Characteristics of a Landslide Occurred in May 2015 in Mt. Hakusan and its Influence on Downstream System

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In May 2015, a large landslide occurred in the headwaters of the Tedori River at the foot of Mt. Hakusan. Airborne LiDAR data and a series of aerial photographs taken over 60 years were used to analyze the topographical features and geomorphological factors that triggered the landslide. The landslide was 800 m long and 300 m wide, with a total sediment volume of 1.3 million m^3. Most of this accumulated at the bottom of the slope and buried the stream channel. However, half of the sediments washed into the river and generated very turbid water for 6 months after the landslide. This influenced the downstream area when the very turbid water entered rice paddies, fresh water, and coastal fisheries, and led to groundwater depletion. Countermeasures were extremely difficult to institute because there was no road access to the landslide, which occurred in a strictly protected national park. Although the Forestry Agency currently uses a helicopter to scatter anti-erosion material, fundamental measures should be taken to ensure the early recovery of native vegetation species, eliminate the source of turbid water, and enhance sedimentation by using sediment ponds.

Key words: Mt. Hakusan, Tedori River Basin, landslide, turbid water, countermeasure

1. INTRODUCTION

In May 2015, a large landslide occurred on Mt. Hakusan (2,702 m asl), Ishikawa Prefecture, Japan, in the headwaters of the Tedori River (**Fig. 1**). The very turbid water generated by this landslide flowed downstream, where it affected the water supply system, freshwater fisheries, farmland, paddies, and the coastal marine ecosystem from late May until June. This landslide became a major concern not only within Ishikawa Prefecture but also at a national level, involving discussions in the prefectural assembly and a petition for countermeasures to diet members.

The volcanic body of Mt. Hakusan formed hundreds of thousands of years ago (*Nagaoka et al*. 1985), and the collapse of mountain bodies is an ongoing geomorphological process. However, erosion can create large alluvial fans downstream. Erosion has many benefits, producing rough terrain, large plains, and beautiful sandy beaches. Because collapse is an inevitable phenomenon, we must be prepared for such occurrences.

This paper analyzed the geomorphological process involved in the 2015 landslide, documented the effects of turbidity on the downstream ecosystems, and discussed future countermeasures.

2. STUDY SITE

The Tedori River is the largest river in Ishikawa Prefecture. It originates from the major Hakusan peaks and is joined by dozens of tributaries, including the Ushikubi, Ozo, and Dainichi Rivers. The Tedori River flows northward and turns west at the town of Tsurugi (**Fig. 2**), ultimately reaching the Sea of

Fig. 1 Whole view of the landslide occurred in May 2015 taken on June 2, 2015 by Ishikawa Forest Management Office.

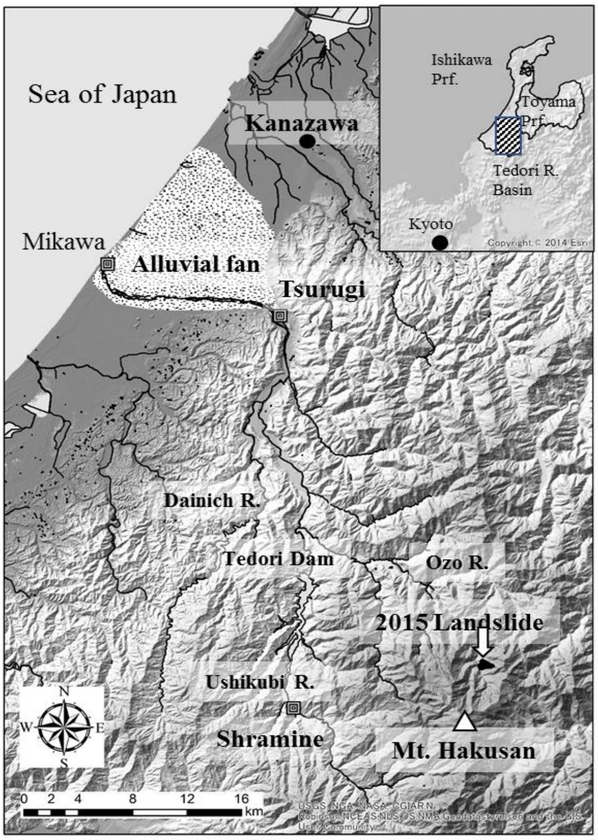

Fig. 2 Location of Mt. Hakusan, the 2015 landslide and Tedori River basin.

Japan. The catchment area is 809 km^2, the main trunk channel is 72 km long, and the average gradient from the source to the mouth of the estuary is 1/27. A typical alluvial fan is formed downstream from Tsurugi. The fan has an area of about 17,000 ha, the elevation of the apex is about 80 m above sea level, and the average gradient of its ground surface is about 1/150 (*Maruyama et al*. 2012). This alluvial fan is mainly used for rice paddies and is the largest area of rice production in the prefecture.

Mt. Hakusan is located in the headwaters of the Tedori River basin (**Fig. 2**). The upstream part of the basin has many steep slopes, and large landslides are common. The geology of the basin ranges from underlying Hida metamorphic rock formed in the Paleozoic to Quaternary volcanic deposits (**Fig. 3**). The metamorphic rocks include gneiss to the east of the Tedori River Dam and in the Ozo River sub-basin. The Tedori group, which is mainly composed of sedimentary rock from the Jurassic to Cretaceous, is distributed upstream in the Tedori River. The eastern part of the Ozo River basin is Nohi Rhyolitic rock from the Cretaceous to the early Paleogene period. Miocene marine volcanic deposits of green tuff are distributed in the middle reach of the Tedori basin. New and old Mt. Hakusan volcanic deposits, from eruptions that occurred from the late Pleistocene to the early Holocene, cover the main peak of Mt. Hakusan and associated ridges. The erosion of the volcano has created barren landforms, such as landslides and slope failures, and generated a large amount of sediment. Most of the old landslide topography formed during the last glacial period until the early Holocene (*Kojima et al*. 2015).

The currently active landslide area involves the southern part of Mt. Hakusan, including the Jinnosuke (*Wang et al*. 2007) and Yunotani Valleys. These landslides occur mainly in an area with a dip flow structure in the Tedori Group. A large landslide area has been also recognized in an altered zone of the Nohi Rhyolitic zone, which is caused by sulfidic alternation (*Koide* 1973). The National Research

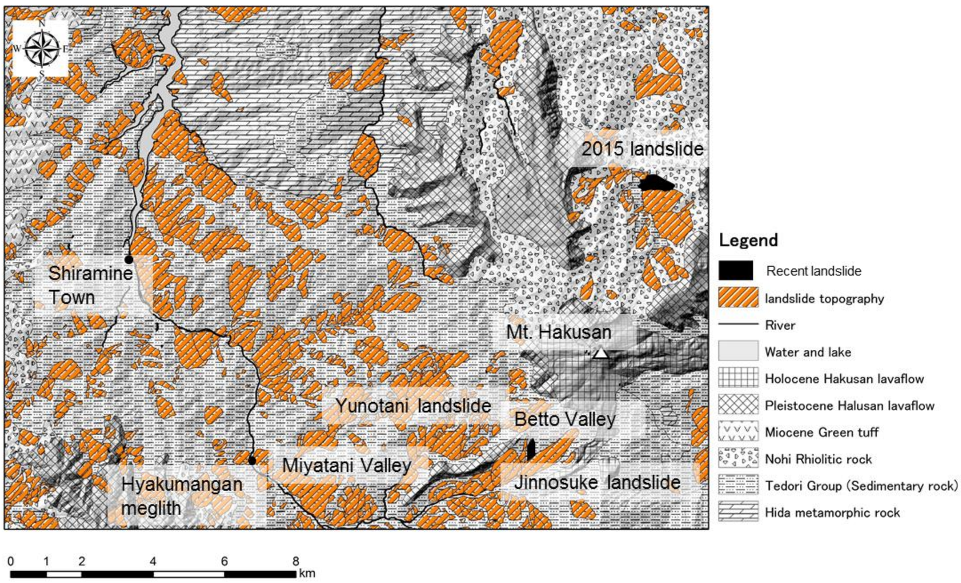

Fig. 3 Geology and landslide topography surrounding the 2015 landslide in Hakusan Mountain Range. Geological data and landslide data were provided by AIST Geological Survey and Integration Center (2016) and Disaster prevention science and technology research institute (2016), respectively.

Institute for Earth Science and Disaster Prevention (2016) identified a landslide more than 1 km long and covering tens of hectares involving the northern part of the Hakusan Volcano.

The biggest natural disaster in the history of Ishikawa Prefecture involved a deep-seated slope failure that occurred in 1934 in the southern part of Mt. Hakusan (*Shimazu* 1996). This collapse occurred in the Betto Valley, was 900 m long and 150–200 m wide, and followed torrential rain in July 1934, which involved a total rainfall of 466 mm with a maximum daily rainfall of 352 mm. The discharged sediments reached the other side of the river, and the debris flow seriously damaged the village of Shiramine located downstream (*Shimazu*, 1996). The estimated collapse area was 16.9 ha and the volume of collapsed sediment was 164,100 m^3 (*Nishikawa* 1988). Another debris flow in the Miyatani Valley transported a megalith measuring more than 16 m high and 52 m in circumference. This rock was called the "one-million-kan rock" (more than 4,800 tons) and was designated as a prefectural natural monument to remember the tragic disaster.

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3. STUDY METHOD

Geomorphological analysis was carried out using airborne Light Detection and Ranging (LiDAR) data for the ground surface to calculate the sediment volume and sediment budget. The LiDAR data were collected before (August 2014) and after (June and October 2015) the landslide by the Kanazawa River National Highway Office. A series of aerial photographs was used to analyze the process leading to the 2015 landslide. The oldest aerial photographs were taken in 1955 by the US Air Force and were georeferenced using ArcGIS 10.3.1. More recent aerial photographs taken in 1977, 2009 were imported into ArcMap from the Geographical Survey Institute web (2016) using the ESRI import tool. The recent photographs taken before and after the 2015 landslide were provided by the Kanazawa River National Highway Office.

The hydrological analysis was performed using AMeDAS precipitation data collected in Shiramine, Hakusan, which is located 10 km south of the 2015 landslide. Discharge and turbidity data were collected using an automated measurement system installed in Tsurugi by the Ministry of Land, Infrastructure and Transport. These data were used to analyze the relationship between turbidity and hydrological conditions.

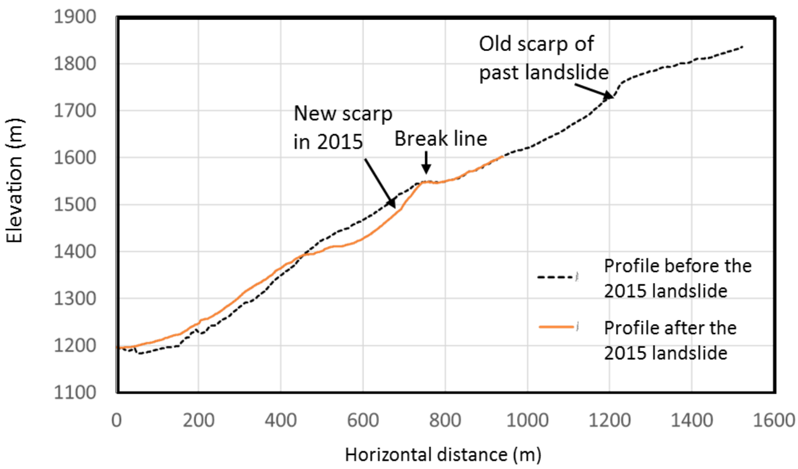

Fig. 4 Longitudinal profile before and after the 2015 landslide.

4. RESUT AND DISCUSSION

4.1 The topographical change before and after the landslide in 2015

Fig. 1 shows an overall view of the landslide, which was 800 m long and 300 m wide. The scarp was 400 m long and 300 m wide; the collapse depth was up to 45 m; and the elevation difference was about 400 m. The cross-sectional profiles generated from digital elevation models before and after the landslide are also shown in **Fig. 4**. A large scarp at

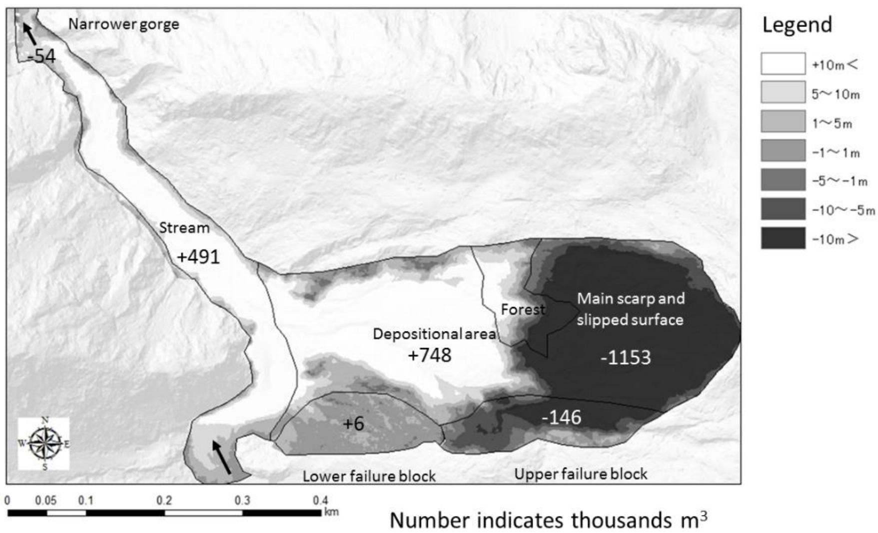

Fig. 5 Elevational change between Oct 2014 and June 2015. The numbers indicate degraded and aggraded sediment volume (thousands m^3).

around 1,700 m in elevation, which was formed by previous movement, already existed and a break line was recognized in the middle slope at 1,500 m. The new scarp formed by the 2015 landslide was located below the break line at 1,390–1,550 m; the collapsed area was 6.4 ha. Before the landslide, an old-growth forest composed of birch (*Betula ermanii*) and beech (*Fagus crenata*) covered an area of 5 ha. However, this forest was destroyed completely by the landslide and buried in the streambed. Some forest slipped down from the upper slope and was retained on the middle slope, which looks as though it has not moved. Nevertheless, many of the tree trunks in this area now tilt in various directions, and most trees were seriously damaged and withered.

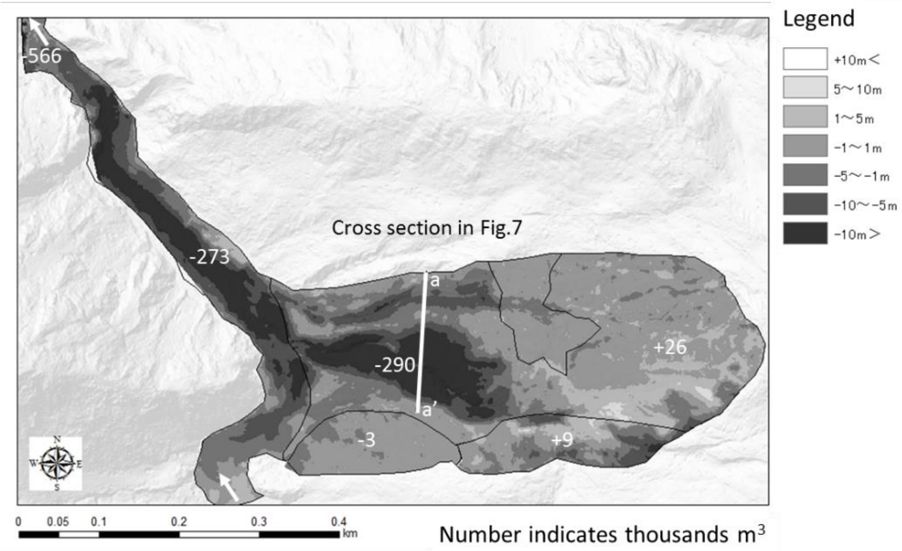

Fig. 6 Elevational change between June and October 2015. The numbers indicate degraded and aggraded sediment volume (thousands m^3).

4.2 Sediment volume produced by the landslide

The generated sediment volume was 1.154 million m^3. The minor scarp on the southern flank also collapsed. The fallen slope was divided into two blocks; the upper failure block covered 5 ha, had a depth of 8.5 m, and a sediment volume of 146,000 m^3. Totally, 1.3 million m^3 of sediment was produced by this landslide.

The collapsed sediment covered the original slope up to 500 m from the downstream portion of the slide, which had a maximum thickness of 35 m (mean 11 m) (**Fig. 5**). The deposited sediment volume was 748,000 m^3. There was a narrow gorge 500 m downstream from the bottom of the collapsed slope, and most of the transported sediments were stored there. These sediments created a sand bar about 100 m in width, and the riverbed was raised about 10 m above its original level. The sediment accumulated in the 500-m section from the landslide slope to the gorge had an estimated volume of 491,000 m^3. The volume stored on the lower slope and in the stream section was 1.25 million m^3, sediment transported farther downstream was 50,000 m^3.

4.3 Generated sediment volume after the landslide

After the landslide, the collapsed deposits (about 750,000 m^3) that accumulated on the slope eroded into the stream. **Fig. 6** shows the eroded sediment volume from June 20 to October 2015 determined from the LiDAR data; the denuded volume was also calculated. On the slipped surface in the upper part of slope, the topographical change was slight, and sediment (26,000 m^3) supplied from the upper rim of the scarp was retained within the slipped slope. Two gullies, which were buried by the landslide debris, have since been carved out with a large amount of landslide deposits. The estimated amounts of degraded deposits were 290,000 m^3 from the slope and 273,000 m^3 from the channel; in total 563,000 m^3 of sediment flowed downstream.

In August 2015, the forest management office sprayed mortar on the slide to prevent surface erosion. This material remained on most of the upper slope and on the left and right sides of the lower slope, but none remained in the center of the lower slope, where a deep gully formed. **Fig. 7** shows a

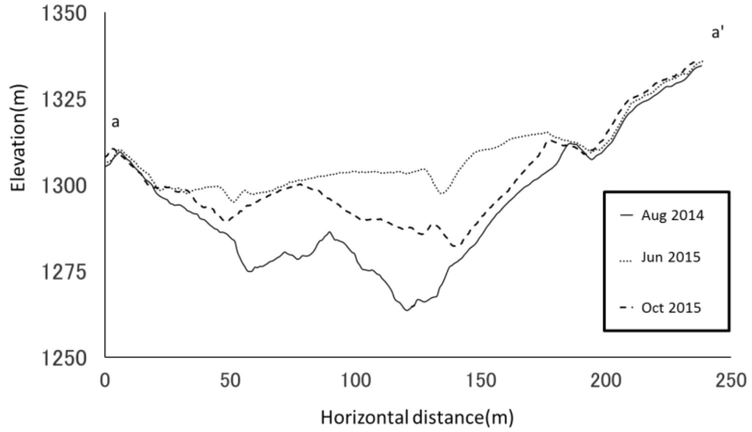

Fig. 7 Cross sections before, just after and a half year later of the 2015 landslide at the bottom of landslide.

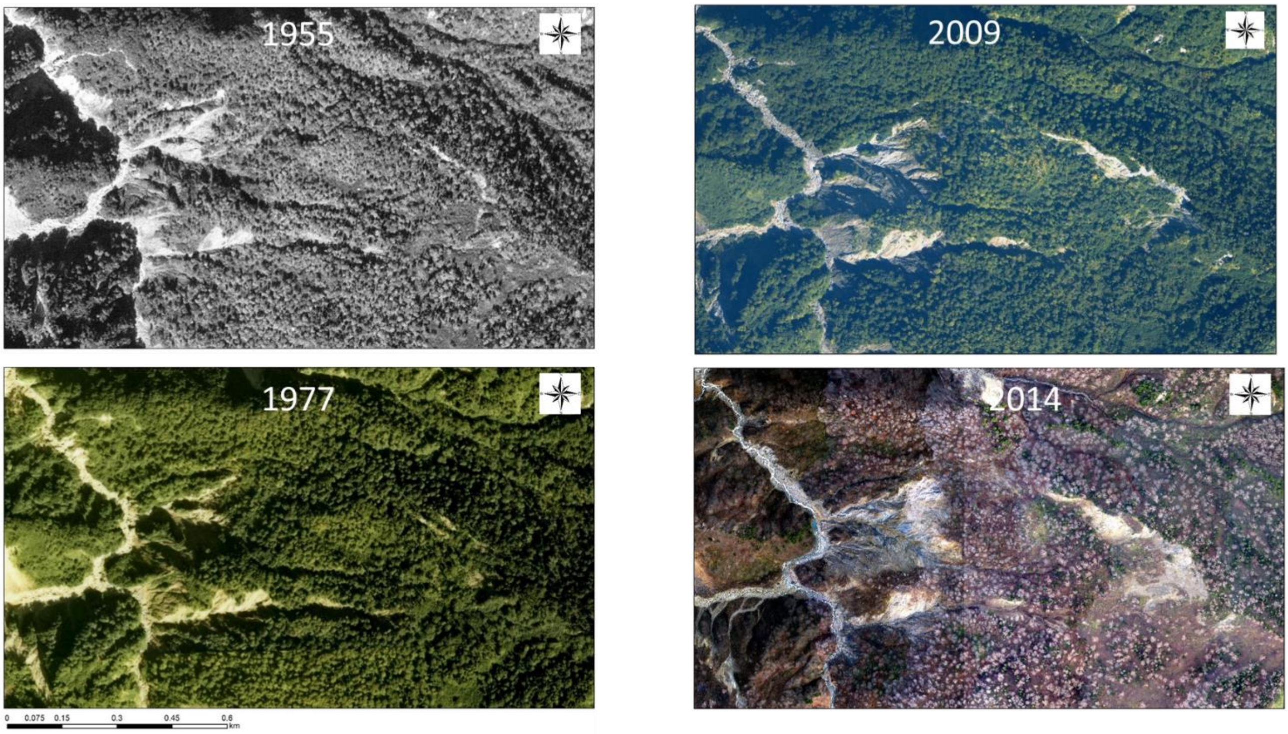

Fig. 8 A series of aerial photos since 1955. Upper left: taken by US Airforce in 1955, Lower left: Color photo taken by Geographical Survey in 1977, Upper right: photo taken by Geographical Survey in 2009 and Lower right: taken by Kanazawa River and National Highway Road Office in 2014.

cross-section of the lower slope, where the accumulated deposits were deeply incised. In the spring of 2015, just after the landslide, the slope was deeply covered with landslide deposits over a horizontal distance of 200 m. However, this surface changed drastically: within 6 months, a 20-m-deep V-shaped valley had formed in the middle section, and the deposits flowed downstream.

4.4 Precursor phenomenon for the 2015 landslide

Several phenomena were regarded as precursors of the landslide. The scarp of the older landslide block is clearly recognized in the oldest photo taken by the US Airforce in 1955 (**Fig. 8**), although it was not quite as wide as at present. A large bare slope also existed on the bottom of the lower part of the 2015 landslide. A color aerial photograph taken by the Geographical Survey Institute in 1977 shows no initial change compared with aerial photographs taken in 1955. In 2009, this changed dramatically. The crack in the scarp reopened and the area of bare slope along the channel became larger, indicating that the landslide movement had been accelerating since 1977.

A small portion of the lower edge of the middle slope collapsed in October 2014. This had an area of 2 ha and a collapse volume of 50,000 m^3. Subsequently, the movement of the landslide became

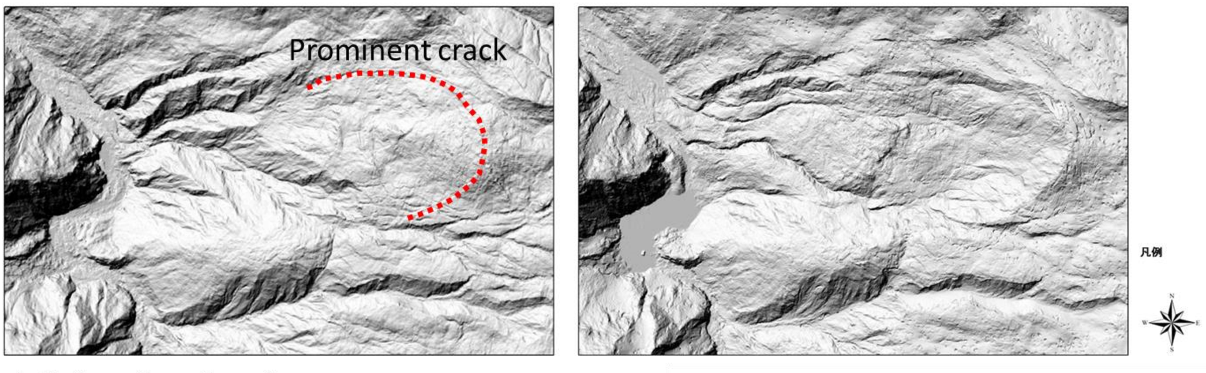

Fig. 9 Micro-topography comparison before (left, November 2014) and after (right, June 2015) the 2015 landslide. Break line indicates boundary of landslide block analyzed by LiDAR data.

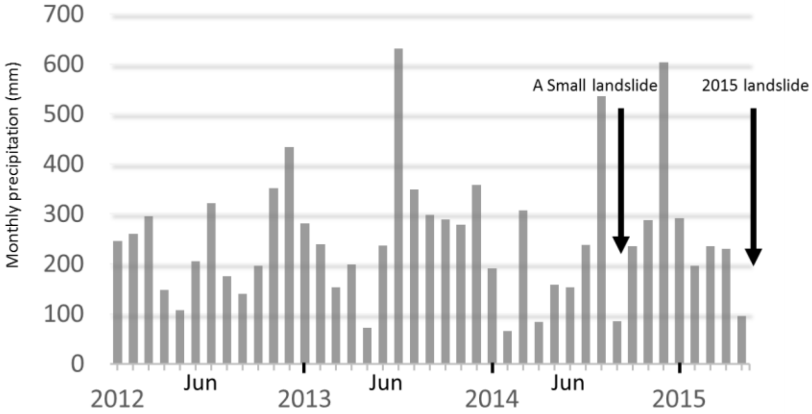

Fig. 10 Monthly precipitation from 2012 to 2015 before the landslide at Shiramine weather observation point.

prominent, and numerous cracks became visible in the center of the landslide. **Fig. 9** compares the topography before and after the landslide. Before the 2015 landslide, the lower part of the slope had been denuded and bedrock was exposed, while the upper part of the slope had been torn by many arc-shaped cracks. The crack shown by the dashed line was prominent, and this coincided precisely with the scarp of the 2015 landslide. This implies that the landslide had already begun moving before 2015. Therefore, it should be possible to predict where a landslide will occur by searching for such microtopography.

4.5 Meteorological factors that caused landslides

The metrological factors affecting the 2015 landslide were analyzed using AMeDAS data. **Fig. 10** shows the monthly maximum rainfall over the past 4 years in Shiramine, Hakusan. High rainfall occurred in the period from 2013 to 2014 and the monthly precipitation in July 2013 was 630 mm. This intense rainfall caused serious flooding damage downstream in the Tedori River. In 2014, torrential rain also occurred, with monthly rainfall of 535.5 mm and hourly rainfall of 29 mm. After this rainfall event, a small slope failure that presaged the 2015 landslide occurred at the lower end of the landslide area. The amount of snowfall in the winter of 2014 was high and the monthly precipitation in December reached 603 mm. The 2015 landslide was very likely caused by melting of the snowfall that accumulated on the slope in December 2014.

4.6 Generation of turbid water

The aerial photographs taken in June 2015 showed that turbid water was generated from two gullies that formed in the collapsed area, and this water was clearly different from the stream water flowing from the upper part of the landslide. The muddy water flowed down from this point to the Ozo River, and there was a distinct difference in water color at the confluence of the Ozo River and the main

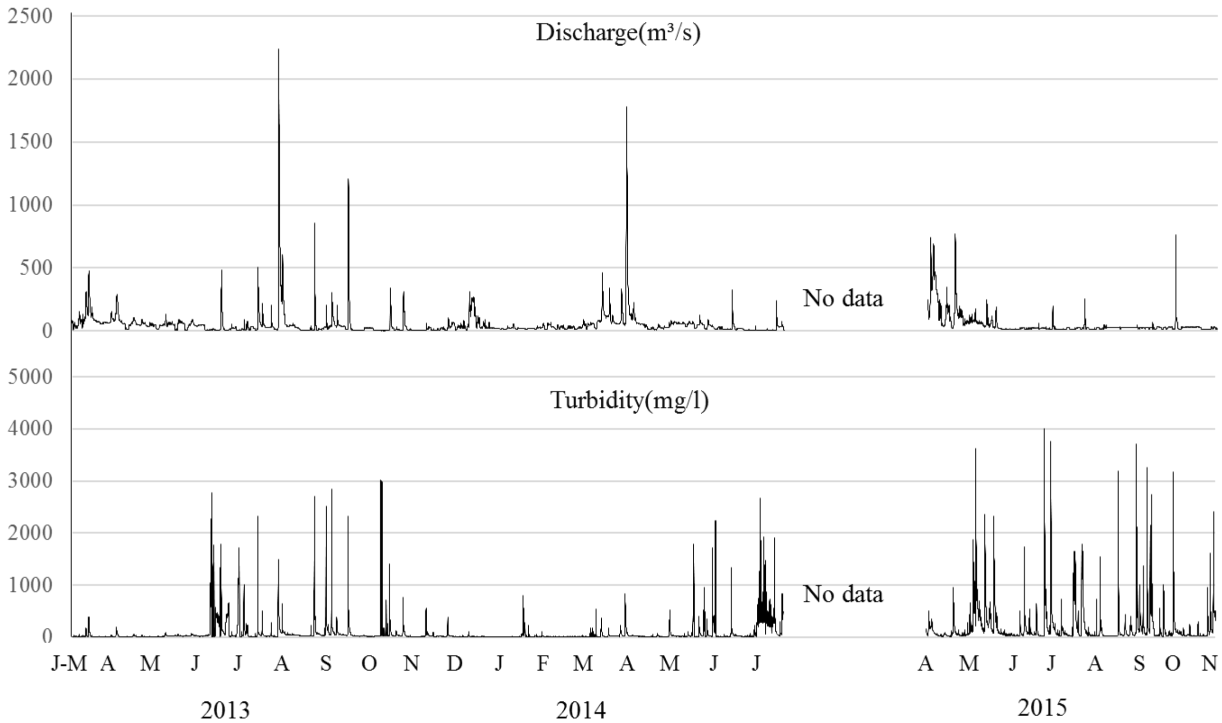

Fig. 11 Discharge and turbidity from 2013 to 2015 at Tsurugi gaging station.

channel of the Tedori River. **Fig. 11** shows the turbidity and discharge over the 3 years from 2013 to 2015 measured at Tsurugi gaging station. Turbidity exceeding 2,000 mg/l was observed once in 2013, but not in 2014. In comparison, turbid discharge exceeding 2,000 mg/l occurred frequently after May 2015, and a peak turbidity exceeding 4,000 mg/l was recorded in June when the discharge was the lowest. During the summer, turbidity tends to increase when the rainfall exceeds 40 mm, and the peak turbidity in June was recorded when rainfall exceeded 80 mm.

4.7 Influence of turbid water on downstream system

Sediment generated by turbid water flowed to the vicinity of the water intake of the Shichikayosui Irrigation Network, which supplies the paddy fields of five cities and one town in the Tedori River alluvial fan. Although there was concern about a decline in crop growth, the effect was limited, and the rice yield in some places exceeded the annual average. In sedimentation ponds installed near the water intake, the deposition was more than 10 times higher than normal. In addition, the inner water surface and coastal fishery were directly influenced by the turbid water. In the river, plans to release juvenile ayu (*Plecoglossus altivelis*) for leisure fishing in May were suspended because of the turbid water. Ice gobies (*Leucopsarion petersii*; shirauo in Japanese), which spawn over gravel in the estuary, could not be captured because of the fine sediment accumulation. Furthermore, the turbid water that diffused in the coastal area caused mud to adhere to fishing nets (**Fig. 12**), which resulted in net breakage. As coastal area in Kaga region has been suffering from serious erosion (*Hayakawa et al*. 2010), these sediments may contribute to prevent coastal erosion. Further study is needed to clarify the coastal topographical change before and after the landslide.

In the alluvial fan, a marked decline in groundwater was observed from just after the landslide until mid-November 2015. This decline was the largest in the last 20 years in terms of both the rate of decline and the minimum water level (*Yanai et al.* 2016). A significant decline of percolation on paddy fields after the landslide was observed and groundwater recharge from paddy fields was reduced by 36 % (*Tanaka et al.* 2017). Fine sediment accumulation on paddy field from turbid water was apparently responsible for this marked decline of groundwater.

Freshwater species of stickleback (P*ungitius* sp.) dwell in brooks originating from spring water, and are designated as both rare wild species in Ishikawa Prefecture and Ishikawa Prefecture endangered species type I. The lowering of the groundwater level caused the riverbed to dry up for the longest period in 20 years and the extent of the dry area was the largest in the lower part of the Tedori River. As a result, submerged aquatic vegetation disappeared and the sticklebacks that dwell among it were unable to survive. The decline in the infiltration rate from river to underground had a devastating impact on their populations (*Yanai et al*. 2016).

Fig. 12 Fine sediment adhered with Squid fishing net.

4.8 Future measures

Countermeasures against this landslide were very difficult to institute for several reasons. First, as there is no access road, it is impossible to implement any erosion control works. Second, because the area is a special protection area in a national park, we need to consider biological diversity, including the protection of native species and prevention of the invasion of exotic species. The Forestry Agency planned to spray a mixture of an organic material with cement to fix the denuded soil from a helicopter. Standard greening techniques that use a mixture with exotic grass seeds could not be used there to conserve native plant species.

To achieve early vegetation colonization, it is essential to stabilize the ground surface because serious surface erosion results from the high elevation, fragile geology, and freeze–thaw action. After stabilizing the soil surface, it is necessary to perform a variety of bioengineering tasks, which include collecting seeds from the surrounding trees to scatter widely. As willow (*Salix sachalinensis*), poplar (*Populus maximowiczii*), and alder (*Alnus maximowiczii*) are typical pioneer species in the area surrounding the affect slope, the planting of willow cuttings is one effective measure to promote vegetation establishment. Furthermore, as mentioned above, sediment ponds are very efficient for capturing sediment. Therefore, this type of facility should be included within drainage areas to minimize high turbidity water in the event of the future occurrence of a landslide.

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