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Recovery of Riverbed Features and Invertebrate Community in Degraded Channels by Sediment Supply through Bypass Tunnel

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ABSTRACT

Sediment, which deposits and damages the function of reservoirs, is an essential element of aquatic habitats in downstream ecosystems. We reviewed ecosystem features of degraded channels associated with sediment deficiency below dams and ecosystem responses to changes in sediment conditions after management practices in Japan. Sediment bypass tunnel (SBT) is an effective way to transport sufficient amount of sediment to downstream ecosystems. Based on a concept of suitable mass and size of sediment for ecosystem, some effects and limitations of SBT on downstream ecosystems were discussed.

KEY WORDS: dam; sediment; bypass tunnel; channel degradation; riverbed; grain size; invertebrate community.

INTRODUCTION

Sediment deposition is a main issue in the sustainable management of reservoirs as well as of river channel. Sediment accumulations that increase after a flood event in reservoirs are critical for the longevity of dams. Different measures have been proposed to reduce sediment in the reservoirs (Sumi and Kantoush 2011). Concerning to river channels, sabo works that prevent erosion and sediment supply from hillslopes and headwaters, large dam constructions in the main stem of drainage systems, and direct excavations have reduced sediment deposition especially downstream reaches and coastal areas (Fujita et al. 2008). Such sediment reduction has caused substantial changes in riverbed conditions including a loss of easily entrained bed materials (e.g., sand, gravels), bedrock exposure, bed stabilization, and channel incision. Accordingly, many endemic species were replaced by exotic species due to their requirements for certain bed and flow conditions. In addition, overgrowth of particular plants were promoted due to the bed stabilization. Sediment should be increased in the river channels if we wish aquatic community and ecosystems to recover to a state, in which people can enjoy benefits from riverine production and biodiversity. However, measures to increase sediment in the channel have been less conducted probably because we concern more on flood risk reduction and less on increasing the potential of ecosystem services.

Considering the future water demands and increasing importance of reservoirs, sediment management measures of reservoirs are the limited possibilities to increase sediment in downstream rivers. Replenishment of sediment excavated from reservoir has been conducted in several dams in Japan (Kantoush and Sumi 2011). However, due to limitations in excavation, transportation, placement, and available discharge for flushing, as well as the cost of these works, the amount of sediment supply is usually low (<1,000–10,000 m^3 per year). Flushing/sluicing techniques of sediment through dams are effective for transporting large amount of sediment to downstream reaches. Sediment bypass tunnel (hereafter SBT) is intended to route sediment around a dam that otherwise accumulates in reservoirs (Vischer et al. 1997). Sediment transport through SBT during flood is another effective way of supplying large amount of sediment to downstream. 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 conducted field monitoring and also collected environmental and ecosystem data from different sources of several dams with SBT to understand the effect of SBT operation on ecosystem recovery of the downstream reaches (Awazu et al. 2015). In this paper, we firstly showed important habitat components for river organisms, and the changes of their habitat by channel degradation in Japan. Secondary, we showed some of the effects of SBT system on the recovery of riverbed and ecosystem features based on the results of our study. We also mentioned about approaches to evaluate the recovery of river environment. Finally, based on a concept of the suitable amount and size of sediment for ecosystems, we discussed the limitations of SBT system on the recovery of downstream environment. Here, we focused on benthic invertebrates (mainly insects) as a representative of riverine ecosystem. Invertebrates are an important component in the food web of riverine system, because they control the primary production by algae and are also the main food source for various fish and bird species. Invertebrates are also rich in species so that community composition can change clearly to environment of various aspects.

SEDIMENT AND RIVER HABITAT

Habitat refers to a living place of organisms. In rivers, it usually means by locations of different flow, depth, and substrate (i.e., bed material) conditions (Fig. 1). For example, riffles (shallow, fast flow, coarse bed) and pools (deep, slow flow, fine bed) are different habitats. Habitats can be also defined at smaller spatial scales within riffles and pools based on flow and substrate (called microhabitats, Fig 1). The pool-riffle geomorphic (bedform) structure usually occur in every reaches of gravel-bed river, but topography, surface flow, and bed materials differ according to the sediment condition. Some other habitats, such as secondary channel flows and temporal ponds, are associated with a development of bars (Fig. 1). Invertebrate biomass and species richness

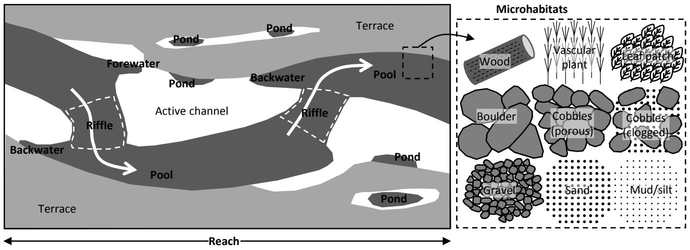

Fig. 1 Example plan view of river reach with definitions of habitats

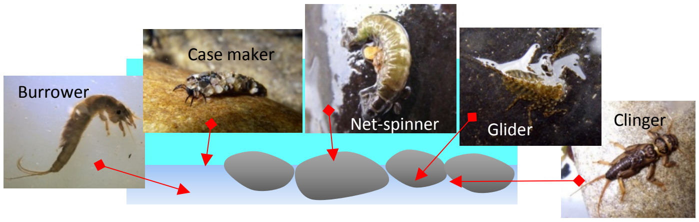

Fig. 2 Some invertebrate species and their life type

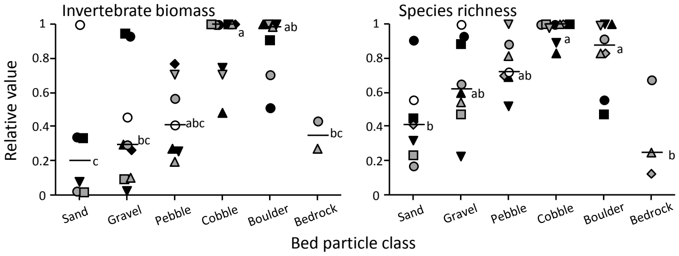

Fig. 3 Relationship between bed material and invertebrates (from a review study of Kobayashi and Takemon 2012)

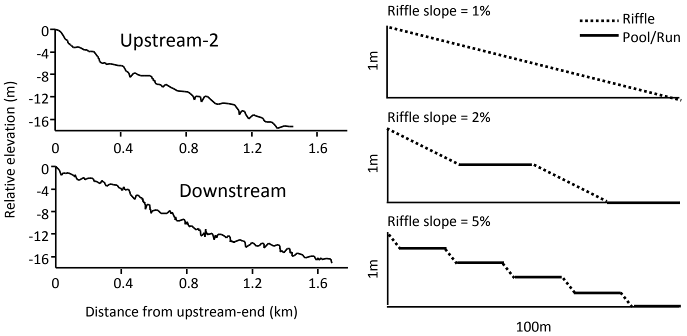

Fig. 4 Longitudinal bed profile of above and below dam reaches (left) and schema of the change in riffle length with riffle steepening (right) (from Kobayashi et al. 2012)

are often higher in riffles than pools within a given reach. Thus, researchers sometimes focus on riffles to make comparisons between reaches if the time and effort are limited. Potentially more different species can live in riffles or reaches with various bed materials (i.e., more microhabitat types).

Bed material size is an important determinant of the occurrence of each invertebrate species, and also of the potential (i.e., maximum) total species and biomass that can live in a given bed area. Different species have different preferences for bed materials according to their mode of existence (e.g., burrow into sand, cling on stable coarse material) and their flow preference (e.g., some species are abundant in cobble beds because the flow is swift) (Fig. 2). Generally, when all invertebrates are considered, species richness and biomass increase along representative bed size from sand to cobbles, and decrease from cobbles to bedrock (Kobayashi and Takemon 2012, 2013) (Fig. 3). Not only the representative grain size but also the combination of different sizes are also important (Kobayashi and Takemon 2012). For example, cobbles do not provide suitable interstices for invertebrates without sand and gravel, while cobbles embedded in too much fines are also unsuitable.

DEGRADED CHANNELS

Degraded channels are typically deeply incised with cross-sectionally concentrated flow, lack of developed sediment bars and related habitats (i.e., secondary channel flow, temporal ponds, Fig. 1), and over-representation of boulders and bedrock. Accordingly, flow and bed materials are considered to be spatially more uniform within reaches. The shape of pool-riffle structure also associates with the grade of the channel. Individual riffles are often steepened as finer particles are removed and coarser particles are remained (Kobayashi et al. 2012, Fig. 4). As a consequence, individual riffles shrink while pools expand in degraded reaches. Sometimes swift flows (e.g., >1 m/s) are lost in degraded reaches without any changes in the discharge.

According to the relationship between bed material size and invertebrates, invertebrate community composition, species richness, and biomass change with degradation. For example, species that utilize sand for their living (e.g., cased caddisfly) are less (Katano et al. 2010), while species that prefer coarse and stable substrate (e.g., net-spin caddisfly) are more below dams (Hatano et al. 2005). Invertebrates that utilize underneath cobbles (e.g., stonefly) require certain amount of sand and gravel for suitable interstices, and they are less in uniformly cobble/boulder and bedrock exposed beds. Highly degraded channels with immobile bed materials often promote overgrowth of attached algae on stones. Invertebrates that require clean surface cobbles (e.g., glider and swimmer mayfly, blackfly) are less below dams (Hatano et al. 2005). Some invertebrate species that require finer materials (e.g., burrower mayfly, aquatic worms) are sometimes more in the degraded channels. This is probably due to their preference of slow-flow conditions. Invertebrate species that adapted to swift flows can also decrease with riffles in degraded reaches. Invertebrate species richness is expected to be low in degraded reaches if the spatial heterogeneity in flow and substrate is reduced. On the other hand, total invertebrate biomass may be higher below than above dam due partly to increased bed stability and food supply.

EVALUATION OF RECOVERY AFTER SBT OPERATION

Methods of Evaluation

One of the recommended approaches for evaluating effects of SBT operation on downstream ecosystem is to monitor downstream site from before the SBT operation. It is better to monitor also for a reference site and analyze by the Before–After Control–Impact design. Another recommendation is the space-for-time substitution approach, in which downstream change is evaluated by comparing present state of various reaches (dams) with different years of SBT operation. We mainly adopted the latter approach to grasp a rough but whole image of

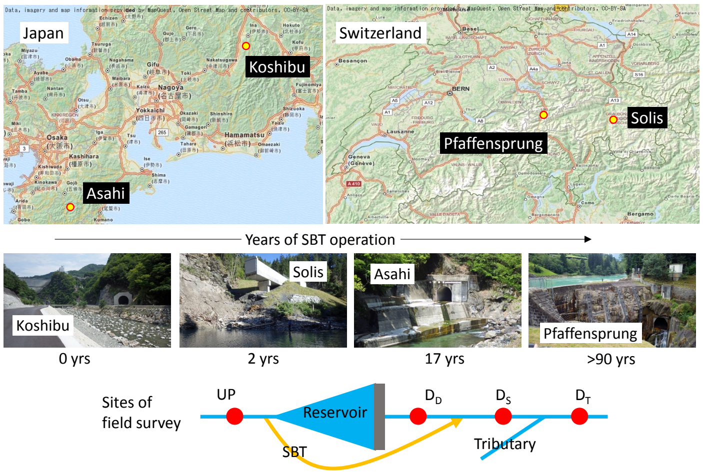

Fig. 5 Surveyed dams with SBT (upper), the space-for-time approach (middle), survey sites each dam (lower)

the recovery, by field surveys at 4 dams in Japan (Koshibu, Asahi) and Switzerland (Solis, Pfaffensprung) (Fig. 5). SBT is new for Koshibu (no operation) and Solis (operation for 2 years), while old for Asahi (17 years) and Pfaffensprung (>90 years). In addition, we examined a long-term change of a downstream of Asahi after the SBT operation. At each dam, we set up 4 sites with different sediment conditions (UP: upstream, D_D: below dam but upstream of SBT, D_S: downstream of SBT, D_T: downstream of tributary confluence, Fig. 5). Comparisons between D_D and D_S also give us insights on the effect of SBT.

At each site, we measured grain size of bed materials, microhabitats, and invertebrates. Grain size distribution was evaluated by photos taken on the ground and 30-m up from the ground using a drone. We defined 18 types of microhabitats such as bedrock, boulders, cobbles, embedded cobbles, gravel, sand, moss-mat, algal-mat, wood, leaves, and mud. The abundance of each type was recorded by four levels (0: no, 1: minor, 2: frequent, 3: major). Benthic invertebrate were sampled in riffle and pool using a D-framed net for 10 to 20 minutes by two persons. Most of the invertebrates were mayfly, stonefly, or caddisfly, and the detail species were identified using a microscope. We separated the abundance (number of individuals) of each species into 4 levels (0: no, 1: 1-10, 2: 11-100, 3: 101 or more). Each species was classified into groups by life type or habitat preference. Life types are swimmers, gliders, clingers, burrowers, net-spinners and case makers. Habitat preferences are riffle dweller, pool dweller, and no preference.

Certain indices are needed to evaluate environmental recovery. Common indices are richness (number of species or types) or diversity (evaluate both richness and evenness). However, we found these indices do not always response clearly to the sediment recovery. Indeed, invertebrate species richness was higher in D_S of Koshibu with no SBT operation. Instead, we consider a pristine state as a goal of recovery, and evaluate how much the state of a given time is close to the pristine one. Because no data of the pristine state (i.e., before construction of dam) was available, we used UP site as a reference. We evaluated Bray-Curtis Similarity Index (*BC*) between UP and D_S as

$$BC = \sum_i \min\left(\frac{n_{iUP}}{N_{UP}}, \frac{n_{iDs}}{N_{Ds}}\right) \tag{1}$$

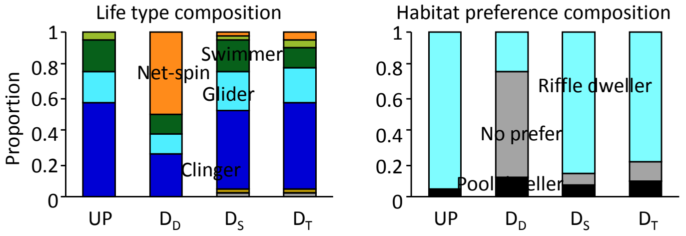

Fig. 6 Difference in invertebrate community among sites in Asahi

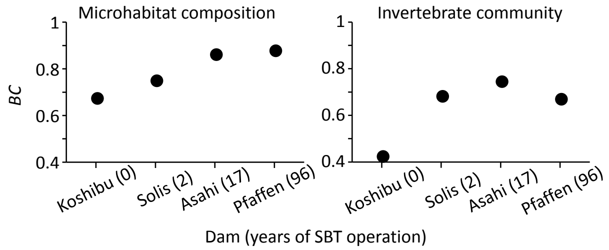

Fig. 7 Relationship between years of SBT operation and *BC* (similarity between UP and D_S)

where n_i is abundance of each type or species, and N is sum of the abundance of all types or species. *BC* ranges from 0 when no common type or species between the two sites to 1 when exactly the same composition between the two sites.

Results from Different Data

We found substantial differences in bed materials, microhabitat, and invertebrate composition between D_D and D_S sites of Asahi Dam with 17 years of SBT operation. Because the two sites had similar channel conditions and water discharge of non-flood period, most of the differences were caused by with/without sediment through SBT. The bed of D_D was dominated by boulders, while that of D_S was dominated by cobbles with sand and gravels as matrix, which was similar to that of UP. Invertebrates of D_D were much dominated by net-spinners in terms of life type, and pool dweller and no-preference in terms of habitat preference (Fig. 6), which are typical of degraded channel as mentioned. Invertebrates of D_S were much dominated by swimmers, gliders, clingers, and by riffle dweller, which was similar to UP. On the other hand, differences in microhabitat and invertebrate composition between D_D and D_S of Solis Dam with new SBT were not as large as Asahi.

The recovery of downstream environment was also evident from the space-for-time substitution approach. Representative grain size, D_{60}, was larger in D_S than UP for Koshibu and Solis with new SBT, while similar between D_S or D_T and UP for Asahi and Pfaffensprung with old SBT. *BC*, the similarity index, for microhabitat composition between UP and D_S tended to increase with years of SBT operation (Fig. 7). This is explained by the change in size of dominant bed materials and in the abundance of moss- and algal-mat, which are typical of degraded channels with stable bed. *BC* for invertebrate community between UP and D_S also tended to increase with years of SBT operation (Fig. 7). This is explained by the changes in life type composition and habitat specialty type as we observed between UP and DS of Asahi (Fig. 6). Increase of gliders that prefer clean stone surface while decrease of net-spinners that prefer stable substrates suggest that bed mobility and disturbance increase with years of SBT operation. Dimensionless shear stress, which was greater in D_S of older SBT and UP of all dams, supported this idea. Increase of riffle dweller while decrease of pool dweller suggest an increase of fast flow and decrease of slow flow with years of SBT operation. This process was supported by a following study that surveyed micro-topography using aerial photos (Kobayashi et al. 2016). Protruded stones that act as obstacles against flow and boulder steps that dissipate flow energy were abundant in D_S and D_T of Koshibu Dam, while these structures were less abundant in D_S and D_T of Asahi Dam and UP of these dams.

Yearly data of invertebrates for 16 years since the SBT operation in the Asahi Dam also showed an increase in *BC* of invertebrate community between above and below dam sites with years. Changes in community composition in terms of life type and habitat specialty, which we showed in the previous paragraphs, were evident. The yearly data also showed that most obvious changes in invertebrate community below dam occurred within a few years after the operation.

KEY GRAIN SIZE FOR DOWNSTREAM RECOVERY

Results of our study suggest that riverbed conditions and invertebrate community in degraded channel below dams will recover with years after the operation of SBT (Fig. 8). Sediment transported by SBT, which is finer than the bed materials of degraded channel, firstly fills micro-concave topography, makes longitudinally smoother bed, and increases swift flows. Covering of bed surface by these materials will further increase the chances of bed material mobility. These changes contribute to establish invertebrate community typical for the natural rivers. The change in bed conditions and invertebrate community may then affect fish community. Further increase of sediment in the channel may also develop gravel bars, generate habitats of secondary channels, and elevate water-filtration capacity of bed.

Although we showed a positive effect of SBT on environment recovery, the effect may differ according to the amount and size of sediment through SBT. Only sand or finer sediment are expected to be transported through SBT in certain dams to reduce maintenance cost of tunnel abrasion. Such supply of fine sediment may have no effect or even negative effect on downstream ecosystem. First, sand and finer materials are easily entrained by small floods and unlikely remain in the reach without gravel and small cobbles. Even if they remain, cobbles or boulders embedded by such fines are unsuitable for benthic invertebrates as mentioned previously. For Koshibu Dam, the shortage in the downstream reaches was much severe for gravel than sand (Kobayashi et al. 2016). Gravel and small cobbles are likely to be the key for the ecosystem recovery of the reaches.

Although bed and invertebrate community below Asahi Dam appears to have been recovered by SBT operation, we also noticed that large cobbles and boulders were less represented below than above the dam (Kobayashi et al. 2016). This evidence may suggest that not all sizes of bedload materials but smaller size materials are selectively transported through SBT. Although the reduction of large cobbles and boulders are essential for the recovery of the degraded channel, over-reduction of these materials can deter the recovery as these materials are also important elements of invertebrate habitats. SBT of most of the dams are considered to have some limitations for transporting large sediment. Additional ideas for transporting large materials, which deposit in upstream reaches of SBT inlet, may be required for a full recovery of the downstream environment.

Fig. 8 Schema of the environmental recovery after SBT operation

CONCLUSION

We showed that sediment transport through SBT can promote the environmental recovery of degraded channels below dam. However, SBT seems to have limitation in transporting some of large materials.

REFERENCES

Awazu, Y., Kobayashi, S., Sumi, T., and Takemon, Y. (2015). Riverbed environment and benthic invertebrates in the downstream of dams with sediment bypass. Annuals of DPRI, Kyoto Univ., No 58B, pp 527-539.

Fujita, K., Tomita, Y., Oonuma, K., Oro, T., Ito, K, Yamahara, Y. (2008). Facts and introductory knowledge about downstream effects of dams on the physical environment of rivers in Japan: for building a common and scientific basis for discussion on dams and the river environment. Technical note of National Institute for Land and Infrastructure Management, No 445, 52 pp.

Hatano, K., Takemon, Y., Ikebuchi, S. (2005). Characteristics of benthos community and habitat structure in the downstream reaches of reservoir dams. Annuals of DPRI, Kyoto Univ., No 48B, pp 919-933.

Kantoush, S.A., Sumi, T. (2011). Sediment replenishment measures for revitalization of Japanese rivers below dams. Proc. 34th IAHR World Congress, pp 2838-2846.

Katano, I., Negishi, J.N., Minagawa, T., Doi, H., Kayaba, Y. (2010). Extraction of indicator species to test restoration effects by sediment replenishments in downstream reaches of dam. Proc. River Engineering, JSCE, Vol 16, pp. 519-522.

Kobayashi, S., Auel, C., Sumi, T., Takemon, Y. (2016). Effects of sediment supply by bypass tunnels on bed topography, grain size, and invertebrate habitat. Proceedings of IAHR-APD 2016, in press.

Kobayashi, S., Nakanishi, S., Akamatsu, F., Yajima, Y., Amano, K. (2012). Differences in amounts of pools and riffles between upper and lower reaches of a fully sedimented dam in a mountain gravel-bed river. Landscapes and Ecological Engineering, Vol 8, pp 145-155.

Kobayashi, S., Takemon, Y. (2012). River habitat evaluation using sediment load and grain size distribution. Annuals of DPRI, Kyoto Univ., No 55B, pp 537-545.

Kobayashi, S., Takemon, Y. (2013). Historical changes of riffle morphology for benthic invertebrate habitats in the Kizu River. Annuals of DPRI, Kyoto Univ., No 56B, pp 681-689.

Sumi, T. (2015). Comprehensive reservoir sedimentation counter-measures in Japan. Proceeding of the First International Workshop on Sediment Bypass Tunnels, Zurich, Switzerland, pp 1-20.

Sumi, T., Kantoush, S.A. (2011). Sediment management strategies for sustainable reservoir. Proc. Of the International Symposium on Dams and Reservoirs under changing challenges, 79th ICOLD, 356-362.

Vischer, D.L., Hager, W.H., Casanova, C., Joos, B., Lier, P., Martini, O. (1997). Bypass tunnels to prevent reservoir sedimentation. Q74-R37, in Proc. 19th ICOLD Congress, Florence, Italy, pp 605-624.