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Problems of Bedrock Exposure and a Trial to Recover Gravel-beds Below a Dam in Mountain Rivers

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ABSTRACT
Bedrock exposures are often observed below dams in many Japanese rivers and can degrade ecosystem integrity. Exposed bedrocks are increasing in the channel of the downstream section of the Kurobe Dam, which was constructed in 1912 in a mountain reach of the Kinu River, since 1990's. The analysis of the past aerial photos suggests that the bedrock exposures are partly explained by channel excavation, which was conducted most actively in 70's and 80's. The increment of bedrock exposure in the downstream section is also likely to be associated with the scarcity of 10-40 cm materials, which appears to be trapped at immediately upstream of the dam. Sediment reduction and subsequent bedrock exposure can affect benthic invertebrate community through reducing the habitats that provide sufficient bed interstices for invertebrate taxa and support high total invertebrate biomass. We made a trial to recover gravel-beds at bedrock exposed reaches by using geotextile bags without using power vehicles. The bags contributed to sediment deposition and recovery of gravel-beds during floods of 100-200 $m^3 s^{-1}$, but were damaged and partially exported during floods of >500 $m^3 s^{-1}$. Limitations and possibilities of using geotextile bags on river restoration works were discussed.

Keywords: river ecosystem, sediment reduction, bedrock exposure, gravel-bed, invertebrates

1. INTRODUCTION

Bedrock exposures at previously gravel-bed reaches are often observed below dams and reservoirs in many Japanese rivers due to a reduction of sediment supply from upstream. Such bedrock exposures can degrade ecosystem integrity. For example, many aquatic animals that comprise river food webs rely on bed topography and interstices, which are associated with gravel-bars, as their habitats. Some efforts are required to prevent a loss of important habitats, which can lead to a large reduction of species diversity and ecosystem function.

Restorations of gravel-beds at bedrock exposed reaches are increasing in Japan, though it is not an easy task and there are few reports that sufficiently show the processes of bedrock exposures and the effects of restoration works based on field monitoring studies. We have been studying the causes and effects of bedrock exposure below a small dam in a mountain river. In this paper, we showed some processes that can induce bedrock exposures and major consequences of bedrock exposures on invertebrate community, and also reported results of a trial to recover gravel-beds in mountain river reaches.

2. BEDROCK EXPOSURES BELOW A SMALL DAM IN THE KINU RIVER

The Kurobe Dam is one of the oldest concrete gravity dam in Japan; it was constructed in 1912 in the mountain reach of the Kinu River to generate electric power. It is a small dam with height of 28.7 m and reservoir capacity of 2,360,000 m^3 as the dam can control discharge only under baseflow. The Kurobe dam is located at the middle of the two flood-control dams, the Kawamata in the upstream, the Kawaji in the downstream, as shown in Fig. 1. A tributary 3 km below the Kawamata dam supplies a large amount of sediment to the main river. Sediment from upstream can pass through the Kurobe dam during floods, because the dam is fully-sedimented and the gate is open during floods. The annual sediment deposition at the Kawaji Dam was 213,000 $m^3 y^{-1}$ during 1984-2004 and most of the sediment seems to be those transported through the Kurobe Dam. Mean channel width was 45.2-60.6 m in the upstream of the Kurobe dam and 46.1 m in the downstream of the Kurobe dam. Also, the mean channel gradient was 1/66-1/55 in the upstream and 1/80 in the downstream.

Exposed bedrocks interspersed in the downstream section of the Kurobe Dam, despite alternating gravel-bars in the upstream section of the dam, as shown in Fig. 1. Bedrock occupied more than one third of the total length of the downstream section at the mid-channel in 2008 (Kobayashi et al. 2009). Bedrocks are evident in aerial photos since 1990's. The rate of the bedrock increment was revealed to be greater in 2000's than in 1990's from a field monitoring study (Nakamura 2011).

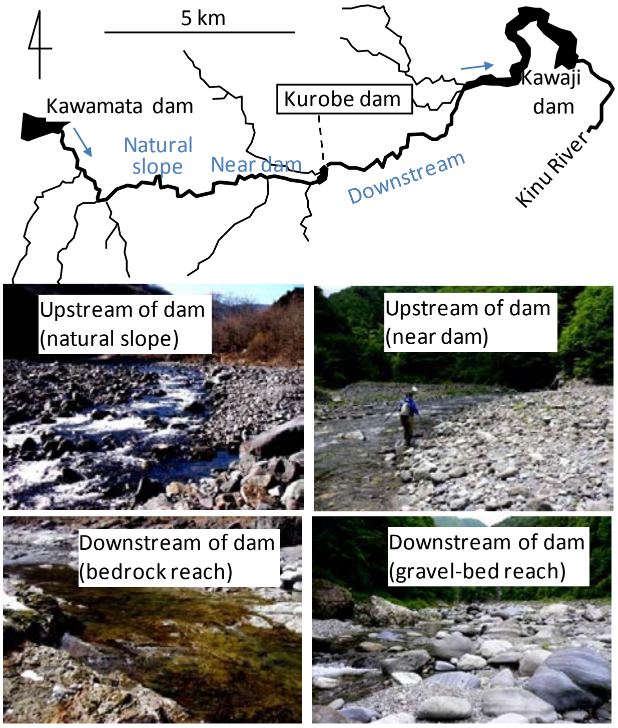

Figure 1. Upstream and downstream of Kurobe dam

Measurements of bed elevation from past aerial photos based on a triangulation method revealed that bed elevation was degraded up to 6 m in the upstream section, and 3 m in the downstream section during 70's and 80's, as shown in Fig. 2. Gravel mining was conducted most actively and exceeded 100,000 m^3 y^{-1} in these periods in the upstream section. Although the mining was not conducted in the downstream section, the bed degradation of the upstream appears to have extended to the downstream. Sediment deposition in the channel seems to have been thinner in the downstream than in the upstream by 70's, because bedrock has been exposed only in the downstream while the magnitude of the bed degradation was greater in the upstream. The bed degradation may have occurred in the downstream section by early 20th after the construction of the Kurobe dam in 1912, while in the upstream the bed may have been elevated by upstream retention of sediment by the Kurobe dam.

3. REDUCTION OF MIDDLE-SIZED MATERIALS AND BEDROCK EXPOSURES

Since sediment transport that pass through the Kurobe Dam appears to be still abundant, the bedrock exposures only in the downstream section cannot be fully explained only by the supply amount of sediment.

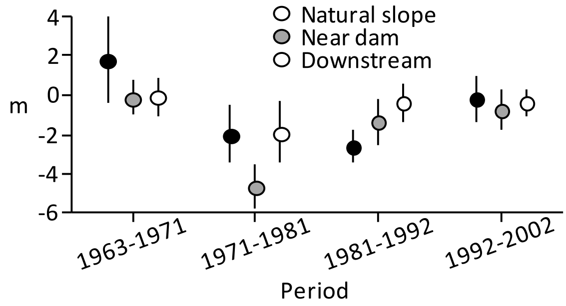

Figure 2. Mean change of bed elevation (±SD)

We found that 10-40 cm materials, which are the middle size of the whole size range, were scarce in the downstream section (Kobayashi et al. 2009). Bed materials were surveyed by a random sampling of 100 materials based on line-intercept method for 38 reaches in the natural slope and near dam section, both of which were the upstream of Kurobe dam, and the downstream section. In the upstream sections, the grain size distribution was S-shaped with a most dominance of 10-40cm materials for most of the reaches, as shown in Fig. 3. In contrast, although the distribution varied among the reaches in the downstream section, the dominance of 10-40 cm materials was observed for few reaches. At the whole section, the percentage of 10-40 cm materials was 41-45% in the upstream sections, while only 22% in the downstream sections. The shortage of 10-40 cm materials was much evident for the main bed materials consisting riffle beds, as shown in Fig. 4.

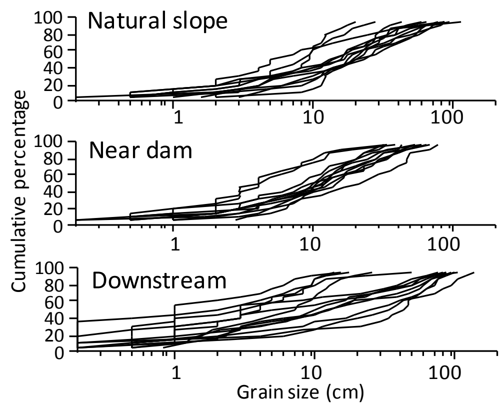

Figure 3. Cummulative grain size curve

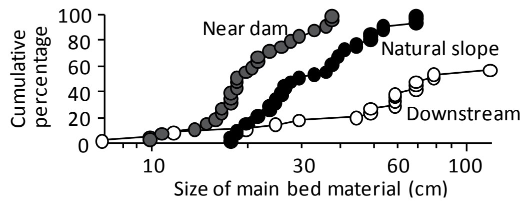

Figure 4. Main bed materials of riffles

The shortage of 10-40cm materials in the downstream is likely due to retention of these materials at immediately upstream of the Kurobe Dam. The movable bed material size during floods was simply estimated from channel width and gradient using known equations of flow resistance and critical shear stress for particle motion, as shown in Fig. 5. Large materials that exceed 50 cm are movable in many of the reaches both in the upstream and downstream during floods of 500 $m^3 s^{-1}$, which occur with an interval of 4-5 y, and 1000 $m^3 s^{-1}$, which occur with an interval of 8-10 y. Smaller materials such as 10 cm materials are movable by 200 $m^3 s^{-1}$, which occur with an interval of 1-2 y. However, movable materials were <10 cm even during floods of 1000 $m^3 s^{-1}$ at reaches immediately upstream of the Kurobe dam with channel width of >130 m and channel gradient of <1/1000. Although the estimation was simple, our field surveys of particle movement using a radio tracer tracking technique during floods showed that the major material size in transport was roughly consistent with the previous estimation (Kobayashi et al. 2010). Therefore, although large amount of sediment is still transported downstream through the Kurobe dam, the sediment appears to consist mostly of materials with <10cm in size.

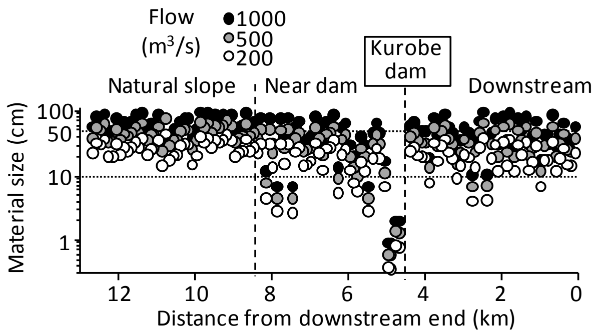

Figure 5. Movable bed materials during floods

The shortage of middle-sized materials is considered to promote bedrock exposures in the downstream section. Without these materials, finer materials are more likely to be entrained and transported. Without finer materials, then, huge boulders are much exposed to flow and are much prone to be isolated and transported. The huge boulders that are still remained in the downstream section will be moved and lost in future, which leads to further expansion of bedrocks. Thus, not only the amount of sediment but also materials of certain sizes are important for the restoration of gravel-beds.

4. BEDROCK EXPOSURES AND INVERTEBRATE COMMUNITY

We conducted quantitative samplings of invertebrates in riffles, pools, and runs at the 6 sites in the up- and downstream sections. Riffles are areas with steep water surface slope and shallow, pools are areas of almost no water surface slope and deep, and runs are areas with intermediate characteristics of riffles and pools. For all sites and all seasons, riffles had greater invertebrate biomass than pools and runs. Invertebrate biomass in riffles was averagely 8.6-fold of that in pools and 4.6-fold of that in runs, as shown in Fig. 6 (Kobayashi et al. 2011). This trend was most conspicuous for invertebrate taxa of grazers that feed on periphyton and filterers that feed on transported organic matter. Among riffles of various types, the biomass of total invertebrates and taxa that requires interstices for habitat, such as mayflies, stoneflies and caddisflies, was the greatest in riffles with main bed materials of 10-30 cm, as shown in Fig. 6. For bedrock riffles, community was mostly dominated by taxa that use bed surface as habitat, such as blackflies, and the total biomass was less than one third of the riffles with 10-30cm materials.

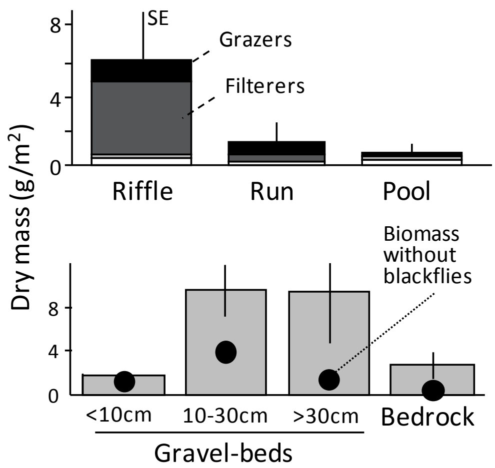

Figure 6. Total invertebrate biomass of different beds

Our study suggests that sediment reduction and subsequent bedrock exposure have significant effects on invertebrate community by at least two ways. First, decrease of 10-30 cm materials and increase of bedrock as habitats within reaches potentially cause a dominance of limited species mainly blackflies, while depress total invertebrate biomass. Second, a shortening of riffle length within the reaches, which is associated with sediment reduction, can also depress invertebrate biomass. The total length of riffles per 100-m channel reach was half in the downstream than in the upstream sections, while the total length of pools was four times in the former than the latter, as shown in Fig. 7. This is because in the downstream section, riffles with 10-40 cm materials, which were moderately steep and long, were few, while riffles with >50 cm materials and bedrocks, which were steep and short, were dominant, as shown in Fig. 7. As a consequence of shorter riffles and longer pools in the reaches, the biomass of total invertebrates and especially of taxa with grazers and filterers are estimated to be 2 to 6 times smaller in the downstream section than in the upstream sections.

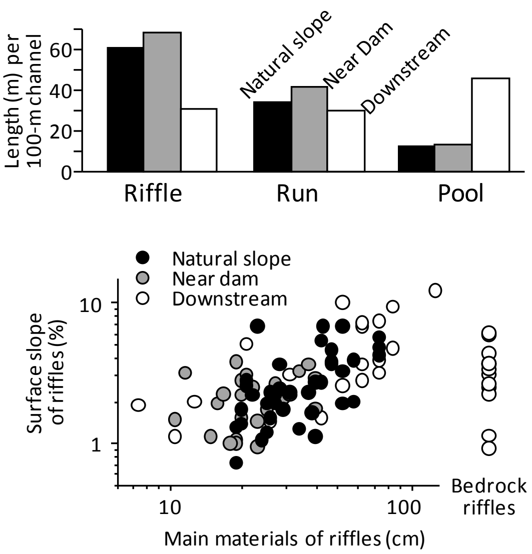

Figure 7. Total length of riffles/pools (upper) and relation between bed material size and slope of riffles (lower)

5. A RESTORATION WORK AT BEDROCK EXPOSED REACHES

As a restoration of gravel-beds at bedrock exposed reaches, there are some reports of installing groins or huge boulders that enhance retention of sediment (Fukushima et al. 2010, Mori et al. 2009). In many of these cases, power vehicles are used for digging bedrocks or the placement of huge boulders. However, there are many places where no trails are available for using power vehicles, especially in mountain channels with steep hillslopes.

It is possible to set up a structure to promote the retention of sediment without power vehicles, for example, if we can make clusters of stones by using bags or chains in the channel. We made a trial to recover gravel-beds by making and placing geotextile bags that are filled with stones without using power vehicles (Yajima et al. 2011).

Geotextile fabric is far lighter than steels, but it shows certain strength against physical impacts and ultraviolet rays, and also it is flexible. We used box-type geotextile mesh bags, which are made from non-joint polyethylene mesh, with mesh size of 25 mm, total net size of 2m length, 1m width, 0.5m hight, and the mesh was double-layered, as shown in Fig. 8. Each bag can be filled with stones of 1 m^3 or 1500 kg. Two bags were piled up before filling stones in order to reduce the risk of breaking. We filled 5-15 cm materials, which were collected from nearby bank areas, in the bags. Totally 12 bag units, with each unit consist of 2 bags, were set up at locations where the bed slope was inverse at the mid-channel to reduce possibility of their movement and to increase their effects on transported sediment as much as possible, as shown in Fig. 8. Among the 12 untis, 3 or 6 units were connected to make the cluster bigger, while these units were not fixed to bedrock.

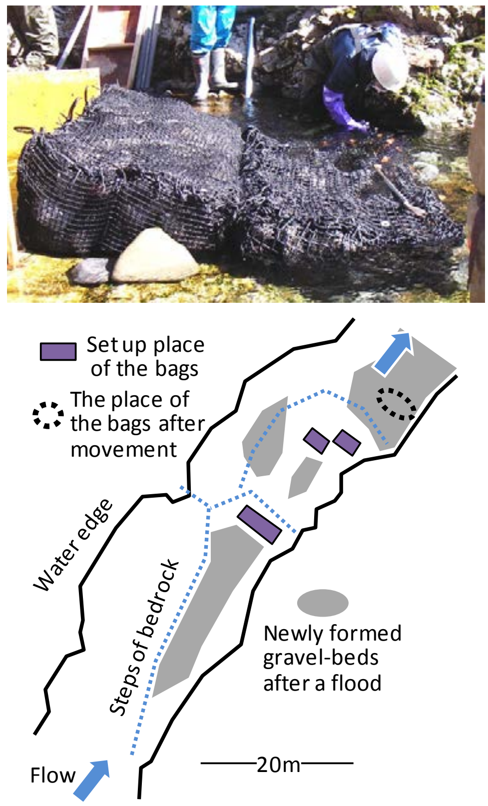

Figure 8. Geotextile bags filled with stones (upper), and the location where the bags were set up (lower)

Floods of 100-200 m^3 s^{-1} occurred a few times in 2010 and 2011. The bedrock-exposed reach was covered by pebbles and gravels at upstream areas of the installed bags after these floods, as shown in Fig. 9. Although some bags were moved 8-10 m downstream by the first flood, they contributed to the deposition of pebbles and gravels at the downstream side of the bags. Deposited sediment was primary <5 cm materials, while it is evident that 10-20 cm materials were also in transport during these floods. Since no damage was found for all the bags, it is suggested that these bags can be used for sediment deposition and retention at least for the flood of this magnitude.

However, by a flood of 500 m^3 s^{-1}, some bags were moved to and settled near the bags that were moved by the previous flood, some other bags were disappeared, and bedrocks was re-exposed for most of the area. The sediment deposit behind the moved bags was remained. The net of the bags was broken especially for upstream- and up-side. We found that some huge boulders with 50-100 cm in diamter newly appeared nearby the study reach. Collision of such boulders to net is likely to have broken the net. Although we had 1000 m^3 s^{-1} flood two weeks after the 500 m^3 s^{-1} flood, no further changes were observed for the bags and sediment deposition.

The effect of geotextile bags at this set up scale (i.e., 12 units) on sediment deposition was little and the loss and damage was too big for the flood exceeding 500 m^3 s^{-1}. It may be possible to make the bags more stable by stacking the bags in an imbrication manner or if we can stack these bags on pre-existing huge boulders. Although the mesh nets of the bags were broken, we did not find damage for ropes (diameter: 12 mm), which were the frame of the bags. Thus, these ropes can be used to protect the nets. Some of the bags, which were moved but contributed to sediment deposition, might have damaged by 100-200 m^3 s^{-1} flood, if we had fixed these bags on bedrocks. It is worth considering the use of these geotextile bags by making full of their flexible features.

Figure 9. Change of bed after a flood

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