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An Experimental Study on Deposition of Fine Particulate Organic Matter affected by River Channel Morphology

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Synopsis

We investigated the spatial distribution of FPOM (fine particulate organic matter) and its relation to geomorphic features such as damming pool and alternate bar structures by conducting a series of experiment on FPOM deposition using two types of pine pollen as analogue. Then we examined the relations of deposition density of both floating pollen(ρ_{dep}-F) and sinking pollen(ρ_{dep}-S) to lateral elevation difference (Δz) and surface flow velocity (u_s). In damming pool structure, ρ_{dep}-S was higher than ρ_{dep}-F and was negatively correlated with u_s. While, in alternate bar structure, ρ_{dep}-S showed no difference from ρ_{dep}-F and was negatively correlated with u_s and Δz. These results indicate FPOM in running water may be differently distributed by its source origin and geomorphic features through specific deposition process even in reach scale distance. Advantages of pine pollen as FPOM analogue for evaluating dam impact on river ecosystem were also discussed.

Keywords: channel morphology, FPOM, deposition density, pine pollen

1. Introduction

The understanding on spatial distribution of FPOM in streams has been increasingly required for habitat management and restoration, since FPOM dynamics has been considered to influence on heterotrophic food webs by providing energy resources and in conditioning microhabitats for benthic animals such as macro invertebrates and fish.

Spatial distribution of FPOM has been often considered in segment or watershed scale resulted from longitudinally changed environmental gradients (Vannote et al., 1980), flooding event (Junk et al., 1989) and riverine productivity (Thorp and Delong, 1994). Recent studies, however, have suggested reach scale variation of FPOM distribution is significantly occurred by geomorphologic features such as pool-riffle, bar, meandering structures (Tockner et al., 2002; Takemon et al., 2008), canopy cover (Doi et al., 2007) and bed material (Walters et al., 2007). From an applied aspect, hydraulic and geomorphological factors facilitating the trapping efficiency of the riverbed such as water quality purification in rivers will benefit to enhance ecosystem function.

We focused on FPOM dynamics in downriver below dam reservoir. This dam tailwater ecosystem has been considered to be distinctly different from natural river ecosystem. Tropically the supply of large amount of lentic plankton derived from reservoir alters the balance of FPOM after resulting in a thick accumulation of epilithon (Benthic POM) on the riverbed. Moreover changed geomorphologic features derived from riverbed degradation and bed material armoring by deduced sedimentation load is expected to significantly impact on transport and deposition processes of FPOM. Consequently, for habitat management and restoration in dam tailwater ecosystem, it is essential to evaluate and predict how FPOM density and source composition including lentic plankton are spatially distributed by river geomorphological characteristics in reach scale channel. In previous study, we estimated and compared the transport distance and deposition velocity by means of tracing lentic plankton in four different tailwater channels for accessing FPOM trapping efficiency, and showed increasing complexity of bed morphology such as hydraulic radius can minimize the transport distance, whereas bed degradation and armored bed materials may lead to increase the transport distance (Ock and Takemon, 2008). All of these recent studies indicated that deposition densities of suspended FPOM will be influenced by reach scale geomorphological features.

This present study aims to investigate how, where and how much would FPOM be deposited to riverbed by influence of channel geomorphology. A series of hydraulic experiments for this purpose were conducted using two types of pine pollen as FPOM analogue under various channel morphologic forms. The spatial distribution of deposition density in two types of pollen was analyzed in relation to bed elevation, surface flow velocity and lateral flow velocity.

2. Materials and Methods

2.1 Laboratory Experiment

A series of hydraulic experiments were carried out in a straight flume of 0.5m width, 0.5m depth and 21m length at the Ujigawa Open Laboratory, DPRI, Kyoto University. For this experiment, the channel slope was adjusted to be 1/200. The detailed experimental set-up was depicted in Fig.1.

Weir (or small dam) model made of 12cm height wooden pieces was placed below the movable bed zone, which had 8cm set-up thickness made of mixed silica sand with 1.56mm of mean diameter. Various bed configurations were produced by result of a set of the weir removal cases. In this study, ‘CASE Initial’ was an initial equilibrium bed configuration formed under a stable discharge. ‘CASE 1’ was the equilibrium bed configuration changed from ‘Case Initial’ by 3cm height weir removal (1/4 falling) under the same discharge condition. The detailed experimental conditions are given in Table 1.

When channel morphology reached an equilibrium condition where bed movement stabilized, two types of pine pollen that had been prepared within 1L bottles were uniformly released at uppermost site of the flume to make rapid mixing of the pollen particle with the channel flow.

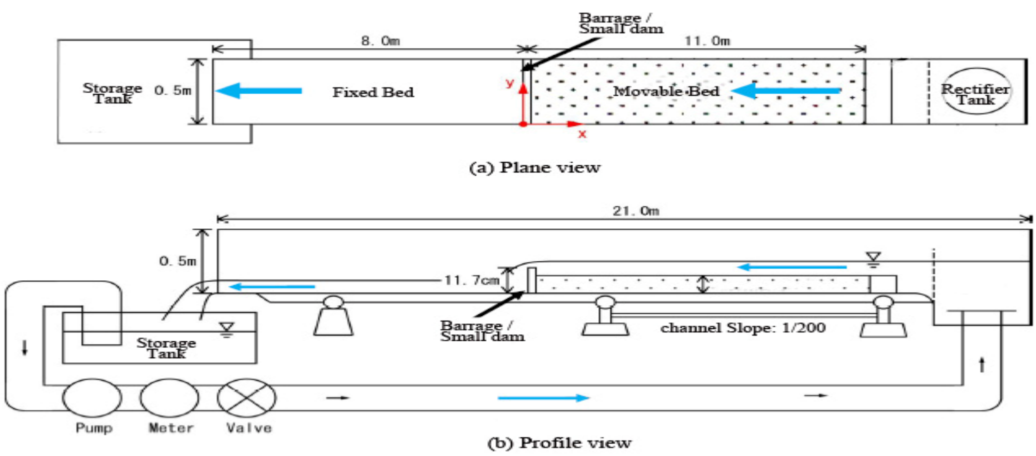


Fig.1 Experimental setup diagram (modified from Nambu 2009). Pollen was released at upper movable bed uniformly during a few minutes, all amount of transported pollen were trapped using net at mouth of flume in storage tank.

Discharge continuously supplied until pollen was enough to deposit on movable bed. All amount of transported pollen was trapped using 20um mesh net at mouth of flume not to be circulated again to upper channel by pump.

Table 1. Details of experimental conditions

	CASE Initial	CASE 1
Weir removal type	Initial	1/4 height
Hydraulic condition		
Discharge (Q)	$8.16\ cm^3/s$	
Normal depth(h)	4.18 cm	
Mean velocity (u)	39.0 cm/s	
Shear velocity (u_*)	4.53 cm/s	
Bed material condition		
Mean size (d_m)	0.155 cm	
Critical shear velocity(u_{*c})	4.32 cm/s	
Dimensionless critical bed shear stress (τ_{*c})	0.074	

2.2 Channel Morphology and hydraulics

As shown in Fig. 2, the bed morphology of 'CASE Initial' could be characterized by 'damming pool near weir and inflow channel structure'. Damming pool was formed up to approximately 4 m distance from weir model location (x=0), and in upstream reducing backwater effect, an asymmetrical inflow channel was produced. In particular, the highest front was outstandingly built in boundary of pool and inflow channel. The surface velocity was higher at inflow channel in upstream than damming pool, and reflected the backwater effect of weir.

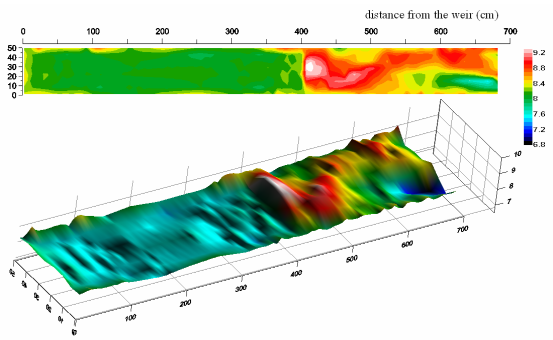
However, the pool was disappeared by weir removal in CASE 1 (Fig. 3), 'the alternate bar structure' was developed with a distinctive longitudinal thalweg, the deepest continuous line along the channel, in the whole reaches.

2.3 FPOM Analogue: Two types of pine pollen

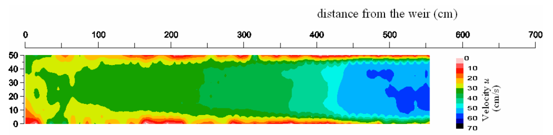
FPOM dynamics research in field experiment has been enhanced together with development of application of tracer particles such as lentic diatom, Lycopodium spores, leaves particle, radioactive ^{14}C labeled seston, fluorescently labeled yeast and corn pollen (Georgian et al., 2003).

For this hydraulic model experiment, we tried to apply pine pollen with 72.85um of mean grain size in water because of some merits as suspended FPOM analogue; it has two types in water, floating type buoyant in water and sinking type falling to bottom. In natural condition, most of pine pollen is buoyant in water due to air bladders (Fig. 4a). However, we could transformed a floating type of pine pollen into a sinking type with 3.14 m/h of

CASE Initial



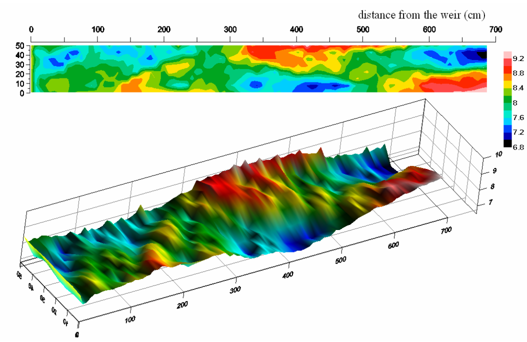
(a) Bed elevation and configuration



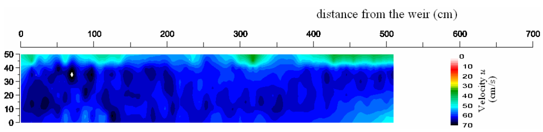
(b) Surface velocity distribution

Fig.2 Channel morphology and surface velocity in CASE Initial; damming pool zone near small dam was formed

CASE 1

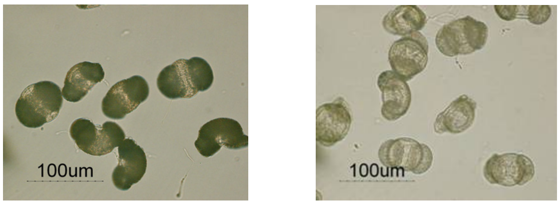


(a) Bed elevation and configuration



(b) Surface velocity distribution

Fig.3 Channel morphology and surface velocity in CASE 1; alternate bar structure was developed settling velocity without shape or size alteration by removal of inside air using chemical surfactant (Fig. 4b).

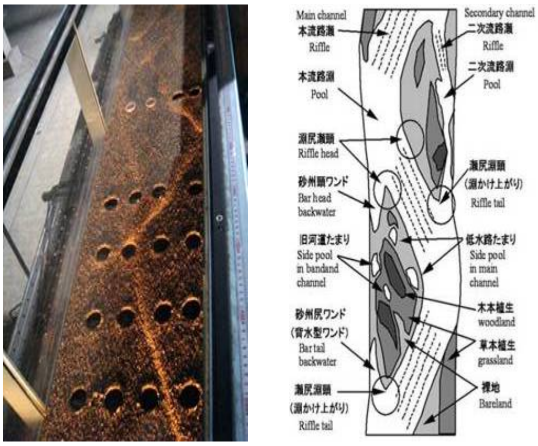


(a) Floating type (b) Sinking type

Fig. 4 Shape comparison of two types of pine pollen grains

2.4 Sample collection and identification

When most of water was drained sufficiently from bed, samples of deposited pollen particles were collected with bed material from about 1.5 cm depth bed surface using core sampler with 4.6cm of diameter at lattice section (Fig. 5a). Sites and number of samples were considered of microhabitat sandbar structure in river channel morphology (Fig. 5b).



(a) (b)

Fig. 5 Collecting Samples of deposited pollens using spot sampling in lattice section(a) in consideration of sandbar habitat structure(b) referred from Takemon (2007)

Collected samples were wet-sieved using 250um meshed sieve to separate the pollen particles from bed material, and were stored to 5ml bottles. After that, we identified both types of pine pollen particles in one drop on slide glass using stereomicroscope under x100 resolution, and counted total number of each type for three times per a sample. Pollen deposition density, ρ_{dep}, was calculated the mean pollen density of each sample using sampling area and dilution rate.

ρ_{dep}*-F or* ρ_{dep}*-S (grains/cm*^{2}*) = Number of pollen particles deposited in bed / Unit area*

where, ρ_{dep}-F and ρ_{dep}-S are Floating pollen density and Sinking pollen density deposited in bed, respectively. And the relative ρ_{dep} means the standardized value to the largest ρ_{dep} designated as 1.0 to compare between cases.

2.5 Measurements

Bed elevation, surface flow velocity (u_s), water surface profile were measured by means of Laser displacement meter, PIV (Particulate image velocimetry) method and point gauge respectively. The longitudinal x-axis, the lateral y-axis and vertical z-axis started from the beginning of the movable bed to upward, the left wall of the flume and the bottom of the flume respectively.

Lateral elevation difference, Δz, at a sampling site represents the elevation difference from mean elevation of the lateral line. A positive Δz means this elevation is higher than mean elevation, and negative Δz means lower. And the relative Δz means the standardized value to the largest Δz designated as 1.0 to compare between cases.

2.6 Statistical analysis

F-test and T-test were used to test for significant differences between two types of pollen and between two different morphological groups. A significant difference among geomorphological groups was examined by single factor analysis of variance. Pearson correlation was used to test relationship between ρ_{dep} and surface flow velocity or bed elevation. Statistics values used represent mean±standard deviation.

3. Results

3.1 Distribution of ρ_{dep} in CASE Initial; damming pool and inflow channel structure

The results of ρ_{dep} of all sampling sites were overlaid with the bed elevation contour and surface flow velocity contour as depicted in Fig 6. For comparison analysis, based on the bed configuration (refer to Fig. 2), the channel was divided into damming pool and inflow channel.

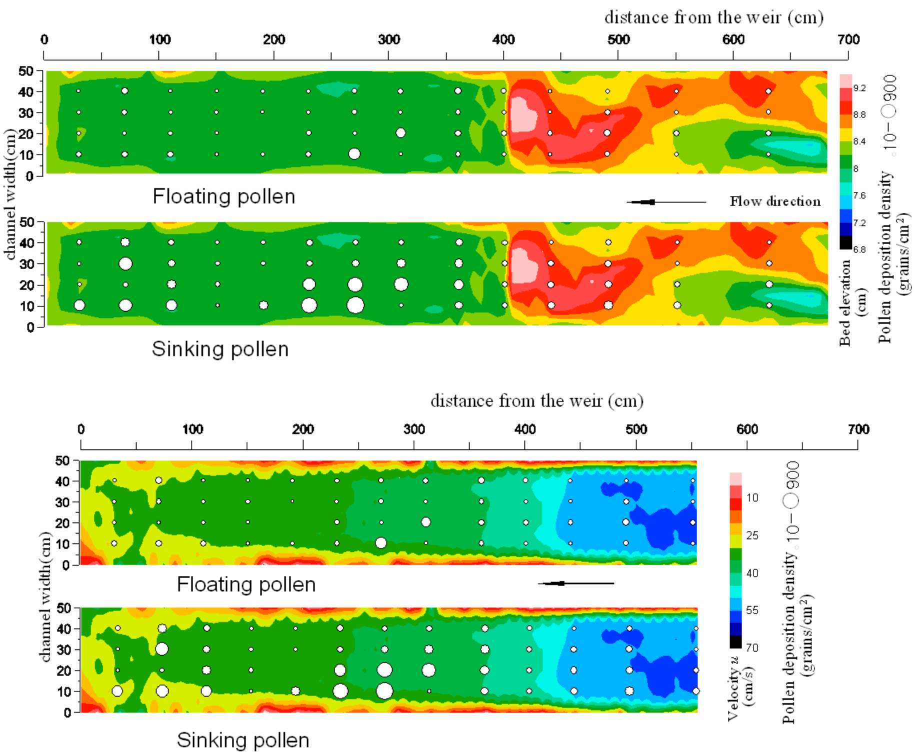
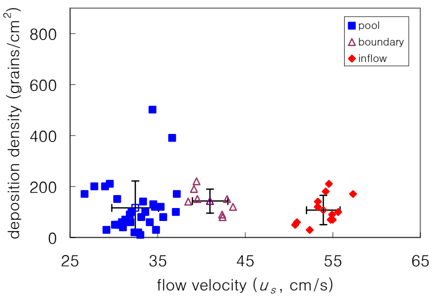
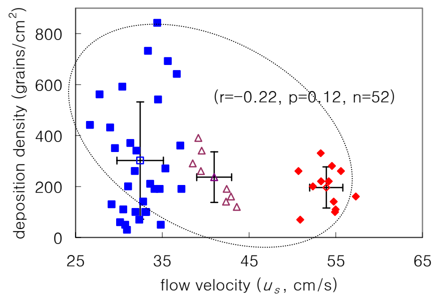


Fig. 6 Distribution of pollen density deposited on experimental channel bed shown with (a) bed elevation contour and (b) surface flow velocity contour for CASE Initial. The numbers of samples for (a) and (b) were n=55 on 14 lateral lines and n=51 on 13 lateral lines respectively.

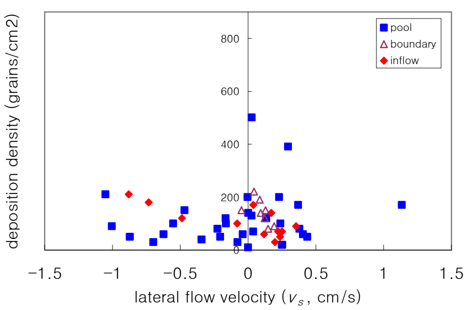


(a) floating pollen

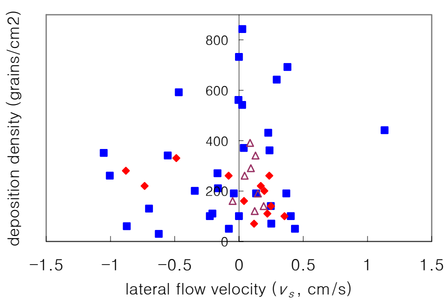


(b) sinking pollen

Fig. 7 Relationship between ρ_{dep} and u_s in CASE Initial



(a) floating pollen



(b) sinking pollen

Fig. 8 Relationship between ρ_{dep} and v_s in CASE Initial

Additionally, the boundary in 9th -10th lines was designated for separating distinctly from two groups. As shown in Fig 6b and Fig. 7, ρ_{dep} in three groups were distinctly separated from one another by surface flow velocity (u_s).

(1) Relation to surface flow velocity

In both damming pool and inflow channel, the sinking pollen showed higher deposition density than floating pollen ($p<0.001$, t-test), (Fig. 7). Also, ρ_{dep}-F showed no significant difference between three groups as well as no correlation with u_s (Fig. 7a), indicating that floating pollen is hard to be deposited to bed in regardless of bed configuration and flow velocity in damming pool. Whereas ρ_{dep}-S was significantly higher in damming pool(301.87±230.07) than in inflow channel (196.42±80.75) ($p<0.01$). Moreover ρ_{dep}-S showed weak negative correlation with u_s ($r=-0.22$, $p=0.12$), (Fig 7b).

(2) Relation to bed elevation

In order to examine the falling process in detail in relation to channel morphology, relationship between ρ_{dep} and the lateral elevation difference(Δz) was analyzed. As shown in Fig.8, distribution of ρ_{dep}-F was largely flat without consideration of Δz, whereas ρ_{dep}-S in damming pool was distributed in high values near $\Delta z=0$ range not in larger $|\Delta z|$.

3.2 Distribution of ρ_{dep} in CASE 1; Alternate bar structure

The results of ρ_{dep} of all sampling sites were overlaid with the bed elevation contour and surface flow velocity contour as depicted in Fig 9. According to channel morphology in CASE 1 characterized as alternate bar structure, all sampling sites were grouped into bar and thalweg.

(1) Relation to surface flow velocity

As shown in Fig 9a, ρ_{dep}-F and ρ_{dep}-S appeared a similar distribution pattern resulting in no significant difference between them in both bar and thalweg ($p>0.05$, t-test), (Fig 10).

ρ_{dep}-F was significantly higher in bar (186.48±153.61, n=27) than in thalweg (83.49±65.12, n=34), ($p<0.01$, t-test). Whereas

(a)

(b)

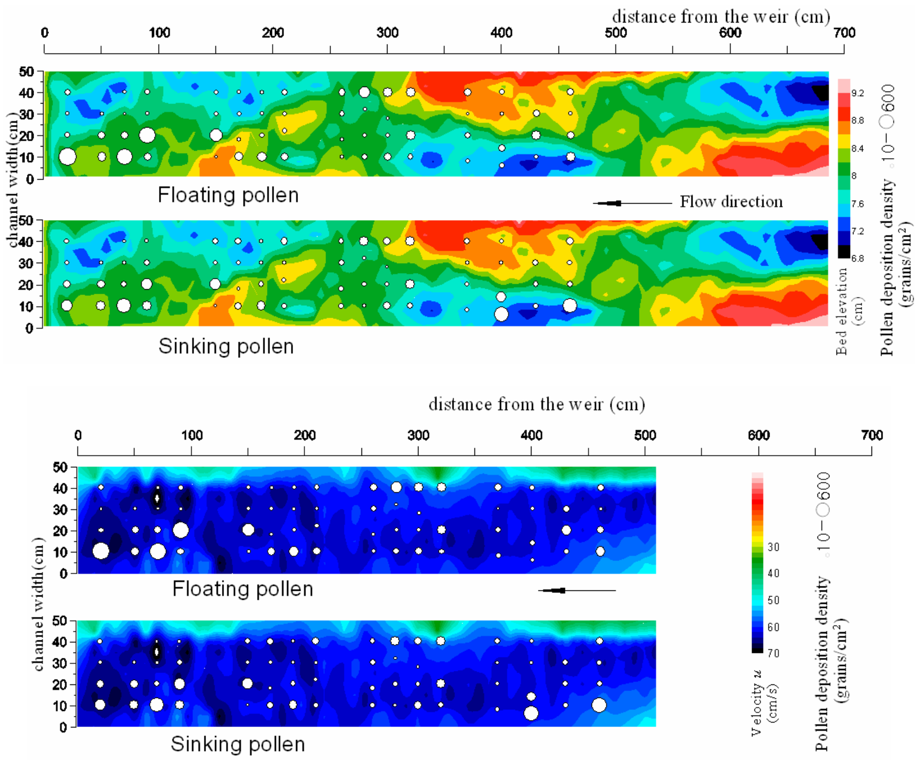
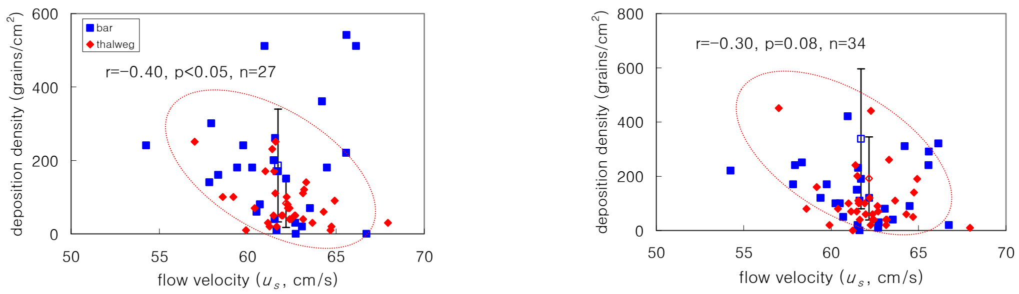
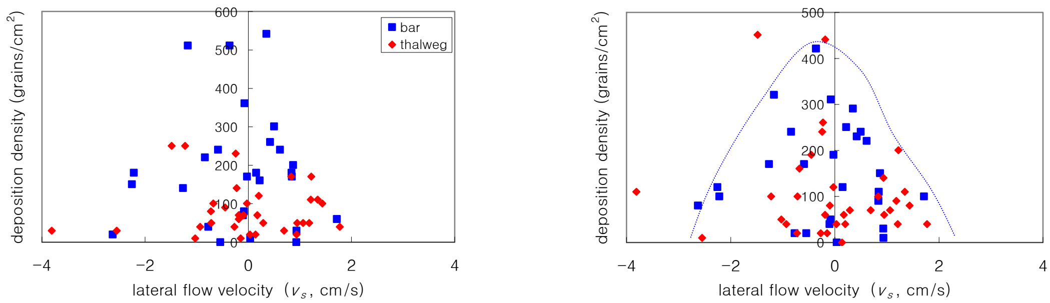


Fig. 9 Distribution of pollen density deposited on experimental channel bed shown with (a) bed elevation contour and (b) surface flow velocity contour for CASE 1. The numbers of samples for (a) and (b) were n=62 on 16 lateral lines.



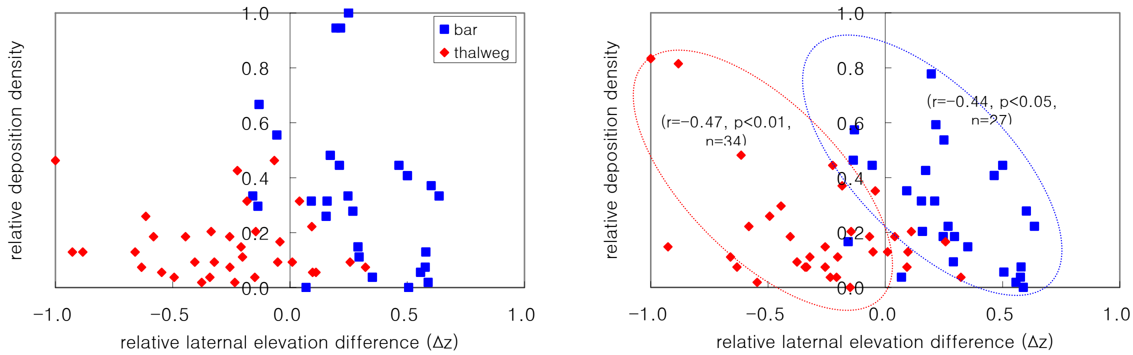
(a) floating pollen (b) sinking pollen

Fig. 10 Relationship between ρ_{dep} and u_s in CASE 1.



(a) floating pollen (b) sinking pollen

Fig. 11 Relationship between ρ_{dep} and v_s in CASE 1.



(a) floating pollen (b) sinking pollen

Fig. 12 Relationship between ρ_{dep} and Δz in CASE 1.

ρ_{dep}-*S* did not show the difference between bar (338.42±258.04) and thalweg (192.05±1536.07), (p>0.05, t-test) (Fig 10).

In bar, both of ρ_{dep}-*F* and ρ_{dep}-*S* did not show any correlation with u_s. Whereas in thalweg, ρ_{dep}-*F* appeared to increased as u_s decreased (r=-0.40, p<0.05) (Fig. 10a), and ρ_{dep}-*S* showed weak negative correlation with u_s (r=-0.30, p<0.1) (Fig. 10b). On the other hand, ρ_{dep}-*S* showed the highest value at downward direction near vs=0,but decreased as $|v_s|$ increased (Fig. 11b)

(2) Relation to bed elevation

To examine the filtering or falling process in alternate bar and thalweg structure, the relation of Δz to ρ_{dep} was tested. It was found that the largest two ρ_{dep}-*S* were resulted from the lowest thalweg sites, moreover ρ_{dep}-*S* in thalweg showed negative correlation with Δz (r=-0.47, p<0.01), and ρ_{dep}-*S* in bar was negatively correlated with Δz (r=-0.44, p<0.05) as shown in Fig. 12b. This means the sinking pollen deposition both in thalweg and bar was increasing with decreasing |Δz|.

4. Discussion

4.1 Pine pollen as FPOM analogue in dam tailwater ecosystem

In mountain streams, since most of POM entering streams is primarily in the form of allochthonous CPOM, leaves and woody debris from surrounding terrestrial forest, most FPOM transportable to downstream is also abundant of allochthonous type through physical breakdown and detritus decomposition processes relative to autochthonous type of algal production. Thus experimental researches on the FPOM transport in mountain streams has largely used single type tracer with a similar settling velocity such as leaves particle, radioactive 14C labeled seston, corn pollen (Georgian et al. 2003).

On the other hand in tailwater channel below dam reservoir, since large amount of lentic plankton flushed from the upstream reservoir contributes critically to important FPOM source as well as terrestrial leaves and instream epilithic algae, it is necessary to trace each source of FPOM separately for understanding FPOM dynamics in dam tailwater channel. However, few experimental studies on FPOM transport and deposition in dam tailwaters has been found in the literature partially due to lack of tracer or analogue. In this sense, our methodology to use pine pollen as FPOM analogue seems to be worthwhile to apply for experimental study on FPOM dynamics in dam tailwaters as follows; the floating pine pollen buoyant in still water can be represented as lentic plankton drifting mainly in surface water due to relatively light specific weight. While sinking pine pollen can be regarded as allochthonous FPOM comprised of leave and detritus particles because of its settling velocity of 3.14 m/h, which is between natural FPOM with 5.58 m/h (composition is 72% of vascular plant and 12% of inorganic particles), (Cushing et al., 1993) and corn pollen with 1.12 m/h (Miller and Georgian, 1992).

In addition, pine pollen is easy to identify using microscope due to air bladders like Mickey Mouse cap appearance. Also this method is relatively simple, inexpensive and safe to use without toxicity and hazard in health and water quality.

4.2 Influence of damming pool structure on FPOM deposition

FPOM deposition mechanism is generally composed of falling process by settling velocity, physical filtering by bed material and biological filtering by organisms. Results in CASE Initial characterized as damming pool and inflow channel showed sinking pollen was found to be acceleratedly deposited both in geomorphologically damming pool and hydraulically lower flow velocity and near downward direction. These strongly indicate damming pool is predominant of falling process of sinking pollen.

On the other hand, floating pollen showed significantly lower deposition density than that of sinking pollen in whole reaches and was not significantly related to surface and lateral flow velocities, probably due to drifting to downward overflowing the weir without mixing to riverbed.

Consequently, from these findings we may draw the important implication that damming pool structure can make sorted pattern of FPOM origin sources in dam tailwater, because most of lentic plankton will drift to downward without deposition like floating pollen, whereas terrestrial leaves and wood particles will deposit to riverbed by falling process like sinking pollen. This is highly corresponded to the empirical fact from Takemon et al.(2008) that benthic FPOM in backwater reach above check dam comprised of higher portion of allochthonous origin upto 70% than that of upper reaches.

4.3 Influence of alternate bar structure on FPOM deposition

From the results of CASE 1 we found that large amount of floating pollen could deposit to whole reaches particularly in bar. It is outstandingly different from result of CASE Initial. However, since the deposition process of floating pollen in bar was difficult to explain by means of surface flow velocity and lateral elevation difference due to no significant relations (Fig. 10a, Fig. 12a), physical filtering process by bottom flow velocity differentiating from surface flow probably due to turbulence and vertical mixing may be dominant in alternate bar structure.

On the other hand, sinking pollen was found to be deposited in thalweg under lower surface flow velocity (Fig 10b), and comparatively deeper depth condition (Fig 12b) and downward direction (Fig 11b), indicating falling process may be predominant of sinking pollen deposition in thalweg.

The sinking pollen deposition in bar can be explained as physical filtering process because of negative correlation with Δz (Fig 12b). Especially in bar structure, both floating pollen and sinking pollen showed higher deposition density near Δz=0 not to high elevation. This result indicates that physical filtering can be highly occurred in slope area of bar instead of the highest elevation.

Consequently, in alternate bar structure in dam tailwater channel, lentic plankton will be deposited in bar slope area rather than thalweg. And terrestrial leaves and wood particles will be largely deposited in pool by falling process and bar slope by physical filtering process.

In near future, we will apply such knowledge on reach scale variation in trophic sources affected dynamically by channel morphology for evaluating benthic habitat diversity including spatial distribution of functional feeding group in dam tailwater ecosystem.

Acknowledgements

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河川地形が微粒状有機物の堆積に及ぼす影響に関する実験的研究

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要　旨

河川地形が微粒状有機物の堆積に与える影響を調べるため, 浮遊型/沈降型の二タイプのマツ花粉をトレーサーとして, 堰上流にダム型淵（湛水域）が形成されている水路床と, 交互砂州の発達し河床近傍の流れが蛇行する水路床で水理実験を実施した。その結果, ダム型淵においては沈降型の堆積が卓越した。交互砂州においては, 砂州域に沈降型と浮遊型の両方の堆積密度が高い現象が見出された。また, 流心線沿いの河床には沈降型がより多く堆積することがわかった。それらの結果は比重の異なる微粒状有機物の河床堆積様式と対応していると考えられる。

キーワード：河川地形，微粒状有機物，堆積密度，マツ花粉