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Roles of Riffle and Pool Structures in Particulate Organic Matter Dynamics in the Downstream Reaches of Dam Reservoirs

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Synopsis

The present study aims to elucidate the functions of riffle and pool structure in retention process of the drifting plankton supplied from dam outlets, and to find better configuration of the geomorphic features for increasing the retention efficiency. Two dam tailwater reaches with different riffle and pool structures were selected and relative contributions of three source origins to particulate organic matter (POM) were estimated by means of a stable isotope mixing model. The relative contribution of the plankton was reduced at riffles and that of terrestrial plant decreased in pools. In addition, the amount of reduction in the contribution of 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 morphological configuration have roles in POM 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, plankton retention, stable isotope, channel geomorphology

1. Introduction

River geomorphology and particulate organic matter (POM) are indispensable to aquatic organisms as matrix of habitat and primary energy resource, respectively. Despite dam contributions to water resources supplies, security from flooding and generation of electricity, after several decades of dam construction, modification of flow regimes and interrupting the continuity of sediment transport by dam reservoirs have brought negative downstream effects on channel geomorphology and the quality and quantity of POM. Herein, ecological deteriorations derived from the effects have been pointed out as a social issue and restoration measures to make river ecosystems healthy are increasingly required in the world.

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). Therefore, 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 2008; 2010). Ock *et al.* (2009) also tried to elucidate deposition processes in detail depending on the falling velocity of POM particles and bed morphology through a hydraulic experiment using pine pollens as surrogates, showing that the deposition density of each pollen was significantly different according to bed morphology such as a damming pool and an alternative bar channels. These 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.

2. Materials and Methods

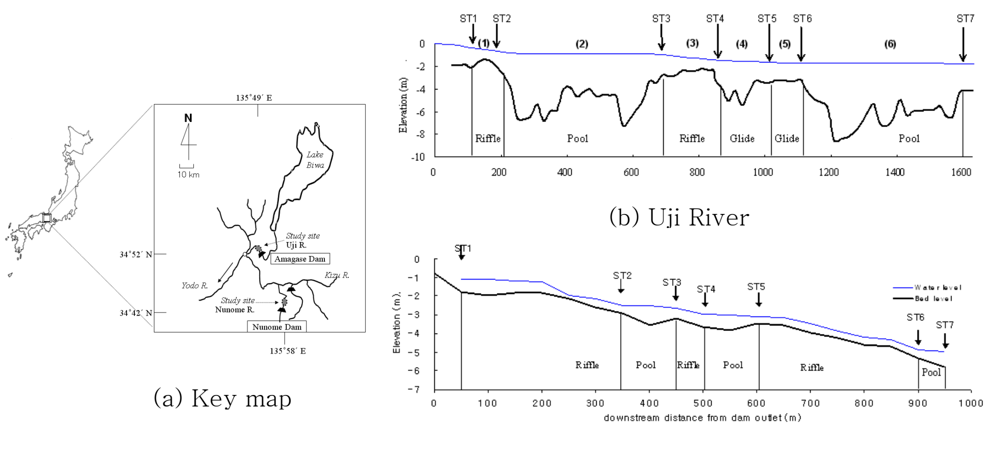
2.1 Site description

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 (Photo 1). 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 (Photo 2). 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.

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

Photo1 Amagase Dam in the Uji River and its downstream channel with long pool

Photo 2 Nunome Dam in the Nunome River and its downstream channel with long riffle



(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

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 as shown in Fig 2.

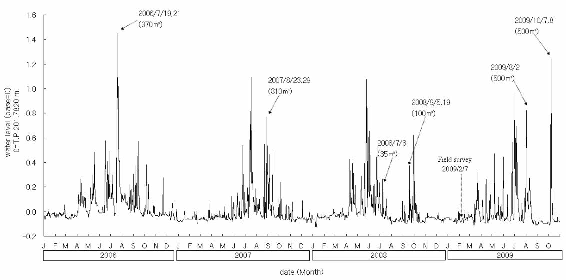


Fig.2 Temporal information about the date and volume of the replenished sediment since 2006 and filed survey in the Nunome River. The values below dates represent amount of supplied sediment in the day.

2.2 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.

2.3 Stable isotope analyses and a 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):

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

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).

$$\begin{aligned} f_{B,p} + f_{B,t} + f_{B,s} &= 1 \\ f_{C,p} + f_{C,t} + f_{C,s} &= 1 \\ f_{N,p} + f_{N,t} + f_{N,s} &= 1 \end{aligned} \quad (2)$$

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

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

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.

2.4 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.

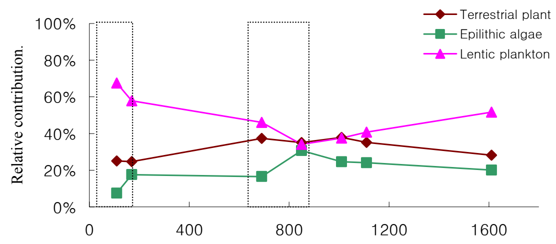
$$F(x) = exp(-kx) \quad (5)$$

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, 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.

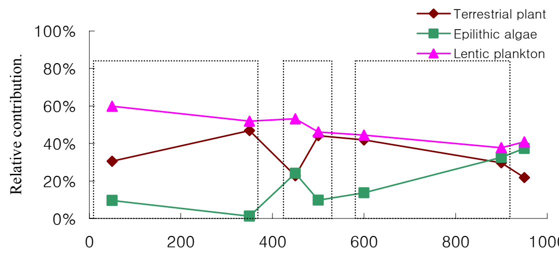
3. Results and Discussion

3.1 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.3a).



(a) Uji River



(b) Nunome River

Fig.3 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.3b). 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.

3.2 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.4. 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.

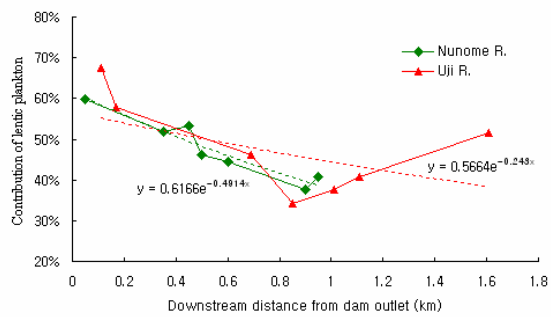


Fig.4 Reduction patterns in contribution of lentic plankton between the Uji River and the Nunome River. The retention coefficient (k) in Uji R. and Nunome R. were calculated as 0.243 and 0.491, respectively.

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.

3.3 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, the sediment replenishment, a sediment bypass tunnel and the 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

Table 1 Comparison of retention coefficient and hydromorphological parameters between the Uji River and 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

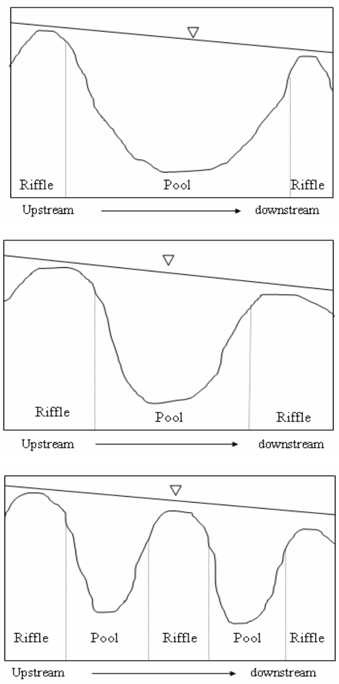
Table 2 Variation of retention rate and efficiency of plankton in the riffles between Uji River and Nunome River

	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

habitat for benthic communities due to loss of pools, the optimum F_R adjusted in the channel should be applied (Fig. 5).



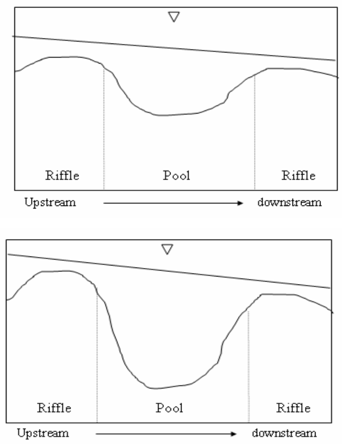
(a) F_R=(1+1)/10=0.2

(b) F_R=(3+3)/10=0.6

(c) F_R=(2+2+2)/10=0.6

Fig.5 Management of the fraction of riffles (F_R) for increasing retention efficiency. The higher F_R with long riffles and short pool (b) is efficient for retention of lentic plankton relative to short riffles and long pool (a). If the F_R is constant, several numbers of short riffles and short pools are efficient for retention for the plankton (c).

(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 (Fig. 6).



(a) low h_P/h_R

(b) high h_P/h_R

Fig.6 Management of the depth of pools for increasing retention efficiency. High h_P/h_R is efficient for retention for terrestrial plant source.

(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 (Fig. 7).

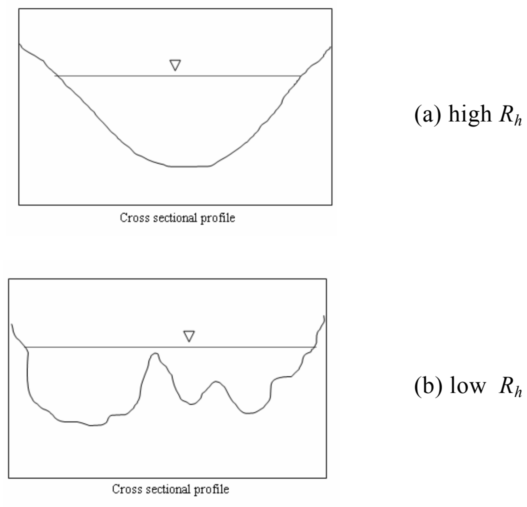


Fig.7 Management of hydraulic radius for increasing retention efficiency. If a maximum depth is constant, the low R_h with complex wetted perimeter is efficient for retention for lentic plankton

4. 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.

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貯水ダム下流河川の粒状有機物動態における瀬と淵の役割

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要　旨

貯水ダム下流域の劣化した河川生態系を修復する上で不可欠となる貯水池由来物質の定量化方法を検討して河床による粒状有機物の捕捉効率と河道地形条件との関係を研究した。宇治川の天ヶ瀬ダム下流域と土砂還元が実施されている布目川の布目ダム下流域を調査対象として，炭素−窒素の安定同位体混合モデルを用して，粒状有機物を構成する３種起源物の寄与率が瀬−淵による変化を検討した。瀬ではダム由来プランクトンの捕捉率と付着藻類の放出率が高く、淵では逆にプランクトンの捕捉率が低く陸上植物の捕捉率が高いことを明らかにするともに，瀬淵の長さ，深さ，径深，水面勾配，流速などの水理地形特性がその捕捉率と強い相関を持つことを見出した。本論文は河道の粒状有機物の起源推定の定量的な手法の確立に寄与するともに，貯水ダムの河川生態系への影響を軽減する際に，目標となる河床地形や土砂供給量設定するための基礎を提供する。

キーワード：粒状有機物，プランクトン捕捉率，安定同位体，　河床地形