The Effects of Hydraulic Structures on Streams Prone to Bank Erosion in an Intense Flood Event: A Case Study from Eastern Hokkaido

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Bank erosion can induce huge financial damage by eroding lands and destroying properties and infrastructures along the river. Understanding the process is first necessary so that hydraulic structures could be placed efficiently to prevent disasters. This study examined the process during an intense storm in August 2016 in Pekerebetsu and Kobayashi Rivers, the eastern Hokkaido Island in Japan, which caused disastrous damage in the area. The analyses of airborne LiDAR data, satellite imagery, and field survey revealed that debris flows produced from weathered granites in the headwaters triggered drastic channel widening by eroding banks consisted of incoherent periglacial colluviums in the upstream reaches. Sediment produced there deposited in the next gentler downstream reach (< 2 degrees), naturally in Kobayashi River, and by a dam in Perekebetsu River. For the former reduction in the amount of sediment transported limited bank erosion in the further downstream. In contrast, for the latter flow travelled encouraged vertical and then lateral erosion at the outlet of a reach containing a gorge and groundsills. Sediment produced from there aggraded beds in the further downstream to cause more bank erosion in turn. The results suggested that change in hydraulic condition created by valley configuration or hydraulic structures should be first understood for efficient and effective disaster prevention planning not only at a reach scale but also a catchment scale.

Key words: bank erosion, debris flow, periglacial colluvial deposits, hydraulic structure

1. INTRODUCTION

Bank erosion is globally recognized as a major sediment source for a basin [*Janes et al.*, 2018]. It can cause huge financial damage to the area by eroding lands and destroying properties and infrastructures along the river. It occurs when the lateral force of the flow dominates vertical one, so that either sediment deposition or channel incision can induce the phenomena [*Simon and Rinaldi*, 2006]. For example, bed aggradation across the valley, or bar formation with excessive amount of sediment supplied to a channel reach will offer flow more opportunities to contact banks and undercut their feet. In contrast, prominent channel incision, which is likely to happen with flow containing small amount of sediment, can result in the exposure of bedrocks on the bed, to redirect erosion force laterally. Once a bank is eroded, the phenomena could propagate downstream with materials yielded from there, which may aggrade beds in its downstream reaches in turn. Since the installation of hydraulic structures is a common practice for disaster prevention and the effect can

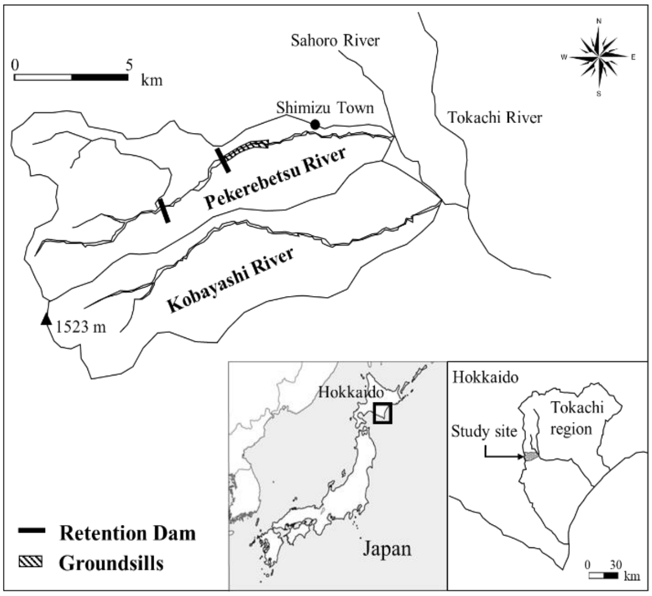

Fig. 1 Study site

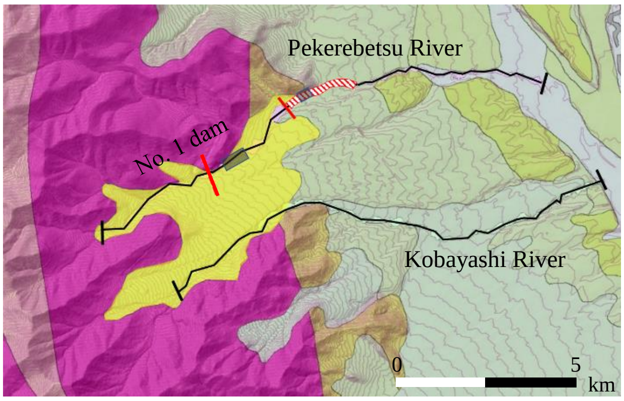

Fig. 2 Geological map of the study area (Based on Seamless Digital Geological Map of Japan, AIST, JAPAN). The study reaches were also shown with solid black lines.

Table 1 Study reaches

River	Catchment area at the downstream end (km^2)	Study reach length (km)
Kobayashi	41.9	14.3
Pekerebetsu	46.6	14.1

propagate through the channel course, a good understanding of bank erosion process is first required in planning for efficient and effective erosion control at a catchment scale. In this study, the process during an intense storm was examined for two neighboring rivers of the Tokachi River Basin, Pekerebetsu and Kobayashi Rivers, in the eastern Hokkaido Island, Japan (**Fig. 1**). Their channel feature had changed drastically through the courses to damage the area by the Typhoon Lionrock in August 2016. Totally more than 500 mm of rainfall was recorded for three days at most of the meteorological stations in the basin. The catchments are geomorphologically and geologically resembled, while two dams and groundsills were equipped in Pekerebetsu River (**Fig. 1**, **Fig. 2** and **Table 1**). Comparison of the channel responses of these rivers to the event will help understand not only the propagation process of the phenomena but also appraise the roles of the structures in the event. The outcome will also present a clue for catchment management planning considering and utilizing natural channel processes.

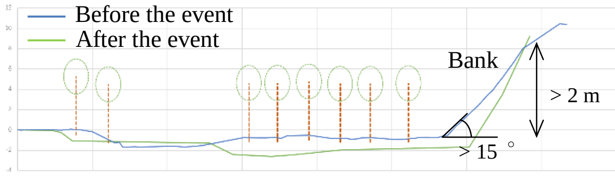

Fig. 3 Schematic image of cross section

2. STUDY SITE

Pekerebetsu River and Kobayashi River run from the East flank of Hidaka Mountain Range. The region is usually dry in summer months. The rivers appeared to be stable with channel width from 10 to 20 m prior to the event, while even-aged riparian forests along the rivers suggest that the floods of the same magnitude as in 2016 occasionally occurred in the past. Weathered granites intruded in the headwaters (**Fig. 2**), from which a sequence of debris flow produced during the 2016 event. At the feet of granites, periglacial colluvial deposits are widely distributed. Further downstream, a floodplain was spread between the terraces formed in the last glacial period. In Pekerebetsu River, peritic hornfels form two gorges. The channel reach installed a series of groundsills contains one of them. The channel beds for both the rivers were composed of materials mainly from sand to boulders.

3. METHODS

This study examined bank erosion process in association with the spatial pattern of net aggradation and degradation. Based on field observation, a bank was defined as a morphologic feature that the cliff by the river floor is steeper than 15 degrees and the height is over 2 m in this study (**Fig. 3**). The degree of bank erosion was appraised with the help of change in channel width measured for the pre- and post-event every 100 m along the rivers on aerial photographs and high-resolution satellite imagery from Worldview-2 and 3. The resolution of the imagery is 0.46 m and 0.31 m, respectively. Since the expansion of channel width is caused by not only bank erosion but also overbank deposition, the distinction was made with airborne LiDAR survey data taken after the event or field evidence, depending on the data availability.

The magnitude of channel aggradation and degradation was estimated based on cross section which was set every about 500 m along the rivers. The elevation for the lines were obtained from either airborne LiDAR data, otherwise field survey. The area laterally eroded was also given from these cross sections.

To highlight change in bank erosion process through the courses, this study divided the channel courses into three reaches based on channel slope. Channel slope was measured along the stream centerline at about 200 m intervals with LiDAR data, otherwise by field survey with a laser rangefinder. Smoothing channel slope by moving average for every 600 m, the reach above 2 degrees was termed as 'Upper Reach', for it is the slope that debris flows generally stop the motion. In field, these reaches are confided by either valley walls, terraces, or periglacial colluviums. On the other hand, 'Lower Reach' runs through an alluvial plain and channel slope was almost stable to be around 1 degrees. The reach situated between them is 'Middle Reach', along which channel slope fluctuates between 1 and 2 degrees.

4. RESULTS

Spatial changes in cross-sectional area and width caused by the event are presented in **Figs. 4** and **5.** Field photographs and selected cross sections representative of those changes are also shown in **Figs. 6** and **7**. Bank erosion processes characteristic of each reach are summarized below.

4.1 Upper Reach

4.1.1 Kobayashi River (4.7 – 9.4 km)

Debris flows induced bank erosion in the reach, as mainly incising the beds, down to 7 km (**Fig. 4** and **Fig. 6-A**). After the event the width of the section was mostly below 50 m but expanded to be above 70 m locally (**Fig. 5**). From 7 to 9 km, debris flow deposition triggered intensive lateral erosion into periglacial colluviums, forming the beds measured about 100 m (**Fig. 4, Fig. 6-B,** and xs1k in **Fig. 7**). The river starts flowing in a flood plain at 9 km. From there overbank deposition was observed down to 9.4 km.

4.1.2 Pekerebetsu River (3.8 – 8.0 km)

It was typical in this reach that debris flow deposition redirected channel courses to undercut the feet of incoherent periglacial colluvium and induce bank erosion (**Fig. 6-C** and xs1p in **Fig. 7**). As a result, channel width expanded up to 100 m, similarly to the upper reach of Kobayashi River (**Fig. 5**). No. 1 dam at 6.9 km then trapped coarse materials, although it was destroyed during the event. Boulders carried with debris flow stopped at the inlet of gorge (7.5 km, **Fig. 4**). Little morphological change occurred through the gorge.

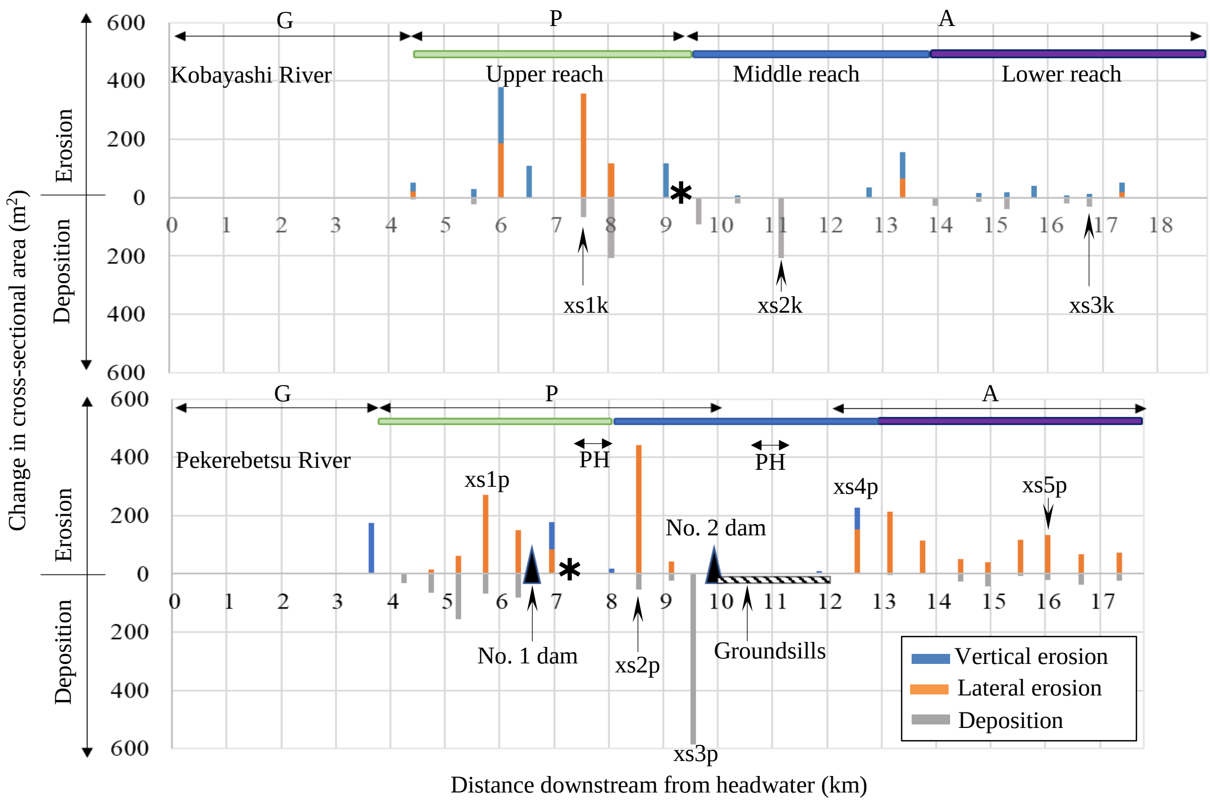

Fig. 4 Sediment deposition and channel erosion by the typhoon Lionrock. G: granite, P: periglacial colluvial deposits, A: alluvial deposits, and PH: pelitic hornfels forming gorges. ∗: The most downstream point that debris flow deposition was found.

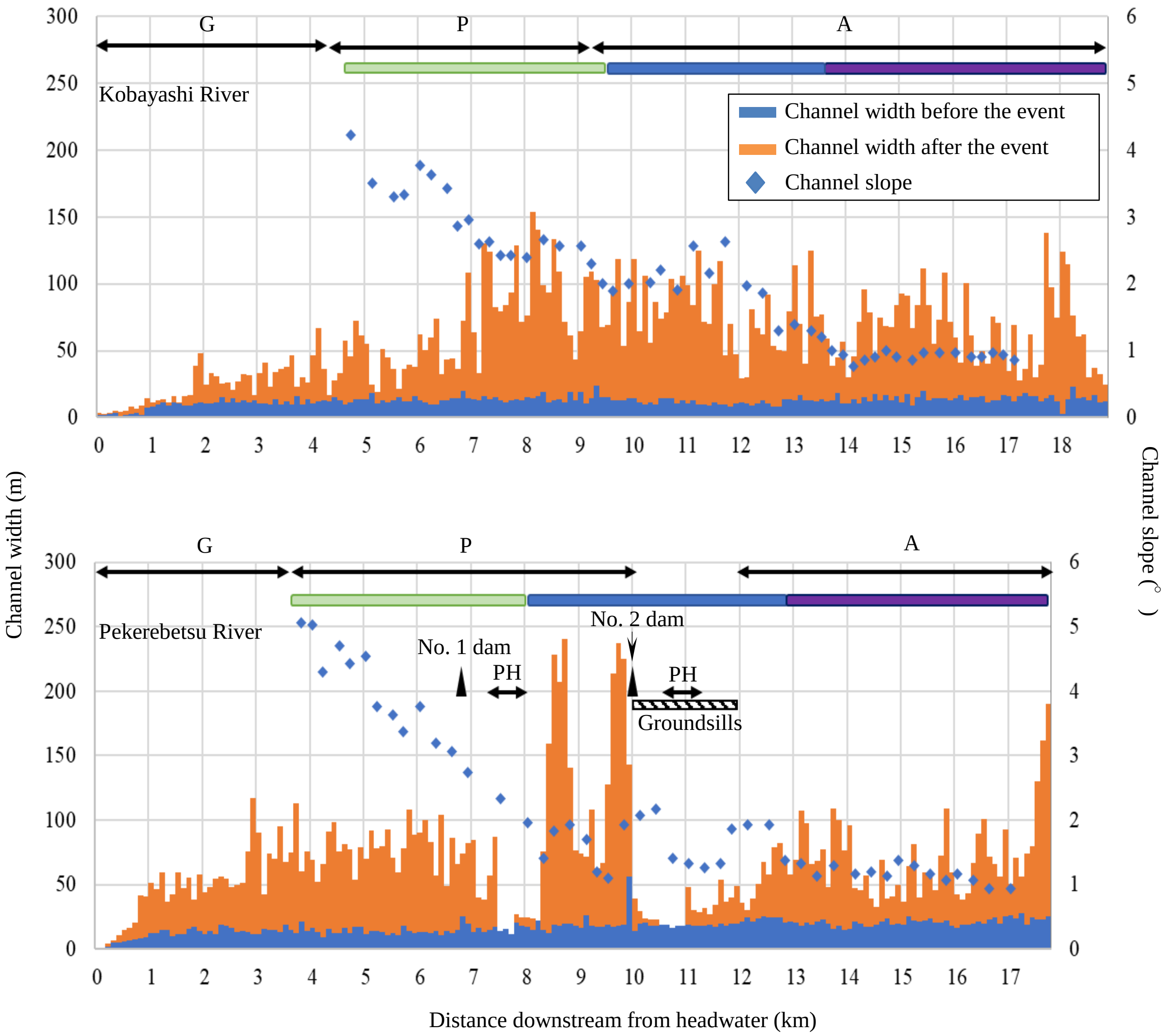

Fig. 5 Channel slope and change in channel width before and after the typhoon Lionrock in 2016

4.2 Middle Reach

4.2.1 Kobayashi River (9.4 - 13.7 km)

Overbank sediment deposition was dominant and bank erosion was not evident in the reach (**Fig.4**, **Fig. 6-D** and xs2k in **Fig. 7**), most probably resulting in decrease in the amount of coarse sediment travelled further. Channel width including the deposition area was mostly between 50 and 100 m along the course (**Fig. 5**).

4.2.2 Pekerebetsu River (8.0 – 12.8 km)

The most intensive bank erosion occurred in the reach starting from the outlet of the gorge (8.0 km, **Fig. 4**, and **Fig. 6-E**), which was caused by channel aggradation (e.g. the right bank of xs2p in **Fig. 7**). Eroding the bank composed of periglacial colluvial deposits, the channel width increased up to over 200 m for 300 m in distance from 8.5 km to 8.7 km (**Fig. 5**). Sediment deposition by No. 2 dam at 9.8 km also brought about the beds wider than 200 m over 300 m upstream of the dam (**Fig. 5**). This expansion, however, was caused by mere bed aggradation (xs3p in **Fig. 7**), and not accompanied with bank erosion. In the reach stretching over 2 km downstream of No. 2 dam, a series of groundsills prevented either vertical and lateral erosion or sediment deposition, similarly to the gorge in the upper reach (**Fig. 4**). At the down end of the sequence channel bed was incised, to have exposed bedrocks and then caused excessive bank erosion from 12.0 to 12.8 km **(Fig.4, Fig. 6-F** and xs4p in **Fig. 7**).

4.3 Lower Reach

4.3.1 Kobayashi River (13.7 - 18.8 km)

The magnitude of change in cross sectional areas were much smaller than Pekerebetsu River (**Fig. 4**), and aggradation and degradation cyclically appeared along the course (**Fig. 4**). Newly transported sediment mantled thinly over the old channel bed, on which riparian forests grew (**Fig. 6-G** and xs3k in **Fig. 7**). The bank was rarely eroded. Average channel width after the event was 65.3 m in this reach.

4.3.2 Pekerebetsu River (12.8 - 17.7 km)

A large amount of sediment supply from the down end of the middle reach triggered to widen the beds

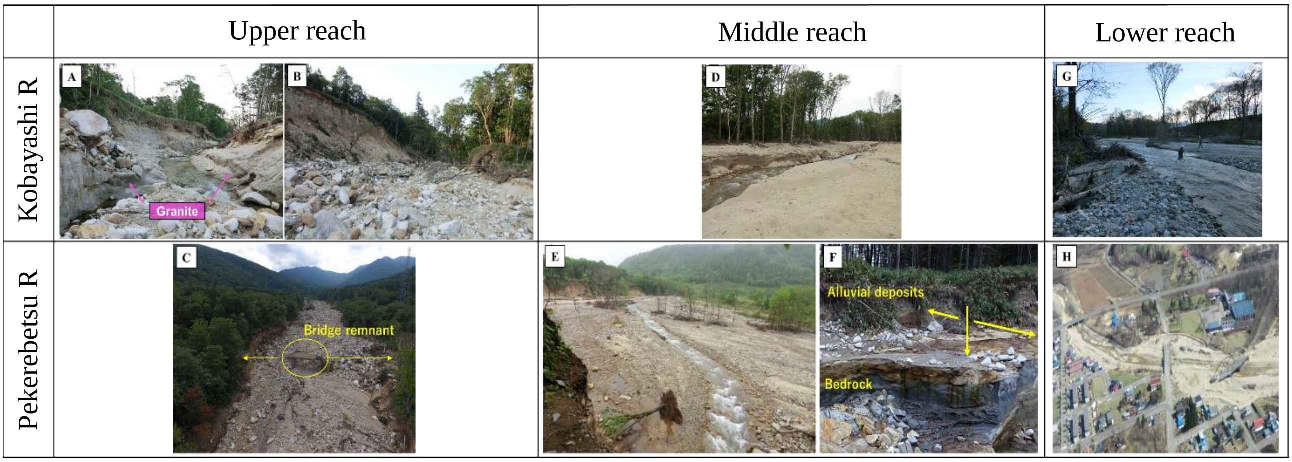

Fig. 6 Field photographs taken after the event. Upper reach: A; Debris flows stripped sediment off as they ran down the stream, B and C; Debris flow deposition triggered lateral erosion into periglacial colluvial deposits. Middle reach: D; Fresh sediment deposition covered old beds, E; Sediment deposition at the outlet of a pelitic hornfels gorge triggered expansive lateral erosion, F; Bedrock denudation on the channel floor by intense flow subsequently induced extensive bank erosion. Lower reach: G; Deposition of coarse materials, H; Shimizu Town damaged by sediment overflow and floodplain erosion.

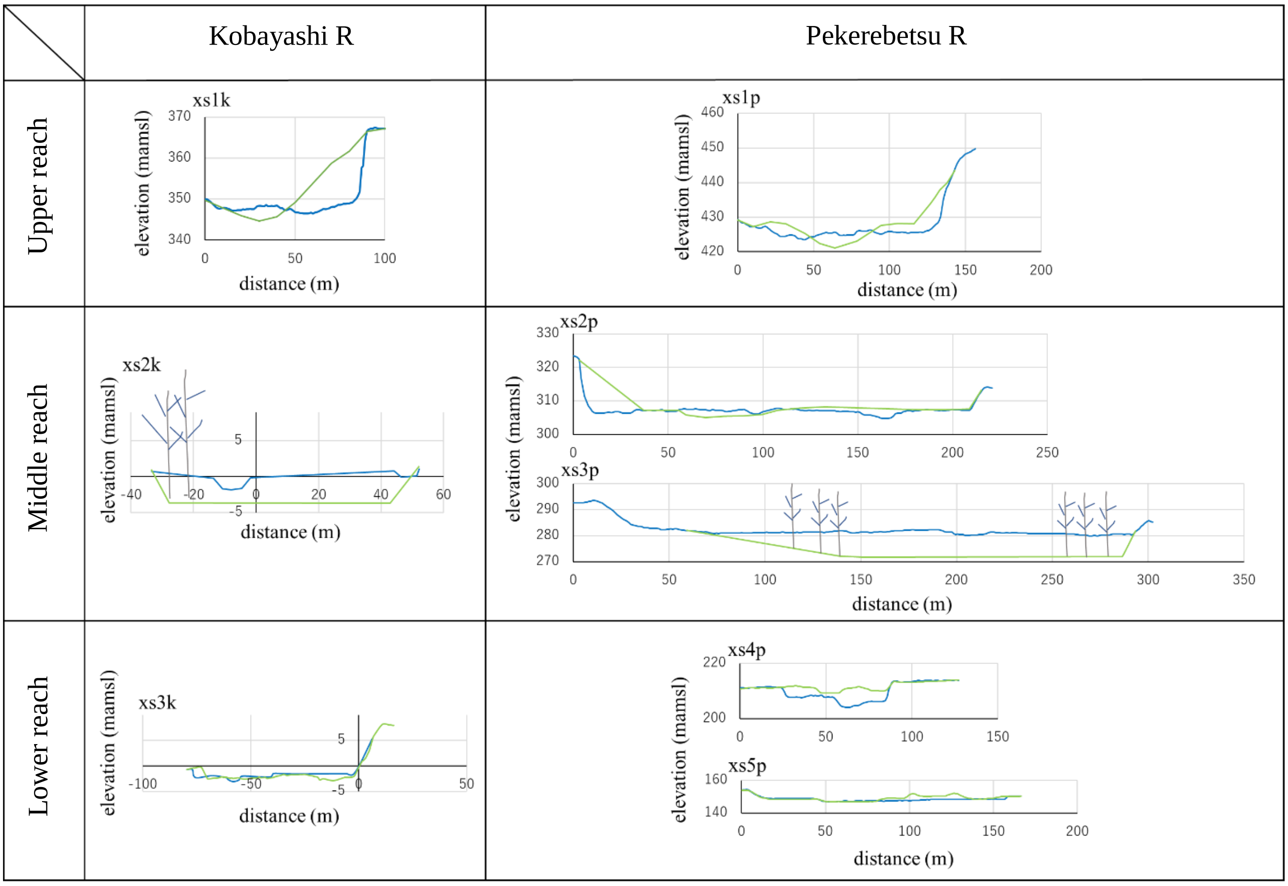

Fig. 7 Representative cases of cross-sectional changes. The locations are indicated in Fig. 4

of the reach as well (**Fig. 4**), consequently damaging bridges, houses, and roads along the course in Shimizu Town (**Fig. 6-H**). Bank erosion process in the reach was driven by sediment deposition that leveled the bed across the lines and offer water course to contact the existing banks (**Fig. 4** and xs5p in **Fig. 7**). Average active channel width in the lower reach was 71.4 m, similarly to Kobayashi river.

5.DISCUSSION

In both the upper reaches, debris flows played a major role on bank erosion. Since periglacial slope deposits nearby the channel courses were incoherent and erodible, channel width could drastically expand and the banks became a significant sediment source for both the rivers. Sediment transported into the middle reach then deposited there whether there was a dam or not. This deposition did not necessarily induce bank erosion except for the section at the outlet of the gorge in Pekerebetsu River. Reduction of a large amount of materials transported probably induced by this deposition in the middle reach could be responsible for limiting change in channel forms and bank erosion in the lower reach in Kobayashi River. Although the active channel width during the flood was similar to Pekerebetsu River, the exchange of sediment between flow and the river bed, including the past deposits, was a major process for the width expansion. In comparison, volumetric sediment contribution from the lower reach estimated from cross sectional changes was much larger in Pekerebetsu River. This is due to intense bank erosion, or the creation of sediment source at the end of the section with groundsills, although it is uncertain whether the phenomena attributed to the structures or the gorge itself. At least the case indicates that the interruption of sediment flux in the upstream was not a solution to control bank erosion for the downstream course in Pekerebetsu River. Rather, the outlet of a gorge is a key site to control change in channel morphology not only at a reach scale but also a catchment scale. There sudden increase in the amount of sediment deposition due to the reduction of transport capacity, caused by channel widening and lowering the depth of flow, can induce extreme lateral erosion if the bank consists of erodible materials. The results highlighted the importance of the recognition of intrinsic roles that each reach owns regarding sediment delivery, in planning hydraulic structures to control bank erosion at a catchment scale.

6. CONCLUSION

This study compared bank erosion process in an extreme flood between two similar sized rivers from the Tokachi river basin. In both the upper reaches, debris flows played a major role on bank erosion. In Kobayashi River, the nature of the middle reach to deposit sediment could work on buffering the event impact for the downstream channel forms. On the other hand, lithological and artificial control in the middle reach could have enhanced bank erosion in the lower reach, in Pekerebestu River. The results suggested that change in hydraulic condition created by valley confinement and underlying geology should be understood first for efficient and effective structure planning to prevent from unwanted bank erosion and related disasters.

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