Temporal changes of aquatic insect assemblages by sequential sediment additions through a sediment bypass tunnel

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Abstract

Conservation of stream ecosystems at downstream of dams often requires long-term, sequential restoration trials. Five sediment additions through a sediment bypass tunnel were conducted in the Koshibu Dam from September 2016 to March 2018 to improve instream environments and biota in the Koshibu River, central Japan. To analyze the effects of sediment additions with high flows on substrate environments and aquatic insects, in this study, we measured the substrate cover of different particle sizes, and collected insects at impacted (downstream of the Koshibu Dam) and reference reaches (upstream of the Koshibu Dam and Toyama River) from June 2016 to March 2018. We found that the downstream reach lacked gravels (2–16 mm) and pebbles (16–64 mm), and the biotic assemblages in the impacted reach were significantly different compared to the reference reaches before sediment additions. After the first and second sediment additions, we found no difference in gravel cover between the impacted and reference reaches, while pebble cover and biotic assemblages were different between the reaches. However, after the fourth and fifth sediment additions (November 2017 onward), biotic assemblages in the impacted and reference reaches were close. The fourth and fifth sediment additions occurred within 8 days and showed a higher flow discharge compared to other sediment additions. Therefore, shifts in insect community assembly would be because of intensive disturbance due to high amounts of supplied sediments.

Keywords: benthos, downstream of dam, long-term response, substrate particles, restoration

1 Introduction

Flow and sediment regime are fundamental factors forming stream environments and biota, which have been altered by large dams worldwide (Poff *et al*. 1997; Wohl *et al*. 2015). Flow regulation and sediment-starved water from dams stabilize and coarsen downstream riverbeds (Kondolf 1997), altering downstream biota (Katano *et al*. 2009). In addition, annual sedimentation in dam reservoirs decreases the water storage capacity (Sumi *et al*. 2004). To solve these operational and environmental problems, various sediment management strategies are implemented in dams worldwide, such as drawdown flushing, sediment sluicing, and sediment bypassing (Kondolf *et al*. 2014). A sediment bypass tunnel (SBT) connecting upstream and downstream of a reservoir is suitable for passing sediments naturally with high flows (Sumi *et al*. 2004). However, because of the limited numbers of SBTs, the ecological effects are still unclear.

Long-term, repeated trials are often required for restoring downstream ecosystems. Downstream stretches of dams tend to be fragmented and isolated from surrounding source habitats of immigrants, so even benthic invertebrates, which are sensitive to instream environments, show sequential temporal changes over a decade (Robinson 2012). Also, a time-lag between habitat changes and ecological responses was reported in fragmented landscapes (Haddad *et al.* 2015). Therefore, distinguishing between ecological changes from environmental changes is important for the effective restoration strategy. In the Koshibu River, central Japan, an SBT was constructed in 2016 and operated five times in two years. In this study, to test the restoration effects by SBT operation for two years, we observed temporal changes in substrate environments and benthic insects at downstream of the Koshibu Dam, Japan, and compared them to a reference river without large dams.

2 Methods

2.1 Study site

We conducted the study in the Koshibu and Toyama Rivers, which are major tributaries of the Tenryu River, central Japan (Figure 1). Both catchments have similar flow regimes and geology, with areas of 238 km^2 (Koshibu) and 274 km^2 (Toyama), and mostly consist of granite, sand, and mudrocks. The Koshibu Dam, a large dam (>15m in height) constructed in 1969, is located in a lower section of the Koshibu River ~5 km upstream from the confluence of the Tenryu River. The Koshibu Dam's 58×10^6 m^3 storage capacity is reduced by high sediment yields—29% of the capacity was filled by sedimentation in 2012 (Kashiwai and Kimura 2015). In contrast, there is no large dam (>15 m) on the Toyama River, representing reference environments and biota in the study region.

2.2 SBT operations and observations

To reduce sedimentation in the Koshibu Dam and restore downstream environments and biota, an SBT was constructed in 2016. The SBT is 3999 m long and 7.95 m in diameter, has a bed slope of 2% and has a flow capacity of 370 m^3 s^{-1}. The SBT was operated five times from September 2016 to March 2018 at high input flows (Table 1 and Figure 2). Although small flushing was performed at base flows in August 2016, sediments were hardly supplied. The first and second sediment additions (September 20 and 23, 2016) and the fourth and fifth sediment additions (October 22 and 29, 2017) occurred within 4 and 8 days, respectively. The last two sediment additions showed higher maximum and cumulative flow discharges compared to other sediment additions.

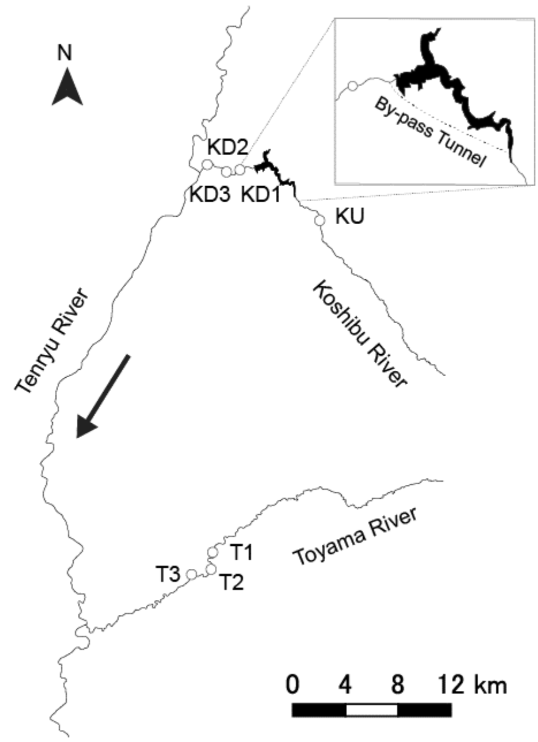

Figure 1. Study sites (open circles) in the Koshibu and Toyama Rivers.

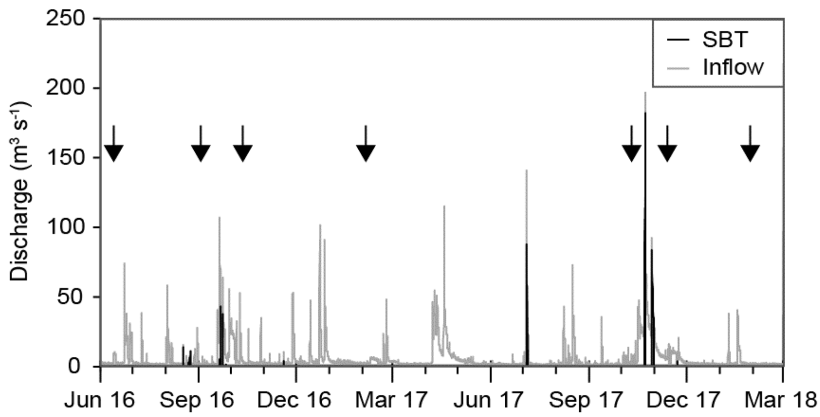

Figure 2. Flow discharge of inflow to the Koshibu reservoir and outflow of the sediment by-pass tunnel (SBT). Black arrows indicate sampling occasions.

We conducted observations seven times in seven study sites (Figures 1 and 2): 3 sites in the downstream reach of the Koshibu Dam (KD1, KD2, and KD3), 1 site in the upstream reach of the Koshibu Dam (KU), and three sites in the Toyama River (T1, T2. and T3). After the third SBT event (October 16, 2017), substrate measurements and insect samplings were not conducted in one site in the upstream reach of the Koshibu Dam and three sites in the Toyama River because of high flows. Also, three downstream sites were located below the outlet of the SBT at 472–509 m a.s.l. with a bed slope of 1.1%–14%, 1 upstream site was located at 675 m a.s.l. with a bed slope of 0.6%, and three sites in the Toyama River were located at 408–477 m a.s.l. with a bed slope of

0.6%–1.0%. In each site, three 0.5 × 0.5 m^2 quadrats were set in a riffle, and the percentages of substrates covered by sand (<2 mm), gravel (2–16 mm), and pebbles (16–64 mm) were measured. These fine and small particles were likely to be lacking downstream of the Koshibu Dam (Auel *et al*. 2017) and were expected to be supplied by SBT operations. In the same quadrat, we collected aquatic insects inhabiting the substrates, preserved them in 70% EtOH, and identified them to the species level as possible.

Table 1. Maximum discharge (max. *Q*), cumulative discharge (cum. *Q*), and duration of five SBT events from September 2016 to March 2016.

Date	**Max. *Q* (m^3 s^{-1})**	**Cum. *Q* (m^3)**	**Duration (h)**
20. Sep. 2016	43.3	564,732	16
23. Sep. 2016	37.7	780,804	8
4. Jul. 2017	87.8	738,000	4
22. Oct. 2017	182.1	4,221,864	10
29. Oct. 2017	83.7	6,937,092	49

2.2 Statistical analysis

To test the effects of observation dates and study reaches (downstream and upstream of the Koshibu Dam and the Toyama River) on substrate environments and aquatic insects, we used two-way repeated-measures (RM) analysis of variance (ANOVA) and post hoc Tukey's test for each substrate cover, taxon richness, and total abundances of aquatic insects. Taxon richness and total abundances were log(x+1)-transformed for normal distribution. In addition, we used nonmetric multidimensional scaling (NMDS) and permutational multivariate analysis of variance (PERMANOVA) with Bray–Curtis dissimilarity to test the effects of observation dates and study reaches on insect community structures. The statistical program R 3.4.3 (R Core Team 2017) was used for all analyses.

3 Results

3.1 Effects of sediment additions on substrate environments

The results showed that the sand cover increased with the lapse of time, was the highest after the fourth and fifth sediment additions (November 2017 and February 2018; Tukey's test: $p < 0.05$), and did not significantly differ among study reaches. On the other hand, the pebble cover did not differ among dates and was lower in the downstream reach of the Koshibu Dam compared to other reaches (Tukey's test: $p < 0.05$). The average sand covers in all study sites were 5.4% before SBT sediment additions, 8.5% after the second sediment addition, 6.7% after the third sediment addition, and 18.3% after the fifth sediment addition. An interaction between dates and study reaches was detected in the gravel cover (two-way RM ANOVA: $p < 0.05$); the cover was lower in the downstream reach compared to other reaches before SBT sediment additions (June and September 2016; Tukey's test: $p < 0.05$). The average gravel cover downstream of the Koshibu Dam was 3.8% before sediment additions, 14.7% after the second sediment addition, 17.2% after the third sediment addition, and 30.3% after the fifth sediment addition.

3.2 Effects of sediment additions on aquatic insects

Significant effects of dates, study reaches, and the interaction were detected in taxon richness and total abundance of aquatic insects (two-way RM ANOVA: $p < 0.05$). Both indices (taxon richness and total abundance) were higher in the downstream reach of the Koshibu Dam compared with other reaches and was lowest just after the fifth sediment addition (November 2017; Tukey's test: $p < 0.05$). There were no differences in both indices between the downstream reach and upstream reaches or the Toyama reach just after the second sediment addition (October 2016; Tukey's test: $p < 0.05$) and after the fifth sediment addition (November 2017 and February 2018; Tukey's test: $p < 0.05$).

There were significant effects of dates, study reaches, and the interaction on insect assemblages (PERMANOVA: $p < 0.05$). Insect assemblages in the downstream reach were different from that in other reaches before the fourth and fifth sediment additions (June 2016–October 2017), but changed substantially after the fifth SBT sediment addition and were close to that of other reaches (Figure 3).

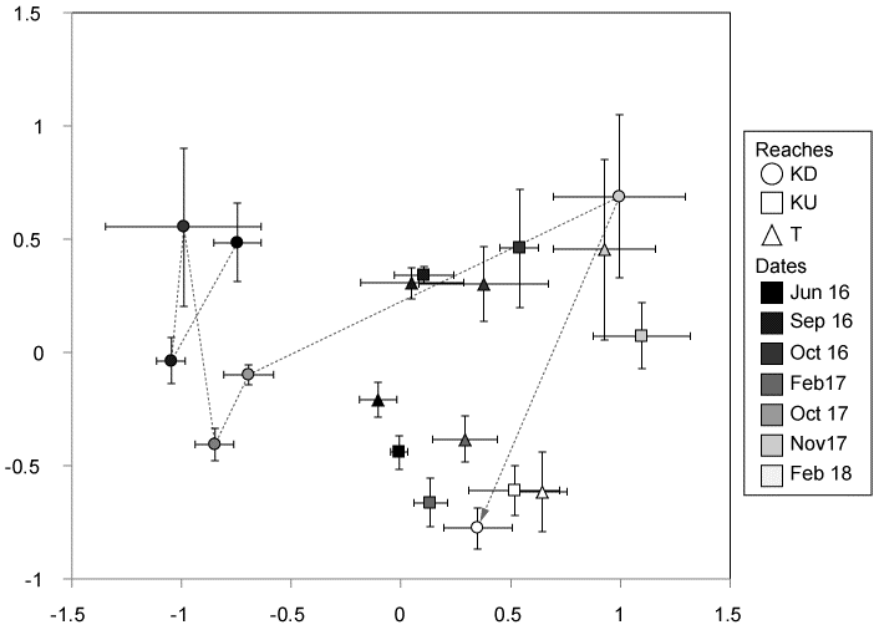

Figure 3. NMDS plots of aquatic insect assemblages based on Bray–Curtis dissimilarity. Symbols and colors indicate study reaches (KD, downstream reach of the Koshibu Dam; KU, upstream reach of the Koshibu Dam; T, Toyama River) and dates, respectively. The dashed line indicates the temporal change of insect assemblages in the downstream reach of the Koshibu Dam. NMDS, nonmetric multidimensional scaling.

4 Discussion

The sediment additions had significant effects on substrate environments and aquatic insect assemblages. The increase in the gravel cover after the first and second sediment additions and the lower pebble cover in the downstream reach compared to reference reaches throughout the study period indicated that sediments finer than gravel (<16 mm) could be transported to downstream sites through the SBT. The two weirs located at upstream and downstream of the inlet of SBT would trap large particles and decrease pebble content in the inflow to SBT.

The decrease in taxon richness and total abundance of aquatic insects just after each sediment addition in all study reaches showed the effects of disturbances by high flows on aquatic insects, which is a general pattern in rivers worldwide (McMullen and Lytle 2012). However, the first to third sediment additions did not have significant effects on community structures. The shift in insect community assembly after the fourth and fifth sediment additions would be because of the intensive disturbance caused by the highest flood magnitude (i.e. a high amount of sediments) during the study period. The high flow increased sand and gravel covers on substrates in all study reaches, which would diminish species intolerant to flooding and sedimentation, thereby homogenized community structures among study reaches. Robinson (2012) tested the effects of artificial floods on macroinvertebrates over a decade and suggested that macroinvertebrates change to become more disturbance-resistant assemblages, with a decrease in less-disturbance-resistant taxa and an increase in more-disturbance-resistant taxa, followed by colonization by new taxa. As shown by the lowest taxon richness and total abundances of aquatic insects after the fourth and fifth sediment additions, the insect assemblages in downstream reaches would be transitional states to disturbance-resistant insect assemblages with a decrease in flooding- and sedimentation-intolerant taxa.

Finally, temporal changes in benthic invertebrate assemblages depend on the operation characteristics (timing, frequency, magnitude, and duration) of SBTs (Martín *et al.* 2017). Therefore, we need to observe future changes in the insect assemblages in the downstream reach of Koshibu Dam in order to test whether they recover to reference states or return to pre-operation states.

Acknowledgement

We thank the Koshibu dam operation office for valuable information and cooperation, and members of Aquatic Restoration Research Center for helpful discussion and assistance in the field survey.

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