Roles of riffle and pool structure for increasing retention of lentic plankton in dam tailwater reaches

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Abstract: As dam tailwater ecosystems depend on lentic plankton supplied from dam outflows as a major trophic source, the retention efficiency of lentic plankton, an ability of the channel to reduce the drifting plankton, is critical for recovering a normal state of trophic structure in the stream ecosystem. The present study aims to estimate the functions of riffle and pool structure in transport and retention of the lentic plankton in the field, and to find configuration of riffle and pool geomorphs increasing the retention efficiency. Two dam tailwater reaches with different riffle and pool structures were selected and longitudinal changes in relative contribution of lentic plankton were estimated by means of the concentration-weighted stable isotope mixing model using dual $\delta^{13}C$-$\delta^{15}N$. Relative contribution of lentic plankton was generally reduced at riffles and that of terrestrial plant was decreased in pools. Amount of reduction in the contribution of lentic plankton was in proportional to the length of riffle, but the retention efficiency was higher in short riffles than in long riffles. The results indicate that riffle and pool structure and their configuration have roles in particulate organic matter dynamics in stream ecosystem according to its source origins. Some recommendations of geomorphological management for restoration of dam tailwater reaches were discussed.

Keywords: particulate organic matter (POM), retention efficiency, stable isotope, concentration weighted model, riffle-pool, sediment management

Introduction

Dam tailwater ecosystems below dam reservoirs are continuously disturbed by input of large amount of plankton from dam outflows (Richardson and Mackay 1991; Akopian et al., 1999; Doi et al., 2008), and the nearest ecosystem from dam outlets is supposed to be highly reliant on the plankton as energy source (Tanida and Takemon 1999; Hatano et al., 2005). The retention efficiency of lentic plankton, an ability of the channel to reduce the drifting plankton, is critical for recovering a normal state of trophic structure in the stream ecosystem. However, the factors affecting or controlling the retention efficiency in dam tailwater ecosystems have not been understood enough despite their applicable importance for river managements.

In our previous study, we estimated the mean transport distance of lentic plankton as an indicator of the retention efficiency in dam and lake tailwater reaches and found that simplified channel geomorphology (i.e., riverbed degradation, channel incision, loss of riffle-pool structure and disappearance of bar structure) by dam impacts can lead to reduce the retention efficiency of lentic plankton (Ock and Takemon 2010). This finding indicates that the retention efficiency is highly related with the channel geomorphological conditions, and also suggests that geomorphological management is required for recovering or restoring the degraded tailwater ecosystem. In the present study, we focus on understanding retention processes of particulate organic matter (POM) and finding better configuration of geomorphic features for increasing the retention efficiency.

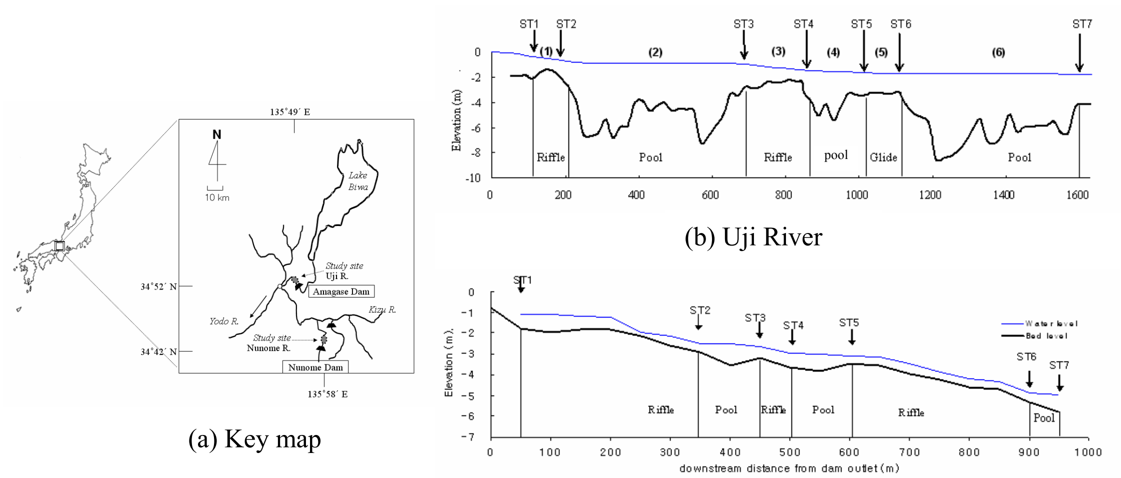
Riverine POM in ordinary natural rivers is trophically the mixture comprised of two sources; the allochthonous terrestrial inputs and the autochthonous instream production, and the fractional contribution of allochthonous to autochthonous provides a fundamental understanding on material cycling, food web structure, biodiversity (Wallace et al., 1982; Webster and Meyer 1997) and functional feeding groups (FFGs) of benthic invertebrates (Merritt and Cummins 1996; Takemon 2005). Estimation of the fractional contribution of the two sources has been developed by application of stable isotopic two-sources mixing model using single $\delta^{13}C$.

In dam tailwaters, the POM is supposed to be three sources mixture due to introduction of lentic plankton, which means ‘dam originated source’, together with allochthonous inputs and autochthonous production. Thus effect of lentic plankton on tailwater ecosystems can be quantified by its relative contribution to POM. The present study aims to estimate the relative contribution of lentic plankton in the tailwater POM by means of the three-sources mixing model using combined dual $\delta^{13}C$-$\delta^{15}N$, to investigate the longitudinal retention properties in riffle and pool structures, and finally to suggest recommendation for geomorphological management of riffle and pool structure in the tailwater ecosystem.

Materials and Methods

Site description

The filed study was conducted in two dam tailwater channels with different riffle and pool structures in the Yodo River system in central Japan; the first is Uji River reaches (34°52′ N, 135°49′ E) below the Amagase Dam (the arch dam with 73 m height and 26.3 million m^3 storage capacity) constructed in 1964. The other is Nunome River reaches (34°42′ N, 135°58′ E) below Nunome Dam (the concrete gravity dam with 72 m height and 17.3 million m^3 storage capacity) constructed in 1992. The flow discharges in both channels are stably regulated by dam operation (Fig.1a). The climate of the basin is typical monsoon and the basin is surrounded of mountain forest.



(a) Key map

(b) Uji River

(c) Nunome River

Fig.1 Map of study sites in the downstream reaches of the Uji River and Nunome River. Seven sites were established at the border of riffle and pool in each river

The study sites in the both rivers were selected at each border of riffle and pool within 2 km reaches of distance from dam outlets. The longitudinal profiles of the reaches and sampling sites in the field are shown in Fig.1. The Uji River is morphologically characterized by a combination of short riffles and long-deep pools (Fig.1b) probably due to riverbed degradation as a dam impact, whereas the Nunome River is characterized as long riffles and short-shallow pools (Fig.1c), as a result of peakcut dam operation and partially of artificial sediment replenishment works conducted for 6 years before the present study.

Field survey

Suspended POM samples were collected 7 sites for each river using a POM net sampler with 100㎛ in mesh size and 30cm in diameter of flame size in January to February 2009. Three replicates were collected at each site. Each suspended fine POM (S-FPOM) samples was filtered in situ using the sieve of 1.0 ㎜ mesh size to separate it from suspended coarse POM (S-CPOM).

Terrestrial plant leaves, epilithic algae and lentic phytoplankton were also collected as potential POM source origins. Special care was paid to when taking epilithic algae, because of difficulty for separating pure algae from biofilm including other several materials (Finlay 2001; Hamilton et al. 2004). The collected epilithic algae were washed several times in the river water and rinsed using distilled water in laboratory to remove impurities. The purity was confirmed using a microscope in laboratory. Samples for lentic plankton were taken in the nearest site from dam outlet and then the lentic plankton was extracted from other seston particles by means of repetitive settling process where rapidly sinking particles were repetitively excluded in a settling chamber. After that the extraction were also confirmed using a microscope. For preventing from decomposition before analysis, collected samples for stable isotope analysis were preserved in a ice box during transportation to the laboratory.

Stable isotope analyses and Concentration-weighted three-source mixing model

All isotopic samples were dried at 60℃ for 24 hours and then ground to homogenized bulk samples with a mortar and pestle in the laboratory. Stable isotope ratios of carbon and nitrogen were measured by a continuous-flow isotope ratio mass spectrometry system with an elemental analyzer composed of EA1108 (Fisons, Milan, Italy), ConfloII and Delta-S (Finnigan MAT, Bremen, Germany). The concentration of organic carbon and nitrogen were measured simultaneously. Stable isotope ratios are expressed by the standard δ notation as the following equation (Eq.1):

$$\delta^{13}C \text{ or } \delta^{15}N\ (‰) = (R_{sample}/R_{standard} - 1) \times 1000 \quad \text{(Eq.1)}$$

where R is $^{13}C/^{12}C$ for $\delta^{13}C$ or $^{15}N/^{14}N$ for $\delta^{15}N$. The standards were PeeDee Belemnite for $\delta^{13}C$ and atmospheric nitrogen for $\delta^{15}N$. DL-alanine was used as working standard and the analytical precision was ±0.2 ‰ for the $\delta^{13}C$ and the $\delta^{15}N$.

We assumed that POM drifting in dam tailwater ecosystem is a mixture comprised of three origins; lentic plankton supplied from dam reservoir, terrestrial plant products and instream epilithic algae. In order to estimate relative contribution of each source, the concentrated-weighted three sources mixing model using dual $\delta^{13}C$-$\delta^{15}N$ were applied since the elemental (C-N) concentrations is distantly different among the three end members (Phillips and Koch, 2002). The following equations (Eq.2,3,4) were modified from Phillips and Koch (2002) and Newsome et al. (2004).

$$f_{B,p} + f_{B,t} + f_{B,s} = 1 \qquad f_{C,p} + f_{C,t} + f_{C,s} = 1 \qquad f_{N,p} + f_{N,t} + f_{N,s} = 1 \quad \text{(Eq.2)}$$

$$f_{C,i} = \frac{f_{B,i} \times [C]_i}{\sum_i \left(f_{B,i} \times [C]_i\right)} \qquad f_{N,i} = \frac{f_{B,i} \times [N]_i}{\sum_i \left(f_{B,i} \times [N]_i\right)} \quad \text{(Eq.3)}$$

$$\delta^{13}C_{POM} = \sum_i \left(f_{C,i} \times \delta^{13}C_i\right) \qquad \delta^{15}N_{POM} = \sum_i \left(f_{N,i} \times \delta^{15}N_i\right) \quad \text{(Eq.4)}$$

where $f_{B,i}$, $f_{C,i}$ and $f_{N,i}$ represents a fractionation of biomass, carbon and nitrogen, respectively, contributed to the POM by source i ; herein, composed of lentic plankton (p), terrestrial plant (t) and instream algae (s). Values of $f_{C,i}$ and $f_{N,i}$ were given by the concentration-dependent mass balance equations. In addition, $[C]_i$ and $[N]_i$ represents the C and N concentration, which is a percentaged fraction of elemental mass to total mass in the source i, respectively. POM source combinations were considered to be feasible solutions if the predicted POM isotopic signatures $\delta^{13}C_{POM}$ and $\delta^{15}N_{POM}$ matched the observed values.

Retention efficiency of lentic plankton

For quantitative analysis of downstream reduction patterns of lentic plankton, the relative contribution of lentic plankton at the uppermost site was set to 100% and then relative ratios were calculated longitudinally. It is known that concentration of FPOM particles decreased exponentially downstream (Jones and Smock 1991; Cushing *et al.* 1993; Thomas *et al.* 2001), indicating that the fraction of lentic tracer plankters would follow a negative exponential function with channel distance as shown in Eq.5.

$$F(x) = exp(-kx) \qquad \text{(Eq.5)}$$

where $F(x)$ is the fraction remaining at downstream sites, x is downstream distance and k is the longitudinal loss rate. In the study, the k value was used as a retention coefficient (m^{-1}), which is related to the proportion of contribution diminishing per metre, for indicating 'retention efficiency of the river channel'. Larger values of k indicate higher rates of retention.

Results and Discussion

Longitudinal changes in the relative contribution of three sources along riffles and pools.

The contribution changes of S-FPOM along both channels showed spatial trends according to riffle and pool structures. In the Uji River, it was found that even within a distance of a few reaches's scale of 1.6 km, S-FPOM composition can be dynamically changed being strongly affected by the riffle and pool structure. During passing through both riffle zones, $f_{B,p}$ decreased about 9.7% points from 67.5 to 57.8% in St1-St2 and 11.9% points from 46.1 to 34.2% in St3-St4. In contrast, $f_{B,s}$ increased 10.1 and 14.1% in the riffles respectively. There were little variations in $f_{B,t}$ in the riffles and in the glide zone (St5-St6) made of partially exposed bedrock. In the pool zones, on the other hand, $f_{B,t}$ showed various patterns in the Pool1(St2-St3) and Pool2 (St6-St7). $f_{B,t}$ increased 12.6% points during passing the Pool1, whereas it decreased 7.0% points in the Pool2 (Fig.2a).

(a) Uji River

(b) Nunome River

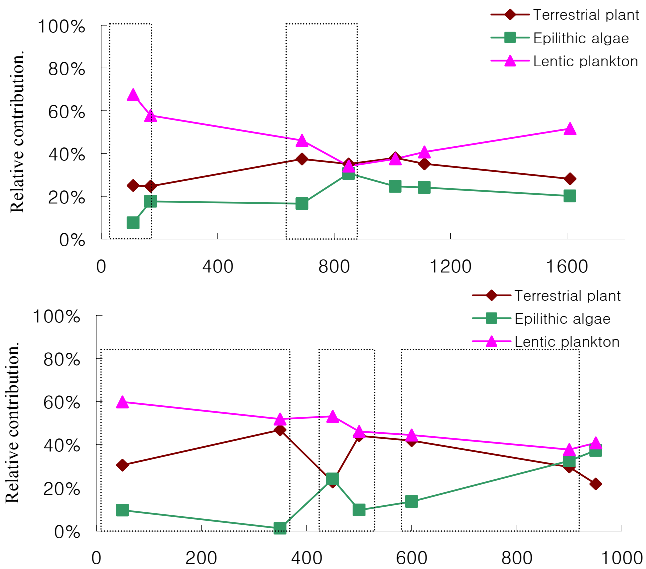


Fig.2 Downstream changes in relative contributions of the three sources to S-FPOM in the Uji River and Nunome River. Dotted-rectangulars represent the riffle zones.

In the Nunome River, the contributions of lentic plankton decreased in all riffles, where those of terrestrial plant increased in two of the three riffles probably due to supply from adjacent forest and riparian plant. However, the contributions of terrestrial plant decreased in all pools. But the contribution of instream algae showed an increase in the short pools but no trend in the long riffles. The relative contribution of lentic plankton decreased 6.8-8.0% points during passing riffles, whereas that of the terrestrial plant source decreased 2.3-24.1% points during passing pools (Fig.2b). Unlike the Uji R., however, any certain patterns in contribution of autochthonous epilithic algae along reaches was difficult to be found in association with riffle and pool. The contribution of epilithic algae, however, gradually increased along reaches irrespective of riffle and pool.

Reduced contribution of lentic plankton in the riffles may be attributed to both physical filtering by substrate and biological filtering by filter-feeding animals. Also reduced contribution of allochthonous terrestrial source during passing pools could be due to settling down by comparatively deep depth and low velocity. These findings can provide an interesting implication that riffles tend to remove lentic plankton, and pools can trap the terrestrial plant particles, consequently riffle-pool sequences in dam tailwater channels may play a role in spatially different contributions of S-FPOM according to its source origins.

Retention efficiency of lentic plankton depending on riffle-pool structure

Reduction patterns of contribution of lentic plankton were compared between the two rivers. Although both rivers revealed overall downstream decreasing pattern along channel, the retention coefficient (k) was approximately 2 times larger in Nunome R. (0.491) than in the Uji R. (0.243) as shown in Fig.3. The result means that the downstream channel of the Nunome R with relatively long riffles-short pools structure has higher retention efficiency than that in the Uji R. with short riffle-long pool structure, implying that configuration of geomorphic features is also important for retention efficiency of drifting plankton.

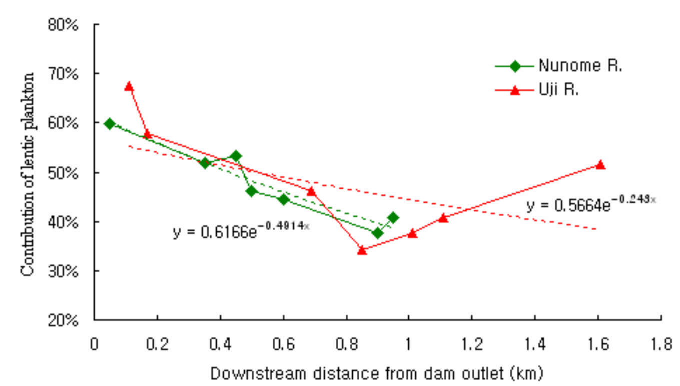


Fig.3 Reduction patterns in contribution of lentic plankton between the Nunome River and the Uji River. The retention coefficient (*k*) in the Nunome R. and Uji R. were calculated as 0.491 and 0.243 respectively.

Table 1 Retention coefficient and hydro-geomorphological parameters between the Uji River and the Nunome River

	Retention coefficient k (km^{-1})	Riffle Fraction F_R (%)	Depth Riffles h_R (m)	Depth Pools h_P (m)	h_P/h_R	Hydraulic radius R_h (m)	Mean velocity u (m/s)
Uji River	**0.243**	**15.5**	0.67	2.20	**3.30**	**1.87**±0.91	0.61±0.23
Nunome River	**0.491**	**68.4**	0.34	0.61	**1.76**	**0.34**±0.13	0.47±0.15

In the study, differences in the configuration of riffle-pool feature can be characterized by some morphological indices (Table 1); Riffle fraction in reaches (F_R), which represents the relative size of riffle to pool can be quantified by the ratio of the riffles distance to the total distance, characterize the longitudinal configuration to influence the filtering rate of riffle for drifting plankton. The F_R in the Nunome R. (68.4%) was much higher than that in the Uji R. (15.5%). In addition, the depth ratio of pool and riffle (h_p/h_R) characterize the vertical configuration to affect the settling rate of pool for terrestrial plant particles. The h_p/h_R in the Nunome R. (1.76) was much less than that in the Uji R. (3.30). Subsequently increasing F_R and reducing h_p/h_R can lead to decrease the values of hydraulic radius (R_h), which characterize the cross sectional difference. R_h of the Nunome R. was 0.34 m, which was 5.5 times lower than that of the Uji R. of 1.87 m.

Such configuration differences between the two rivers characterized by longitudinal, vertical and cross sectional indices may attribute the driving factors to the degree of river-bed degradation and sediment management in the two rivers. The Amagase Dam in the Uji River has stopped the bed-load transport over 40 years since its construction so that the downstream reaches has been degraded in bed to an extent of bedrock exposure and pool may deepen and lengthen. Ock and Takemon (2010) showed that more simplified changing channel cross-section represented by lower R_h can lead to increase the mean transport distance of lentic plankton indicating of the low retention efficiency. In contrast, the downstream reaches of the Nunome Dam has shallow-short pool and long riffle maybe due to diminishing flood flushing by peakcut dam operation and partially the sediment supplies artificially by sediment replenishment works. Higher retention efficiency in the Nunome R. can partially attribute to effect of the sediment replenishment and consequently it will be a necessity and importance for sediment management for downstream ecosystem.

Geomorphological management for increasing retention efficiency of lentic plankton

Recently, some mitigation measures through sediment management are increasingly planed or already implemented in dam tailwaters to restore continuity of sediment transport and budget between upstream to downstream of dams for restoration of geomorphology as well as ecology in dam tailwaters. For instance, a sediment replenishment, a sediment bypass tunnel and a flood mitigation dam without impoundment (Sumi, 2005). However, assessing the effects of the mitigation measures on downstream ecosystems were hardly implemented yet due to ambiguity of ecosystem response and lack of its quantification methods. Our results derived from the present study can provide conceptual criteria for evaluation the measures and also give practical suggestions in designs for increasing the retention efficiency.

(a) Riffles were found to have higher filtering capacity than other features. Therefore, in order to increase the filtering capacity of riffles, it is more efficient to increase the fraction of riffles (F_R) in channel (Table 1). In case the F_R is fixed or same condition, the length, numbers of riffles and their arrangement in channel should be considered. In both of the two rivers, the short riffles with high velocity appeared to be highest retention efficiency ($\Delta f_{B,p}$/m) than those in riffles with longer distance (Table 2). Thus several numbers of short riffles will be more efficient than one long riffle when the total channel length is limited. However, since the maximizing F_R may result in adverse effect on habitat for benthic communities due to loss of pools, the optimum F_R adjusted in the channel should be applied.

Table 2 Comparison of retention efficiency of plankton in the riffles between the Nunome River and the Uji River

	Reaches	Geo-morphologic features	Length (m)	Water surface velocity (m/s)	Water surface gradient (%)	Retention rate (%) $\Delta f_{B,p}$*	Retention efficiency (%/m) $\Delta f_{B,p}$/m**
Uji R.	St1-St2	Riffle	**68**	0.93	0.43	9.7	**0.14**
	St3-St4	Riffle	180	0.78	0.28	11.9	0.07
Nunome R.	St1-St2	Riffle	300	0.41	0.48	8.0	0.03
	St3-St4	Riffle	**50**	0.69	0.69	7.1	**0.14**
	St5-St6	Riffle	300	0.53	0.60	6.8	0.02

*$\Delta f_{B,p}$: retention rate means the reduction rate of $f_{B,p}$ in the riffle
**$\Delta f_{B,p}$/m : retention efficiency means the reduction rate per metre of $f_{B,p}$ in the riffle

(b) Pools were found to be a settling place of terrestrial plant due to relatively heavy specific weight compared with the lentic plankton. If the deposition of terrestrial plant particles is required, a depth and low velocity enough for settling should be sustained. In particular, if an appropriate structure of pools were restored or created, sustainable management is required not to progress the river bed degradation.

(c) The hydraulic radius (R_h) defined by the ratio of cross sectional area to wetted perimeter showed a positive correlation with the mean transport distance. It indicates that the retention efficiency for lentic plankton increases with decreasing R_h. Hereby in order to decrease the R_h, the cross sectional area should be either decreased by reducing flow discharge or lengthen a wetted perimeter by complicating river bed.

Conclusion

Retention is the process of which removes matters from transport within the reaches so that it can make available for reduction the suspended materials and for utilization by stream biota. In dam tailwater ecosystem, the retention of lentic plankton is important for recovering from trophically reservoir dependant state to a normal state of lotic ecosystem. The present study focused on elucidating the retention processes in relation to channel geomorphology, particularly in riffle and pool structure. Results showed that the relative contribution of lentic plankton was generally reduced within the riffle zone and that of terrestrial plant was decreased in the pool zone. Although the reduction rate in the contribution of lentic plankton was in proportional to the riffle fraction (F_R) in the channel, the retention efficiency (*k or* $\Delta f_{B,p}$/m) can be higher in several short riffles than in the long riffle when the total channel length is limited. The results indicate that riffle and pool structure has an important role for transport and retention of POM in downstream reaches below dam reservoir, and moreover riffle-pool structure contributes to increase spatial heterogeneity of POM according to its source origins. Nowadays channel geomorphology in downstream reaches of dam reservoirs is altered to more simplified such as the loss of riffle-pool structure and sand/gravel bar structure by dam impacts. In this sense, the present study provides some practical suggestions in sediment management in dam tailwater channels for sustaining and enhancing the ecosystem.

Acknowledgement

We are grateful to Dr. Yoshikazu Kato and Ms. Hiromi Uno for their assistance with field works. Stable isotopes analysis was conducted using Cooperative Research Facilities of Center for Ecological Research, Kyoto University. This work was partially supported by Grant-in-Aid for Scientific Research No.19360224 and MLIT grant for the construction technology development program.

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