Prolonged Effects of Large Sediment Yield Events on Sediment Dynamics in Mountainous Catchments

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Large amounts of unstable sediment induced by landslides might be stored in basins and could have considerable impacts on alpine sediment discharge. Although field evidence is increasing, information about the prolonged effects of large-scale sediment yield on sediment dynamics at the basin scale remains limited. We have compiled existing data on two basins, the upper Kawabe basin and Hasama basin, in Japan. In the upper Kawabe basin, rainstorm events have triggered a number of shallow landslides in the past 30 years. In the Hasama basin, a large earthquake in 2008 induced several huge landslides and many small landslides. We added new data and analyzed the effects of intense sediment yield on sediment dynamics in these basins. We found that, unless evacuated, landslide materials will remain for several decades to hundreds of years. We also indicate that, once a landslide dam forms, sediment dynamics are strongly controlled by the landslide dam stability. We found that the elevated discharge can occur at least five years after the intense sediment yield.

Key words: sediment discharge, prolonged effects of catastrophic event, landslide, landslide dam

1. INTRODUCTION

In steep mountainous regions, linkages of sediment dynamics between hillslopes and stream networks are key issues for comprehensive understanding of the variability in alpine sediment flux [e.g., Gomi et al., 2004; Schwab et al., 2008]. Landsliding is the dominant process of sediment movement on hillslopes and regulates the erosion rate in these regions [e.g., Hovius et al., 1997; Larsen et al., 2010]. Therefore, landsliding is a major sediment source and can supply a large amount of unstable sediment to stream networks [e.g., Korup, 2005; Mikoš et al., 2006]. The sediment transport capacity of mountain rivers is commonly not enough for evacuation of unstable sediment in a single event [e.g., Ohmori, 1992 Koi et al., 2008; Lin et al., 2011]. Thus, much of the sediment produced in upper basins often does not immediately migrate downstream, but is instead deposited in the riverbed, resulting in channel aggradation [e.g., Kasai et al., 2004].

A large amount of unstable sediment induced by landslides might be stored in a basin and could have a large impact on alpine sediment discharge. Several studies revealed that large earthquakes and the heaviest rainfalls were followed by a period of enhanced mass wasting and fluvial sediment discharge [e.g., Koi et al., 2008; Hovius et al., 2011]. For example, Koi et al. [2008] indicated that recent sediment discharge contains landslide debris from an earthquake that occurred more than 80 years ago. Dadson et al. [2004] studied the sediment dynamics that resulted from the $M_W = 7.6$ Chi-Chi earthquake in Taiwan and found that most coseismic landslide material remained on hillslopes and that downslope transport of sediment into the channel network occurred during later storms. Hovius et al. [2011] indicated that the Chi-Chi earthquake was followed by a period of enhanced mass wasting and fluvial sediment evacuation, peaking at more than 5 times the background rate, but returning progressively to pre-earthquake levels in approximately 6 years.

These field evidences suggest that large sediment yield event could give a large and long impact on sediment discharge from mountainous basin. Thus, clarifying about effects of large sediment yield event
on sediment discharge from mountainous watershed is one of essential issues for basin-scale sediment management. Although field evidence is increasing, information about the prolonged effects of large-scale sediment yield on sediment dynamics at the basin scale remains limited. There are many questions about the prolonged effect of large-scale sediment yield, such as the following.

-How long does a large sediment yield event affect sediment discharge?
-How much sediment is evacuated in a given period after a large sediment yield event?
-What are the main controls of the duration of the affected period and the degree of increase of sediment discharge?

To answer them, we compiled existing data on two basins, the upper Kawabe basin and Hasama basin, in Japan (Fig. 1). We added new data and analyzed the effects of large, intense sediment yield events on sediment dynamics in these basins.

2. MATERIALS AND METHODS

2.1 Study sites

The Kawabe River (area 533 km²) is the largest sub-catchment in the Kuma-kawa River in Kumamoto, western Japan (Fig. 2). This region is temperate and wet. Mean annual precipitation in Kaimochi (see Fig. 2) was approximately 2,800 mm from 1982 to 2010. We focused on the upper basin of the Hounoki sabo (sediment control) dam, constructed in 1980 (Fig. 2). The catchment area is 97 km² and underlain by sedimentary rocks and covered by forest.

In this basin, the Kyushu Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism (KRDB-MLIT) has conducted sabo works (sediment control works) since 1968, constructing 11 sediment control dams between 1968 and 2000. The volume of the sediment pool in the Hounoki dam is 1,100,000 m³ and that of other check dams ranges from 6,000 to 210,000 m³. The total volume of the sediment pools of the check dams, excluding the Hounoki dam, is approximately 770,000 m³.


The Hasama River is a sub-catchment of the Kitakami-kawa River in Miyagi, northern Japan. This region is also temperate and wet. Mean annual precipitation in Komanoyu (see Fig. 3) was approximately 2,100 mm from 1998 to 2012. We focused on the upper basin of the Hanayama Reservoir, constructed in 1958. The volume of the water pool of the reservoir is approximately 36,000,000 m³. The catchment area is 127 km² and underlain by volcanic rocks and covered by forest. The catchment is located south of the Kurikoma volcano.

The $M_w = 6.8$ Iwate-Miyagi earthquake occurred in the Iwate prefecture on June 14, 2008. The earthquake had a reverse fault focal mechanism,
dipping toward the northwest. This earthquake induced a number of landslides, including deep-seated rapid landslides [e.g., Takezawa et al., 2012; Meunier et al., 2013]. Several landslide dams were created by these deep-seated rapid landslides [Yoshino et al., 2011] (Fig. 3). To address this, the Touhoku Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism (TRDB-MLIT) started building countermeasure works just after the earthquake.

2.2 Data and analysis

2.2.1 Upper Kawabe basin

We used five landslide maps made by the KRDB-MLIT. These landslide maps were produced in 1966, 2004, 2005, 2006, and 2009. Using aerial photographs taken in 1976, 1984, 1992, and 1999, we made an additional four landslide maps. If the time interval between two landslide maps was shorter than 5 years, we used the two landslide maps to clarify any new landslide that occurred in the interval between the two landslide maps. If the time interval was longer than 5 years, we considered old landslide scars to be already covered by vegetation. However, detailed information about the timing of landslide occurrences was difficult to clarify. Based on the KRDB-MLIT survey, we picked out major rainfall events that triggered sediment disasters and made two assumptions about the timing of landslide occurrences: (1) Landslides in a given interval occurred at the major rainfall event in the interval, and (2) the landslide rate in a given interval was constant. We found five events that triggered sediment disasters in the Kawabe basin, including not only our study area but also the lower part of the Kawabe basin, in 1982, 1991, 1998, 2004, and 2008. In 1991 and 1998, no obvious disaster occurred in our study area (i.e., the upper Kawabe basin), and the rainfall magnitude in Kaimochi was relatively small. Thus, we combined two previous assumptions and assumed that, except for the interval of included years affected by three major events (i.e., 1982, 2004, and 2008), the landslide rate was constant in each intervals. Then, we considered the background landslide rate in the intervals affected by the three major events and assumed that the landslide rate was the same as the mean background landslide rate. The landslide rates in 1982, 2004, and 2005 were calculated by subtracting the background landslide rate in other years from the total landslide volume in a given interval.

Several empirical scaling relations between landslide area ($A$) and landslide volume ($V$) have been proposed [e.g., Guzzetti et al., 2009; Larsen et al., 2010]. For example, Guzzetti et al. [2009] compiled a 677 worldwide landslide inventory and showed the relation as $V = 0.074 A^{1.45}$. Also, the KRDB-MLIT conducted field surveys of the depths of landslide scars and showed mean landslide depths for landslides where smaller than 500 m$^2$ was 0.5 m. Also, KRDB-MLIT reported that mean depths of intermediate (area 500-4,000 m$^2$) and large (area more than 4,000 m$^2$) landslides were 1.5 and 3.0 m respectively. We used these results and found that the mean landslide depth in the upper Kawabe basin was 75% of the average landslide depth of the Guzzetti et al. [2009] data set, if the landslide area was the same. For the Kawabe basin, we revised the equation as $V = 0.0555 A^{1.45}$, to calculate landslide volume from landslide area.

The KRDB-MLIT conducted almost yearly field surveys to clarify sediment deposition amount in 11 sediment control dams. We used this data set to clarify sediment dynamics in this catchment. We also collected precipitation data at the Kaimochi observatory, which is managed by the KRDB-MLIT. Although several additional rainfall gauges were located in this catchment, except for Kaimochi, the observations started after the beginning of our study period. To remove sampling bias, we only used data from Kaimochi.

2.2.2 Hasama basin

We used five landslide maps made by the TRDB-MLIT. These landslide maps were produced
by use of aerial photographs or satellite images taken in 1987, 2006, 2008 (just after the Iwate-Miyagi earthquake), 2009, 2010, 2011, and 2012. Because, except for the Iwate-Miyagi earthquake, no obvious event induced sediment disasters in the study period, we assumed that the landslide rate was constant before the earthquake.

We also collected LiDAR data gathered by the TRDB-MLIT surveys in 2008 (just after the Iwate-Miyagi earthquake), 2011, and 2012. Spatial resolution of LiDAR data is 1 m. Using multi-LiDAR data, we clarified the sediment budget in the river (Fig. 3). We analyzed the LiDAR data at the main river and the tributaries where landslide density was relatively large. We excluded tributaries where landslide density was small from this analysis. We divided the analyzed area into eight sections (Fig. 3). In this analysis, we did not consider the deposition in the water pools at the upper stream of the landslide dam, because no data about it were available. Also, several parts of the riverbed were strongly affected by countermeasure works, so we excluded those parts from this analysis. We also collected data regarding the volume of deposited sediment in Hanayama Reservoir, gathered by a Miyagi Prefecture survey.

According to the field survey by the TRDB-MLIT for 13 landslides induced by Iwate-Miyagi earthquake, the landslide depth in the Hasama basin was relatively large, compared with the landslide depth of Guzzetti’s data set. For the Hasama basin, based on the result of the TRDB-MLIT field survey, we revised the equation as $V = 0.166A^{1.45}$ to calculate landslide volume from landslide area (Fig. 4).

Although several rain gauges were located in the Hasama basin, the data did not cover our study period. We used the precipitation data from the Komanoyu observatory, managed by the Japan Meteorological Agency, located approximately 15 km north of Hanayama Reservoir.

3. RESULTS

3.1 Upper Kawabe basin
3.1.1 Landslide volume

The total volume of landslides in the study period was approximately $3.5 \times 10^6$ m$^3$, and the mean annual landslide rate was $1.1 \times 10^5$ m$^3$ (Fig. 5). The largest storm was found in 2005, and the maximum daily rainfall was approximately 500 mm. Because the heaviest storm induced many landslides and the total landslide volume was $1.3 \times 10^6$ m$^3$, the annual landslide rate in 2005 was 10 times larger than the...
mean annual landslide rate. The second largest daily rainfall was approximately 460 mm and occurred in 2004. According to Assumption 3 in Fig. 5, the landslide rate in 2004 was approximately $3.9 \times 10^5$ m$^3$/y and 4 times larger than the mean landslide rate. Also, in 1982, the third largest daily rainfall was observed (348 mm), and the landslide rate was $3.1 \times 10^5$ m$^3$/y, based on Assumption 3. If we use Assumption 3, we can find good agreement between maximum daily rainfall and landslide rate. Assumption 3 may be the best of our three assumptions, and hereafter, we use the temporal pattern of landslide rate based on Assumption 3.

In the upper Kawabe basin, mean and median landslide area are 1,752 and 1,300 m$^2$. The volume for each landslide was relatively small, mostly less than $1.0 \times 10^4$ m$^3$ (Fig. 6). There were small temporal differences in the relation between landslide volume and appearance frequency.

3.1.2 Sediment deposition rate at the Hounoki dam

The total volume of deposited sediment at the Hounoki dam during the study period was approximately $4.7 \times 10^5$ m$^3$, and 14% of the total landslide volume occurred in the same period (Fig. 5). The annual deposition rate at the Hounoki dam in 2005 was the largest ($1.3 \times 10^5$ m$^3$/y) and 9 times larger than the mean annual deposition rate ($1.4 \times 10^4$ m$^3$/y). This rate was 10% of the annual landslide rate in 2005. The annual deposition rate at the Hounoki dam in 1982 was also large ($1.3 \times 10^4$ m$^3$/y) and in conjunction with the intense landslide occurrence. In 1982, the ratio of the annual deposition rate to the annual landslide rate was relatively large (22%). However, the deposition rates in the years after these intense sediment yields, such as in 1983 and 2006–2007, were very small. Annual deposition rates in 1985, 1995, and 2008 were relatively large, although no major events occurred.

3.1.3 Sediment deposition rate at check dams

The total volume of deposited sediment at the

![Fig. 6](image-url) Relation between landslide volume and appearance number, (a) Upper Kawabe, (b) Hasama.

![Fig. 7](image-url) (a) Cumulative volume of landslide and deposited sediment in Hasama Basin, (b) and (c) Annual landslide and deposition rate. (d) Annual precipitation and maximum daily precipitation of Komanoyu.
check dams, excluding the Hounoki dam, was approximately $1.1 \times 10^6$ m$^3$, and 31% of the total landslide volume occurred in the same period (Fig. 5). Several peaks occur in the temporal patterns of the annual deposition rates, in 1982, 1995, 2001, 2002, 2004, 2005, and 2008. Most of these peaks are in conjunction with the peaks of the annual deposition rate in Hanayama Reservoir.

The peaks of the annual deposition rates in 1982, 2004, and 2005 correspond with the intense sediment yield. The annual deposition rates in 1982, 2004, and 2005 were 3, 8, and 10 times larger than the mean annual deposition rates, respectively. These rates were approximately 28%, 70%, and 26% of the landslide volume triggered by the heavy storm in the same year. In contrast, the deposition rate at 1 year after these peaks, that is, 1983 and 2006, were negative.

3.2 Hasama basin
3.2.1 Landslide volume

The volume of landslides caused by the Iwate-Miyagi earthquake was approximately $1.2 \times 10^7$ m$^3$ (Fig. 7). This volume was approximately 280 times larger than the mean annual landslide volume before the earthquake. Approximately 800 landslides occurred in the study area, and seven landslide dams formed in the basin (Fig. 4). Landslides were concentrated in the upper part of the Hasama basin and landslide density in the lower part of the basin was relatively small. In Hasama basin, mean and median landslide area due to Iwate-Miyagi earthquake are 2,018 and 1,750 m$^2$. Thirty-one landslides were larger than $1.0 \times 10^5$ m$^3$ (Fig. 6). Before the Iwate-Miyagi earthquake, no landslides were larger than $1.0 \times 10^5$ m$^3$.

The largest landslide occurred at Yubama, and the volume of the Yubama landslide was approximately $2.2 \times 10^6$ m$^3$. The landslide at Yunokura was also relatively large, and the volume was approximately $8.3 \times 10^5$ m$^3$. Thus, 24% of the total landslide volume resulting from the Iwate-Miyagi earthquake in this basin was at Yubama and Yunokura. These two landslides created landslide dams on the main channel of the Hasama River.

The annual landslide rate in 2009 was relatively small compared with coseismic landslides ($3.4 \times 10^5$ m$^3$/y) but 10 time larger than the mean annual landslide rate before the earthquake ($4.0 \times 10^4$ m$^3$/y) (Fig. 7). The number of landslides larger than $1.0 \times 10^5$ m$^3$ after the Iwate-Miyagi earthquake was small (Fig. 6).

3.2.2 Sediment deposition rate in Hanayama Reservoir

Approximately 60% of the sediment yielded by the coseismic landslides was deposited on the observed sections of the riverbed (Fig. 7), whereas only approximately 2.5% of the sediment was delivered into Hanayama Reservoir. The sediment deposition rate in Hanayama Reservoir in 2008 (2.9 $\times 10^5$ m$^3$/y) was approximately 10 times larger than that before the earthquake (2.6 $\times 10^4$ m$^3$/y) (Fig. 7). The deposited sediment volume in Hanayama Reservoir between 2009 and 2011 (0.4–1.4 $\times 10^4$ m$^3$/y) was small compared with that before the earthquake. The deposited sediment volume in 2012 (2.8 $\times 10^5$ m$^3$/y) was similar to that of 2008 and 10 times larger than before the earthquake.

3.2.3 Riverbed variation

Approximately $7.0 \times 10^5$ m$^3$ of sediment was eroded in the riverbed in 2008–2011, although only $3.3 \times 10^4$ m$^3$ of sediment was deposited in Hanayama Reservoir in 2009–2011 (Fig. 8). Except for Section 7, riverbed degradation commonly occurred. Especially in the upper part of the basin. Sections 1, 2, 3, and 5 were largely eroded during this period.

In contrast, in 2011–2012, except for Section 3, the riverbed aggradation occurred throughout the basin. Approximately $2.7 \times 10^5$ m$^3$ of sediment accumulated in the riverbed.

4. DISCUSSION AND CONCLUSIONS

4.1 Sediment budget

We found discharged sediment volumes in the basins. Deposition sediment volumes at the Hounoki dam and in Hanayama Reservoir were smaller than the landslide volumes, suggesting that much of the unstable sediments from landslides remained in the basins.

In the upper Kawabe basin, if we focus on sediment dynamics in 2004–2010, the ratio of
sediment volume discharged at the Hounoki dam to the landslide volume was around 18%. The ratio of deposited sediment volume at the check dams to landslide sediment was 28% in 2010, suggesting that these check dams regulated sediment discharge from the basin. Approximately 64% of the landslide sediment was still stored on the hillslope and in the riverbed or outflow from the basin. However, fine sediment, such as washload, might not be trapped at the Hounoki dam. In the future, for more precise estimations, we have to consider the effects of fine sediment discharge.

In the Hasama basin, less than 3% of the landslide sediment discharged into Hanayama Reservoir. Although there is a possibility that very fine sediments passed into the reservoir, most of the sediment was stored in the basin. LiDAR data indicated that approximately 60% of the sediment was stored in the riverbed, suggesting that approximately 40% of the sediment remained on the hillslopes in the 4 years after the Iwate-Miyagi earthquake. These trends well agreed with the results of previous studies of large-scale seismic landslide events [e.g., Dadson et al., 2004; Koi et al., 2009, Lin et al., 2011].

We estimated the time period in which all landslide materials evacuated from the basin. For this estimation, we assumed that most of sediment was trapped at the Hounoki dam or in the Hanayama Reservoir. Also, we estimated background sediment discharge from the data before the intense sediment yield. In Kawabe, the sediment discharge just after 1982 was affected by sediment yield from the storm in 1982. Thus, we used only 10 years of data (1994–2003) for calculation of background sediment discharge. In Hasama, we assumed background sediment discharge as the mean annual deposition rate before the earthquake. Then, the sediment discharge contribution to evacuated landslide materials was estimated by subtracting the background sediment discharge from the sediment discharge rate after the intense sediment yield. This method should be has some uncertainties. For example, since some washload might not be deposited in Hounoki dam and Hanayama Reservoir, the sediment discharge rate after the event might be underestimated. While, the sediment deliver rate from hillslope to stream might decrease with time, suggesting that the sediment discharge rate after the event might be overestimated.

Consequently, we estimated the time periods over which all landslide materials were evacuated from the basins, and achieved estimated values of 33 and 208 years for the Kawabe and Hasama basins, respectively (Table 1). Although our analysis has some uncertainties, this finding agrees with previous studies. For example, Koi et al. [2008] indicated that recent sediment discharge contains landslide debris that was produced by the earthquake that occurred more than 80 years ago. Also, Pearce and Watson (1986) indicated around half of sediment yielded by the huge earthquake in 1929 in New Zealand still remained in the watershed at the 50 years after since the earthquake. We suggest that landslide materials will remain for several decades to hundreds of years before being evacuated.

### 4.2 Effects of landslide dams on sediment discharge

Although a lot of the sediment yielded by landslides caused by the Iwate-Miyagi earthquake remained on hillslopes and in riverbeds, annual deposition rates in Hanayama Reservoir were small in 2009–2011, compared with that before the earthquake. LiDAR analysis indicated that $6.0 \times 10^5$ m$^3$ of sediment was removed from Sections 1, 2, and 4, and this eroded volume was approximately 12 times larger than that of deposited sediment in the lower reaches and in the reservoir (Fig. 8). Much of the sediment was deposited in water pools formed by landslide dams.

In 2012, overtopping erosion occurred at the large landslide dam at Yubama [Kaji et al., 2014]. The height of the landslide dam was degraded approximately 17 m. At the same time, the landslide dam at Yunokura was also partially breached. In 2012, LiDAR analysis indicated that much of the sediments were deposited at Sections 2 (downstream of the Yubama landslide dam), 6, and 7 (downstream of Yunokura). Moreover, the annual deposition rate in Hanayama Reservoir was
significantly large, suggesting that landslide dam breaches induced aggradation of the riverbed at lower reaches and large sediment discharge from the basin.

This evidence indicates that once a landslide dam formed, sediment dynamics were strongly controlled by the landslide dam stability. Similar results were reported by Korup et al. [2004]. They showed if the landslide dam is continuously stable, part of the landslide materials will not be evacuated from the basin and will be stored a long time. Indeed, ancient landslide dams and deposited areas upstream of landslide dams are commonly found in alpine regions. In Japan, large earthquakes and rainfalls often triggered landslide dams in mountain watersheds [e.g., Inoue et al., 2012; Hayashi et al., 2013]. Some landslide dams were continuously stable several years after the formation [e.g., Inoue et al., 2012]. So, we think that the role of landslide dams on sediment dynamics in mountainous basins are often found in Japan after the large-scale sediment yield events.

4.3 Effects of sediment yield on sediment discharge

Many studies showed that the sediment discharge rate after the large sediment yield was relatively large, compared with before the sediment yield [e.g., Koi et al., 2008; Hovius et al., 2011]. We found that the sediment discharges 1 year after the sediment yield event, that is, 1983 and 2006 in Kawabe and 2009 in Hasama, were commonly not so large. In the case of the storm of 1982 in Kawabe, the sediment discharges 2 years after the event were relatively large, compared with background discharge, although no large rainstorms occurred. In the case of the storms of 2004 and 2005, the elevated sediment discharge can be found 3 to 5 years after the intense landslide occurrence. Moreover, in Hasama, the sediment discharge 4 years after the earthquake was large because of a landslide dam breach. To clarify the time period over which the effects of a landslide on sediment discharge disappear, we need additional data, but we found that the elevated discharge could have occurred at least 5 years after the event. Moreover, we can point out two additional points: (1) These elevated sediment discharges might be comparable to the sediment discharge of the year in which a large amount of sediment was yielded (see 2008 data of Kawabe and 2012 data of Hasama), and (2) the increase of sediment discharge after the sediment yield might be delayed a few years.

4.4 A way forward

We compiled and analyzed data on sediment dynamics in headwater basins and examined the effects of intense sediment yield caused by heavy storms and large earthquakes. We showed several preliminary results and found that a part of our results agreed qualitatively with previous studies. Still, several issues remain to be clarified to understand the role of intense sediment yield in sediment dynamics in headwaters. For example, several points that must be resolved are the time period over which all landslide materials are evacuated from the basin, the time period over which the effects of landslide on sediment discharge disappear, whether the effects are controlled by landslide volume, and characteristics of landslide materials. We will compile an additional data set for other basins, for a comprehensive understanding of the roles of intense sediment yield on sediment dynamics.

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REFERENCES


distribution and topography of mountainous river bed by landslide dam failure, (this volume)


