EFFECTS OF SEDIMENT SUPPLY BY BYPASS TUNNELS ON BED TOPOGRAPHY, GRAIN SIZE, AND INVERTEBRATE HABITAT

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Abstract

To understand the effects of sediment bypass on environmental recovery of the degraded channels below dams, bed topography and bed materials above and below dam reaches were surveyed by ground-based measurements and aerial photos using quadrocopter. Coarse bed materials such as boulders were more represented below than above the Koshibu dam, where the bypass tunnel had not been in operation yet. The coarse materials formed steps and protruded in the water column within riffles and runs, both of which can increase slow-flow areas, below the dam. On the other hand, sand, gravel, and cobbles were abundant below as much as above the Asahi dam, where the bypass tunnel had been operated for >17 years. The downstream environment in terms of bed topography and grain size seems to have almost been recovered for the Asahi dam. However, less representation of large cobbles and boulders below the dam suggested a possibility of a selective deposition of coarse materials at the upstream of the bypass tunnel inlet.

Key Words: Sediment bypass, downstream environment, bed materials, quadrocopter

1. INTRODUCTION

River environment below dams are often degraded by armoring of riverbed with coarse bed materials (Ward and Stanford, 1979; Kondolf, 1990). Such changes sometimes cause a reduction of endemic species, an invasion of undesired species, and finally, a loss of ecosystem integrity (Ward & Stanford, 1979; Boon, 1988; Bunn & Arthington, 2002). Construction and operation of a sediment bypass tunnel (SBT), which is mainly intended to route sediment around a dam that otherwise accumulates in reservoirs (Vischer et al. 1997), may have significant effects on environmental recovery of degraded reaches by supplying a sufficient amount of sediment from the upstream. The construction of SBT in the world is still limited, and most of them are located in Japan and Switzerland so far (Sumi, 2015).

We have been examining the environmental and biological recovery of below-dam reaches by the operation of SBT, based on field surveys in the upstream and downstream reaches for dams with SBT (Awazu et al., 2015). One of the findings of our pilot survey is that the invertebrate community was similar between above and below dam reaches with long-time SBT operation. Invertebrate species that prefers slow-flowing water (i.e., pool specialist) dominated the community below dams with no or limited bypass operation. Invertebrate species that prefer fast-flowing water (i.e., riffle specialist) dominated the community below dams with a long-time SBT operation. The finding suggests that the sediment supplied through SBT to the downstream over a long period almost covered the formerly coarse-bed channel and generated a smoother-bed with less flow-stagnant area, which is similar to the condition upstream of the dams.

To know the grain size distribution (GSD) and bed topography in more detail and in more spatially distributed manner, we further had field surveys using an unmanned aerial vehicle to collect images of the whole reach above and below Koshibu and Asahi dams, Japan. The SBT of the former dam had been constructed but not been operated in 2015 (the regular operation was planned to start in 2017). The SBT of the latter dam had been operated since 1998; the gate was opened and released sediment from upstream during high flows several times a year. In this study we focused on elements of bed topography that affect flow patterns during baseflow in a few reaches above and below the two dams. We also focused on the particle size classes that are required for the environmental recovery of degraded reaches below dams.

2. STUDY SITES AND METHODS

2.1 Study sites

Field surveys were conducted in river reaches (sites) at each dam in late May, 2015 when the water was in baseflow (Fig 1). The Koshibu dam in Nagano Prefecture was constructed 1969 in the Koshibu River, a tributary of the Tenryu River, for the purpose of power generation, flood control and irrigation, operated by the Ministry of Land, Infrastructure, Transport and Tourism. The catchment area of 288 km^2 was almost covered by forest with some slope failures near the channel. The mean annual inflow and flood is 3.4 m^3/s and 331 m^3/s, respectively. The mean outflow flood is reduced to 203 m^3/s. The Asahi dam in Nara Prefecture was constructed 1978 in the Asahi River, a tributary of the Kumano River, for the purpose of power generation, operated Kansai Electric Power Company. The catchment area of 39.2 km^2 was mostly covered by forest with some slope failures near the channel. The mean annual inflow and flood were 2.5 m^3/s and 299 m^3/s, respectively, and the outflow was supposed to have similar values.

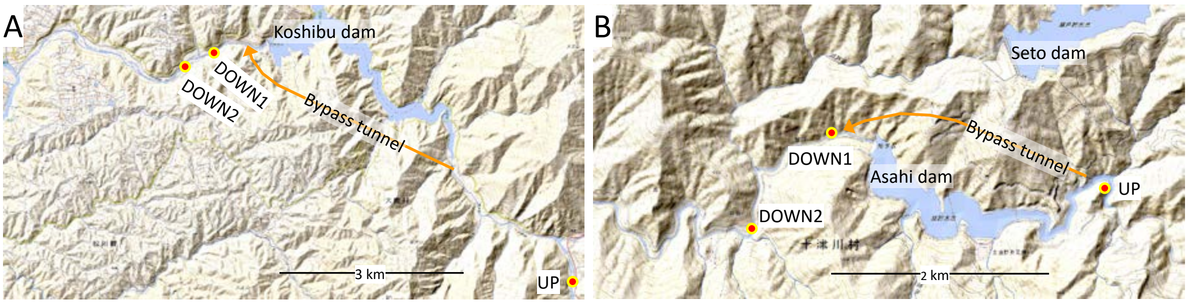

Fig 1. The locations of survey sites relative to the dams (A: Koshibu, B: Asahi)

For each dam we set up three reaches including upstream of dam (UP) and downstream of dam (DOWN1 and DOWN2) (Fig 1). DOWN1 was located below the SBT outlet. DOWN2 was located downstream of the first tributary from the dam. The length of each reach was roughly 100 m. The mean width and slope of the channel are shown in Table 1.

	Koshibu			Asahi		
	UP	DOWN1	DOWN2	UP	DOWN1	DOWN2
Mean local bed slope (%)	1.30	2.05	0.38	1.74	3.03	2.00
Mean bankfull width (m)	65.0	26.0	32.0	25.9	22.2	31.8

Table - 1 Channel characteristics of survey sites

2.2 Measurements

At each reach, we classified the river flow longitudinally into riffles with shallow and fast flows, pools with deep and slow flows, and runs with a condition intermediate between the former two. Bed slope for riffles, runs, and pools was measured by a digital level (SOKKIA SDL30, Topcon Corp.).

We defined several types of inorganic microhabitat according to the bottom material and evaluated the relative abundance at each reach. These types are bedrock, boulders, cobbles, embedded cobbles in finer material, gravel, and sand. Each microhabitat covers bed of more than 0.01 m^2, so we did not count, for instance, sand accumulations smaller than a foot. Other microhabitat types such as woody debris, leaves and mud, were also counted but we do not present in this study. The relative abundance of each microhabitat was recorded by 4 levels: 0-not present, 1-minor, 2-frequent, 3-major.

We took photos of the bed surface materials with a ruler by handy digital camera every 5 m or 10 m of scales set along the river. In each photo, we measured the second longest axis (b axis) of particles under 25 nodes of grids superimposed on the image using a free software (ImageJ, Schneider et al., 2012). In total, more than 250 particles were measured each reach.

As quadrocopter DJI Phantom2 (DJI Science and Technology Co., Ltd.) mounted with a GoPro Hero4 Silver Edition (GoPro Inc.) was used. The flight height over the ground varied between 15 to 30 m depending on the existence of trees and electric cables nearby. Photos with a resolution of 3840×2160 pixels were taken by a time-lapse function of the camera, which was facing vertical to the ground, to cover the whole area of the reach with a 5 or 10-m pitch scale along a side of the river.

Totally more than 50 images were taken by the quadrocopter each site, but we used 8 to 10 of them for further analysis. A fish-eyed lens effect of the images was removed by a free software of GoPro. The images were used, after superimposing a 1 m grid on the image, to analyze bed topography and GSD (Fig 2). For the topography, we evaluated the number of steps and the abundance of emerged stones. The steps are stair-like appearances typically formed from accumulations of boulders and cobbles in a continuous line perpendicular to flow direction (Knighton, 1998). We defined steps in the images by a clear sequence more than 1 m in length of boulders and cobbles, and the evidence of white water due to hydraulic jumps. We expressed the length of steps per unit river width by dividing the total length of all steps by the average river width and the longitudinal length of riffle or run. We evaluated the area of stones emerged from the water surface by counting the number of grids with having such stones and rough percentage of the stones within grids (i.e., 10%, 30%, 50%, 75%). We expressed the abundance of emerged stones as a percentage of the whole area of riffle or run. Steps dissipate energy within a short distance whereas emerged stones have a stagnant flow upstream and downstream. Thus, these elements are supposed to increase slow-flow area in riffles and runs with a given discharge and channel characteristic.

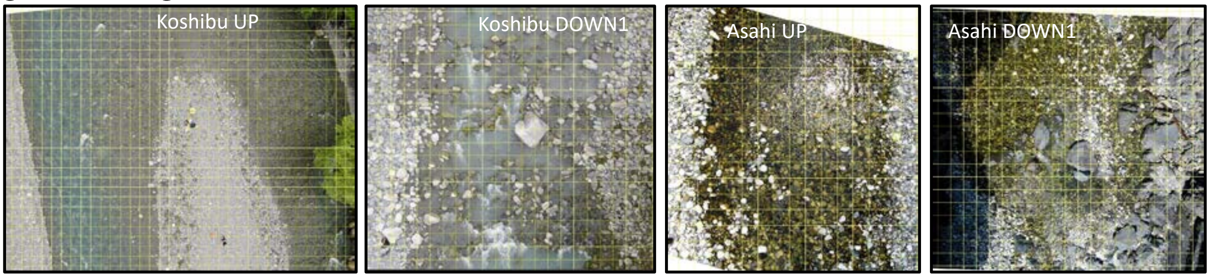

Fig 2. Example of image taken by quadrocopter with grid superimposed

The software BASEGRAIN (Detert and Weitbrecht, 2013) was used to analyze GSD for the images taken by the quadrocopter. We found in our study that the images taken by the quadrocopter were more feasible for detecting stones by this software than the images taken by the hand-held camera. This was partly due to colorful and rough-surface patterns of bed materials. As a shortcoming, particles less than 3 to 5 cm were hardly detected for the quadrocopter image due to the resolution of the image. Eight to 12 frames of 25 m^2 were clipped along the river sides and used for the grain analysis each reach. More than 200 to 2000 particles were detected each frame and the b-axis of all the particles was automatically obtained (Fig 3). The area of each particle was used to calculate the percentage of each size particles. The void area (i.e., non-particle area), which varied from 10% to 65%, was assigned as the percentage of particles less than the minimum size detected. The result was compared with the GSD obtained with the handy camera.

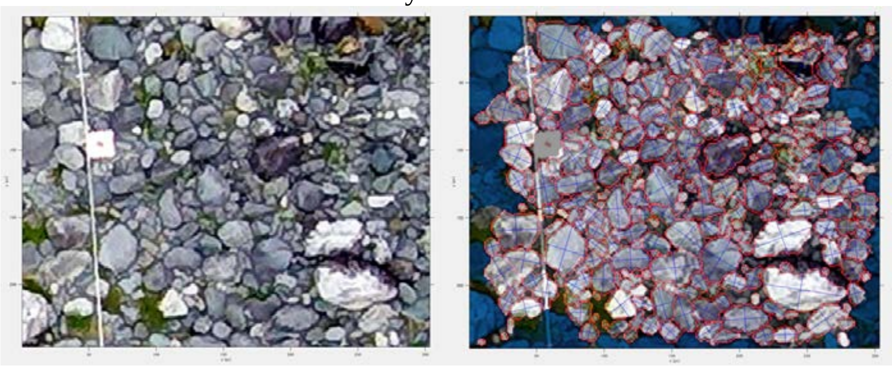

Fig 3. Example of the grain size analysis by Basegrain (right: detected particles)

3. RESULTS
3.1 Bed slope

The bed slope was highest for riffles and lowest for pools across the reaches (Fig 4), except for UP and DOWN1 of Koshibu with a relatively uniform slope profile. The steepest and gentlest riffles were recorded at DOWN1 and DOWN2 of Koshibu, respectively.

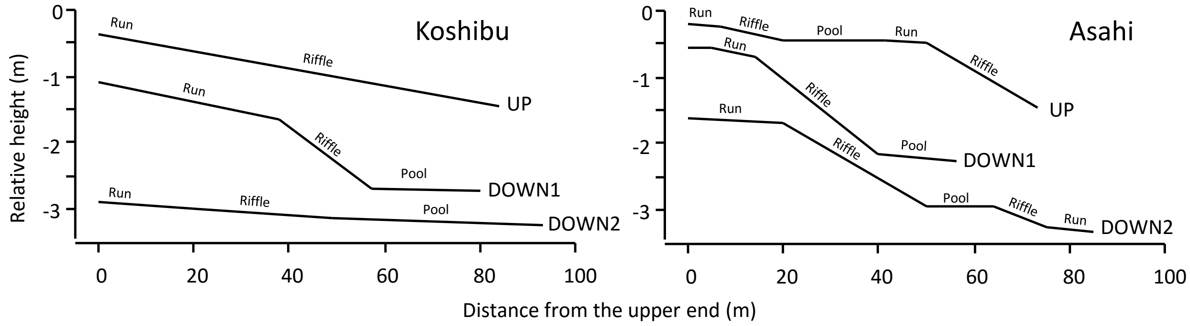

Fig 4. Bed slope profile of each site

3.2 Bed topographic elements

The total step length, standardized by river width and longitudinal river length, and the abundance of stones emerged from the water surface, expressed as the percentage of the whole water area, were both greater in riffles than in runs across the reaches (Fig 5). The step length was substantially greater in DOWN1 than UP and DOWN2, and greater in DOWN2 than UP for Koshibu. For Asahi, the difference in step length between UP and the two DOWN reaches was small compared to Koshibu. The abundance of emerged stones was again substantially higher in DOWN1 than UP and DOWN2 for Koshibu. For Asahi, the abundance of emerged stones were less in DOWN2 than UP and DOWN

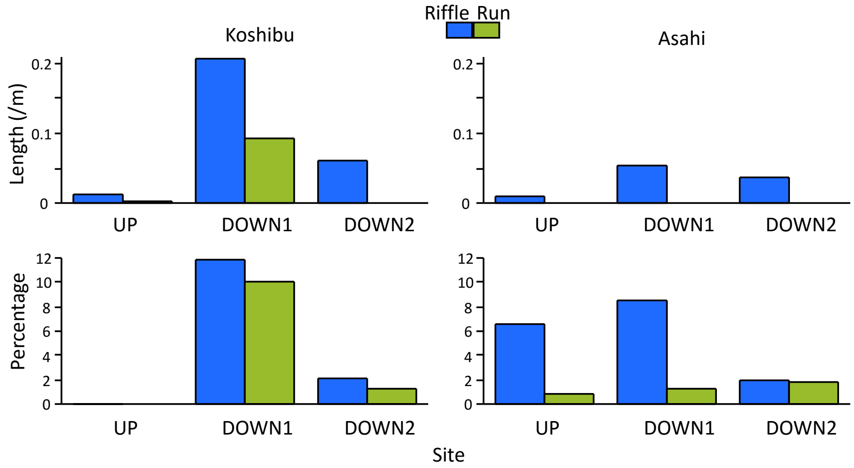

Fig 5. Step length (upper) and abundance of emerged stones (lower) in each site

3.3 Microhabitat occurrence and abundance

Microhabitat types of cobbles and embedded cobbles were abundant across riffles, runs, and pools, in all of the surveyed sites, while sand, gravel, boulders were scarce in part of the sites (Fig. 6). For Koshibu, boulders was less in UP than DOWN1, while sand and gravel were less in DOWN1 and DOWN2 than UP. For Asahi, sand and gravel were less in DOWN1 than UP and DOWN2. Bedrock was scarce for the reaches, in which the river flowed middle of channel, and thus, was far from the channel bank with bedrocks, such as UP and DOWN2 of Koshibu.

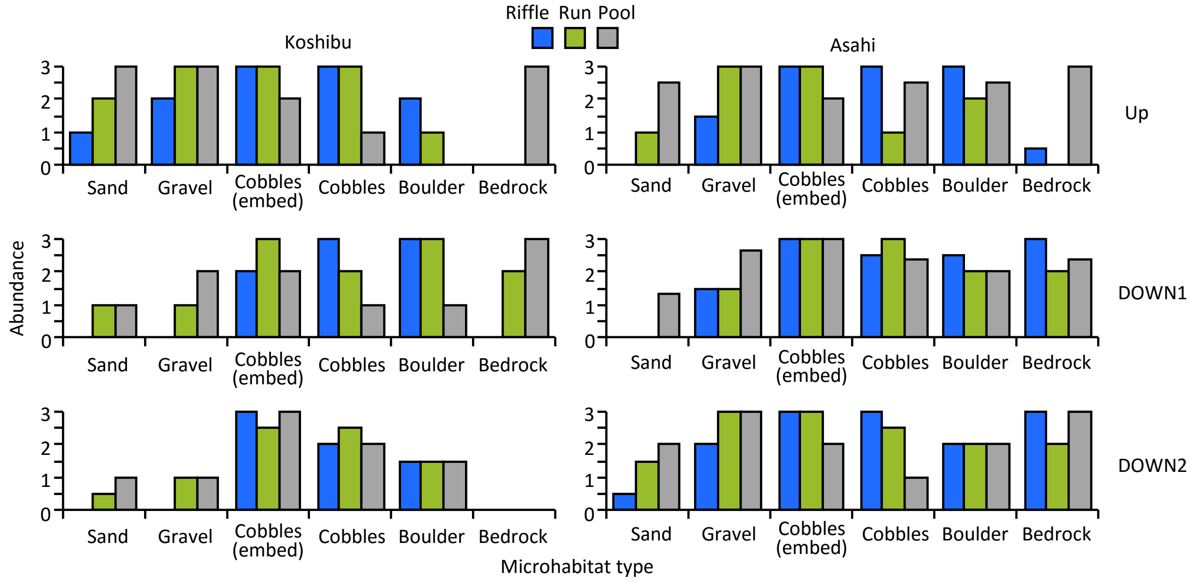

Fig 6. Occurrence and relative abundance of microhabitats each site

The difference in abundance of each microhabitat type between UP and DOWN ($\Delta_{\text{DOWN-UP}}$) roughly indicates the elements that were higher or lower below than above the dam (Fig 7). If a microhabitat is more below than above, the Δ is positive, and vice versa. For Koshibu, it is obvious that sand and gravel were less in the two DOWN reaches than UP, while boulder was more in DOWN1 than UP especially in riffles and runs. For Asahi, $\Delta_{\text{DOWN-UP}}$ was small or inconsistent among riffles, runs, and pools compared to the Koshibu cases. It is notable that boulders were slightly less in the two DOWN reaches than UP for Asahi.

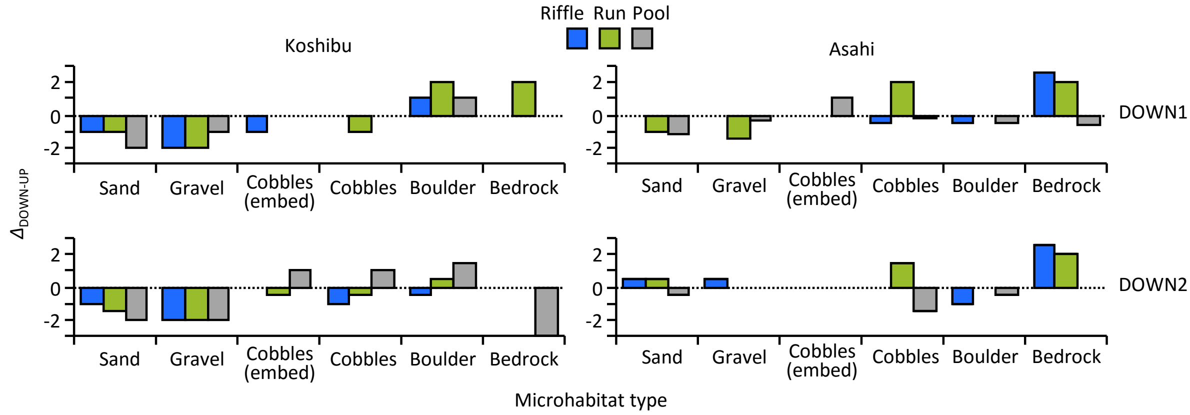

Fig 7. Difference in abundance of microhabitats between UP and Down sites, $\Delta_{\text{DOWN-UP}}$

3.3 GSD of bed surface materials

The results by the handy camera showed that GSD of the two DOWN reaches was coarser than UP for Koshibu (Fig 8). A representative grain size, D_{60}, was 31 mm for UP, 222 mm for DOWN1, and 112 mm for DOWN2. The GSD of UP and DOWN1 was coarser than DOWN2 for Asahi. D_{60} was 85 mm in UP, 70 mm in DOWN1, and 40 mm in DOWN2. GSD was also evaluated by the same method in some identical reaches in Awazu et al. (2015), in which D_{60} was almost the same for UP (86 mm) and DOWN2 (63 mm) of Asahi, but was slightly coarser for UP (57 mm) of Koshibu.

The GSD obtained from the images by quadrocopter camera showed a pattern similar to that of the handy camera (Fig 8); GSD of the two DOWN reaches was coarser than UP for Koshibu, and GSD of UP and DOWN1 were coarser than DOWN2 for Asahi. However, GSD was always coarser for the results of quadrocopter than those of the handy camera for all the reaches. The difference between the results of quadrocopter and handy camera may be derived from the different ways of detecting particles (see METHODS), though measuring the b-axis and GSD being based on the proportion of area of particles were common in the two ways. Photo of the surface bed materials of river sides were taken in both ways. The images of the handy camera can detect finer materials at minimum of a few mm, while the images of quadrocopter covered large bed area. Some failures in detecting particles in the software used for the images by quadrocopter, such as taking 2 or 3 particles as single particle, may also be possible.

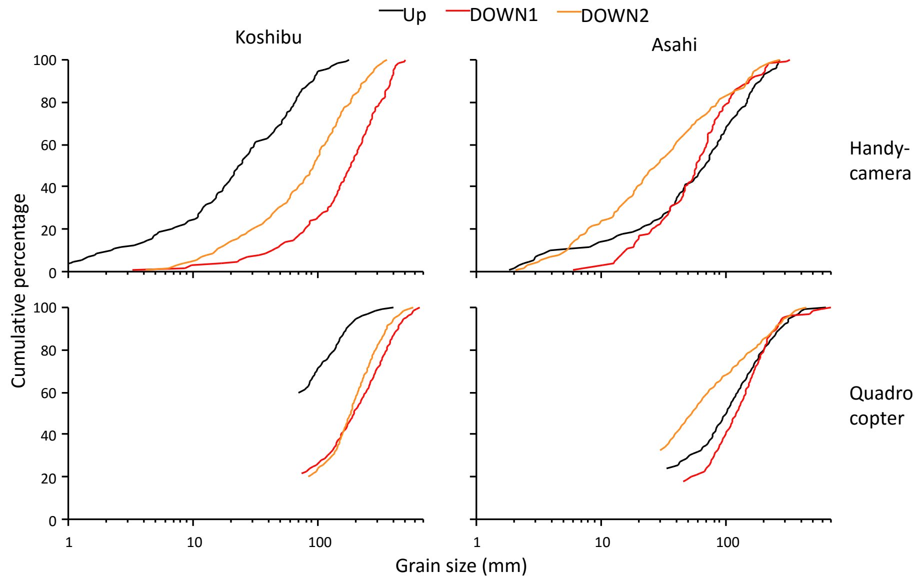

Fig 8. Grain size distribution of surface bed materials analyzed from the images taken by handy (upper) and quadrocopter (lower) camera

A positive correlation was observed between representative grain size, D_x, of the image obtained by handy camera and quadrocopter (Fig 9). The correlation was better for the large representative size. The correlation suggests that the images from handy and quadrocopter cameras reasonably evaluated at least the difference in grain size among the different reaches. The size ratio of quadrocopter to handy camera in D_{50}, D_{60}, D_{84} ranged from 1.06 with the coarsest reach (i.e., Koshibu DOWN1) to 2.25 with the finest reach (Koshibu UP).

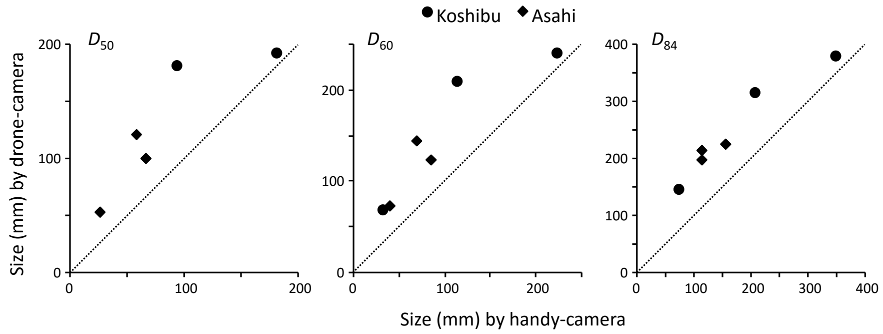

Fig 9. Relationship between representative grain size obtained from different images

The difference in percentage of each grain size class between UP and DOWN was calculated as $\Delta_{\mathrm{DOWN\text{-}UP}}$ (Fig 10). If the $\Delta_{\mathrm{DOWN\text{-}UP}}$ is positive, the size class was disproportionately more in DOWN than UP, and vice versa. For Koshibu, particles smaller than 64 mm were less while particles larger than 128 mm were more in the two DOWN reaches than UP according to the result of both handy camera and quadrocopter. For Asahi, finer particles such as less than 32 mm were more but coarser particles such as larger than 128 mm were less in the two DOWN reaches than UP according to the result of the handy camera images. Less coarse particles in the two DOWN reaches than UP for Asahi was also suggested from the quadrocopter images.

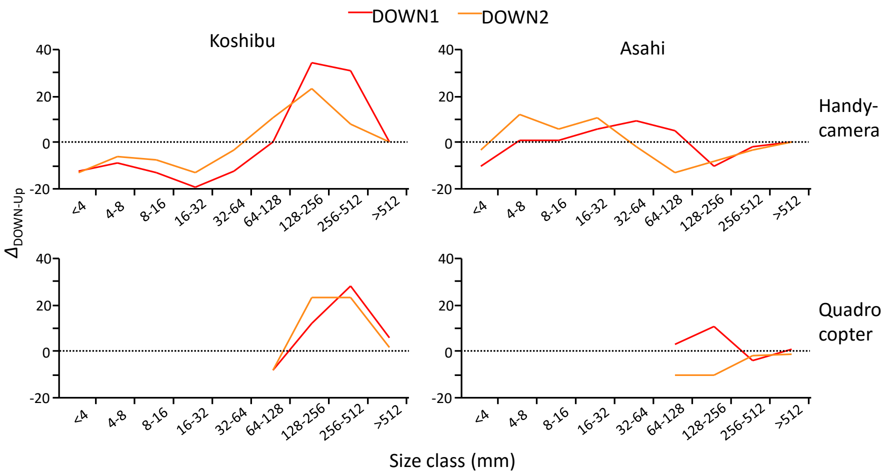

Fig 10. Difference in percentage of each grain size class between UP and DOWN, $\Delta_{DOWN-UP}$, obtained from handy camera (upper) and quadrocopter (lower)

4. DISCUSSION AND CONCLUSION

We evaluated bed topography and GSD above and below the two dams with SBT by field surveys using handy camera, quadrocopter, and of microhabitats. We demonstrated that the surface bed materials were coarser throughout riffles, runs, and pools in the downstream reaches than upstream of the Koshibu dam, where almost no supply of sediment below the dam with pre-start of the bypass operation. Particles finer than 64 mm such as sand and gravels were disproportionately less in the downstream, and these particles are supposed to have been selectively transported further downstream during past floods. Thus, a sufficient supply of sand and gravels after SBT operation is desirable to recover environment conditions of the downstream similar to the upstream. Because sand and finer materials are easily transported by small floods and unlikely remain in the reach by themselves, supply of gravel may be a key to the environmental recovery after the start of the bypass operation.

Particles large than 128 mm such large cobbles and boulders, which were more represented in the downstream of the Koshibu dam, contributed forming steps in a steep riffle (Fig 2, 4). Increased bed roughness by coarse bed materials partially exceeded the water depth during baseflow, which was shown by the greater abundance of stones emerged from the water surface. Hydraulic jumps that dissipate flow energy below the steps as well as stagnant flows that develop behind the emerged stones may together promote the occurrence of slow-flow areas even in steep riffles. This topographic characteristic is a possible reason of the abundance of pool specialist invertebrates, which prefer slow-flowing water, below dams with no or limited bypass operation (Awazu et al., 2015). The steepening and shortening of riffles and the increased longitudinal range of pools are another mechanism that promote the dominance of pool specialists in a degraded mountain channel below dams (Kobayashi et al., 2012).

On the other hand, the formerly degraded channels in the downstream of the Asahi dam had been filled with sand, gravel and cobbles by sediment supply through SBT operating for more than 17 years. This study showed that the bed roughness that provides steps and emerged stones in the downstream was as low as the upstream of the dam. The abundance of pool specialist invertebrates was low and the abundance of riffle specialists was high below the dam (Awazu et al., 2015). An increase of invertebrate species richness since the bypass operation has also been shown (Harada et al., 2000; Mitsuzumi et al., 2009). The recovery of sandy bars below the dam has also been shown by Osada et al. (2012). Thus, the downstream environmental conditions in terms of bed topography and invertebrate habitat have largely recovered. However, we also revealed that finer materials were more and coarse materials larger than 128 mm were less represented in the downstream than upstream. A selective deposition of coarse materials upstream of the tunnel inlet, which results in a selective transport of the finer materials may have been occurred (Osada, 2012). Because cobbles and boulders are also important elements of habitat formations (Kobayashi and Takemon, 2012), downstream transport of these materials may be also required for a full recovery of the environment.

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