000	14-24 September 1999	248	284	52	yes (No.16,18)

Rain gauge station: Dogawa Dam, Observation periods: 1961-2005

The total amount of continuous rainfall was calculated to characterize long-term rainfall. The top nine continuous rainfall events are shown in Table 3. Such rainfall events were recorded twice per year in 1971 and 1999. For the rainfall event in 2005, the cumulative 24-h rainfall had an estimated return period of 186 years.

These rainfall events were all caused by typhoons, except for the 1997 event (Table 3); these rainfall events also varied widely in rainfall duration. For example, the August 1999 event lasted 391 h and was caused by three consecutive typhoons passing over the area. In contrast, one typhoon was associated with the September 2005 event, in which rainfall lasted 84 h.

Typhoons cause most of the heavy rainfall events in this region. The heavy rainfall events can be divided into those caused by one typhoon over a short duration and those caused by two or three typhoons over a long duration.

History of landslide occurrence and vegetation recovery

To determine the landslide history of the area, landslide occurrence and subsequent vegetation recovery processes were examined using aerial photographs. Relatively large-scale landslides were visible on 1961, 2004, and 2006 photographs, and comparatively smaller-scale landslides were identified on 1961, 1969, 1999, and 2004 photographs. No other landslides were detected. In 1961 and 2004, landslides occurred in all the watersheds; almost all the landslides were at different locations. Although the 2006 photograph showed large landslides of similar scale to those in 1961 and 2004, there were fewer smaller landslides in the 2006 photograph compared with the 1961 and 2004 photographs.

The rainfall events that triggered the landslides were identified as follows. Disaster reports indicate that the rainfall event in September 1954 likely caused the landslides shown in the 1961 photograph (Fukuoka District Meteorological Observatory, 1964; Miyazaki Local Meteorological Observatory, 1967; Tani, 1976). The landslides in the 1969 photograph were probably triggered by a rainfall event in September 1968, which had rainfall of 105 mm/h; no other remarkable rainfall event occurred during that period. The landslides in the 1999 photograph were caused by a rainfall event in October 1997, which was the only remarkable rainfall of

Table 4. Characteristics of the rainfall events and landslide occurrence

Event No.	Date	Total amount of continuous rainfall (mm)	Rainfall duration (h)	Mean rainfall intensity (mm/h)	Maximum 24-hour rainfall (mm)	Maximum 1-hour rainfall (mm)	Landslide occurrence
1	11-14 September 1954	913	45	20.3	703	62	◎
2	22-25 September 1968	472	80	5.9	454	105	○
3	2-5 August 1971	1,400	87	16.1	768	71	×
4	27-30 August 1971	1,160	72	16.1	1,023	59	×
5	17-27 July 1972	1,343	222	6.0	490	38	×
6	25 July-4 August 1989	1,547	228	6.8	664	62	×
7	12-16 October 1997	1,387	89	15.6	955	88	○
8	25 July-10 August 1999	2,244	391	5.7	625	59	×
9	14-24 September 1999	1,000	248	4.0	284	52	×
10	27-30 August 2004	1,125	68	16.5	962	81	◎
11	3-7 September 2005	1,973	84	23.5	1,421	96	◎

Notes for landslide occurrence; duble circle is large landslide, circle is small landslide, and cross is no landslide

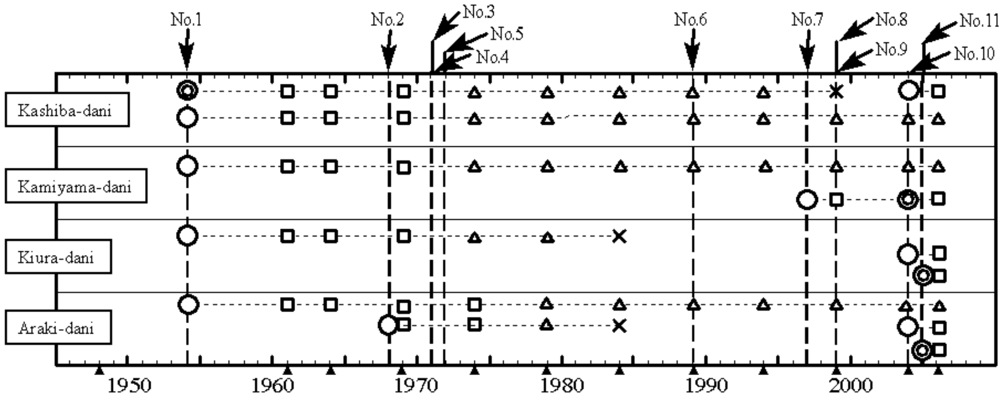

Fig. 3. History of landslide occurrence and vegetation recovery using time-series aerial photograph in each watershed. Marks: Arrows is The rainfall event No. (See Tab.4), double circle is larger landslide occurrence, circle is smaller landslide occurrence, square is no vegetation in landslide site, triangle is defectively covered by vegetation, cross is completely covered by vegetation and black triangle is flyover year.

that period. Further, rainfall in August 2004 triggered the landslides in the 2004 photograph; a September 2005 event caused the landslide in the 2006 photograph. No other episodic events occurred between the 2004–2006 photograph dates.

Table 2 lists most of the rainfall events that triggered landslides. Two additional rainfall events were also related to landslides. Table 4 lists the rainfall characteristics of these 11 rainfall events, consisting of nine heavy rainfall events and two rainfall events (No. 1, No. 2) related to landslide occurrences. The cumulative rainfall for each event is shown in Fig. 2, with the mean rainfall intensity given as an index of the scale of the event. Mean rainfall intensities were calculated by dividing the total amount of continuous rainfall by the rainstorm duration.

The landslide history of each watershed and the years of episodic rainfall events are shown in Fig. 3. An example of the landslide history and vegetation recovery is shown in Photo 1. Subsequent recovery processes following landslides were classified into three categories as follows (Numamoto *et al.*, 1999): (1) no vegetation at the landslide site, (2) patchy vegetation cover, and (3) complete vegetation cover. Much of the 1954 landslide area had still not completely recovered by 2006, although vegetation had begun to recover in 1974. Although the 1954 landslide area at Kashiba-dani had recovered by 1999, another landslide occurred at the same location in 2004. Vegetation had completely invaded the 1968 landslide area by 2006. Except for the 1997 landslides, many of the landslides occurred in different locations from past landslides. Vegetation recovery may have taken such a long time at the 1954 site because almost all the unstable sediment may have flowed out in that event, making it difficult for vegetation to immediately re-invade.

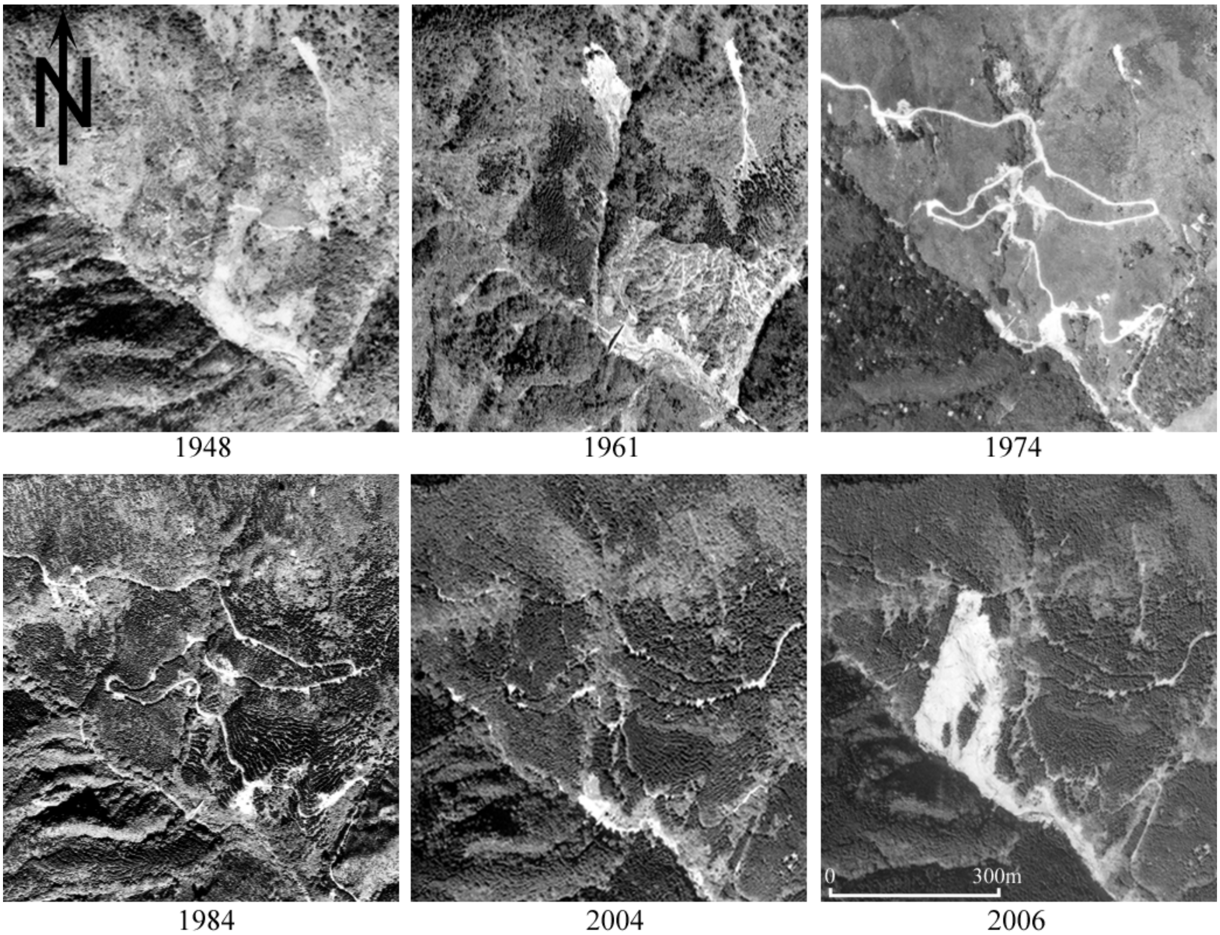

Photo. 1. Example of landslide history and vegetation recovery at Kiura-dani. The 2004 photo was taken after the 2004 rainfall event (No.10). The 1948 photo adopted from Geopraphical Survey Institute.

Table 5. Landslide area and year of occurrence

Watershed	Year of landslide occurrence				
	1954	1968	1997	2004	2005
Kashiba-dani	4.69 ha	-	-	0.45 ha	-
Kamiyama-dani	1.31 ha	-	0.99 ha	4.64 ha	-
Kiura-dani	0.66 ha	-	-	-	5.57 ha
Araki-dani	0.91 ha	0.82 ha	-	-	3.20 ha

Comparison between landslide area and rainfall scale

The landslide area was measured for the following landslides (Table 5): comparatively large landslides in 1954 (at Kashiba-dani), 2004 (at Kamiyama-dani), and 2005 (at Kiura-dani and Araki-dani); sporadic landslides in 1968 (at Araki-dani); the 1997 landslide located at the head of a 2004 landslide (at Kamiyama-dani); and the 2004 landslide that took place at the site of a past landslide (at Kashiba-dani). Landslide areas of < 0.45 ha were not measured. Landslides were comparatively categorized as large-scale landslides (> 3.0 ha), which occurred in 1954, 2004, and 2005, and small-scale landslides (< 3.0 ha).

The relationship between landslide scale and rainfall was examined. The relationships between the landslide area and 1-h rainfall, 24-h rainfall, and the total amount of continuous rainfall are shown in Fig. 4. Although there was a weak correlation ($R^2 = 0.27$) between the landslide area and the total amount of continuous rainfall (Fig. 4, C), there were no definite correlations between the rainfall at each scale and the

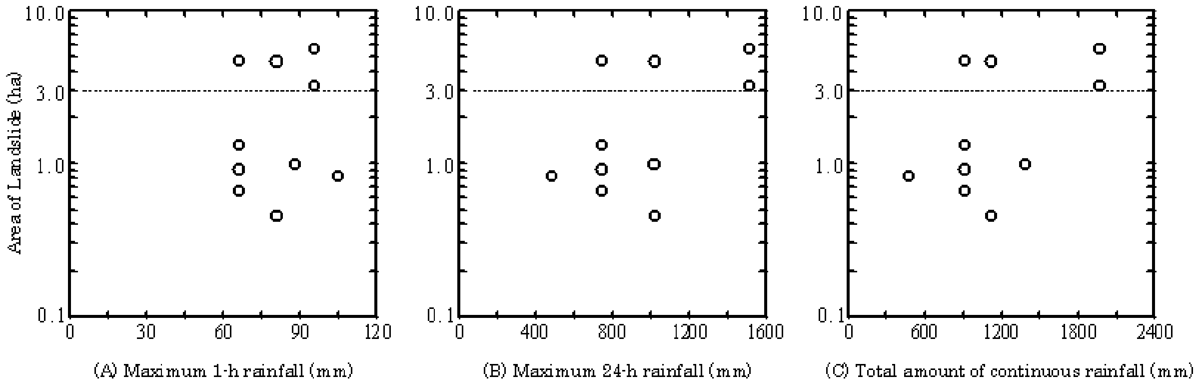

Fig. 4. Relationship between area of landslide and (A) Maximum 1-h rainfall, (B) Maximum 24-h rainfall, (C) Total amount of continuous rainfall

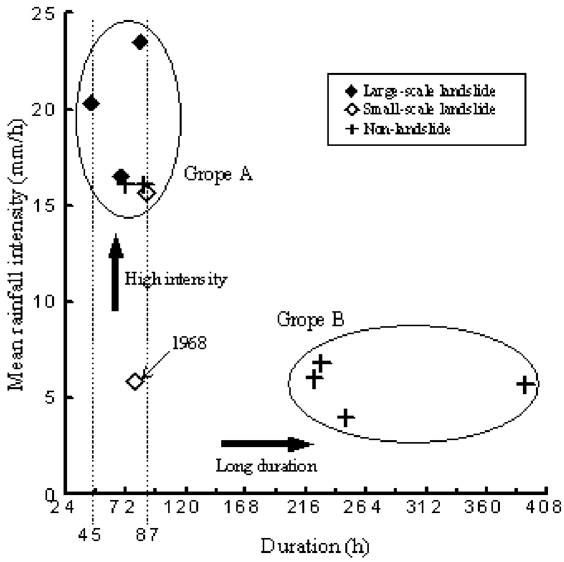

Fig. 5. Relationship between rainfall duration and intensity

landslide area. This suggests that landslide scale is not necessarily determined by differences in rainfall scale, and other factors may be involved.

Relationship between rainfall intensity and landslide occurrence

The relationship between mean rainfall intensity and the duration of each rainfall event listed in Table 4 is shown in Fig. 5. Heavy rainfall events were classified into two groups: Group A, with high rainfall intensity over a short duration (45–87 h) near the y-axis, and Group B, with relatively low rainfall intensity over a long duration near the x-axis (Fig. 5).

These rainfall events were also classified into three categories based on their association with large, small, or no landslides. All landslide events were associated with Group A, except for the 1968 event, which belonged to none of the categories. The 1968 rainfall event had the highest 1-h rainfall recorded at the study site. Consequently, heavy rainfall events with high rainfall intensity induced landslides in this region.

Two non-landslide events in Group A occurred in 1971. Both 1971 rainfall events had similar characteristics to the 1954, 1997 and 2004 events, which were induced landslides. This suggests that before 1954 rainfall event, no heavy rainfall event had occurred for a relatively long time at this site (Maruyama *et al.*, 1956). Thus, unstable sediment had accumulated and almost all unstable sediment in the study site failed in the 1954 event. The 1971 rainfall events had the potential to cause landslides; however, until the 1971 events, no unstable slopes were present because they had all failed during the large 1954 landslide. These data suggest that landslide recurrence may be unlikely for several decades, and that there is a periodicity to landslide occurrence.

Conclusions

We examined the landslide occurrence and subsequent vegetation recovery process in a mountainous region in Japan that has experienced a number of heavy precipitation events. The relationship between rainfall characteristics and landslide history was also investigated. The results of these analyses suggest the following. Typhoons cause most of the heavy rainfall events in this region. These heavy rainfall events can be divided into two types: those associated with one typhoon and having a short duration and those associated with two or three typhoons and having a long duration. Large-scale landslides occurred in 1954, 2004, and 2005. In addition, small-scale landslides occurred in 1968 and 1997. These landslides were caused by heavy rainfall events. At the 1954 landslide site, vegetation did not begin to recover until 1974. There was no correlation between rainfall at each scale and the landslide area, suggesting that the landslide scale is not necessarily determined by differences in rainfall characteristics. All landslides were caused by heavy rainfall events, except for the 1968 event, which was associated with high maximum 1-h rainfall. Although two 1971 rainfall events did not trigger landslides, these rainfall events were similar to the rainfall that caused the 1954 landslide. Almost all unstable sediment in the basin failed in the 1954 landslide. This suggests that in such cases, landslide recurrence may be unlikely for several decades, and that there is a periodicity to landslide occurrences. These results further suggest the importance of a broad survey of the relationship between landslide history and long-term rainfall events to manage landslide risks.

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*Approval code, date and measurement planning agency are as follows (in Japanese); 18林国経14号　平成18年7月28日　林野庁承認

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