Invertebrate community changes in the downstream of dam after the operation of sediment bypass tunnel

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Abstract

To understand the effect of sediment bypass tunnel (SBT) on the recovery of invertebrate community in degraded channels below dam and the time required for the recovery, 17-years monitoring data since the start of SBT operation in Asahi Dam were analyzed. Invertebrate community recovered toward an upstream state within 2–3 years after the SBT operation, in terms of taxon richness and Bray-Curtis similarity index (*BC*). Taxon richness in the downstream was lower in the last few years, partly because it was also affected by flood occurrence of the years, while *BC* was consistently high in the later years. Data of national survey done every 5 years were used to analyze invertebrate community patterns in Miwa and Koshibu dams with SBT. Although the downstream channel of Koshibu was degraded before the SBT construction, taxon richness was higher in the downstream than upstream, while *BC* between upstream and downstream was consistently low. *BC* is suggested to be better as indicator of environmental recovery of downstream than taxon richness. Although SBT had been operated for more than 7 years in Miwa, no evidence of the recovery in invertebrate community was detected.

Keywords: downstream of dam, invertebrate community, recovery, taxon richness, similarity index

1 Introduction

Channel degradation by reduced sediment supply from upstream or excavation is an important environmental issue in many Japanese rivers especially for downstream reaches and coastal areas (Fujita *et al*. 2008). Degraded channels are typically incised cross-sectionally, homogenized longitudinally, and dominated by coarse materials (Petts *et al*. 1993, Kondolf 1997). Substantial loss of gravel bar-generated spatial heterogeneity in flow and loss of bed interstitial layers after degradation excludes many aquatic species that require certain flow and bed conditions for their life. On the other hand, degradation often induces invasion and overgrowth of undesirable species adapted to the unfavorable conditions, which can finally lead to a development of community unfamiliar to the river.

Sediment bypass tunnel (hereafter SBT) as a countermeasure of reservoir sedimentation (Vischer *et al*. 1997, Boes *et al*. 2014) is an effective way of supplying large amount of sediment to degraded channels in the downstream of dams. The construction of SBTs in the world is still limited, and most of them are located in Switzerland and Japan so far (Boes *et al*. 2014, Sumi 2015). A recovery of bed and flow, aquatic community, and ecosystem to a state before dam construction by SBTs is expected. However, there are few studies of geomorphology and ecology in the downstream of dams with SBT (Facchini *et al*. 2015, Martín *et al*. 2015), and of the recovery of ecosystem by SBT operation (Mitsuzumi *et al*. 2009, Fukuda *et al*. 2012, Awazu *et al*. 2015).

We have examined the environmental and biological recovery of below-dam reaches by SBT operation, based on field surveys of 4 dams in Japan and Switzerland with different years of SBT operation (Awazu *et al*. 2015). We found evidence of the recovery of bed features and invertebrate community with years of SBT operation: beds were coarse and rough in the downstream of dams with new SBT, while beds were finer and smooth and invertebrate community was more like upstream of dams for the downstream of dams with old SBT. In this study, we examined the time required for invertebrate community to recover to a pre-dam state after SBT operation using yearly monitoring data, which have been collected for long years since the start of SBT operation in Asahi Dam (Kansai Electric Power Company) in Nara Prefecture Japan. We used invertebrate taxon richness and community similarity index as indicators of the recovery. To validate these parameters as indicator of the recovery, we also examined invertebrate community of other dams with SBT using public river survey data.

2 Study site and methods

Asahi dam (Kansai Electric Power Co., Inc.) was constructed in 1978 in a tributary of the Kumano River in Nara Prefecture. The original reservoir volume was 15.5×10^6 m^3. The catchment was 39.2 km^2 and mostly covered by forest. The operation of SBT was started in 1998, and 77% of the incoming sediment (average: 100,000 m^3/year) including gravel and cobbles were bypassed since then (Auel *et al*. 2016). The gate of SBT was opened for sediment transport during floods several times a year.

Koshibu and Miwa dams (Ministry of Land, Infrastructure, Transport, and Tourism: MLIT) were constructed in 1969 and 1978 in different tributaries of the Tenryu River in Nagano Prefecture. The SBT operation has begun as test run in 2016 for Koshibu, and has been done since 2004 for Miwa 1–2 times a year and transport half of the incoming sediment (mostly silt, average: 550,000 m^3/year, Kashiwai and Kimura 2015).

In Asahi, surveys of benthic invertebrates were conducted every winter (less-flood season) for 17 years since 1998. The survey was conducted at sites upstream of dam (UP) and downstream of dam (Figure 1); near SBT outlet (D1) and downstream of a tributary confluence (D2). The tributary also had upstream dam (Seto), and thus, cannot be a major sediment source for the main stream. We assumed that the state of UP as a pre-dam state of D1 and D2. Unfortunately, the survey was skipped at UP and D1 during 2001–2011.

At each site, a streambed of 0.5 m^2 was sampled with a Surber sampler (quadrant area: 0.0625 m^2, net mesh size: 0.5 mm) from 8 locations in riffles. For each sample, animals were sorted, identified to genus or species, and enumerated. The number of each taxon was transformed to density (number per unit bed area) by dividing by the sampling area.

Fig. 1: A map showning location of survey sites and photo of each site

We used invertebrate taxon richness and Bray-Curtis similarity index as indicators of community recovery. Invertebrate taxon richness was the number of taxon at the lowest level (mostly genus or species) each habitat each year. Bray-Curtis similarity index (*BC*) was calculated between two communities (e.g., UP and D1).

$$BC = \sum_i \min\left(\frac{n_{iUP}}{N_{UP}}, \frac{n_{iD}}{N_D}\right) \quad [1]$$

where n_i is abundance of each taxon, and N is sum of the abundance of all types or species. *BC* ranges from 0 when no common taxon between the two communities to 1 when exactly the same composition between the two. Density of each taxon was $\log_{10}(x+1)$-transformed before the calculation. We examined how the taxon richness and similarity index changes with years. In addition, non-metric multidimensional scaling (NMDS: a procedure for plotting communities in 2-dimensional space, such that the distances between communities correspond to their dissimilarities) ordination was conducted to see how community composition changes with years.

A survey of the riverine environment is conducted for all dams managed by MLIT every 5 years since 1990. At each dam benthic surveys were conducted for several sites including upstream (U) and downstream (D) of the dam for 3 seasons each corresponding year with almost the same sampling protocol as in Asahi. The data including Koshibu and Miwa were available in the website (http://mizukoku.nilim.go.jp/ksnkankyo/). We downloaded the survey data of 2007 and 2012 and calculated invertebrate taxon richness and Bray-Curtis similarity index as mentioned for each dam.

3 Results

3.1 Change of taxon richness in Asahi

Invertebrate taxon richness at D1 and D2 increased for the first 3 years, and they were almost the same level of UP in year 3, and in the last 3 years (Figure 2a). Because no survey was done before 1998, the pre-SBT state is unknown. But, in our own survey (Awazu *et al*. 2015) the reach upstream of SBT, which can be assumed as pre-SBT state of the downstream, was extremely low (6 taxa) compared to UP, D1 and D2 (22–36 taxa). Taxon richness at D2, where the survey was done for all years, tended to increase in the early half and decreased in the latter half, which was suggested by a significance in regression of the richness by second order polynomial of years (Figure 2a, dotted curve). Taxon richness in the last 4 years was similar or less than the year 1 at D2. Similarly, at D1 taxon richness in the last 3 years was similar or less than year 2 and 3.

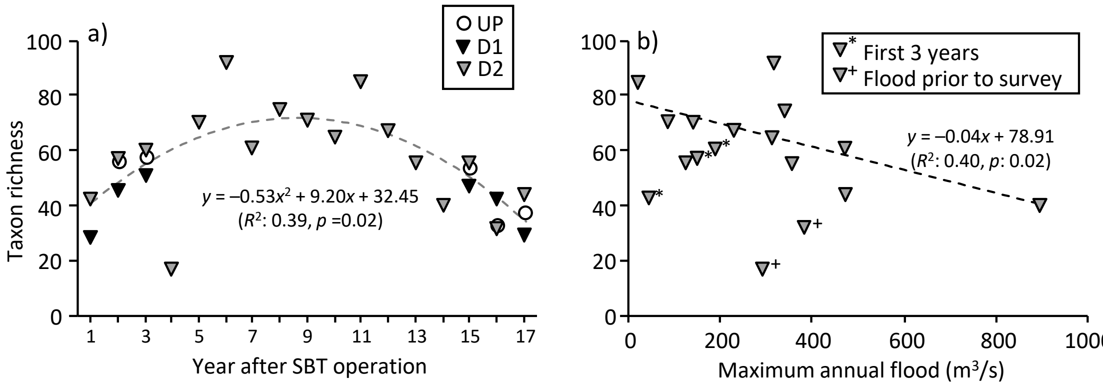

Fig. 2: a) Change in invertebrate taxon richness in riffles after the start of SBT, and b) relationship between annual flood and taxon richness at site D2

Yearly fluctuation in taxon richness was also evident at D2. For example, the richness was low in year 4 (2001) and 7 (2004) than their previous and next years. Part of the fluctuation was associated with floods occurred prior to survey (Figure 2b, dotted line). The taxon richness was the lowest in year 4 and 16 (2013) when a flood occurred within one month before the survey. Except for these two years and year 1–3, the richness was negatively correlated with the annual maximum flood, with the maximum record in year 14 (2011) and the second in year 7. Thus, the decreased richness in the latter half years was partly associated with the occurrence of flood in less-flood season or large flood in flood season.

Biomass (g/m^2) of all invertebrates also changed yearly. The biomass increased for the first 3 years at D1, while it changed but no clear trend at D2. The biomass was more clearly correlated with the annual maximum flood compared the richness.

3.2 Change of similarity index in Asahi

Bray-Curtis similarity index (*BC*) calculated between UP and D1/D2 was less than 0.3 in the year 1, while it was about 0.6–0.8 in the year 2–3 and year 15–16 (indicated by black and gray triangle in Figure 3a). *BC* was below 0.6 in the year 17 (the last year of survey), though our own survey conducted in the same year showed the index of 0.6–0.8 between UP and D1/D2 (Awazu *et al*. 2015, indicated by black and gray diamonds in Figure 3a). *BC* calculated between UP and the upstream reach of SBT, where no sediment supply, was less than 0.1 (dark circle in Figure 3a). Thus, the community composition at D1/D2 in year 1 was not in an extreme situation typical of degraded channel. Because of no data of UP from year 4 to 14, the true value of *BC* is unknown. To roughly understand *BC* in these data missing years, data of year 3 and 15 were used as UP and calculated *BC* between UP and D1/D2 of each year (in the dotted square in Figure 3a). Despite the difference in the survey year, which would likely to decrease the similarity, *BC* was nearly 0.6 and relatively constant except for the year 4. Year 4 was when a flood occurred within one month prior to the survey as previously mentioned,. In summary, the community composition of UP and D1/D2 became similar within 2–3 years after the operation of SBT, and no evident change in *BC* after that until year 17.

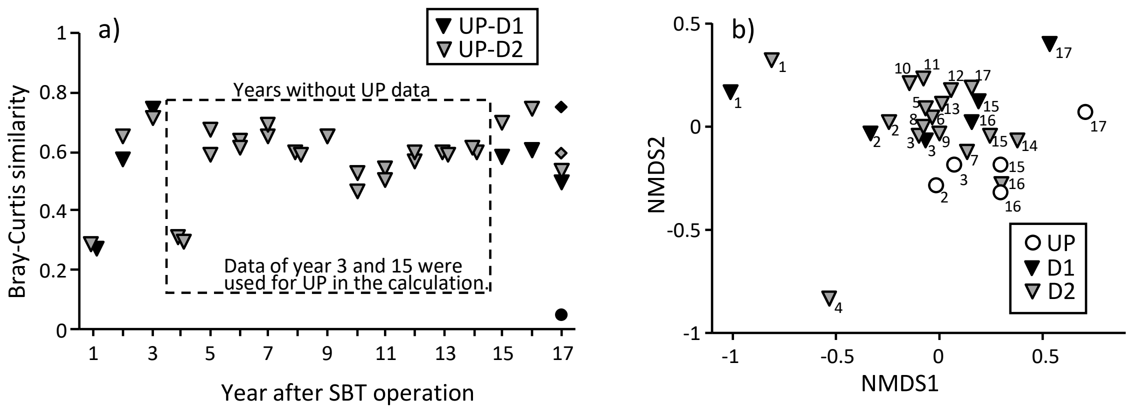

Fig. 3: a) Change in Bray-Curtis similarity in invertebrate community between riffles of UP and D1/D2 after the start of SBT in Asahi, and b) NMDS ordination of invertebrate community of UP, D1, and D2 of different years.

NMDS ordination shows which communities are similar or dissimilar according to the distance in the 2-dimensional space (Figure 3b, the number next to each symbol indicates the year since SBT operation). Communities of D1 and D2 were mixed each other and dispersed in wider range than UP. Communities of D1 and D2 were the farthest from UP in year 1, and got closer to UP in year 2 and 3. D2 community in year 4, when a flood occurred before the survey, got apart from UP communities. D2 community changed little during year 5–13, got much closer to UP communities in year 14–16. In summary, similar to the previous paragraph, the community composition of UP and D1/D2 became much similar within 2–3 years after the operation of SBT. The similarity changed little in the latter years.

3.3 Taxon richness and similarity index in Miwa and Koshibu

Invertebrate taxon richness in Miwa and Koshibu tended to be lower in summer than in spring and winter, while no consistent trend between years each dam (Figure 4a). Taxon richness was always higher in the downstream (D) than upstream (U) of dam every case except for spring 2012 in Miwa. In some cases, taxon richness of D was more than 1.5 times that of U. Because SBT had not been operated in Koshibu, our result suggests that the degraded reach had higher taxon richness than non-degraded reach. The degree of the difference between U and D tended to be greater for Miwa, where SBT started since 2005, than Koshibu.

BC was about 0.2–0.4 throughout the survey periods in both dams except for winter 2012 in Koshibu, when *BC* was nearly 0 (i.e., few overlapping taxa occurrence). *BC* was also lower for Koshibu than Miwa in all periods except for summer 2012. *BC* of Miwa and Koshibu was apparently low compared to that of Asahi after 2–3 years of SBT operation (Figure 3a).

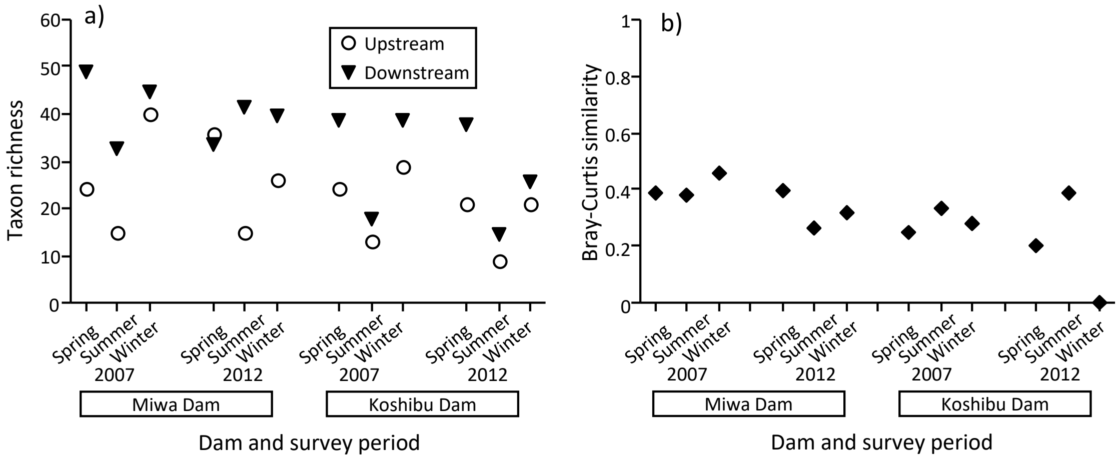

Fig. 4: a) Invertebrate taxon richness in upstream and downstream sites of dam and b) Bray-Curtis similarity index calculated between these sites for different periods in Miwa and Koshibu

4 Discussion

We revealed that invertebrate community in the downstream of Asahi largely recovered toward the state in the upstream of dam within 2–3 years of SBT operation in terms of both taxon richness and community composition. Because the community composition seems to have changed from the one typical of degraded channel even in year 1, the recovery of invertebrate community appears to be quick. The rapid recovery might be due to a large amount of sediment via SBT each year (e.g., 100,000 m^3). The geomorphic processes after SBT operation that encouraged the recovery of invertebrate are unknown. Fukuda *et al.* (2012) reported that the downstream bed of Asahi was largely recovered within 5–6 years in terms of bar formation and the occurrence of pool-riffle structure, while increase in the bed level was evident in limited areas of the downstream reach. After 2–3 years of SBT operation, the recovery of invertebrate community seemed to have stopped or slowed down. Due to a difference in local characteristics, the similarity index between upstream and downstream would not reach 1 even in the future.

Taxon richness was not always a good indicator of the downstream environmental recovery. In Asahi, although taxon richness increased first 3 years of SBT operation, it decreased in the latter half years and was affected by flood occurrence each year. In

Koshibu, the taxon richness was always higher downstream than upstream. This is probably due to frequent disturbance occurrence in the upstream associated with sediment transport. The stable environment with reduced flood frequency and magnitude below dam may support invertebrate populations that otherwise have been flushed out every flood (Death and Winterbourn 1995, Robinson *et al*. 2003). On the other hand, Bray-Curtis similarity index (*BC*) and NMDS (i.e., analysis of community composition) showed expected and consistent patterns in Asahi and Koshibu, and thus, can be a good indicator of the recovery. Our results also suggest that at least several years of monitoring is needed for the evaluation, partly because the status of invertebrate community depends largely on flood occurrence each year.

Although SBT of Miwa started 2005, *BC* between upstream and downstream was as low as in Koshibu even in the 2012 survey. Takato, another reservoir located 2.5 km below Miwa, may trap most of the sediment transported through Miwa SBT and limit delivery of sediment further downstream. In addition, Miwa SBT transports only fine sediment (silt and sand) (Sakurai and Kobayashi 2015). Transport of not only fine sediment (silt, sand) but also coarse sediment (gravel, cobbles) may be required for the full recovery of downstream environment, which needs to be examined in further studies.

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