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Effect of sediment replenishment on downstream reaches of dams: case study of the Futase Dam

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Abstract

Beginning in 2003, a sediment replenishment project was started around the Futase dam, involving the annual removal of around 10,000 m^3 of sediment, for a cumulative total of approximately 100,000 m^3, from two sites above the dam, and sediment replenishment downstream; we monitored the effects on river ecosystems downstream of the dam. In particular, this paper discusses the effects of sediment replenishment on river bed evolution downstream of the dam based on past surveys and on changes in the number and composition of benthic fish (Japanese fluvial sculpin) and invertebrate species that are sensitive to changes in river bed material. A one-dimensional simulation of future bed evolution due to continued sediment replenishment is also presented.

Keywords: Futase Dam, sediment replenishment, downstream reaches of dam, *Cottus pollux*, benthos community

1 Introduction

The Futase Dam is an arch gravity dam constructed at the foot of the Arakawa River (Fig. 1) in 1961. It is a multipurpose dam designed for flood control, irrigation water, and power generation.

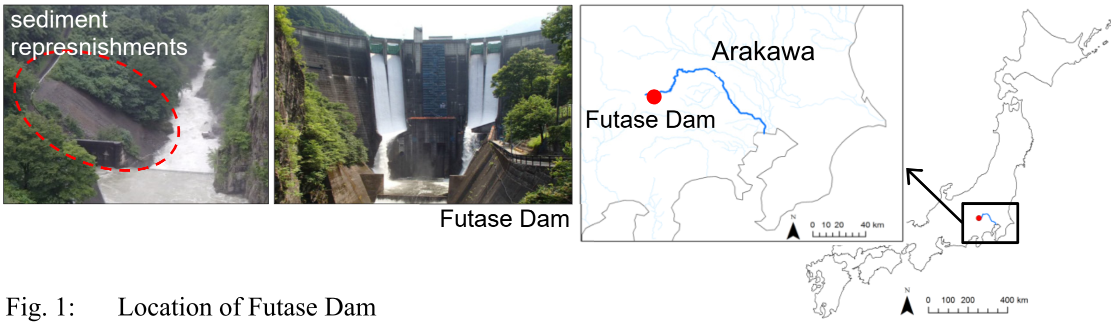

Fig. 1: Location of Futase Dam

A sediment replenishment and monitoring survey project was started because, in the roughly 50 years after the dam was completed, the sediment volume had reached about 90% of sediment storage capacity. Moreover, the riverbed elevation below the dam had dropped noticeably, exposing large boulders and rock masses along the riverbed.

Therefore, the project began in 2003, and has since replenished around a total of 100,000 m^3 of sediment, or about 10,000 m^3 annually, from above a check dam and one other site to the river below the Futase Dam.

In the monitoring surveys, the river bed material, river channel shape (cross sectional profile), landscape, periphyton, and benthic invertebrate and fish species were surveyed to investigate the effects of sediment replenishment. This paper examines the effect of sediment replenishment on riverbed material, benthic invertebrates, and the Japanese fluvial sculpin in the river downstream of the dam. Because the Japanese fluvial sculpin utilize pebbly environments as habitats and sandy environments under large boulders as spawning grounds, they are particularly sensitive to changes in bed material and, thus, are used as indicator species to evaluate the effect of sediment replenishment downstream of Futase Dam. The paper also discusses the area affected by sediment replenishment and changes in river bed material predicted by one-dimensional simulation of bed evolution.

2 Methods

2.1 Present status of monitoring survey

This section outlines the methods used to survey fish species, benthic invertebrates, and bed material from 2003 to 2016.

Fish species survey (monitoring of Japanese fluvial sculpin population)

The fish species surveys were conducted in rapids at four sites (Fig. 2) in the fall. The survey employed electrofishing to quantitatively evaluate the Japanese fluvial sculpin (*Cottus pollux*) population.

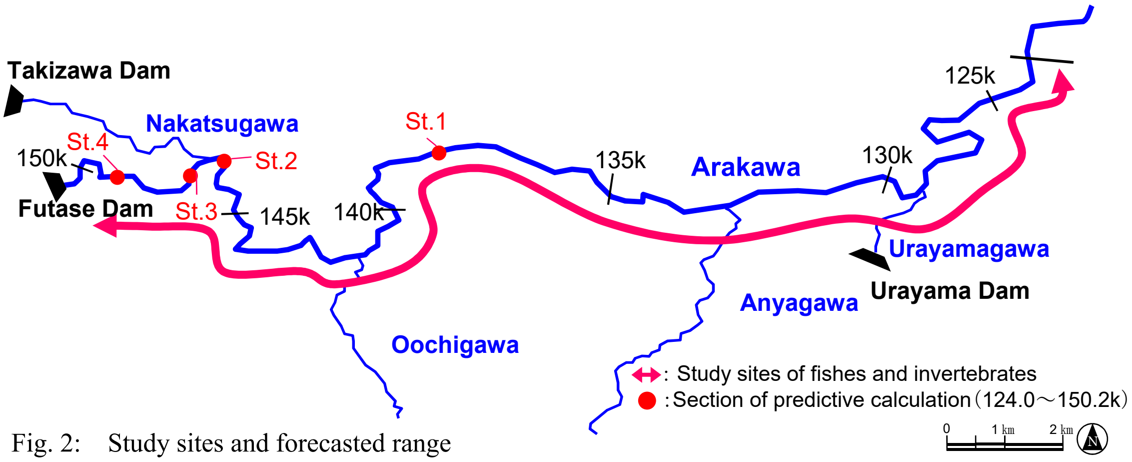

Fig. 2: Study sites and forecasted range

Benthic invertebrates

The benthic invertebrate surveys were conducted at four sites over two fall seasons (Fig. 2). The survey method involved randomly choosing three sites within a given rapid and collecting samples from each site using a 50 cm × 50 cm Surber sampler net. Qualitative samples were collected from riffles and shoals using a scoop net.

Bed material

Grain size distribution of the bed material was evaluated in the winter using the line grid method and grain size classification scheme from Yamamoto (2010).

2.2 Data analysis

To assess correlations among benthic invertebrate species compositions in different locations and sediment replenishment, non-metric multi-dimensional scaling (NMDS) (Manly 2005) was applied to the quantitative results on benthic invertebrates inhabiting rapids at three upstream sites (St. 1 was excluded). The data were categorized using non-hierarchical clusters (k-means method) (MacQueen 1967) based on the NMDS results. Also, environmental factors ($P < 0.05$) and species vectors ($P < 0.01$) found to be significantly correlated with group structure are shown on the NMDS plane. The Bray-Curtis index (Doi and Okamura 2011) was used as a measure of similarity.

Also, generalized linear mixed models (GLMM, response variable: normal distribution, link function: log) were constructed for the same sites with the population of Japanese fluvial sculpin as the outcome variable, environmental factors and sediment replenishment volume as explanatory variables, and year as the random intercept. The model was used to examine environmental factors related to the population of Japanese fluvial sculpin. Data analyses were performed using R (R Core Team 2016).

2.3 Simulation of bed evolution

A one-dimensional bed evolution simulation (mixed sand model) was used to predict changes in bed evolution for the 10-year period starting in 2015.

In this model, cross-sectional profiles were approximated using regular cross-sections and a modified Ashida-Michiue equation (Ashida *et al.* 1991) was used as the sediment transport model. The calculation for the water level assumed a one-dimensional non-uniform flow.

The same model was used to simulate the effects of sediment replenishment over a 10-year period from 2004 to 2014, at a range of sites (5 km) on the Arakawa River directly below Futase dam, which is downstream of the confluence with the Nakatsu River. It was determined that the model could simulate sediment deposition in terms of both bed evolution and grain size distribution with a certain degree of accuracy.

The 10-year period from 2016 to 2025 was set as the simulation period. The hydrological conditions applied were the actual conditions for the 10-year period from 2005 to 2014. The target zone of the simulation begins directly below the Futase dam at (150.2 km) and extends to (124.0 km) (Fig. 2).

With the conditions in 2015 as initial conditions, the model was used to predict and compare the impact of various levels of sediment replacement (0, 10,000, 20,000, and 30,000 m^3/yr) on bed evolution, average grain size, and cross-sectional transport volume after ten years. The water level was calculated as one-dimensional non-uniform flow and bed evolution was calculated using a one-dimensional bed evolution simulation (mixed sand model).

3 Results

3.1 Present status of sediment replenishment and dam discharge

The Futase dam management office has been conducting sediment replenishment tests since 2003. Sediment replenishment involves the collection of sediment from a check dam upstream of the reservoir or gravel from the Kaminakao site in October and November, when the water level drops sufficiently to permit excavation. The sediment is then transported by dump trucks and dumped into the Arakawa River directly below the Futase dam. When the river channel floods the following year, the dumped sediment is carried downriver.

Sediment dumping has been carried out continuously out from 2003 to 2016, except in 2011 and 2012. During this time, 3,900 to 17,200 m^3 of sediment per year (for a cumulative total of 110,000 m^3) was replenished downstream of the Futase dam (Fig. 3, Fig. 4).

The largest water discharges from the dam during the study period were approximately 337 m^3/s in 2007 followed by 281 m^3/s in 2011.

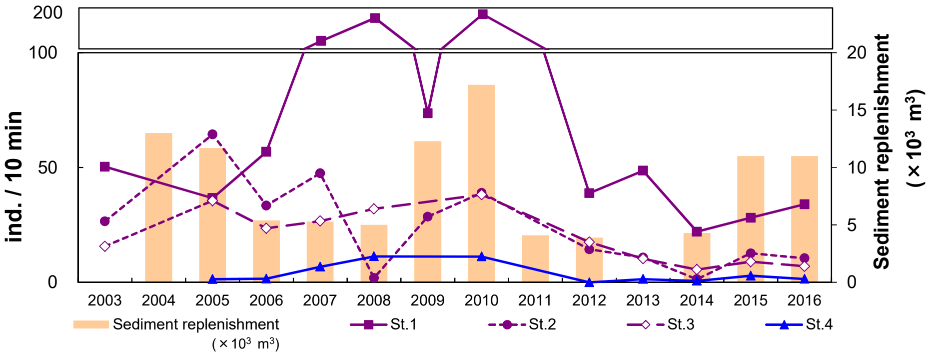

Fig. 3: Japanese fluvial sculpin population

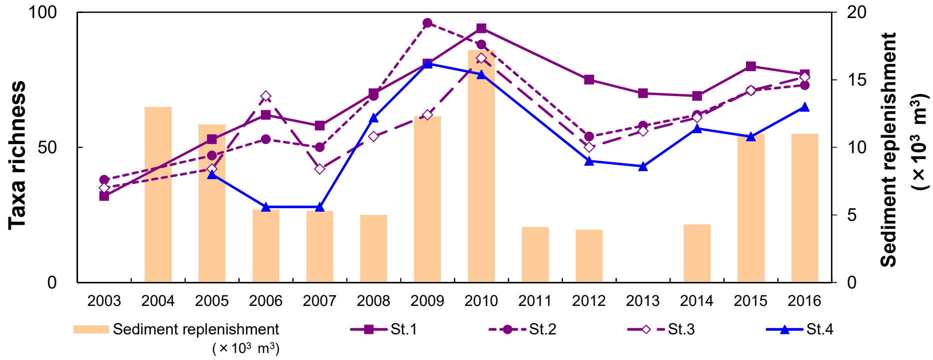

Fig. 4: Benthic invertebrate species richness

3.2 Monitoring survey results

Riverbed material

If we compare the longitudinal distribution for representative grain size of riverbed material (d_{60}) over time, bed material that continuously received sediment replenishment was found to become finer up until the high flow volume in 2010. Bed materials tended to become coarser from 2011 to 2013, when there was heavy flood, sediment replenishment was not conducted, and downstream flow volume decreased. After 2013, the grain size alternated between fine and coarse.

Japanese fluvial sculpin

The Japanese fluvial sculpin population tended to increase over the period up to 2010 in which continuous sediment replenishment was carried out (Fig. 3). However, the population decreased between 2010 and 2012 when heavy flooding occurred in 2011 and no sediment replenishment took place. However, the population rebounded slightly in 2015, after the resumption of sediment replenishment.

Benthic invertebrates

The number of benthic invertebrate species tended to increase over the period up to 2010 in which continuous sediment replenishment was carried out, but decreased in 2012 and 2013 after the heavy flooding in 2011 (Fig. 4). However, the numbers of started to increase again in 2014 and 2015, after the resumption of sediment replenishment.

3.3 Analysis results

Correlation between changes in benthic invertebrate species composition and their environment

Benthic invertebrate species composition is correlated with the volume of sediment replenishment in the previous year, distance from estuary, and grain size of the dominant bed material ($P < 0.05$) (Fig. 5).

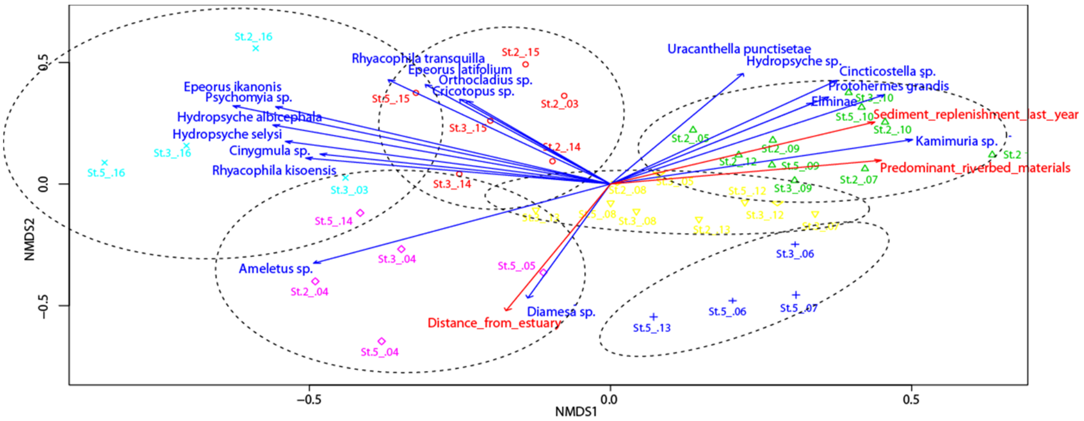

Fig. 5: NMDS. The number after the St.'s number represents the year of investigation.

A significant correlation in the invertebrate group and environment could also be seen in *Epeorus ikanonis* and *Hydropsyche albicephala*, which dwell fixed to the sides of rocks; *Ameletus* sp. and *Diamesa* sp., which inhabit cold water upstream; and *Uracanthella punctisetae* and *Protohermes grandis*, which live along the rocky bottoms of rivers ($P < 0.01$).

Correlation between Japanese fluvial sculpin populations and sediment replenishment

The 'best model with the lowest AIC (Akaike's Information Criterion)' of GLMM included distance from estuary, sediment replenishment volume, last year of sediment replenishment, maximum discharge, and population of Japanese fluvial sculpin in the previous year (Table 1).

The 'best fitting' model suggests that the largest populations of Japanese fluvial sculpin within the downstream survey sites occur in sites that receive high volumes of sediment replenishment and discharges in the same year and in the year previous and where the population of Japanese fluvial sculpin was also large in the previous year.

Also, comparison of normalized coefficients reveals that sediment replenishment volume (0.40), distance from estuary (–0.36) and maximum discharge (0.27) contribute substantially to the Japanese fluvial sculpin populations.

Table 1: Normalized GLMM estimates

	Estimate	Pr(>|z|)	
Intercept	2.50	< 2e–16	***
Distance from estuary	–0.36	6E–07	***
Sediment replenishment	0.40	0.021	*
last year of Sediment replenishment	0.25	0.136	
max of discharge	0.27	0.108	
last year of individuals of *Cottus gobio L.*	0.18	0.005	**

*, **, and *** indicate significance at $P < 0.05$, 0.01, and 0.001, respectively.

3.4 Bed evolution simulation results

If we look at the mean cross-sectional sediment transport volume based on the one-dimensional bed evolution simulation, we find that the sediment transport volume increases to approximately 133 km in all cases where sediment replenishment is carried out compared to the case in which no sediment replenishment occurs (Fig. 6). This trend increase does not change even if the replenishment volume is increased. Accordingly, we believe the range of influence of replenishments below the Futase dam to be close to 133 km from the estuary.

On the basis of the above results predicting the range of influence of sediment replenishment from the sediment transport volume, it is further predicted that the mean grain size (d_{50}) of the riverbed material downstream of the dam will decrease with distance from the dam.

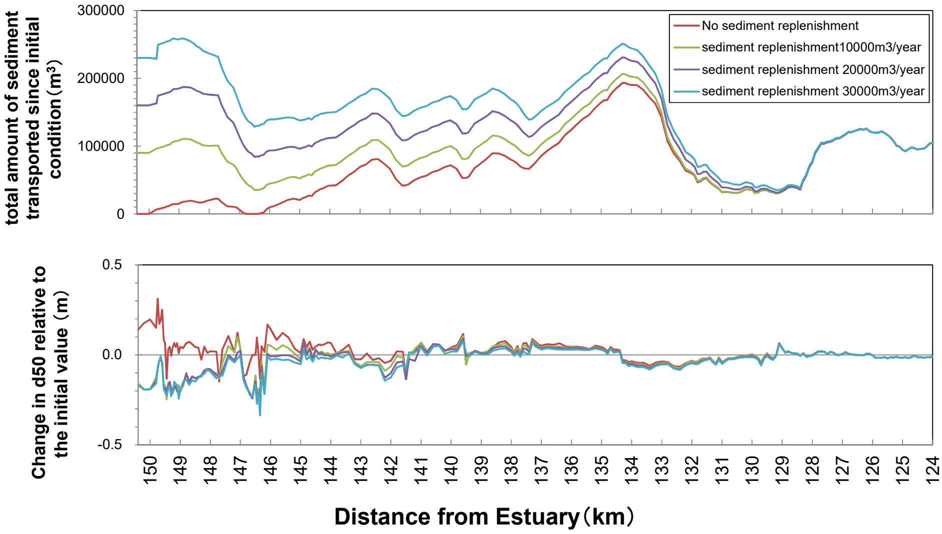

Fig. 6: Simulation results of the average grain size (d_{50}), sediment transport volume and riverbed material due to changes in sediment replenishment volumes

4 Discussion

The monitoring surveys reveal that riverbed material became finer and that populations of Japanese fluvial sculpin and numbers of benthic invertebrate species increased as a result of continuous sediment replenishment. However, the populations of the Japanese fluvial sculpin and benthic invertebrates appeared to decrease after severe flooding in 2011 prevented sediment replenishment from being carried out. Even though the scale of flooding in 2007 was greater than that in 2011, flooding in 2007 was not linked to coarsening of grains in riverbed material nor to decrease in population of the Japanese fluvial sculpin and numbers of benthic invertebrate species. The fact that sediment replenishment was conducted at the time of the floods in 2007, suggests that the different results observed in the two years may be due to the presence or absence of sediment replenishment.

Also, our analyses also indicate that benthic invertebrate species composition and the population of the Japanese fluvial sculpin was influenced by sediment replenishment not only in the current year but, also, in the previous year. This suggests that continuous sediment replenishment is linked to environmental improvement. Moreover, the one-dimensional bed evolution simulation suggests that continuous sediment replenishment will mitigate further coarsening of riverbed material.

Finally, we plan to continue carrying out sediment replenishment and surveys to improve dam functionality and the quality of habitats downstream of the dam.

5 Conclusion

We believe that conducting continuous sediment replenishment has reduced river bed grain size in the reaches downstream of the Futase Dam. However, when sediment replenishment was halted due to severe flooding, the bed material coarsened, resulting in lower numbers of benthic invertebrate species and populations of Japanese fluvial sculpin.

Increases in the population of Japanese fluvial sculpin are affected by the volume of sediment replenishment not only in the current year but, also, in the previous year, while changes in benthic invertebrate species composition are affected by the volume of sediment replenishment in the previous year. Furthermore, according to the bed evolution simulation, continuous sediment replenishment contributes to a healthier river habitat by reversing river coarsening.

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