# Sediment yield from seismically-disturbed mountainous watersheds revealed by multi-temporal aerial LiDAR surveys

**AKIRA MATSUOKA[1], TAKAO YAMAKOSHI[1], KEIJI TAMURA[1], JUN MARUYAMA[2] & KIICHIRO OGAWA[3]**

1 *Public Works Research Institute, Erosion and Sediment Control Research Group, Volcano and Debris Flow Team, 1-6 Minamihara, Tsukuba, Ibaraki 305-8516, Japan*
matsuo44@pwri.go.jp

2 *Hokuriku Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, 1-1-1, Misaki cho, Chuo ward, Niigata City, Niigata Prefecture 950-8801, Japan*

3 *Asia Air Survey, Co.,Ltd., 1-2-2 Manpukuji, Asao Ward, Kawasaki City, Kanagawa Prefecture 215-0004, Japan*

**Abstract** The Mid Niigata Prefecture Earthquake (M = 6.8) that occurred on 23 October 2004 caused numerous landslides and landslide dams in the Imo River basin (A = 38 km$^2$) of Niigata Prefecture, Japan, altering sediment yield and discharge processes. Snowmelt and rain events produced more landslides in the basin in following years. We conducted multi-temporal aerial LiDAR surveys to clarify the post-seismic sediment dynamics in this seismically-disturbed mountainous watershed. The surveys revealed the following: in the 19 months after the earthquake, snowmelt and heavy rainfall events yielded 1.4 Mm$^3$ of sediment (about 19% of that by seismic origin based on fieldwork and aerial photographic interpretation); landslides of seismic origin and those of rainfall or snowmelt origin had very similar distributions; as of May 2006, 70% of the sediment yielded by landslides had not been transported downstream, but remained under the scarps or beside the streams and throughout the periods after the earthquake, river bed deformation in the stream part is larger than the sediment runoff to river course in slope part; and the total amount of post-seismic sediment discharge obtained by the multi-temporal bathymetric surveys coincided fairly well with that of the post-seismic sediment runoff, as revealed by the multi-temporal aerial LiDAR surveys.

**Key words** aerial LiDAR survey; DEM; earthquake; rainfall; sediment yield rate; shallow landslides; snowmelt

## INTRODUCTION

At 17:56 on 23 October 2004, a magnitude 6.8 earthquake occurred in central Niigata Prefecture in northeastern Japan. In the town of Kawaguchi close to the hypocentre, a seismic intensity of 7 – the highest intensity recorded since the beginning of seismometer measurements – was measured on the Japan Meteorological Agency (JMA) scale. Strong aftershocks followed one after another; for example, a seismic intensity of 6 was recorded on four different occasions (Table 1). The earthquake caused numerous landslides around central Niigata Prefecture. In the Imo River basin, located close to the hypocentre, large volumes of landslide sediment accumulated in the river channels, forming landslide dams in 55 places. Five of these dams, with particularly large volumes, formed along the main stream of the Imo River basin (around the areas of Terano, Nanpei, Naranoki, Higashi-Takezawa and Junidaira). These dams and the resultant flooding produced tremendous damage throughout the basin, inundating homes and closing roads. In total, the earthquake caused 1419 shallow landslides and 75 deep-seated landslides in the Imo River basin. After an earthquake, because the ground is generally believed to remain fragile, subsequent rainfall and snowmelt can lead to landslides. Thus, to develop post-earthquake sediment-control plans, understanding post-seismic sediment dynamics is crucial. While Shieh *et al.* (2006) described the sediment budget after the Chi-Chi earthquake in Taiwan, to our knowledge, few other studies have quantitatively examined temporal changes in sediment yield in seismically disturbed mountain watersheds.

In this study, we calculated topographic changes in a multi-temporal digital elevation model (DEM) produced using data from aerial light detection and ranging (LiDAR) surveys. We also conducted bathymetric surveys in landslide ponds that were newly formed after the mid-Niigata earthquake. Our purpose was to clarify the post-seismic sediment dynamics in the Imo River basin, a seismically-disturbed mountainous watershed.

**Table 1** Seismic intensity recorded during the Niigata Earthquake (Press release by JMA, 28 December 2004).

| Date | Time | Maximum seismic intensity* | Date | Time | Maximum seismic intensity* |
|---|---|---|---|---|---|
| 23 Oct | 17:56 | 7 | 24 Oct | 14:21 | 5 upper |
| | 17:59 | 5 upper | 25 Oct | 00:28 | 5 lower |
| | 18:03 | 5 upper | | 06:04 | 5 upper |
| | 18:07 | 5 upper | 27 Oct | 10:40 | 6 lower |
| | 18:11 | 6 upper | 4 Nov | 08:57 | 5 upper |
| | 18:34 | 6 upper | 8 Nov | 11:15 | 5 upper |
| | 18:36 | 5 lower | 10 Nov | 03:43 | 5 lower |
| | 18:57 | 5 upper | 28 Dec | 18:30 | 5 lower |
| | 19:36 | 5 lower | | | |
| | 19:45 | 6 lower | | | |
| | 19:48 | 5 lower | | | |

Seismic intensity data are from JMA HP.

* Classes: 5 lower: most people try to escape from a danger; some people find it difficult to move. 5 upper: many people are considerably frightened and find it difficult to move. 6 lower: difficult to keep standing. 6 upper: impossible to keep standing and to move without crawling. 7: thrown by the shaking, and impossible to move at will.

## OVERVIEW OF THE IMO RIVER BASIN

The Imo River basin, located in central Niigata Prefecture, has a drainage area of 38.4 km$^2$, a channel length of 17.2 km and an average bed slope of 1/70. As a right-hand tributary of the Uono River of the Shinano River drainage system, the Imo River originates around Mt Sarukuradake (679 m asl) and flows from north to south before eventually joining the Uono River (Fig. 1).

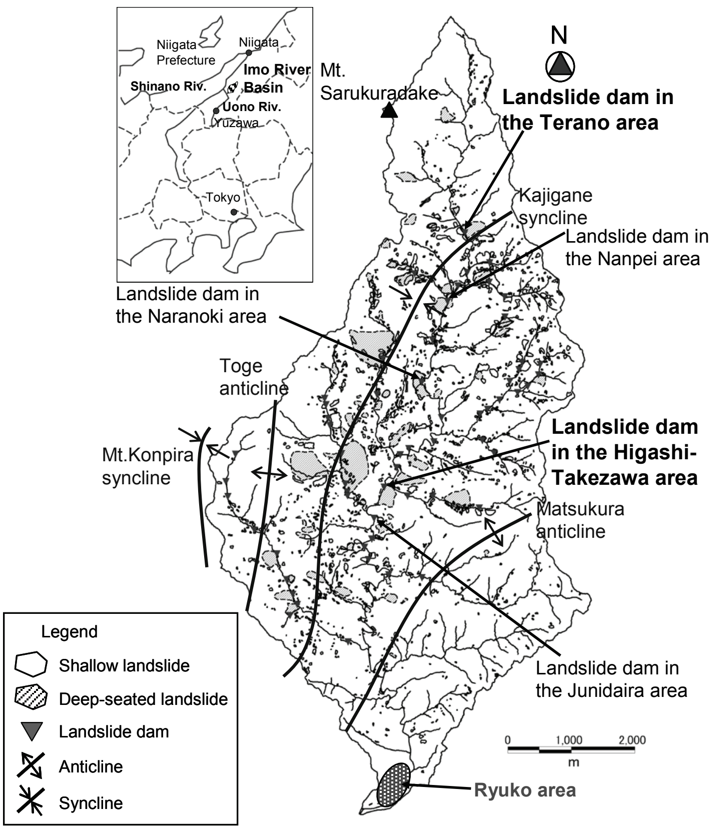


**Fig. 1** Spatial distribution of landslides and landslide dams in the Imo River basin caused by the Mid Niigata Prefecture Earthquake.

The Imo River basin includes formations from the Pliocene Epoch of the Tertiary Period to the Pleistocene Epoch of the Quaternary Period. Composed mainly of sedimentary rocks, such as mudstone, alternating sandstone and mudstone, and sandstone, these formations are distributed from north–northeast to south–southwest and are associated with several fold axes, which have about a 1-km interval between them (Yanagisawa *et al.*, 1986; Kobayashi *et al.*, 1991). Tectonic movements tend to cause cracks in the formations around the fold axes, and the geology along the Imo River basin consists of relatively new and fragile sedimentary rocks of the Neogene Period or later. These sedimentary rocks have been weakened by weathering and can easily become clayey under the influence of groundwater and other factors, making the Imo River basin one of the major landslide-prone areas of Japan. Most of the landslides triggered by the mid-Niigata earthquake occurred in areas located between the Kajigane syncline, which runs north to south in the centre of the basin, and the Toge and Matsukura anticlines, which lie on the east and west sides of the Kajigane syncline, respectively. Enormous amounts of sediment produced by those landslides accumulated in river and stream channels and formed landslide dams at 55 locations in the Imo River basin. Five of these dams formed along the main stream of the Imo River basin (in the areas of Terano, Nanpei, Naranoki, Higashi-Takezawa and Junidaira) and had particularly large volumes.

## METHODS

### Aerial LiDAR survey

Compared to photogrammetric methods, aerial LiDAR surveys allow for faster acquisition of higher density numerical topographic data over a wider area. The measurement accuracy of aerial LiDAR survey is about ±15 cm in a vertical direction (at a height of 1000 m). It is enough accuracy to understand the topographic change. Because these data represent topography over large areas, they are suitable for use in examining sediment dynamics in an entire watershed. Furthermore, because aerial LiDAR does not require measurement-site access, it is useful for producing measurements at inaccessible locations such as natural disaster areas. For these reasons, we considered an aerial LiDAR survey to be the most effective method for clarifying topographic changes in the Imo River basin, which experienced numerous sediment disasters and road closures due to the earthquake. By measuring the last pulse, aerial LiDAR can obtain the shape of the ground surface even under tree cover. However, because measurement accuracy depends on the density of tree crowns, we conducted three aerial LiDAR surveys: one immediately after the earthquake and two more in May 2005 and May 2006, when vegetation had less influence and snow had melted. Table 2 shows the aerial LiDAR survey specifications used in this study. During the aerial LiDAR survey, we also took aerial photographs for use in landslide interpretation. We used the aerial laser data to semi-automatically create contour maps and DEM data (Table 3).

### Analysis of aerial LiDAR data

Using multi-temporal aerial laser data, it is possible to calculate erosional and depositional volumes from elevation differences between periods. To remove the effects of snow cover, human-

**Table 2** Aerial LiDAR survey specifications.

| Performance items | Specifications |
|---|---|
| Machine used | ALTM3100DC |
| Airplane | Cessna 207 |
| Distance from ground | Average 1,500 m |
| Flying speed | 55 m/second |
| Laser pulse frequency | 70 kHz |
| Scanning angle | ±25° (±27° May 2006) |
| Scanning frequency | 27 Hz |
| Measurement point density | Average 0.97/m$^2$ |
| Pulse mode | First/last obtained simultaneously |

**Table 3** Characteristics of the DEMs.

| DEMs | Date | Grid spacing (m) | Data acquisition |
|---|---|---|---|
| 2004 DEM (after the earthquake) | 28 Oct 2004 | 1 | Aerial LiDAR survey |
| 2005 DEM | 11, 17 May 2005 | 1 | Aerial LiDAR survey |
| 2006 DEM | 15, 16 May 2006 | 2* | Aerial LiDAR survey |

*The 2-m grids of the 2006 DEM were converted to 1-m grids for the analysis.

made changes and the water surfaces of landslide dam ponds as much as possible, we calculated the DEM differences separately for slope and stream parts as follows.

In slope areas, we classified shallow landslides based on photographic interpretation for each period (Fig. 2). We refer to the “contracted” landslide area as that where vegetation has recovered; no vegetation recovery was found in May 2005, the first spring after the earthquake. In this study, we analysed shallow landslides only, and not those that were deep-seated. To establish the landslide volume triggered by the earthquake, we calculated the sediment volume by multiplying the landslide area, determined by an aerial photograph interpretation, times the average landslide depth, determined by fieldwork; this method was used due to the lack of precise aerial LiDAR data for the pre-earthquake period. Next, in the stream part, on the basis of photograph interpretations, we created polygons of stream areas of sediment change. We then calculated the sediment change based on the DEM differences in the same way as for the slope part. We thus analysed differences in landslide polygons and in river course polygons. Figure 3 presents an example of the results. Using a geographic information system (GIS), we represented the landslides as polygons; we then calculated the DEM differences between the landslide polygons in the three periods, as shown in Table 4.

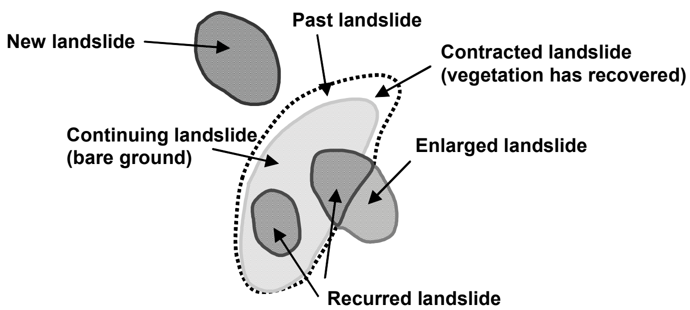


**Fig. 2** Classification of shallow landslides.

**Fig. 3** Method of interpreting differences in the aerial LiDAR data.

**Table 4** Analysis periods.

| | Periods | Days | Events |
|---|---|---|---|
| The Mid Niigata prefecture earthquake | 23 Oct 2004 | | earthquake |
| Period 1 | Oct 2004 – May 2005 | 195 | snowmelt |
| Period 2 | May 2005 – May 2006 | 369 | rainfall and snowmelt |

## RESULTS AND DISCUSSION

### Sediment yield change

Figure 4 presents the temporal changes in the spatial distribution of landslides in the Imo River basin based on photographic interpretation for each period. The concentration of landslides of seismic origin (Fig. 1) coincided with that for landslides of post-earthquake rainfall or snowmelt origin (Fig. 4).

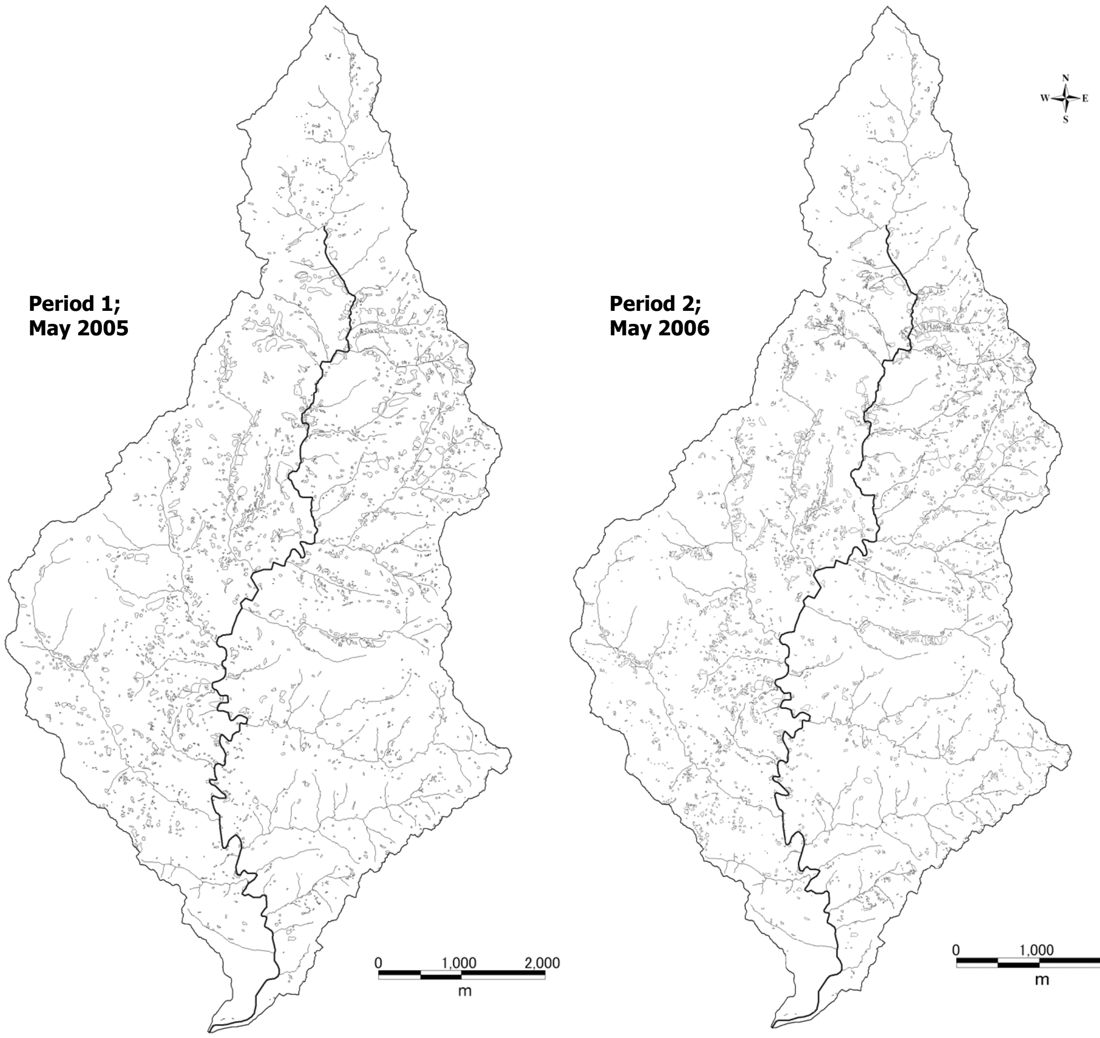


**Fig. 4** Spatial distribution of landslides in the Imo River basin for each period. (This figure shows shallow landslides only and includes continuing landslides.)

Table 5 presents the temporal changes in landslide volume in the Imo River basin, measured by differences in each DEM from each period. The total volume of seismic-origin landslides was

4.8 million m$^3$. Period 1 yielded about 600 000 m$^3$ of sediment (about 13% of that by seismic origin) caused by snowmelt, and period 2 produced about 800 000 m$^3$ of sediment (about 17% of that by seismic origin) triggered by rainfall events and snowmelt. Considering the landslide volume per day as a rate of landslide volume, the rates for period 1 and period 2 were approx. 3100 m$^3$/day and 2200 m$^3$/day, respectively. These results show that sediment yield continued in the Imo River basin, even after the earthquake (Fig. 5).

**Table 5** Temporal change in shallow landslide volume.

| Time | Oct 2004 | Period 1 | Period 2 |
|---|---|---|---|
| Number of landslides | 1419 | 1544 | 2835 |
| Landslide area (km$^2$) | 1.48 | 1.82 | 1.72 |
| Areal rate of landslide (%) | 3.9 | 4.8 | 4.5 |
| Landslide volume (million m$^3$) | 4.8 | 0.6 | 0.8 |
| Rate of landslide volume (m$^3$/day) | – | 3100 | 2200 |

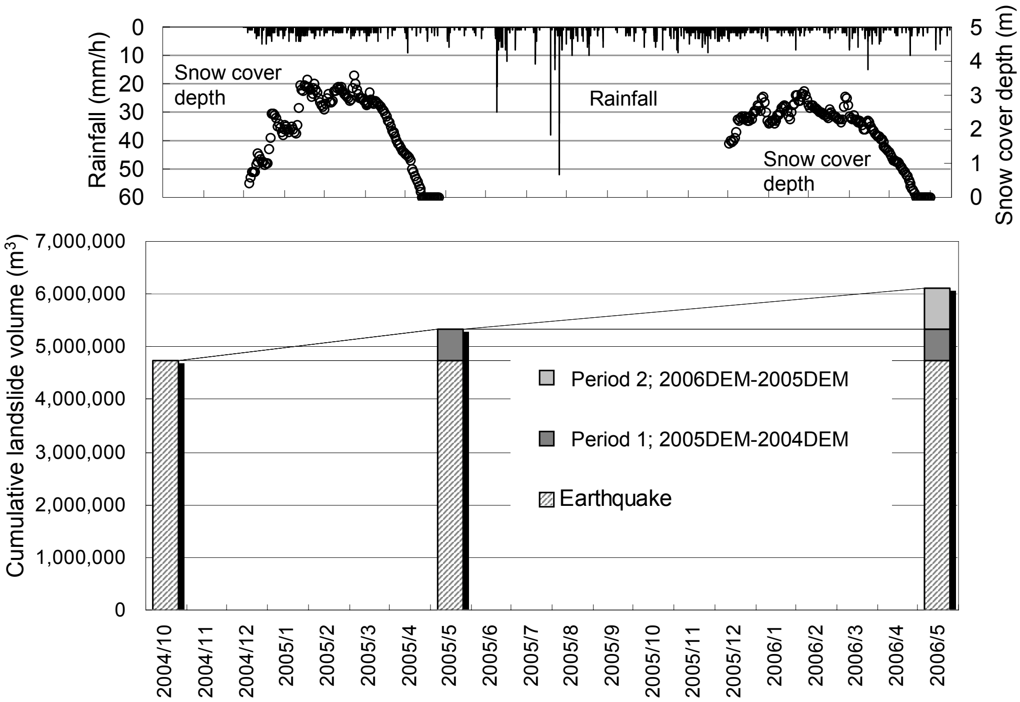


**Fig. 5** Temporal change in landslide volume produced across the entire Imo River basin (not including deep-seated landslides).

## Sediment budget

The sediment budget can help us understand the sediment dynamics across the entire watershed from the time of the earthquake to May 2006. The total sediment runoff was calculated as the sum of the sediment runoff to the river course in the slope parts and the river bed deformation in the stream parts. When calculating the sediment runoff to the river course, we defined the residual rate in each sub basin by the expression shown in Fig. 6. The sediment flowing into the Terano and Higashi-Takezawa areas accumulated at ponds caused by landslide dams that completely closed off the stream. Therefore, from dividing the drainage of the Terano and Higashi-Takezawa areas, the sediment runoff per km$^2$ is shown in Table 6. From Higashi-Takezawa to Ryuko, sediment runoff was heavy during period 1 but not during period 2. However, sediment runoff increased in period 2 from Terano to Higashi-Takezawa, indicating that sediment runoff was still active in the middle part of the Imo River basin. Figure 7 shows flowcharts of the sediment budgets for period 1 and period 2 in the drainage from Terano to Higashi-Takezawa. The figure indicates that landslides continued to provide sediment to the river system, and throughout the periods after the earthquake, river bed deformation in the stream part is larger than the sediment runoff to river course in the slope part. Considering the river bed deformation per day, the rates for period 1 and period 2 were approx. 530 $m^3$/day and 740 $m^3$/day, respectively. This results show a tendency to erosion in the stream area throughout the periods; however, only about 30% of the landslide volume flowed into the river, meaning that 70% of the landslide volume remained at the landslide or beside the stream.

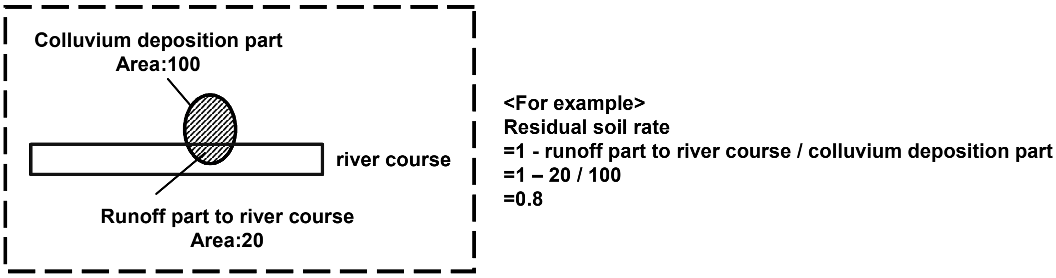


**Fig. 6** Method of measuring the residual soil rate.

**Table 6** Temporal change in sediment runoff.

| | Drainage area ($km^2$) | Sediment runoff ($m^3$) | | Specific sediment runoff ($m^3/km^2$) | |
|---|---|---|---|---|---|
| | | Period 1 | Period 2 | Period 1 | Period 2 |
| Terano | 3.8 | 59 900 | 15 300 | 15 900 | 4 100 |
| Terano to Higashi-Takezawa | 14.8 | 184 000 | 394 400 | 12 400 | 26 600 |
| Higashi-Takezawa to Ryuko | 19.4 | 583 100 | 312 700 | 30 100 | 16 200 |
| Entire Imo River basin | 37.9 | 807 000 | 722 400 | 21 300 | 19 000 |

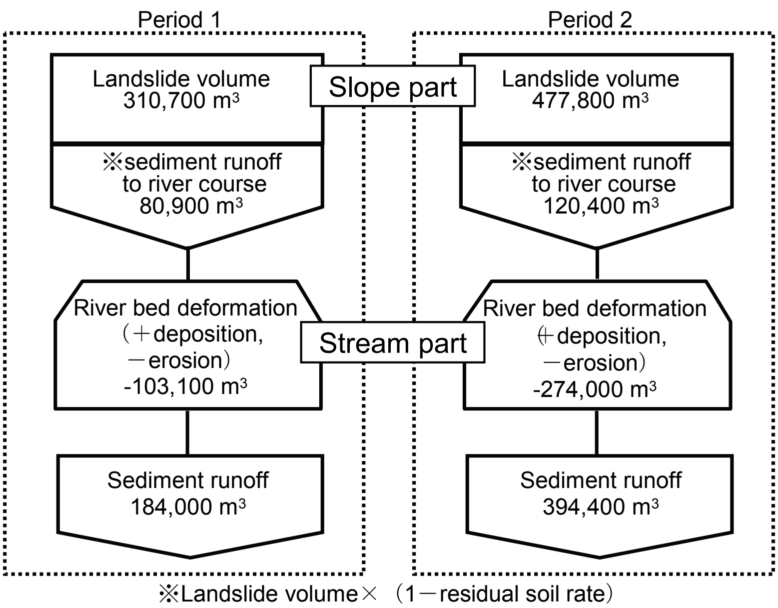


**Fig. 7** Sediment budget at the Higashi-Takezawa landslide dam.

## Change in the erosion rate after the earthquake

The landslide volume and sediment runoff in the Imo River basin suggest that not only did the earthquake change the sediment yield but also that sediment dynamics remained active after the earthquake. We calculated the sediment runoff rate in the entire Imo River basin to be about 40 mm/year in period 1 and about 19 mm/year in period 2. In contrast, Fujiwara *et al.* (1999) reported an erosion rate of 2–3 mm/year in a mountainous area of the northeast Japan back-arc. We assume that over time, erosion in the Imo River basin returned to a stable rate. However, compared with the normal rate in this region, the erosion rate was at least one order of magnitude greater for one and half years after the earthquake.

## Comparison to bathymetric surveys

The earthquake produced several major landslide dams in the Imo River basin. The largest of these dams formed in the Higashi-Takezawa area on the main stream; a large amount of sediment accumulated in the pond after the earthquake, transported by the melted snow and the rainfall. Bathymetric surveys carried out continuously at the Higashi-Takezawa pond after the earthquake showed that 613 300 $m^3$ of cumulative sediment was deposited from the time of the earthquake to June 2006. Table 7 shows sediment runoff calculated by the sediment budget (Fig. 7) and by the bathymetric surveys. As of May 2006 (deposition measurement: June), both methods produced estimates of approximately the same volume: 578 300 $m^3$ (sediment budget) and 613 300 $m^3$ (bathymetric survey). These results must be interpreted with caution because the change of bulk density in the sediment produced by the landslides and the wash load in the bathymetric surveys were not considered; furthermore, the residual soil rates are the average for each sub-basin. However, the results can be expected to show the general order of magnitude of sediment runoff.

**Table 7** Comparison of sediment runoff and results of the bathymetric surveys.

| Time | Sediment budget | | Bathymetric surveys | |
|---|---|---|---|---|
| | Sediment runoff to Higashi-Takezawa ($m^3$) | Sediment runoff to Higashi-Takezawa (Cumulative) ($m^3$) | Measured deposition at Higashi-Takezawa ($m^3$) | Measured deposition at Higashi-Takezawa (cumulative) ($m^3$) |
| May 2005 | 184 000 | 184 000 | – | – |
| Sept 2005 | – | – | 446 000 | 446 000 |
| May 2006 | 394 400 | 578 000 | – | – |
| June 2006 | – | – | 167 100 | 613 100 |

## CONCLUSIONS

In this study, focusing on the Imo River basin where the mid-Niigata earthquake caused numerous landslides, we used aerial LiDAR data to investigate the temporal sediment dynamics after the earthquake. The results of this research are summarised as follows:

(1) Within the 19 months after the earthquake, snowmelt and heavy rainfall events produced $1.4 \times 10^6$ $m^3$ of sediment (about 19% of that by seismic origin based on fieldwork and aerial photographic interpretation), much more than by the normal sediment yield rate in this region.

(2) Shallow landslides of seismic origin, and those of rainfall or snowmelt origin, had very similar distributions.

(3) As of May 2006, 70% of the landslide sediment had not been delivered downstream, but remained under scarps or beside streams, and throughout the periods after the earthquake, river bed deformation in the stream part is larger than the sediment runoff to river course in the slope part.

(4) The total amount of post-seismic sediment discharge obtained by the multi-temporal bathymetric surveys coincided fairly well with that estimated by the total sediment amount

yielded by snowmelt- and rain-triggered post-seismic landslides and the total decrease in channel sediment storage, which were revealed by the multi-temporal aerial LiDAR surveys.

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