PARTICULATE ORGANIC MATTER DYNAMICS IN THE DOWNSTREAM OF DAM RESERVOIRS : ROLES OF CHANNEL GEOMORPHOLOGY AND RESPONSES OF BENTHOS COMMUNITIES

Giyoung OCK

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ABSTRACT

River geomorphology and particulate organic matter (POM) are indispensable to aquatic organisms as matrix of habitat and primary energy resource, respectively. After decades of dam construction, however, 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 then restoration measures to make river ecosystems healthy are increasingly required in the world.

As dam tailwater ecosystems are supposed to rely highly on lentic plankton continuously supplied from dam outflows, the retention efficiency which is the ability of the channel able to reduce the plankton is critical for recovering the ecosystem health in dam tailwater channels. The purposes of this thesis are to estimate longitudinal changes in the contribution balance of the three sources of dam tailwater POM (i.e. lentic plankton, terrestrial plant and epilithic algae) separately in relation to channel geomorphology and ecological responses, and to propose restoration measures of dam tailwater ecosystems by means of geomorphological managements. With these in mind, the several objectives were set to guide the study, including (1) to estimate the lentic plankton impacts on POM source composition using tracers or analogues through testing suitability of some quantitative methods, (2) to investigate roles of geomorphologic features in transport and deposition of POM according to its source origins, (3) to evaluate effects of POM dynamics on benthic communities and (4) to suggest geomorphological conditions for increasing the retention efficiency. For the objectives, five main researches were performed.

First, the mean transport distance and the field deposition velocity of the lentic plankton were estimated in relation to channel morphology in order to evaluate retention efficiency of morphologically different cannels. The results showed the degraded and simplified channel morphology resulted from dam impacts can lead to reduce retention efficiency by lengthening the downstream distance influenced by lentic plankton.

Second, the lentic plankton impacts on tailwater POM source composition were quantitatively investigated. Methodologically, the microscopic examination (ME) and two three-sources mixing models using stable isotopes such as the standard liner mixing model (SLM) and the concentration weighted mixing model (CWM), were compared to test the suitability for quantification. The Results showed that both ME and SLM overestimated the concentration of lentic plankton, and underestimated that of terrestrial plant source relative to CWM. As the results by CWM, the lentic plankton contributed highly to the composition of suspended fine POM relative to other POMs.

Third, the role of riffle-pool features in POM dynamics and its ecological response were investigated in the Uji River below the Amagase Dam. The results clearly showed that riffles had high retention efficiency for the lentic plankton by physical filtering and biological filtering processes, while pools showed a relatively high retention efficiency for the terrestrial plant by falling process. In addition, it was found that such source specific changing patterns of dam tailwater POM composition highly influence the spatial distribution of benthic communities. In particular, the spatial distribution of filter-feeding mussels was strongly correlated to the retention efficiency for the lentic plankton in riffles.

Fourth, effects of sediment replenishment on POM dynamics were investigated in the downstream of the Nunome River below the Nunome Dam, where a total of 2,585 m^3 of sediment were replenished downstream for 6 years. Interestingly, the tendencies both of lentic plankton in riffles and of terrestrial plankton in pools were similar to those of the Uji R. However, the retention efficiency was higher and the relative abundances of the net-spinners and filterers were less in the Nunome R. than in the Uji R., indicating positive effects of sediment replenishment.

Finally, the experimental study allowed the findings derived from field studies to be supported in detail or complemented. In the experiment, floating and sinking types of pine pollen were applied as analogues of lentic plankton and terrestrial plant respectively. By analysis of deposition density of two pine pollens in the damming pool channel and in the alternate bars channel, the influences of riffles, pools and bars on retention of the lentic plankton and the terrestrial plant particles could be explained.

Some recommendations for increasing retention efficiency of river channels are presented based on the findings from the present study. They are necessary for the sediment management through geomorphological restoration in sustaining and enhancing the ecological integrity of rivers.

Keywords; POM dynamics, dam impacts, retention efficiency, lentic plankton, stable isotope mixing model, riffle and pool, pine pollen, freshwater golden mussel, sediment replenishment, sediment management, Uji River, Nunome River

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CHAPTER 1

General Introduction

1.1 PROBLEM IDENTIFICATION: Downstream effects of dam reservoirs

River geomorphology and particulate organic matter (POM) are indispensable to aquatic organisms as matrix of habitat and primary energy resource, respectively. Dams have served human society with many benefits by providing reliable water resources supplies, security from flooding and generation of electricity copping with accelerating population growth, expansion of urban area and continuing spread of irrigation agriculture. Despite contributions of dams, however, modification of flow regimes and discontinuity of sediment transport downstream since dam reservoirs were constructed have brought a lot of negative downstream effects on channel geomorphology and quality and quantity of POM.

Various geomorphological effects resulted from the discontinuity of sediment transport occur along the sediment routing system as shown in Fig.1-1. Sedimentation in the reservoirs causes the back sand accumulation in the upstream leading to decrease of storage capacity. In the downstream of the dams, the reduced sediment transport produces the riverbed degradation, bedmaterial coarsening, channel incision, channel fixation, loss of riffles and pools, loss of bars and vegetation invasion to channels. In addition, coastal erosion and shoreline retreat are problematic issues derived from reduced volume of transported sediment to the coastal areas (Kondolf 1997; Tsujimoto 1999; Graf 2006). The effects of dam reservoirs on POM are represented as the continuous supplies of large amount of lentic plankton produced in dam reservoirs and the increases of fine sized organic matters by results of settling of most coarse ones in the reservoirs (Ward and Stanford 1983; Walks and Cyr 2004). Consequently, ecological deteriorations resulted from alteration of the physical habitat structures and the quality and quantity of POM and solving the adverse downstream effects have been pointed out as social issues (Ligon *et al.* 1995; Hatano 2006).

Today, as constructions of new dams become difficult and the requests for restoring the river ecosystem increase, development of management measures intended for existing dams is increasingly required for mitigating the geomorphological-ecological downstream effects by dam impacts and for recovering the ecosystem health. Therefore, the main purpose of this thesis is to contribute the knowledge for developing the management measures in dam tailwater ecosystems.

1.2 MOTIVATION:

Needs of sediment management through channel geomorphological restoration for recovery of ecosystem health in dam tailwaters

Interdisciplinary studies among engineering, ecology and geomorphology evaluated the downstream effects of dams and had showed both effects of geomorphology and ecology were not separated but largely related together (Kondolf 1997; Petts and Gurnell 2005). This means that for mitigating and enhancing the ecosystem health in dam tailwaters, it is necessary to restore continuity of sediment transport and budget between upstream to downstream of dams.

Indeed, recent mitigation measures focus on the downstream sediment management. For instance in Japan, a sediment replenishment which is artificial sediment supply by transporting excavated sediment from reservoirs to the downstream during flood event (e.g. Nunome Dam, Managawa Dam and Nukui Dam), a sediment bypass tunnel connecting from up to downstream (e.g. Miwa Dam and Asahi Dam) and a flood mitigation dam without impoundment (e.g. Masudagawa Dam) are implemented for the purpose (Sumi 2003; Okano *et al.* 2004; Sumi 2005). However, assessing the effects of the mitigation measures on downstream ecosystems were hardly implemented due to ambiguity of ecosystem health in dam tailwaters and lack of its quantification methods. In contrast, without the appropriate evaluation criteria and methods, the practical problems will be accompanied to decide how much, how sediment causes geomorphological restoration to what extent.

From the perspective of an ecosystem health (Costanza and Mageau 1999), a resilience which is the ability to return its reference state in the face of external forcing (Reynolds 2002) and a resistance which is the degree to sustain the system despite perturbation (Tilman and Downing 1996; Potts *et al.* 2006) are significant to recover the ecosystem against external disturbance. In the present study, dam tailwater ecosystems are continuously disturbed by input of large amount of plankton from dam outflow (Fig.1-2). It is supposed that the nearest ecosystem from dam outlets is highly reliant on the plankton like the lentic system in a reservoir. If the tailwater ecosystem has resilience and resistance, the lentic system may be recovered to lotic system through a hybrid step, as contribution of the plankton to the energy resources of the ecosystem decreased. In this sense, a healthy ecosystem in the dam tailwaters can rapidly recover the lentic system to the lotic system with a short recovery length (e.g. C type in Fig.1-2), which is assumed to depends on the retention efficiency of the channel for reducing the plankton. However, the factors affecting or controlling the retention efficiency for the plankton in dam tailwater ecosystems have not been understood enough despite their applicable importance for river managements. In this study, it is hypothesized that the retention efficiency is highly related with the channel geomorphological conditions. Therefore, the retention efficiency according to channel geomorphology should be a significant indicator for the ecosystem health in dam tailwaters.

For the integrated researches on downstream effects of dam impacts, however, it is required of the good messengers able to responding the changes in channel geomorphology, to quantify the retention efficiency for lentic plankton and to influence benthic communities. In this study, the particulate organic matter (POM) dynamics is used as the messenger by the following reasons: First, The plankton can influence the POM composition in dam tailwaters as major component and the contribution of the plankton to the POM can be quantified (Yamamoto 2006; Ock and Takemon 2010), Second, the POM dynamics can respond to the condition of channel geomorphology (Takemon *et al.* 2006; Takemon *et al.* 2008). Finally, the benthic communities are responding to the POM dynamics as food resources and channel geomorphology as physical habitat structure (Merritt and Cummins 1996; Takemon 2005)

Therefore, this study deals with the following questionnaires using the POM dynamics as the messengers and the retention efficiency as the index of ecosystem health: First, the assessment of how the channel geomorphology changed by impacts of the existing dams will influence the downstream ecosystems. Second, the prediction of how and what extent the geomorphology have to be restored to recover ecosystem health

1.3 APPROACH

1.3.1 POM dynamics in dam tailwater ecosystems

Particulate organic matters in a stream play an important role for supporting heterotrophic food webs by providing energy resources to primary consumers and by conditioning microhabitats of stream organisms. The POM is a unknown mixture and the information on POM composition is known to give a detailed and integrated recording of natural and anthropogenic activity within basin (Hedges *et al.* 1986). In addition, the transport and retention of POM in stream ecosystems have been closely related with ecological structure and function such as material cycling, primary production, water quality (Glushchenko 1989) and heterotrophic foodwebs (Wallace *et al.* 1982; Webster and Meyer 1997).

Riverine POM has been classified into some groups by criteria of standing location, particle size and source origin. According to location, POM is divided into suspended POM (SPOM) and benthic POM (BPOM). SPOM is mostly transported to downstream in the surface layer, whereas BPOM was located on river bed. Particle size fraction can divide POM into coarse POM (CPOM, Φ>1.0 mm) and fine POM (FPOM, 0.45um<Φ<1.0mm). In the present study, POM is divided into four types including Suspended-Fine POM, Suspended-Coarse POM, Benthic-Fine POM and Benthic-Coarse POM as depicted in Fig.1-3.

From the perspective of source origin, riverine POM generally derived from allochthonous terrestrial inputs (e.g. forested tree leaf and twig, floodplain macrophytes) and autochthonous instream production (e.g. algae, bryophytes and cyanobacteria) (Bilby and Bisson 1992). In dam tailwater ecosystem, however, lentic plankton supplied from dam outflows can be an independent source contributed to POM composition (Angradi 1993; Doi *et al.* 2008). Indeed, some researches showed the dam tailwater foodwebs were highly dependent on dam outflows because of the lentic plankton (Richardson and Mackay 1991; Akopian *et al.* 1999; Doi *et al.* 2008).

POM in running water repeats processes of supply, transport, deposition and resuspension, transforming its locations (SPOM and BPOM), sizes (CPOM to FPOM) and its source composition shifts along reaches through physical, chemical and biological processes (Doi *et al.* 2007; Takemon *et al.* 2008). Also, benthic communities are adaptive to such POM dynamics particularly in functional feeding groups (FFGs) of benthic invertebrates.

Consequently, in this study, POM dynamics can be explained with following qualitative and quantitative changes of POM characteristics; (1) Source composition change (2) Size fractionation and (3) transport, deposition and resuspension (Fig.1-4).

1.3.2 Retention process in dam tailwater ecosystems

Retention is the process of which removes matters from transport within the reaches and makes it available for reduction the suspended materials and for utilization by stream biota. The retention function of the reaches was quantified as the spiral length (Newbold *et al.* 1982), the discontinuity distance (Ward and Stanford 1983) and the mean transport distance (Cushing *et al.* 1993; Hunken and Mutz 2007).

In the present study, retention process is divided into largely deposition in substrate and suspension in water (Fig.1-5). Deposition is a process that suspended POM changed into benthic POM in river bed in relatively long time scale. Suspension is a temporary process occurred before deposition to riverbed or transport to the downstream. Moreover deposition can be divided into not only filtering process by physical trapping of substrate or benthic organism but also falling process by gravitational settling of relatively heavy particles.

Retention efficiency in river ecosystem is the ability of system with specific geomorphological condition and it is assumed to determine how rapidly or how much the target suspended material will be reduced.

1.4 PURPOSES AND OBJECTIVES

The goals of this thesis are to estimate longitudinal changes in the contribution balance of the three sources of dam tailwater POM (i.e. lentic plankton, terrestrial plant and epilithic algae) separately in relation to channel geomorphology and ecological responses in dam tailwater channels, and to propose restoration measures of dam tailwater ecosystems by means of geomorphological management. With this in mind, the several objectives were set to guide the study, including;

(1) to estimate the lentic plankton impacts on POM source composition using tracers or analogues though testing suitability of some quantitative methods,

(2) to investigate roles of geomorphologic features in transport and deposition of POM according to its source origins,

(3) to evaluate effects of POM dynamics on benthic communities, and

(4) to suggest geomorphological conditions for increasing the retention efficiency

1.5 METHODOLOGY: a brief overview

The procedures of the present research study consist of filed surveys in several tailwater channels with diverse channel morphology, laboratory analyses of physio-bio-chemical properties of POM and physical experiments in the artificial flume.

1.5.1 Study sites

● Artificial canals of Lake Biwa: the Kamogawa Canal and the Sosuibubsen Canal running through Kyoto were selected as study sites for estimating the transport distance of plankton in relation to channel morphology. Both canals are connected to Lake Biwa with underground pipe lines to the open canals, thus the flowing water contents plankton produced in the Lake Biwa. Both canals have relatively simple U shape channel morphology built of concrete, but with different characteristics of water depth and width. The former shows a wider and deeper channel shape than the latter.

● Uji River: the river has been degraded in bed during about 40 years since construction of the Amagase Dam. The mean size of bed material is significantly larger for other rivers investigated by armoring effect of the dam. The cross section has been deepened thereby gradually changed into a simple cross section like canal shape.

● Kizu River: the river shows various sandbar structures in the channel due to continuous sediment supply from the upstream and tributaries.

● Nunome River: in the study reaches of the river, sediment has been frequently supplied by the sediment replenishment from the Nunome Dam.

1.5.2 Laboratory analyses

For identifying and quantifying POM source composition, microscopic examination and stable isotope analysis were used for the purpose of the research

● Microscopic particle identification: It allows estimation of the transport distance of fine POM and quantifying POM source composition. Samples of organic particles were identified, counted and classified into several taxonomic groups using the optical photo-microscopic system.

● Stable isotope analysis: Stable isotopic signature is a valuable tracer in ecological research field. A dual isotope ($\delta^{13}C$-$\delta^{15}N$) approach was applied for the present research. Two kinds of stable isotope mixing models were used to quantify source contribution to a mixture of different trophic sources.

1.5.3 Physical experiments

For detail explanation of the effects of geomorphic features on retention of POM, laboratory hydraulic experiments were conducted for investigating relations of FPOM density distribution to the riverbed morphology. Pine pollens were used as analogues of the POM in dam tailwaters. Two bed configurations, a damming pool structure and an alternative bars structure, were prepared for the experiments.

1.6 CHAPTER OUTLINE

This dissertation comprised of seven chapters, each of which addresses different issues regarding relations of channel geomorphology to dam tailwater POM dynamics as shown in Fig.1-6.

In the Chapter 1, motivation and objectives of the study, together with a brief review of POM dynamics and methodological descriptions were presented.

Chapter 2 shows methods and results on estimation of the means transport distance and the field deposition velocity using lentic plankters as a tracer. Variations of the mean transport distance obtained by comparative studies among the four tailwater channels with different channel morphology are also presented and effects of channel morphological characteristics on the retention efficiency are discussed.

Chapter 3 describes the multi-source composition of dam tailwater POM. Contribution of lentic plankton to POM composition in the dam tailwater was estimated by calculation of relative distribution of the sources. The characteristics of differentiated POM according to its size fraction (fine and coarse) and location form (suspended and benthic) are presented. Methodological evaluation for the microscopic examination and two stable isotope mixing models (standard linear model and concentration-weighted mixing model) were undergone and advantages and limits of each method are discussed.

Chapter 4 and Chapter 5 focus on effects of geomorphological features such as riffles and pools on transport and deposition of suspended POM in the Uji River and the Nunome River, respectively. The downstream changes in the relative contributions of the three sources were investigated and their relations to geomorphic features were analyzed. Also responses of benthic invertebrates to the dam tailwater POM dynamics were studied. In Chapter 4, the ecological response of filter-feeding mussel to POM dynamics of dam tailwaters is discussed. In particular, comparisons of the Nunome R. with the Uji R. suggest the effects of sediment replenishment on downstream POM dynamics.

Chapter 6 describes experimental study on the deposition process of the sources in relation to the bed geomorphology. The experiments allow supporting in detail or complementing the findings derived from previous chapters. Two types of pine pollens, floating and sinking types, are the first applied as tracers for lentic plankton and terrestrial source particles respectively.

Chapter 7 summarizes the results from each chapter, the entire researches are synthesized and the results obtained in each chapter are concluded. Some recommendations for engineering practices to increase retention efficiency of river channels are given.

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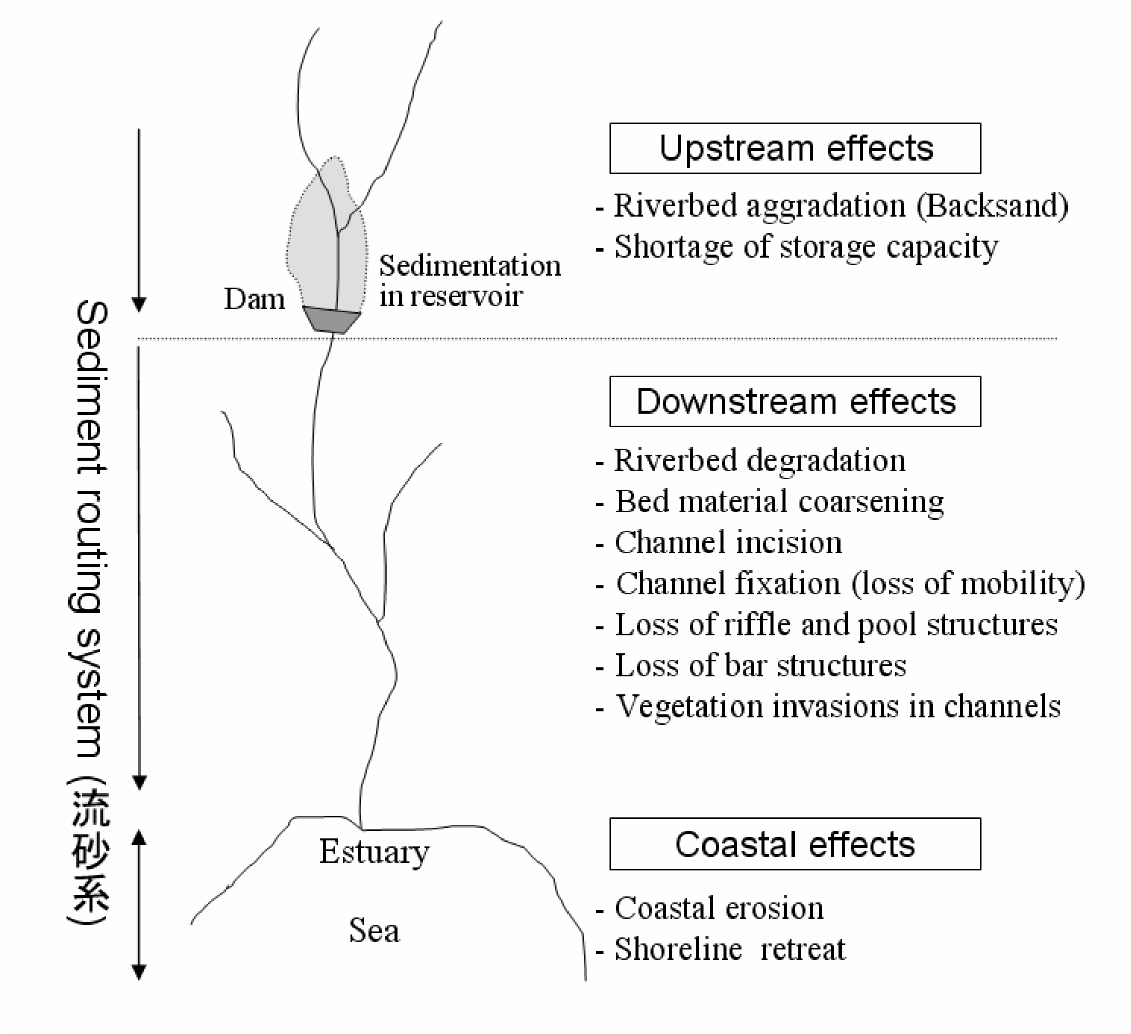

Fig.1-1 Various geomorphological effects of dam reservoir impacts found along a sediment routing system

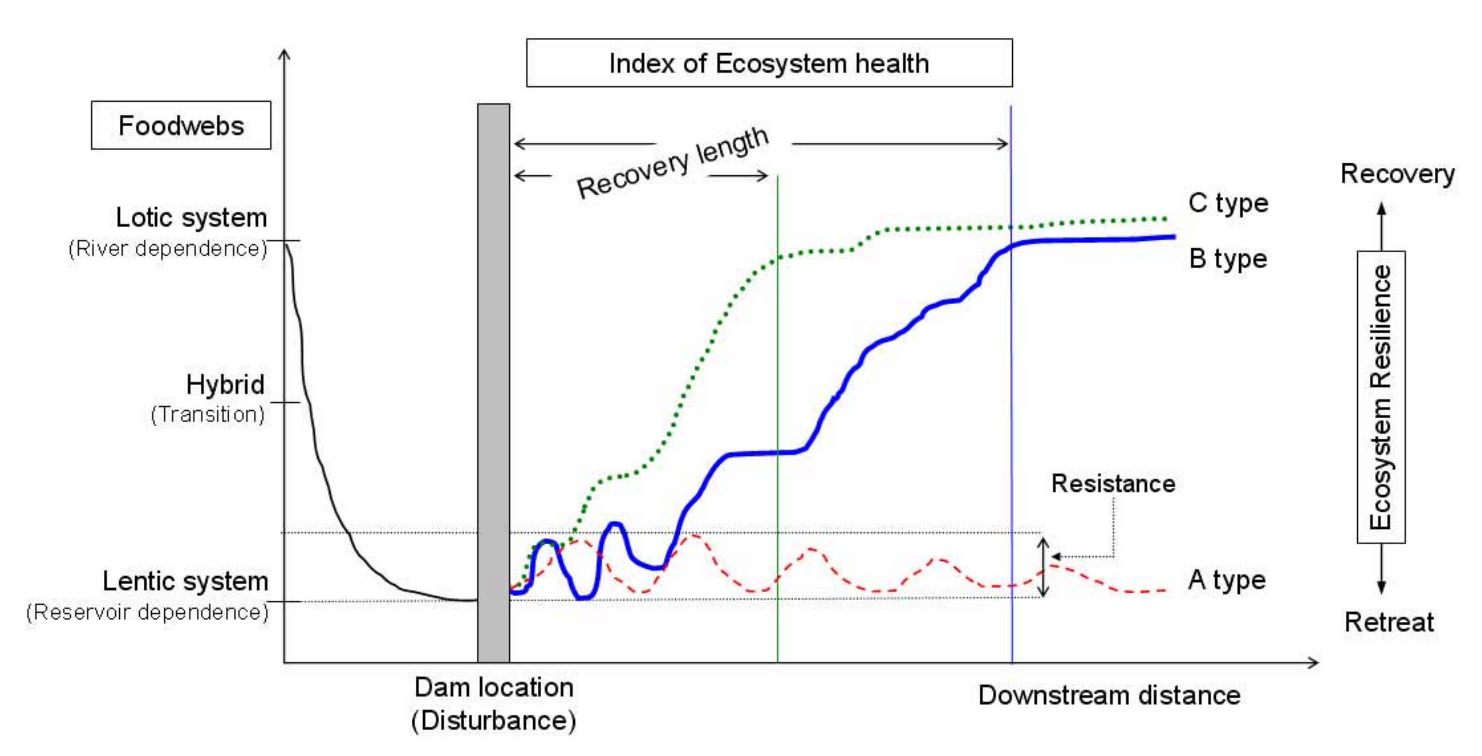

Fig.1-2 Conceptual scheme of the recovery of ecosystem health in dam tailwater ecosystems. An ecosystem has a resilience to recover its structure and function together with a resistance against external disturbance. Response of the ecosystem after facing with the external disturbance (i.e., retreat (A type) or the degree of recovery (B or C types)) depends on the internal capacity of resilience. In the present study, the external disturbance corresponds to the input of lentic plankton supplied from dam outlets, and the internal capacity means the retention efficiency of the channel for reducing the plankton.

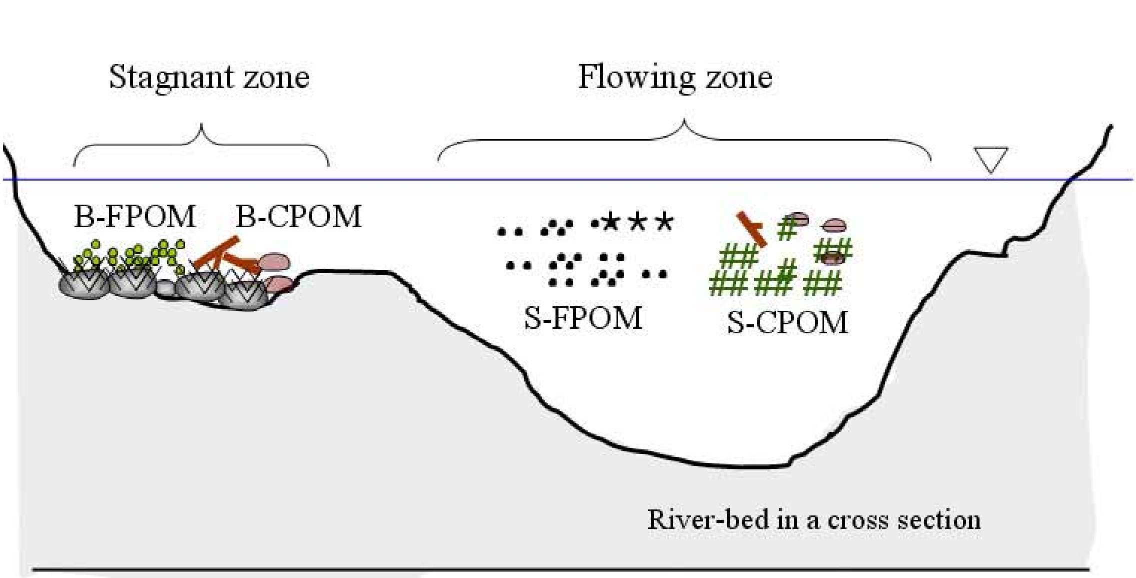

Fig.1-3 Category of POM types distinguished in the present study. Suspended POM and benthic POM were collected in a flowing zone and in a stagnant zone, respectively. Fine POM and coarse POM were divided by their particle size.

S-FPOM: Suspended Fine Particulate organic Matter,

S-CPOM: Suspended Coarse Particulate organic Matter,

B-FPOM: Benthic Fine Particulate organic Matter,

B-CPOM: Benthic Coarse Particulate organic Matter.

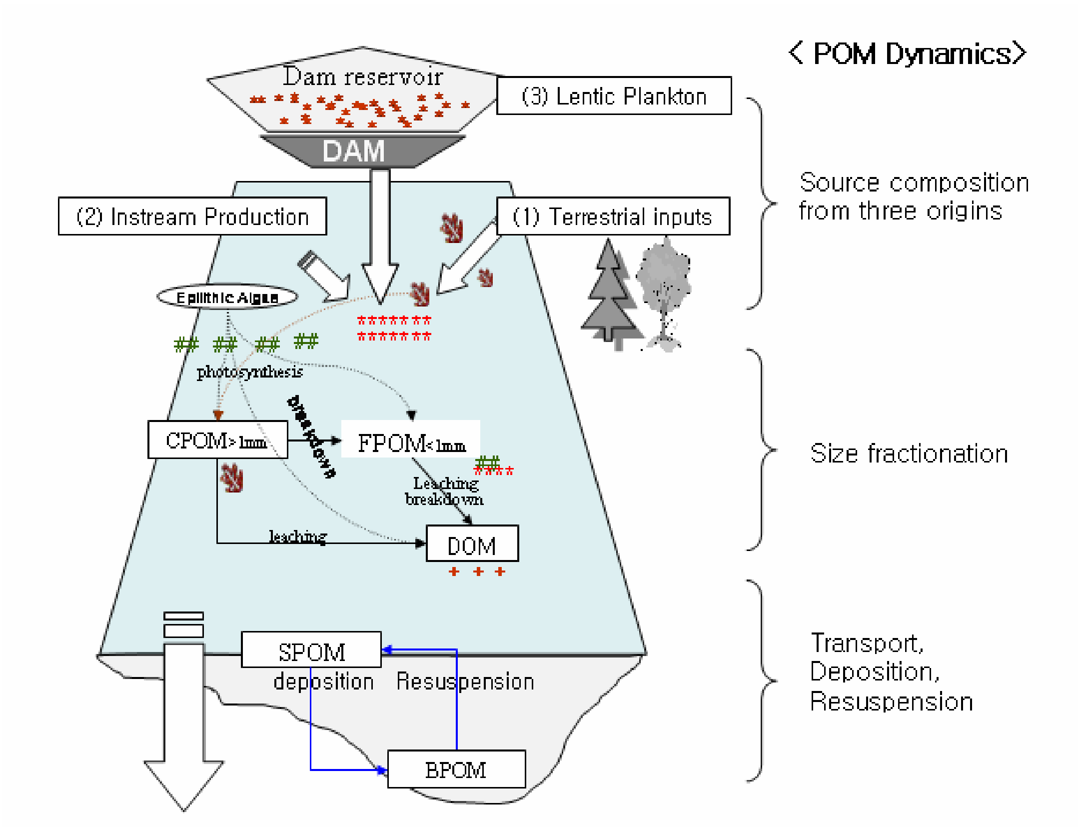

Fig.1-4 Conceptual model for POM dynamics in the downstream channel below dam reservoirs. The lentic plankton is an independent source of POM composition.
In the study, POM dynamics represent a source composition, a size fractionation and a retention process by transport, deposition and resuspension.

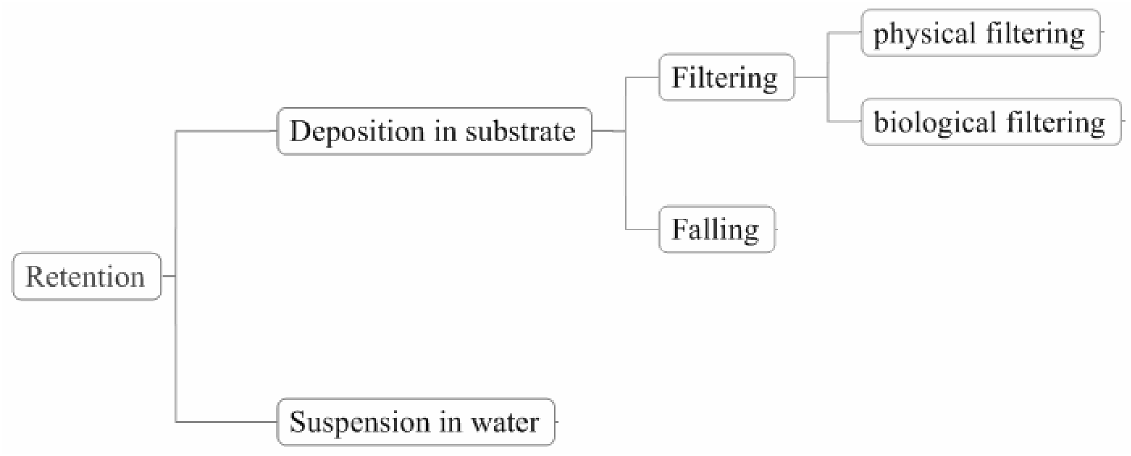

Fig.1-5 Division of the retention process of POM in a river channel. POM is either suspended in relatively stagnant water or deposited in substrate by filtering process of bed material and benthic organism and by falling process by gravitational settling.

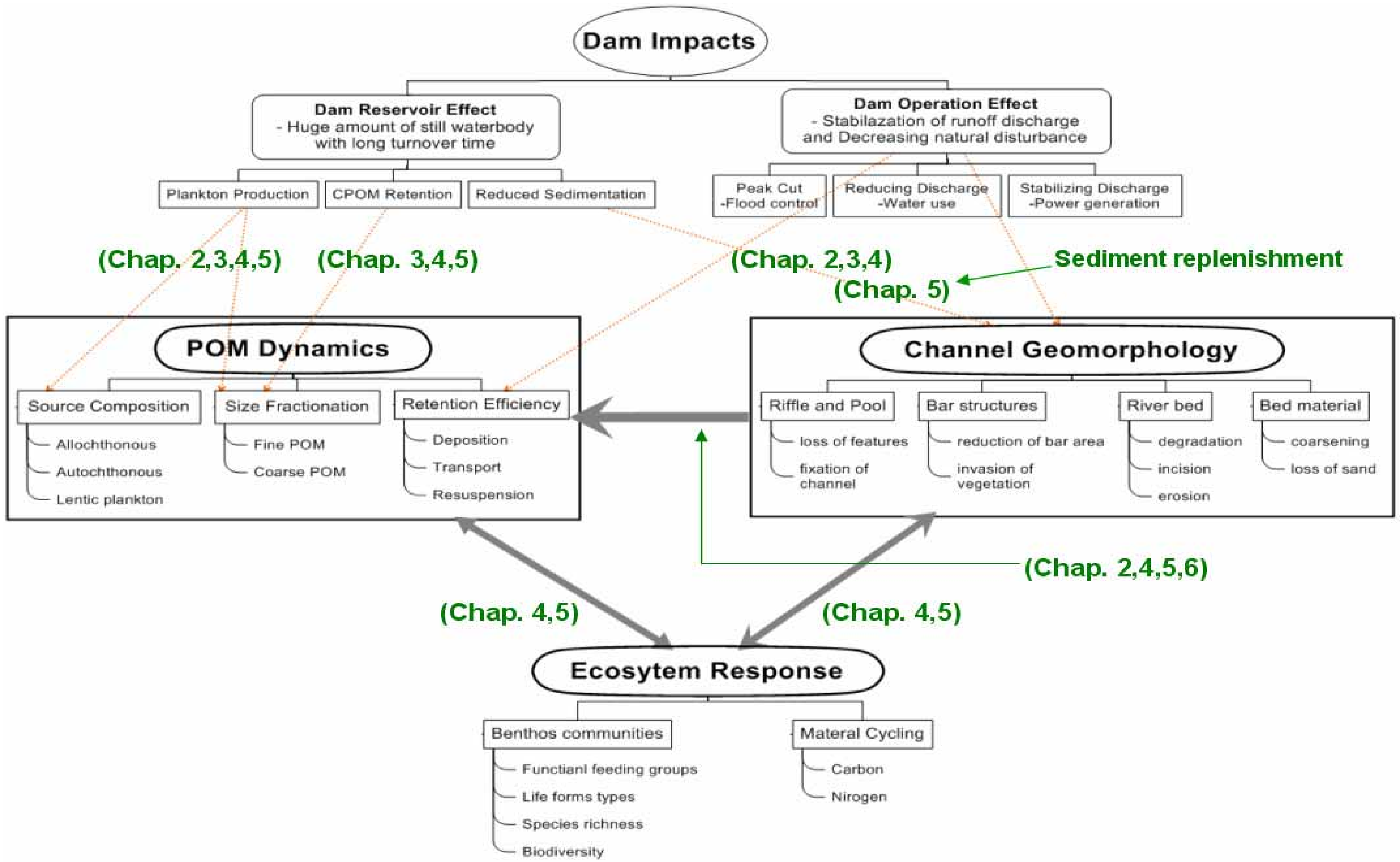

Fig.1-6 Schematic relations of subjects investigated in the present study. Chapter numbers correspond to the relations focused on in each chapter.

CHAPTER 2

Estimation of Transport Distance of Fine POM in Relation to Channel Morphology in Tailwaters of the Lake Biwa and Dam Reservoirs

2.1 INTRODUCTION

Particulate organic matter (POM) in streams plays a critical role in supporting heterotrophic food webs by providing energy resources and in conditioning microhabitats for benthos communities. In general, POM is derived from allochthonous terrestrial plant and autochthonous underwater primary production. Its composition changes dynamically through repetitive retention, resuspension and transport processes in stream channels (Cushing *et al.* 1993), transforming in size from coarse POM (CPOM, >1.0 mm) to fine POM (FPOM, <1.0 mm) through physical breakdown (Fisher and Likens 1972; Tockner *et al.* 1999), microbial decomposition and biologically shredding fragmentation (Cummins and Klug 1979). Such natural balance of POM dynamics was considered to cause the longitudinal changing patterns in functional feeding groups of benthic community (Vannote *et al.* 1980; Hawkins and Sedell 1981; Takemon 2005) and be related to nutrient cycling in lotic ecosystem (Newbold *et al.* 1982).

Although the significance of FPOM has increased as it accounts for a major portion of standing POM budget in streams (Webster and Meyer 1997) and acts as a direct food resource for heterotrophic lotic ecosystems, understanding of FPOM dynamics has been restricted due to complicated interactions among hydrological, morphological and biological factors and partially due to lack of available experimental tracers. Hence, FPOM dynamics research has been enhanced by the development of tracer particles such as lentic diatoms (Maciolek and Tunzi 1968), leaf particles (Webster *et al.* 1987), Lycopodium spores (Wanner and Pusch 2000), radioactive ^{14}C labelled seston (Jones and Smock 1991; Cushing *et al.* 1993; Thomas *et al.* 2001), fluorescently labelled yeast (Paul and Hall 2002), corn pollen (Miller and Georgian 1992; Broekhuizen and Quinn 1998; Georgian *et al.* 2003) and particles derived from lake sediment (Hunken and Mutz 2007)

Quantitative approaches to FPOM dynamics have been focused on measuring the mean transport distance, S_p, which is the mean downstream distance travelled by a tracer particle before deposition to streambed (Young *et al.* 1978; Webster *et al.* 1987; Georgian *et al.* 2003), and on estimating the deposition velocity, v_{dep}, which represents the conceptual velocity at tracer particles deposit through the water column to streambed under field conditions (Thomas *et al.* 2001; Hunken and Mutz 2007). These indices are mainly based on results of field experiments measuring the downstream loss rate, k, between injection concentration of tracer particles and downstream concentration far from the release site. Georgian *et al.* (2003) separated these tracers into two groups, radioactive labelled FPOM and artificial analogues or surrogates such as corn pollen, and pointed out the latter are useful to compare transport dynamics in streams that have a wide variety of geomorphic and hydrologic characteristics. Nevertheless, these methods have been restricted only to relatively small reaches in headwater streams of less than third order. Consequently, information on FPOM dynamics in large rivers has been limited, partially due to difficulty in preparing sufficient tracer particles for downstream collection (Miller and Georgian 1992). In order to overcome this problem, we adopted some lentic plankters produced in lake or reservoir dams as natural tracer, because they were supplied continuously from lake or reservoir dam in large amount of volume not as a snapshot event as in previous methods using artificial analogues. In particular, tracer plankters showing a downriver reduction pattern will reflect real FPOM transport processes under a natural equilibrium condition with continuous supplement, repetitive deposition, resuspension and transport.

The relation between channel morphology and FPOM dynamics is essential for understanding of reach- or segment-scale characteristics in river ecosystem. Channel morphological factors such as riverbed roughness (Webster *et al*. 1987; Minshall *et al*. 2000) and presence of debris dam (Bilby and Likens 1980; Speaker *et al*. 1984; Smock *et al*. 1989) have been considered to affect the trapping efficiency of FPOM. Abundance of filter feeder population such as net-spinning caddisfly was also reported to indirectly influence FPOM transport process (Wallace and Hutchens Jr 2000; Monaghan *et al*. 2001; Watanabe and Omura 2007). In this sense, riverbed degradation and bed material armoring resulting from construction of reservoir dams will have significant impact on downstream FPOM transport. However little is known about the effect of channel morphology on transport distance and deposition velocity of FPOM in dam tailwaters in relation to channel morphology, in spite of the extensive studies regarding impacts of dams on discontinuum of material and nutrients (Ward and Stanford 1983) and aquatic organisms (Power *et al.* 1996).

This study aims to estimate FPOM transport distance and deposition velocity in large channels using lentic plankters as natural FPOM tracer, and to examine how channel morphologic factors affect FPOM dynamics, by comparing four channels with varying hydro-morphological characteristics below Lake Biwa and reservoir dams.

2.2 METHODS

2.2.1 Site description

Four channels with different channel hydro-morphological characteristics were selected in Kyoto, west-central Japan. Two of these channels are artificially constructed canals for irrigation from Lake Biwa (the largest natural lake in Japan, 670.4 km^2 surface area, 2.75×10^{10} m^3 storage capacity) to the urban area. They flow through Kyoto City longitudinally and transversely, and are called Kamogawa Canal and Sosuibunsen Canal, respectively. The others are river channels called Uji River and Kizu River, with comparatively complicated bed shapes. All of them are tailwater channels located below either reservoir dams or Lake Biwa. Five sampling sites in each channel were established along downstream distance (Fig.2-1).

According to physical properties (Table 2-1) and cross-section (Fig.2-2), we characterized the channels as 'deep canal (Kamogawa Canal)','shallow canal (Sosuibunsen Canal)','deep river (Uji River)' and 'shallow river (Kizu River)' to emphasis the hydro-morphological channel differences.

Both canals have simple cross-section of approximately U shape. The deep canal has a comparatively wide and deep channel shape, and large discharge relative to the shallow canal. The bed of the deep river has been degraded since construction of the Amagase Dam in 1965. The cross-section has become deeper by even about 5m at the lowest site, thereby gradually changing its cross-section into a simple canal shape. However, the shallow river channel shows various sandbar structures due to continuous sediment supply from the upstream (Photo 2-1).

2.2.2 Field surveys

Suspended POM (SPOM) samples were collected at each site using POM net sampler (diameter 30cm, mesh size 100μm) for approximately 2 min, which depends on flow velocity and SPOM concentration. In some sites of canals with difficult access to low-flow channel, SPOM samples were taken from surface water using a bucket from the middle of a bridge. Then FPOM samples were collected by filtering with 1mm-mesh sieve to remove coarse particles. Collected samples were preserved in 2% formalin solution to prevent decomposition before identification work. Samplings in the four channels were performed from upstream to downstream and were finished within daytime to minimize the influence of diel fluctuation in plankton composition.

Hydro-morphological characteristics such as width, depth, velocity, discharge and hydraulic radius of channel were also measured at each site and are summarized at Table 2-1 for inter-channel comparison. Field data used in this study were measured at normal flow condition on July 16 and July 24 2007, May 5 and May 26 2005 in the deep canal, the shallow canal, the deep river and the shallow river, respectively.

2.2.3 Lentic tracer plankters for FPOM transport

More than 500 particles from each FPOM sample were identified, quantitatively counted and classified into detritus, plant tissue, insect tissue, skin of zooplankton, phytoplankton and zooplankton using optical phtomicroscopy (Leitz DMRB / Nikon DMX 1200F system) at 100-400 magnification. All plankters were identified possible, to the lowest levels such as species, genus or family. Among identified plankters, 'lentic tracer plankters' for the present study were selected based on three criteria: First, species specific to Lake Biwa or dam reservoirs based on the published information; Second, species showing a downstream reduction pattern; Finally, species with abundance exceeding 3% of total amount at the uppermost site.

2.2.4 Mean transport distance and field deposition velocity

For quantitative analysis of downstream reduction patterns of tracer lentic plankters, the contribution 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), which means that the fraction of lentic tracer plankters would follow a negative exponential function with channel distance, shown as Eq.2-1.

$$F(x) = exp(-kx) \qquad \text{(Eq.2-1)}$$

where $F(x)$ is the fraction remaining at downstream sites, x is downstream distance and k is the longitudinal loss rate.

The transport distance, S_p, and the field deposition velocity, v_{dep}, have been used as quantitative indices for transport and retention processes of suspended FPOM. S_p

represents the mean downstream distance transported by a particle before deposition on riverbed and is calculated as the inverse of the longitudinal loss rate (Eq.2-2).

$$S_p = 1/k \qquad \text{(Eq.2-2)}$$

v_{dep} is the rate at which particles leave the water column and can be viewed as vertical transfer coefficient from the water column to the bed in a field condition and is given by the Equation 3. It is regarded as a standardized alternative to S_{p} because it removes the effect of stream size in the form of depth and velocity from S_{p} (Eq.2-3) (Cushing *et al.* 1993; Hunken and Mutz 2007). Therefore, v_{dep} facilitates comparison of S_p in streams with different sizes and discharges (Cushing *et al.* 1993; Georgian *et al.* 2003). It is different from the falling velocity (v_{fall}) which is calculated as the settling rate of particles in still water governed by gravity.

$$v_{dep} = u \cdot h/S_p \qquad \text{(Eq.2-3)}$$

where u is mean flow velocity and h is mean water depth in the channel.

In addition, in order to assess the effect of gravity on the deposition process in each channel, we measured the ratio of the deposition velocity to the particle falling velocity ($v_{\mathrm{dep}}/v_{\mathrm{fall}}$). The falling velocity of the lentic plankton was assumed to be 0.0625 m/h according to the published datum corresponding to the body sizes of plankton exceeding 100 ㎛ (Bienfang 1980).

2.2.5 Statistical analyses

Nonlinear regression analysis was used to fit the exponential reduction pattern of tracer plankters and to determine k, the longitudinal loss rate. A paired Student's t-test was used to test for differences in S_{p} and v_{dep} between river and canal channels and between deep and shallow channels. Relationships between S_p and specific hydro-morphological factors were examined by regression analysis.

2.3 RESULTS

2.3.1 Downstream changes in lentic plankters as tracers

Fig.2-3 showed the relative contributions of each component, allowing comparison of the FPOM composition within and among channels. Most dominant and subdominant lentic plankton species showed downstream reduction patterns in each channel, and the contribution of detritus gradually increased downstream, whereas plant tissue and filamentous epilithic algae did not show a distinct downstream changing pattern.

Comparing with the four channels, tracer lentic plankters were more abundant in canal channels and less in river channels. In both canals, a total of five phytoplankters were determined as tracers, but with slightly different species composition (Fig.2-4): in the deep canal, *Aulacoseira granulate, Woronichinia naegelianum, Aulacoseria ambigue, Anabaena* sp. and *Staurastrum* sp.: in the shallow canal, *A.granulate, W.naegelianum, Microcystis aeruginosa Sphaerocystis schroeteri* and *Anabaena* sp. However, in both river channels, zooplankter were chosen as tracers (Fig.2-4); in the deep river, three species, *Bosmina longirostris, Kellocottia longispina* and *Fragilaria crotonensis*: in the shallow river, two species , *B.longirostris* and *Volvox aureus* (Photo 2-2).

Downstream reduction patterns of tracer lentic plankters varied widely among channels. The curves of tracer plankters in the deep canal and the deep river dropped off more gently than those of the shallow ones. Especially in the deep canal, there was distinctive inter-species variation in reduction patterns even within a channel. For instance, *A.granulate* showed a relatively gentle reduction curve compared with other plankters.

2.3.2 Estimation of mean transport distance and deposition velocity of FPOM

The reduction curve combined with the total contribution of all tracer plankters and downstream channel distance enabled estimation of a representative S_p value for FPOM in each channel. As shown in Fig.2-5, the total remaining fraction of FPOM decreased exponentially downstream in all channels, but their downstream reduction rates were different among the four channels. The curves of the shallow canal and the shallow river tended to drop off more steeply than those of the deep river and deep canal.

From nonlinear regression curves fitting to the reduction patterns, we measured a channel-specific longitudinal loss rate and calculated the mean transport distance. Based on S_p values, depth and velocity data shown in Table 2-1, field deposition velocities were calculated for inter-channels comparison (Table 2-2).

S_p showed wide variation among channels, ranging from 2.20 km in the shallow canal to 19.19 km in deep canal. According to the results of S_p in the channels, morphologically deep ones; i.e. the Deep Canal and Deep River, had longer S_p than the shallow ones. According to the results of v_{dep}, there was a significant difference between canal and river channels ($p<0.05$). The values for the shallow river and the deep river appeared to be distinctively high (1.03 m/h and 0.89 m/h, respectively), whereas the shallow canal and the deep canal had similar low values (0.19 m/h and 0.16 m/h, respectively). The values of v_{dep}/v_{fall} was more than 1.00 in all channels, and those of the shallow river (16.55) and the deep river (14.29) appeared to be higher than those of the shallow canal (2.97) and the deep canal (2.51).

2.3.3 Relation of transport distance to physical factors of channel characteristics

As shown in Fig.2-6, S_p did not show any association with hydraulic factors such as velocity and discharge. However S_p appeared to be closely positively correlated with depth and hydraulic radius (R^2=0.7244 and 0.7359, respectively).

2.4 DISCUSSIONS

2.4.1 Lentic plankters as natural FPOM tracers in dam tailwater channels

Tracing of lentic plankton as FPOM tracers can be an appropriate method to overcome the river scale restrictions on quantitative study of FPOM transport and deposition mechanisms, although this method has still a limitation only applicable to tailwater channels below lakes and dam reservoirs.

The previous methods have been limited only to small headwater streams due to difficulty in preparing sufficient injection volume of tracer particles for downstream collection. Hunken and Mutz (2007) carried out a field experiment at 18 headwater reaches with 0.44-6.00 m width and 0.006-0.079 m^3/s discharge, resulting in S_p values of 21-556 m of. Cushing *et al.* (1993) compared three reaches varying from 5.8 to 7.1 m in width and from 0.25 to 0.71 m^3/s in discharge, finding S_p values of 580-800 m of. Jones and Smock (1991) found 1.8-84 m values for S_p in small streams of 0.017-0.045 m^3/s discharge. On the other hand, we studied two relatively large river channels with 99-168 m width and 33.6-130 m^3/s discharge, and estimated S_p values of 3.91-6.31 km of in dam tailwater channels by adopting lentic plankton as tracers. This method resulted in about 4.9-7.9 times higher values of S_p than the longest one published (Cushing *et al.* 1993). Our result of increased S_p in dam tailwaters compared with in small streams can be interpreted in part in terms of the river scale effect by which the transport distance of fine particles increases in proportion to the channel size and discharge (Webster *et al.* 1987; Cushing *et al.* 1993). Furthermore, we should also take into account the close to real condition of continuous supplement of FPOM from the upstream. All previous methods using artificial tracers such as corn pollen and radioactive-labelled seston were based on a snapshot injection event into the stream channel. However, natural ecosystem processes such as supply or decomposition of organic matter are continuous phenomena rather than single event. Therefore, our method using the lentic plankton has the advantage of estimating the real average transport distance under a natural equilibrium condition with continuous supply, repetitive deposition and resuspension. In addition, in the snapshot methods, dispersion process should be considered as a retention factor, whereas lentic plankton tracers can compensate for this process.

2.4.2 Relation transport distance and deposition velocity of FPOM to channel morphology

The deep canal and the deep river showed much longer transport distance than the shallow river and the shallow canal. In particular the deep canal had the longest S_p

of 19.19 km. S_p did not show any association with hydraulic factors such as velocity and discharge, but showed strong positive correlation with channel morphological factors such as depth and hydraulic radius. In particular, hydraulic radius could explain 74% of variability in S_p despite different channel hydrology and morphology. This result suggests that increasing complexity of riverbed morphology can increase FPOM retention efficiency and consequently minimize the transport distance. Hydraulic radius can be a probable parameter as a factor of complexity of riverbed morphology, as Speaker *et al.* (1984) focused on for CPOM retention rates.

v_{dep} enabled comparison of channels with different sizes and discharges. v_{dep} was significantly different between canal and river channels ($p<0.05$). This means that, in the standardized river conditions, suspended FPOM deposits about four times faster in river channels than in simple canals condition. Such a difference in v_{dep} between canals and rivers can be interpreted in terms of river geomorphological characteristics related to bed materials, riffle-pool sequence and bar structure. Also, the ratio v_{dep}/v_{fall} reflected channel morphological difference between rivers and canals. Both river channels showed 4.6-6.5 times higher values than did canals, indicating the importance of other factors such as turbulent vertical mixing rather than falling under gravity, particularly in natural rivers (Hunken and Mutz 2007).

Moreover, the greatest difference in S_p in spite of close similarity in v_{dep} between the deep canal and the shallow canal is expected to be affected by flow discharge and water depth. Therefore, transport distance of FPOM in the simple channel condition as in artificial canals is likely to depend mainly on channel size factors such as discharge and depth. Comparing v_{dep} between the river channels, the value for the shallow river was high (1.03 m/h) relative to the deep river (0.89 m/h). This can be explained by the fact that the shallow river had complicated bed morphology due to developed bar structure that can facilitate entrapment and filtering of FPOM compared with the deep river, which had a relatively simple cross-section resulting from riverbed degradation by upper dam.

2.4.3 Roles of river channel morphology for increasing the retention efficiency for FPOM

A well balance of supply, transport and retention of suspended FPOM is required to keep river ecosystems healthy, since FPOM plays an important role both in supplying food resources and in conditioning water quality through consumption of dissolved oxygen. Particularly in dam tailwater ecosystems, introduction of large amount of lentic plankton flows to the downstream have been imposed to alter the balance of POM dynamics in lotic ecosystems (Ward and Stanford 1983; Lieberman and Burke 1993). For instance, when water bloom events by eutrophication occur in reservoirs, the prediction of how far toxic lentic materials can move downstream under various channel conditions, the understanding of how they influences downriver lotic ecosystems and planning for minimizing the transport distance are increasingly required for tailwater ecosystem management. Accordingly, estimation and comparison of S_p and v_{dep} by means of tracing lentic plankton in lotic channels can provide effective indicators for tailwater ecosystem management and restoration.

According to our results, the transport distance was strongly correlated with hydraulic radius, an index of channel morphological complexity, and the deposition velocity was significantly (4.7-6.4 times) greater in natural river channels than in artificial canals. In particular, the shallow channel sustaining a well-developed sandbar structure had a comparatively short transport distance and the fastest deposition velocity. This clearly indicates that downstream riverbed degradation and armored bed materials induced by dam impact may alter river morphology into a simpler form or even to canal shape, thus leading to a decrease in the retention rate and an increase in the transport distance of FPOM.

Consequently, our results suggest that sustaining or restoring more diverse and complicated river channel morphology by means of sediment management can contribute to enhancing habitat restoration and self purification in dam tailwater ecosystems.

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Table 2-1 Hydrologic and morphologic characteristics of the four studied channels in an ordinary flow conditions.

Channel*	No. of sites	Width (m)	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	Hydraulic radius** (m)	Length (km)	Predominant bed material
Deep Canal	5	14.58(±3.36)	1.67(±0.56)	0.50(±0.28)	10.70	1.36(±0.43)	9.15	concrete/sand‡
Shallow Canal	5	3.38(±1.14)	0.27(±0.19)	0.42(±0.09)	0.27	0.19(±0.13)	4.49	concrete/sand‡
Deep River	5	90.89(±27.56)	1.70(±1.00)	0.92(±0.31)	130.00†	1.38(±0.90)	12.90	cobble/boulder
Shallow River	5	111.54(±46.09)	0.54(±0.22)	2.08†	33.60†	0.48(±0.11)	20.00	sand/gravel

The values used represent mean (±standard deviation) of sampling sites in each channel

* The deep canal, the shallow canal, the deep river and the shallow river represent Kamogawa Canal, Sosuibunsen Canal, Uji River and Kizu River in Kyoto, respectively.

** Hydraulic radius is the ratio of cross-sectional area to wetted perimeter of riverbed.

† Values measured by hydrograph measured at the nearest gauging station on sampling date.

‡ Channel is composed of mainly exposed concrete bed, but some reaches had sand on the bed

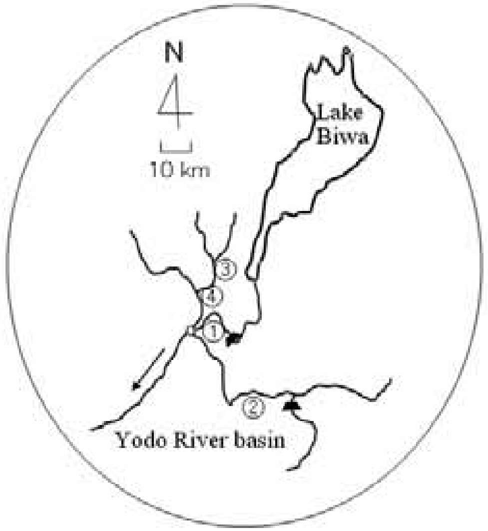
Table 2-2 FPOM transport parameters in the four channels of the present study.

Channels*	k (km-1)	S_p (km)	v_{dep} (m/h)	v_{dep}/v_{fall} **
Deep Canal	0.0521	19.19	0.16	2.51
Shallow Canal	0.4546	2.20	0.19	2.97
Deep River	0.1586	6.31	0.89	14.29
Shallow River	0.2558	3.91	1.03	16.55

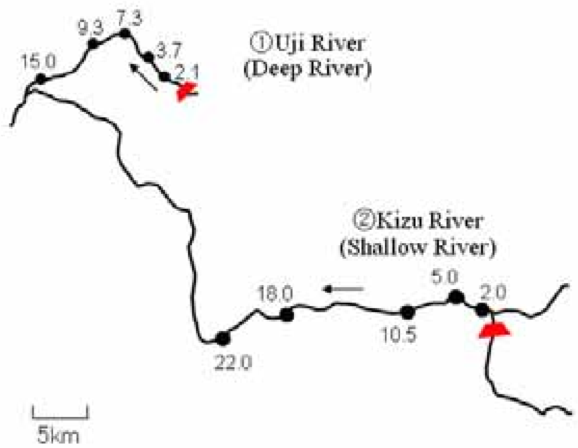
k longitudinal loss rate, S_p mean transport distance, v_{dep} deposition velocity and v_{dep}/v_{fall} ratio of deposition velocity in running water to falling velocity in still water.

* The deep canal, the shallow canal, the deep river and the shallow river represent the Kamogawa Canal, Sosuibunsen Canal, Uji River and Kizu River in Kyoto, respectively.

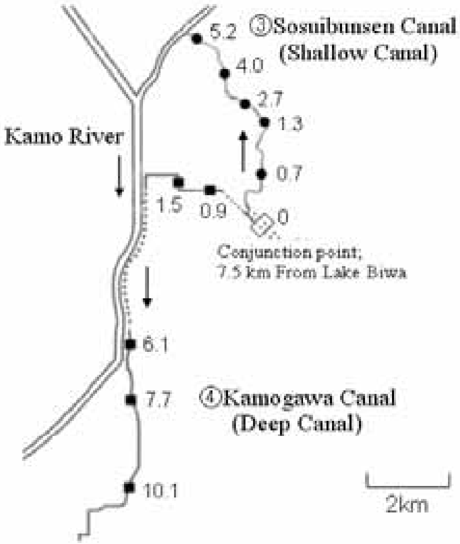
** v_{fall} mean falling velocity. Data for v_{fall} of lentic plankters were referred from published data (Bienfang, 1980), and determined as 0.0625 m/h in consideration of body size: this value is much lower than that of corn pollen of 1.1196 m/h (Miller and Georgian 1992).



(a) key map



(b) river channels



(c) canal channels

Fig.2-1 Map of the study area showing the locations of four channels within the Yodo River Basin, Kyoto, Japan (a). The channels of ③ and ④ are connected by underground pipeline from Lake Biwa to the open canals. Two river channels (b) and two canal channels (c) were selected for survey. Suspended POM samples were collected at five sites in each channel. The values near sampling sites represent a distance (km) from dam outlets or conjunction point of the Lake Biwa Canal

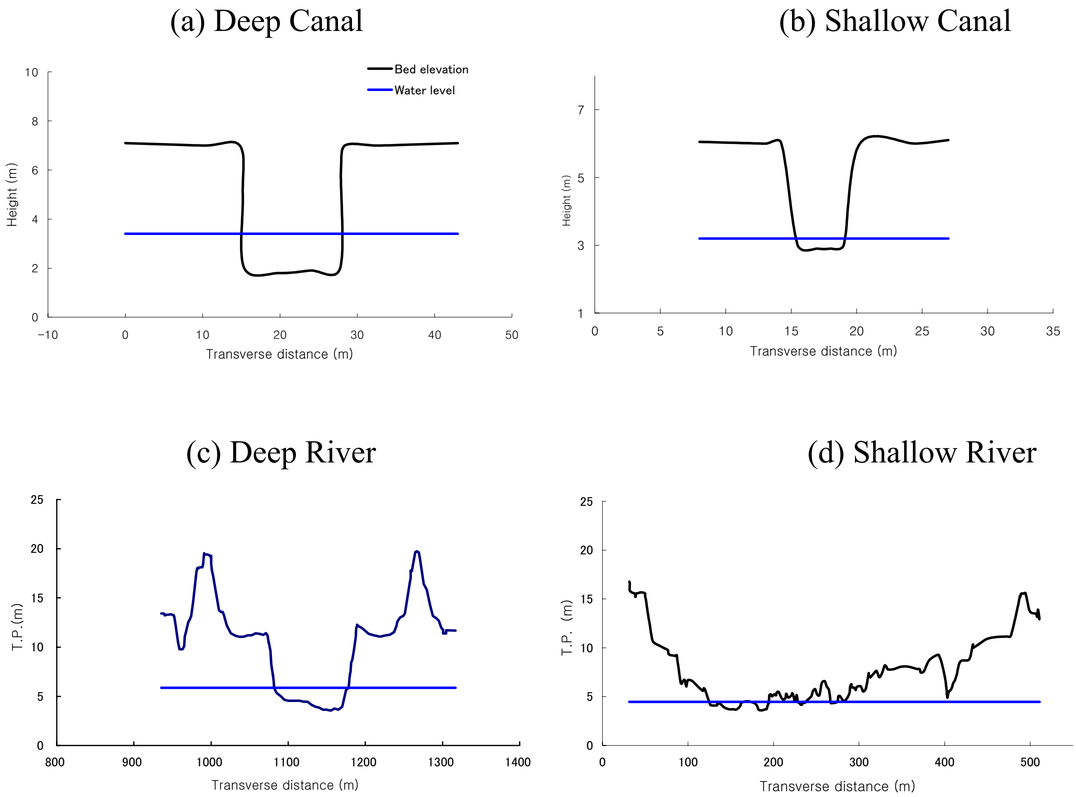


Fig.2-2 Cross sections of the deep canal (a), the shallow canal (b), the deep river (c) and the shallow river (d) in ordinary conditions. Both canal channels had a simple U shape, whereas the shallow river showed a more complicated cross-section due to sandbar structure than the deep river under degraded bed condition.

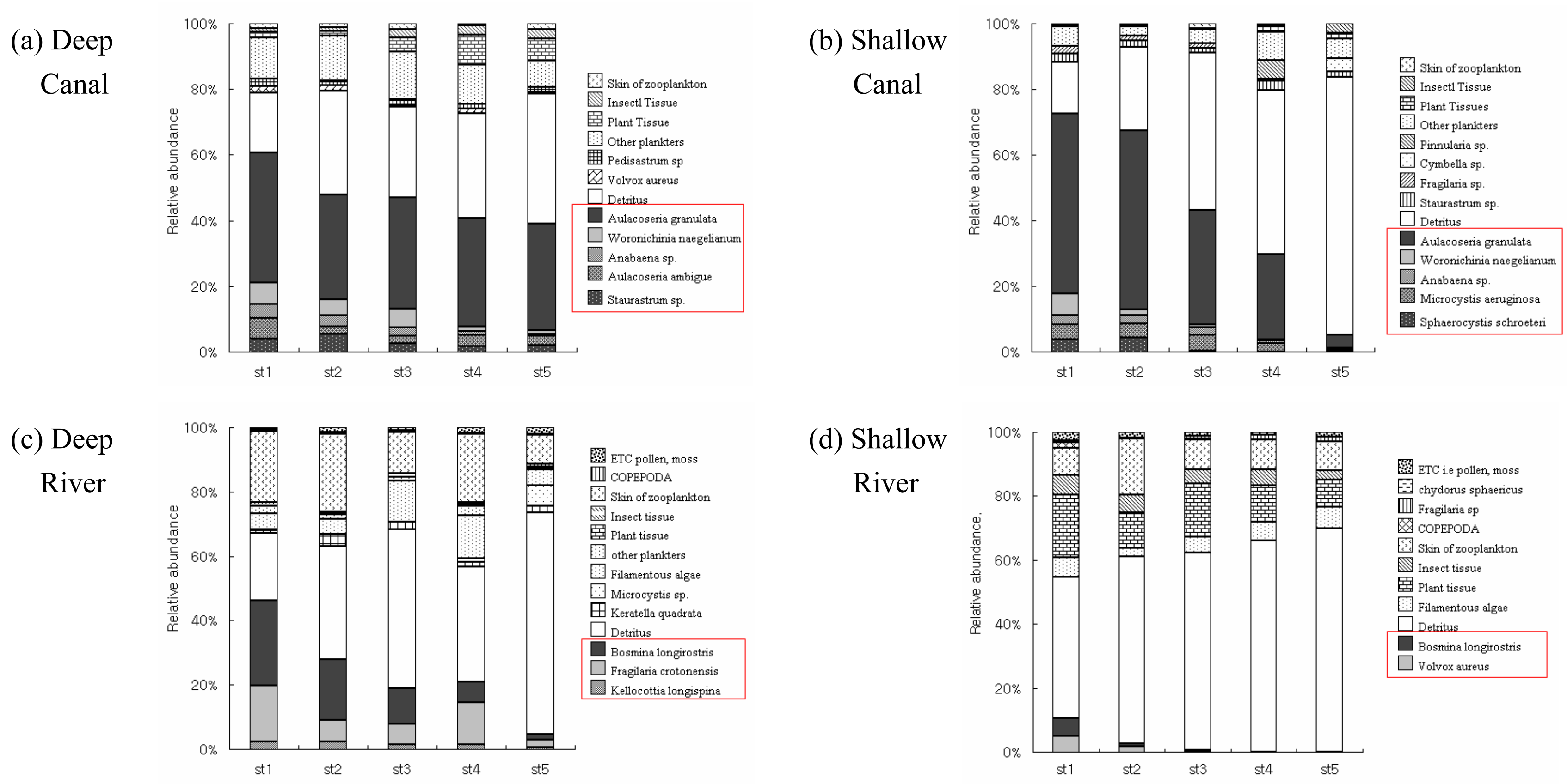


Fig.2-3 Longitudinal patterns of suspended FPOM composition in the deep canal (a), the shallow canal (b), the deep river (c) and the shallow river (d). The fully shaded bars represent the fraction of tracer lentic plankters indicated by rectangular in legends.

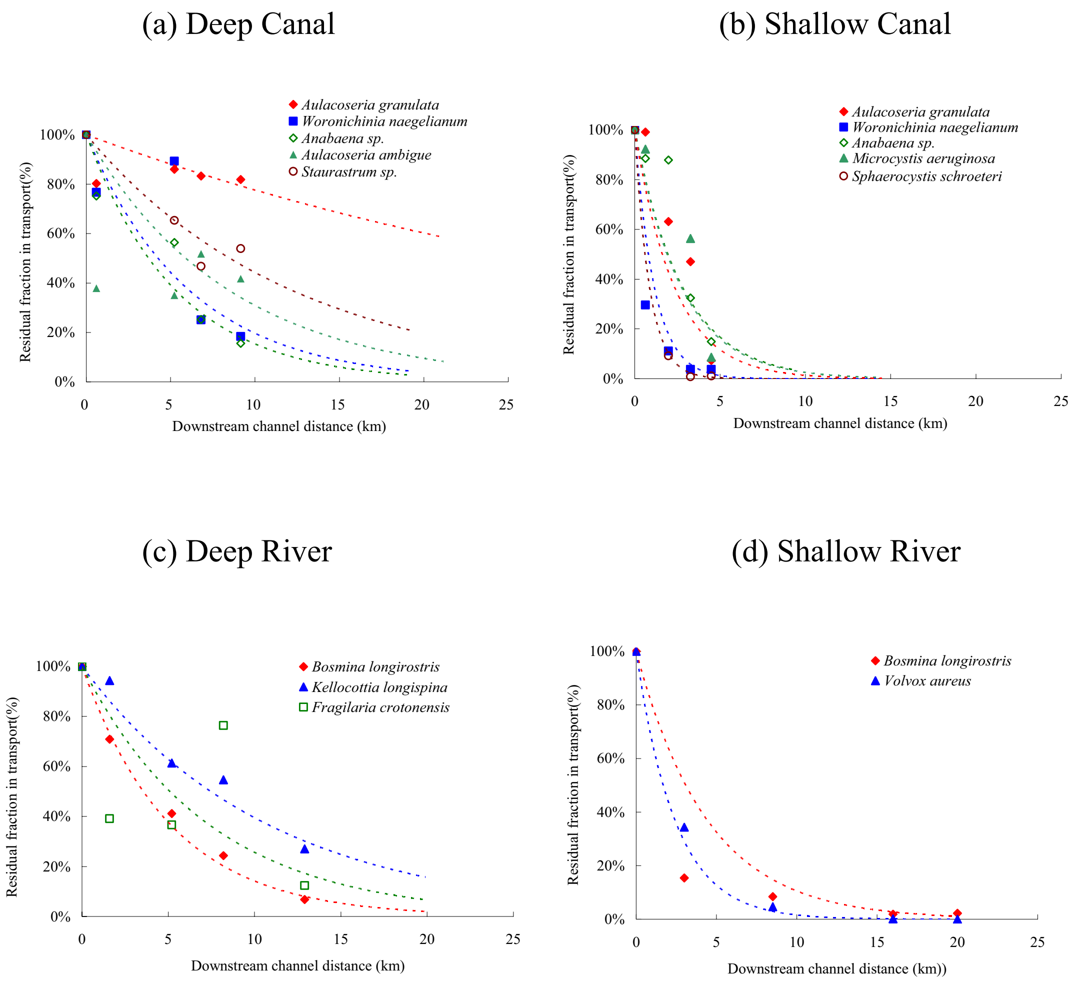


Fig.2-4 Downstream reduction patterns for tracer lentic plankters in the deep canal (a), the shallow canal (b), the deep river (c) and the shallow river (d). Each figure shows the residual fraction by transport and downstream distance.

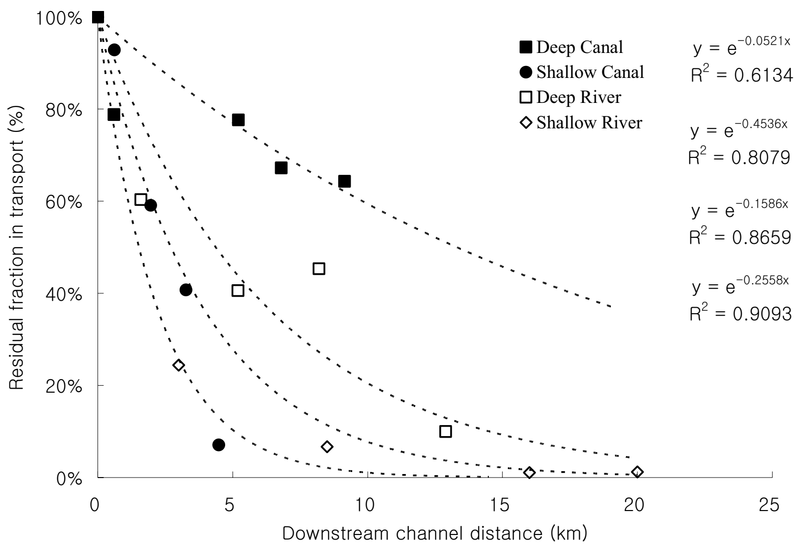


Fig.2-5 Inter-channel comparison of downstream reduction patterns of total tracer lentic plankters. Regression lines fitting well to the exponential reduction patterns were distinctly different among channels.

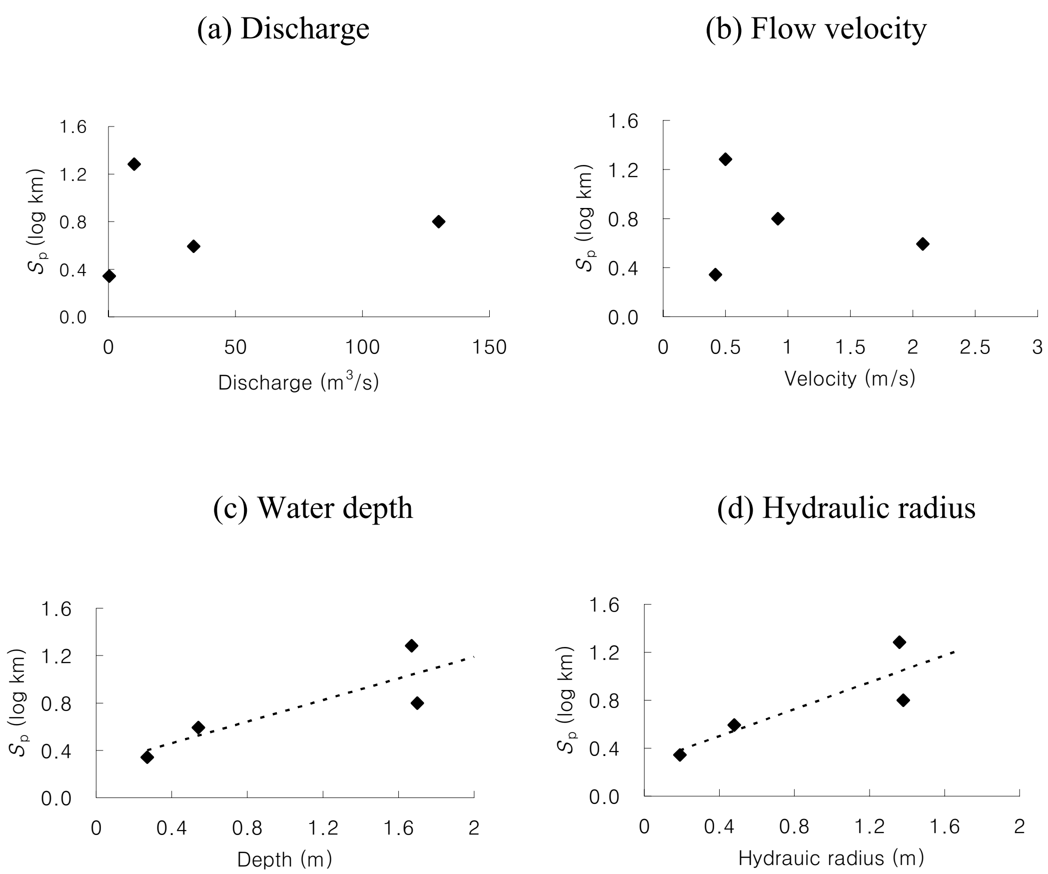
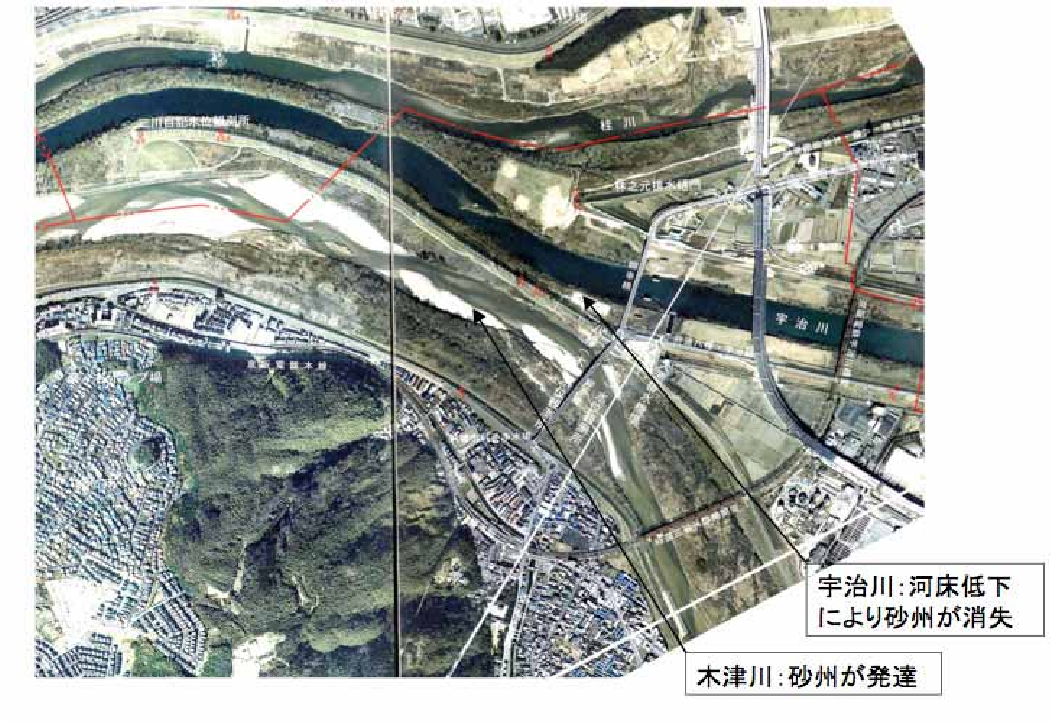


Fig.2-6 Relations between mean transport distance, S_p, and discharge (a), velocity (b), depth (c) and hydraulic radius (d). The values of Sp showed less correlation with discharge and velocity, and higher positive correlation with hydraulic radius (R^2=0.7359) and depth (R^2=0.7244)

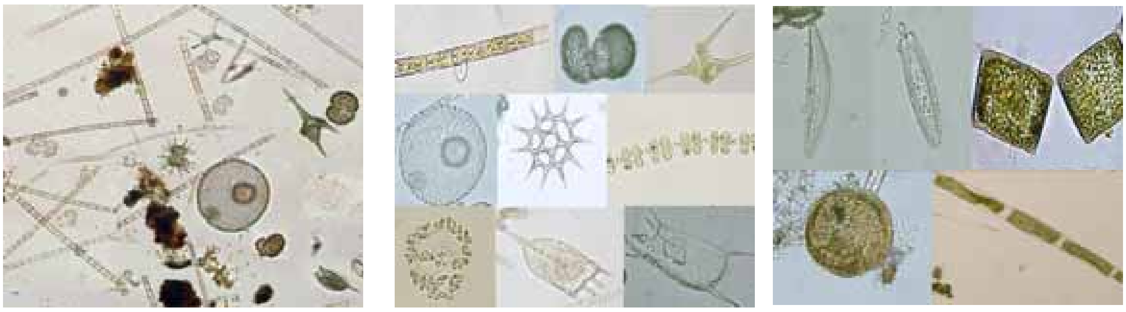
(a) Deep Canal (Kamogawa Canal)

(b) Shallow Canal (Sosuibunsen Canal)



(c) Deep River (Uji River,upper)　　(d) Shallow River (Kizu River,lower)

Photo 2-1 Channel shapes of the four channels. The deep canal (a), the shallow canal (b), the deep river (c) and the shallow river (d).



(a) (b) (c)

Photo 2-2 Optical microscopic images of suspended FPOM

(a) A sight of the microscopic identification of FPOM particles. (b) The lentic plankters; from left-up to clockwise *Aulacoseria granulata, Woronichinia naegelianum, Ceratium hirundinella, Spondylosium moniliforme, Pediastrum simplex, Volvox aureus, Dimorphococcus lunatus, Keratella cochlearis, Keratella quardrata*. (c) The instream algal materials; from left-up to clockwise *Cymbella* sp., *Surirella* sp., *Melosira varians*, *Oedogonium* sp., *Arcella* sp.

CHAPTER 3

Three Sources Contribution to POM in Dam Tailwater Ecosystems

3.1 INTRODUCTION

Since a riverine POM is a mixture comprised of unknown components, information on quantitative contribution of each component will provide a detailed and integrated recording of natural and anthropogenic activity within basin (Hedges *et al.* 1986). The POM is derived trophically from allochthonous terrestrial origins (e.g. forested tree leaf and twig, floodplain macrophytes) and autochthonous instream production (e.g. algae, bryophytes and cyanobacteria). POM transports to the downstream, transforming its location (i.e., suspended POM and benthic POM) and size from coarse POM (Φ>1.0㎜) to fine POM (Φ<1.0㎜). The longitudinal POM balances of composition, location and size have been known to influence downstream spatial distribution of functional feeding groups (Vannote *et al.* 1980; Hawkins and Sedell 1981; Tanida and Takemon 1999; Monaghan *et al.* 2001).

Dam construction in the upstream is likely to alter the balance of POM composition and size fraction in the downstream because of lentic plankton which is produced in dam reservoirs and flushed to the downstream by outflows. Therefore the dam tailwater POM was supposed to be mainly comprised of the three sources i.e. lentic plankton, allochthonous terrestrial plant and autochthonous algae. However, the knowledge on how much and how the plankton influences downstream POM composition and its effects on downstream ecosystem have been poorly understood. From a methodological perspective, the source origin of fine POM is difficult to infer simply by examining POM relative to coarse POM. However studies using a variety of techniques give us some insight into the importance of the multiple sources of POM in dam tailwater channel. Inspection of fine particles by stereo-microscope examination allows direct identification of source materials and can provided a quantitative result on relative abundance of detailed source materials (Nichols and Garling 2000; Ock and Takemon 2010). Stable isotope ratios, in particular carbon and nitrogen have also been widely used to trace POM sources because different sources often have distinct isotopic composition. Indeed, some case studies observed that the lentic plankton could influence the value of $\delta^{13}C$ in SPOM of dam tailwater channel (Angradi 1993; Kendall *et al.* 2001; Chen and Jia 2008; De Junet *et al.* 2009).

Stable isotope mixing model has been applied in a wide range of ecosystem for estimating relative contribution of sources to an unknown mixture (Peterson 1999; Phillips 2001). As to POM source composition, a two source mixing model using single $\delta^{13}C$ have been often applied to calculate the fractional contribution between allochthonous and autochthonous sources (Doucett *et al.* 1996; Finlay *et al.* 2002; Doi *et al.* 2007). In dam tailwater ecosystems, since the lentic plankton is expected to contribute to POM as a major energy source, a multi source mixing model more than two sources should be applied, but little application has been reported. There are three methods available to estimate relative contribution of POM source composition: i.e. a microscopic examination (ME), two stable isotope mixing models combined $\delta^{13}C$-$\delta^{15}N$ such as a standard linear model (SLM) and a concentration-weighted model (CWM). However little information on which is suitable for application in dam tailwater ecosystems has been investigated yet.

The present study aims (1) to test the three quantification methods for POM source composition in dam tailwater ecosystem, and them (2) to show their limitation or merits in application and finally (3) to investigate a variation of the three sources (i.e. lentic plankton, terrestrial plant and epilithic algae) contribution among S-FPOM, S-CPOM, B-FPOM and B-CPOM (*refer to* Fig.1-3).

3.2 METHODS

3.2.1 Site description

The filed study was conducted in downstream reaches below the Amagase Dam, a multi-purposes arch dam with 73 m height and 26.3 million m^3 storage capacity constructed in 1964(JCOLD 2007)., in the Uji River, the tributary of the Yodo River system in west central Japan (34°52′ N, 135°49′ E).

The study was conducted within reaches of 1.6 km in total distance from the dam outlet. The channel has a mean width of 45 m and depth of 1.7 m (Fig.3-1). Flow discharge is regulated by dam operation into a stable condition and bed materials are dominated by cobble and boulder or exposed bedrock due to armoring effect by reduced sediment transport. The climate of the basin is of typical monsoon and the basin is surrounded of 45.3% forest, which is mainly composed of deciduous broad-leaved trees with C3 photosynthesis pathway.

3.2.2 POM Sampling and classification

The reaches consist of subsequent riffle and pool structures. The decision of sampling sites was considered of the balance between the structures. In the present study, we dealt with only the averaged values for representing the reaches and the standard deviation of them may show the variation between the structures. The variations among the sites will be dealt with next study.

A total number of 21 SPOM samples were collected in wadeable flowing sites using a net sampler with 30cm in diameter, 100cm in length and 100㎛in mesh size in January 2009 (Fig.3-2a). The sampler was dipped fully underwater to collect SPOM particles from water surface in the flowing zone. Each sample was taken for approximately one to three minutes until not occurring in adverse flow in net sampler, which depends on flow velocity and particle concentration. 7 benthic POM (BPOM) samples were collected at stagnant shallow sites with comparatively low velocity using a BPOM sampler (Fig.3-2b) which was specially designed for collecting BPOM on surface of riverbed quantitatively (Takemon *et al.* 2008). The sampler was composed of a translucent box opening to plankton net of 25㎛ in mesh size at one side. We brushed softly the top layer of river bed and collected resuspended particles in a gentle manner without disturbing the substrate. The collected both SPOM and BPOM samples were filtered *in situ* using a sieve of 1.0 mm mesh size to separate fine POM from coarse POM. Thus we prepared four types of POM samples: S-FPOM, S-CPOM, B-FPOM and B-CPOM. While BPOM samples was prepared only for stable isotopic analysis, SPOM samples were taken by duplicates work at each site; one for a stable isotope analyses and the other for microscopic examination. For preventing from decomposition before analysis, collected samples for stable isotope analysis were preserved in ice and samples for the microscopic examination were in 2% formalin solution in the field.

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 a distilled water in the laboratory to remove impurities. The purity was confirmed using a microscope. 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. For differentiating $\delta^{13}C_{phytoplankton}$ from $\delta^{13}C_{terrestrial\ plant}$ to avoid overlapping, SPOM samples were collected intentionally in winter because $\delta^{13}C$ of SPOM near dam outlet tended to be most depleted in winter in seasonal variation (Angradi 1993; Chen and Jia 2008).

3.2.3 Microscopic examination

We prepared preparates for a microscope examination using 2-4 drops of 25ul micropipette for each sample. All organic particles within a sight were identified into several taxonomic groups and counted using optical photomicroscope with 100 to 400 magnifications (Leitz DMRB / Nikon DMX1200F system). Inorganic particles like silt and mineral fragment were excluded from the counting. The counting was repeated with changing a sight until the total number of counting exceeded about 800. All algal particles were identified to possible the lowest levels of species, genus or family. Details of taxonomic identifications referred to Hirose and Yamagishi (1977) and Ichise and Wakabayashi (2005). As to unicellular algae, the number of cells was counted. While as to filamentous algae and colony forming algae, the number of filaments and colonies was counted, respectively. Relative abundance given as a ratio of particle numbers of each group to the total number was calculated.

We classified the organic particles into three groups; autochthonous instream algae, terrestrial plant fragments and dam originated lentic plankton. Filamentous epilithic green algae such as *Mougeotia* sp.*, Ulothix zonata* and *Cladophora glomerata* and benthic diatoms such as *Melosira varians* and *Tabellaria fenestrate* and tissue of moss attached on instream stones were included in the autochthonous instream source. Terrestrial plant detritus included woody plant tissue, fragments of reed, fallen leaf and aquatic plant under decomposition in water. The lentic plankton source was judged by the following component indicating reservoir products: i.e. non-filamentous green algae such as *Costerium aciculare, Staurastrum* spp., *Cloeocystis* sp. and *Pedisastrum* spp. and non-filamentous diatoms such as *Aulacoseria granulate, Fragilara crotonensis* and *Asterionella formosa*, blue green algae represented by *Anabaena* spp. and *Microcystis* spp. and rotifer zooplankters dominated by *Keratella cochlearis* and cladoceran zooplankters like *Bosmina longirostris*. Because of difficulties in judgment of origins, following components were excluded from the analysis of origins: i.e. insect tissue, other diatoms, other green algae, other blue green algae, *Uroglena ameriaca* and other zooplankters such as Copepoda.

3.2.4 Stable isotope analysis

All isotopic samples were dried at 60℃ for 24 hours and then ground to homogenized bulk samples in the laboratory. We measured stable isotope ratios and elemental concentration for carbon and nitrogen using the mass spectrometer system composed of EA1108 (Fisons, Milan, Italy), ConfloII and Delta-S (Finnigan MAT, Bremen, Germany). Stable isotope ratios were reported in the standard δ notation as the following equation (Eq.3-1):

$$\delta^{13}C \text{ or } \delta^{15}N\ (‰) = (R_{sample}/R_{standard} - 1) \times 1000 \qquad \text{(Eq.3-1)}$$

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 $\delta^{15}N$.

3.2.5 Three source mixing model using dual stable isotopes

In the present study, we assumed that POM drifting in dam tailwater ecosystem is a mixture comprised of three origin sources; lentic plankton supplied from dam reservoir, terrestrial plant products and instream epilithic algae. In order to estimate relative contribution of each source, two types of the three sources mixing model using

δ^{13}C and δ^{15}N were applied. The first type is a standard linear mixing model (hereafter, SLM) as three source mixing model using a simple linear mass balance (Phillips 2001)

$$\begin{aligned} & f_{B,p} + f_{B,t} + f_{B,s} = 1 \\ & \delta^{13}C_{POM} = f_{B,p} \cdot \delta^{13}C_p + f_{B,t} \cdot \delta^{13}C_t + f_{B,s} \cdot \delta^{13}C_s \\ & \delta^{15}N_{POM} = f_{B,p} \cdot \delta^{15}N_p + f_{B,t} \cdot \delta^{15}N_t + f_{B,s} \cdot \delta^{15}N_s \end{aligned} \quad \text{(Eq.3-2)}$$

where $f_{B,p}$, $f_{B,t}$ and $f_{B,s}$ represents the fractionation of biomass contribution to POM by lentic plankton, terrestrial plant and instream algae, respectively.

Although the SLM was developed for overcoming the limit of a two sources model (ref), the assumption of equal elemental concentrations among three end members (e.g. C % for δ^{13}C, or N% for δ^{15}N) is unlikely satisfied in real ecosystems.

The second one is a concentration-weighted mixing model (hereafter, CWM) being developed for compensating the defect of SLM (Phillips and Koch 2002). The model can take into account the difference of elemental concentration among end members. In the study, the following equations were modified from Phillips and Koch (2002) and Newsome *et al*. (2004) were adopted.

$$\begin{aligned} & f_{B,p} + f_{B,t} + f_{B,s} = 1 \\ & f_{C,p} + f_{C,t} + f_{C,s} = 1 \\ & f_{N,p} + f_{N,t} + f_{N,s} = 1 \end{aligned} \quad \text{(Eq.3-3)}$$

where $f_{C,i}$ and $f_{N,i}$ represents a fractionation of 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 following concentration-dependent mass balance equations.

$$f_{C,i} = \frac{f_{B,i} \times [C]_i}{\sum_i \left(f_{B,i} \times [C]_i \right)}$$
$$f_{N,i} = \frac{f_{B,i} \times [N]_i}{\sum_i \left(f_{B,i} \times [N]_i \right)} \qquad \text{(Eq.3-4)}$$

where $[C]_i$ 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.

$$\delta^{13}C_{POM} = \sum_i \left(f_{C,i} \times \delta^{13}C_i \right)$$
$$\delta^{15}N_{POM} = \sum_i \left(f_{N,i} \times \delta^{15}N_i \right) \qquad \text{(Eq.3-5)}$$

3.3 RESULTS

3.3.1 Relative abundances by microscopic examination

A total of 20 categories groups were classified by microscopic observations of S-FPOM samples collected from 21 sites and the mean relative abundance of each category was summarized in Table 3-1a. The results showed that S-FPOM was composed mostly of algal materials accounting for 88.2% of relative abundance. In particular, diatomic algae were the most abundant reaching up to 59.7%. Chlorophytes of 26.83% was the next abundant. Zooplankton dominated by *Keratella cochlearis* and *Bosmina longirostris* showed a relatively low abundance less than 1%. Detritus was

9.48% of relative abundance. Centric diatomic *Asterionella formosa* and linear diatom *Aulacoseria granulata* dominated accounting for 22.31 and 18.0 %, respectively (Table 3-1a).

Results of the S-FPOM classification into the three source groups were shown in Table 3-1b. It was found that the lentic plankton constituted as a major source of S-FPOM accounting for 70.85% in the downstream reaches, followed by autochthonous instream source (16.68%) and allochthonous terrestrial source (10.15%).

3.3.2 Relative contributions by stable isotope mixing models

Terrestrial plant, epilithic algae and lentic plankton showed distinctive stable isotopic signatures of $\delta^{13}C$ and $\delta^{15}N$ as end members of POM. These isotopic distinctions enabled application of the mixing model to quantify the relative contribution of each source (Table 3-2). Terrestrial plant was most depleted in both $\delta^{13}C$ (-29.60 ‰) and $\delta^{15}N$ (2.82 ‰). Lentic plankton showed -28.32‰ in $\delta^{13}C$ and the most enriched $\delta^{15}N$ of 12.96 ‰, the epilithic algae was characterized to be the most enriched $\delta^{13}C$ of -20.41‰ and large variation. Also the three end members had distinctively different carbon and nitrogen concentrations. Lentic plankton has the lowest [C] and C/N ratio than other two sources whereas terrestrial plant has higher [C] and C/N ratio (Table 3-2).

We calculate the relative contribution of each source to S-FPOM, S-CPOM, B-FPOM and B-CPOM by means of both SLM and CWM. Estimated values of the three sources contribution by the SLM formed a linear mixing triangle (Fig.3-3a), whereas those by th eCWM were plotted as a non-linear mixing triangle (Fig.3-3b). Such different shape of mixing triangles between the two mixing models resulted in different relative contributions (Table 3-3). Biomass contribution of the lentic plankton $f_{B,p}$ was estimated as lower and was that of terrestrial plant $f_{B,t}$ as higher by CWM than the SLM. As to S-FPOM, $f_{B,p}$ of CWM and SLM accounted for 47.0% and 70.1%, respectively. In contrast, $f_{B,t}$ showed 32.8% and 12.3%, respectively. S-FPOM comprised of comparatively balanced composition contributions showing dominant source of lentic plankton ($f_{B,p}$=47.0%). However S-CPOM comprised of mostly terrestrial plant ($f_{B,t}$=59.6%) and filamentous algae ($f_{B,s}$= 35.5%), but showed scarcity of lentic plankton (5.0%). In contrast, BPOM has largely similar composition characteristics irrespective of POM particle size. Both B-FPOM and B-CPOM were composed of mostly allochthonous filamentous algae ($f_{B,s}$ = 69.8 and 66.8%, respectively) (Table 3-3b).

In addition, the CWM provides elemental contributions to mixture and it serves important information on material or nutrient flow in ecosystem. As for B-FPOM and B-CPOM, both the contribution of C and N from instream algae was highest and it is very similar to that of the biomass fraction. However, S-FPOM and S-CPOM showed different contributions between C and N. The highest contribution of C was terrestrial plant ($f_{C,t}$=44.2%) and that of N was lentic plankton ($f_{N,p}$=67.7%) in S-FPOM. In contrast, the highest contribution of C was terrestrial plant ($f_{C,t}$ =65.0%) and the highest contribution N was filamentous algae ($f_{T,p}$=66.5%) in S-CPOM (Table 3-3c and d).

3.4 DISCUSSIONS

3.4.1 Suitability test of quantification methods for POM source composition in dam tailwater ecosystems

For quantification of POM source composition in the dam tailwater channel, we applied three methods; microscopic examination, ME, and stable isotope mixing models, the SLM and the CWM.

The microscopic examination can have an advantage to perform multi-source analysis for more than four sources. The unlimitation of the number of sources is a merit of the method. In addition, even among lentic plankton species produced in reservoirs, the reduction patterns in dam tailwaters are different among species and such species specific contribution in SPOM can be estimated only by the microscopic examination (Ock and Takemon 2010).

However, this method has following restrictions in comparison with stable isotope mixing model; First, the taxonomic identification and counting processes are likely a time-consuming thus demanding a long analytical duration. Second, production of potamoplankton which reproduced in the stream (Sze 1981; Allan and Castillo 2007) may make the source identification confuse. Finally, the method requires mass estimation in order to know the mass balance of some origins since the data are relative abundance of each source. Therefore the relative abundance of terrestrial plant with comparatively heavy weight was found to induce underestimation by 21.1%, while that of light lentic plankton was overestimated by 20.6% when compared with relative contributions determined from the CWM (Fig.3-4a, Table 3-1b and Table 3-3b).

Alternatively, the stable isotope mixing model may solve the restrictions of the microscopic method we mentioned before. The stable isotope mixing model provides mathematical estimation of fractional contribution of possible sources using mass balance equations among the sources and mixture. However, the stable isotope mixing model also has some problems to create application limitation and error; First, different sources can show partially overlapping isotopic compositions and sources can have considerable spatial and temporal variations in isotopic compositions (Kendall *et al.* 2007). Second, quantitative accuracy of the model is highly dependent on purity of end-members (Finlay 2001). In this study, the purities of three sources were assured by a series of sampling procedures including the impurities removal by rinsing out and then microscopic identification. Third, SLM may lead to inaccurate estimation due to different elemental concentrations among the sources because the model is available only when the elemental concentrations of each source are similar. Phillips and Koch (2002) suggested CWM was developed for correcting SLM whenever elemental concentrations vary substantially among the sources. In dam tailwater POM mixture, sources were found to have considerably different elemental concentrations. For example, lentic plankton had much higher [N] and lower C/N ratio, whereas terrestrial plant had higher [C] and C/N ratio than other two sources (Table 3-2). In the mixing triangular structure, lentic plankton and terrestrial plant showed more sensitive changes on iso-contribution lines in combined $\delta^{13}C$ and $\delta^{15}N$ composition axes plot respectively (Fig.3-3).

When SLM were compared with CWM, we found that the terrestrial plant tended to be underestimated by 19.0%, whereas lentic plankton to be overestimated by 21.4% as shown in Fig.3-4b, because plotted locations of S-FPOM responds more sensitively both to terrestrial plant with relatively high [C] and to lentic plankton with high [N]. The underestimated contribution of terrestrial plant by SLM is consistent with results of Philips and Koch (2002). They demonstrated relative contribution of terrestrial plant, which had the lowest [N] among three diet sources of bears, by LSM was much lower by 13-17% than by CWM.

Relative contribution of autochthonous and allochthonous sources in trophic origin has been estimated through several methods in freshwater ecosystems (Table3-4). Among them, SLM has been most popular method for the estimation. Allochthonous contribution are more in the order of headwater>mountain stream>lake>large river. Autochthonous contribution, particularly, focused on as a main trophic sources in river productivity concepts (Thorp and Delong 1994; Thorp and Delong 2002)

However, our results of comparison between contribution values of SLM and CWM indicate that previous estimates on allochthonous contribution based on SLM in aquatic foodwebs can be much higher than expected, whereas autochthonous contribution can be vice versa. Therefore, effects of elemental concentration difference should be reconsidered for the estimation of trophic sources in aquatic ecosystem.

3.4.2 Isotopic characteristics of three sources comprising of dam tailwater POM

In order to determine source components to mixture and to quantify the contribution of each source using a three source mixing model, the coordination plot made from three end members in dual isotopes axes should form triangle structure and target unknown mixtures should located within the mixing triangle (Peterson 1999; Phillips and Gregg 2003; Fry 2006). In the present study, we assumed that dam tailwater POM is a mixture which comprised of three origin sources of dam originated lentic plankton, allochthonous terrestrial plant and autochthonous instream algae. The assumption was supported by our result that all dual isotope plots of S-FPOM, S-

CPOM, B-FPOM and B-CPOM were surrounded by a mixing triangle comprising of the three endmember of origin sources (Fig.3-3). Table 3-2 showed that the terrestrial plant, epilithic algae and lentic plankton had distinctive stable isotopic signatures, which allowed making mixing triangle in dual isotope plots.

Both $\delta^{13}C$ and $\delta^{15}N$ of terrestrial plant tissues in the study showed the most depleted values in $\delta^{13}C$ (-29.60 ‰) and $\delta^{15}N$ (2.82 ‰), which are nearly correspondent to the general observations found in temperate forest. The average $\delta^{13}C$ value of C3 tree is known to be rather constant around -28‰ due to sharing common Calvin photosynthesis pathway using a single form inorganic carbon, CO_2, derived from a large and well mixed atmospheric pool (O'Leary 1981). $\delta^{15}N$ in forest tree tissue and fresh litter generally ranged from about -4 to +3‰ (Fry 1991; Nadelhoffer and Fry 1994) although exceptions were occasionally observed among species and/or location with different nitrogen uptake pathways (Evans 2001).

The $\delta^{13}C$ of the lentic phytoplankton in the study showed -28.32‰ that was not distinctively different from that of the terrestrial plant. It has possibility to be overlapping of $\delta^{13}C$ between lentic plankton and terrestrial plant, because $\delta^{13}C_{pytoplankton}$ often appeared to be much lower value around -30% due to influence of methane production through benthic metabolism which contributes strongly to low $\delta^{13}C_{DIC}$ (Vuorio *et al.* 2006). However, phytoplankton $\delta^{13}C$ was found to be more enriched than terrestrial $\delta^{13}C$ and to be the highest values of $\delta^{15}N$ (12.96 ‰) among the three sources, which enabled lentic plankton to discriminate from terrestrial plant within mixing triangle plots. Stable nitrogen isotope is known to be strongly influenced by urban development, population size and nutrient load in the basin (Lake *et al.* 2001; Kendall *et al.* 2007). Thus the high phytoplankton $\delta^{15}N$ indicates a high anthropogenic activity in the basin. Epilithic algae was characterized by the most enriched $\delta^{13}C$ of -20.41‰ with a large variation, which is partially due to riverine dissolved inorganic carbon with relatively enriched $\delta^{13}C_{DIC}$ compared with that of dam reservoir (Finlay *et al.* 1999; Finlay 2001). These isotopic distinctions enabled the mixing model to quantify the relative contribution of each source.

3.4.3 Contribution of the lentic plankton to C and N flows in dam tailwater foodweb systems

Based on the results from CWM (Table 3-3), we found the disincentive difference in fractional contribution between S-FPOM and B-FPOM. The difference may contribute to quantification of dam impacts on tailwater ecosystem: S-FPOM has possibility to apply as a tracer of dam reservoir product, because lentic plankton supplied from dam reservoir highly influence S-FPOM composition relative to the other POM types. Moreover, it has implication of trophic pathway in benthic animal communities. The filter-feeding invertebrates using S-FPOM as an energy source are susceptible to dam reservoir environment relative to other functional feeding groups. Indeed, spatial expansion of freshwater bivalves and caddisfly in the downstream below a dam were frequently reported (Spence and Hynes 1971; Hatano *et al.* 2005). On the other hand, B-FPOM was mostly comprised of epilithic algae accounting for 69.4% and biomass of S-CPOM was dominated by terrestrial plant fragments (59.6%) (Table 3-3). These results indicate that the flowing zone and stagnant zone (*refer to* Fig.1-3) have spatially different POM source composition, which may lead to separated habitat conditions trophically for aquatic invertebrate. This indicates that spatially various POM source compositions may contribute to the biological diversity in dam tailwater reaches.

Carbon and nitrogen flows are interesting in the dam tailwater ecosystem. The carbon transport in S-FPOM relies on allochthonous terrestrial input (44.2%) despite small biomass fraction in the dam tailwater ecosystem, whereas the nitrogen transport in S-FPOM relies on mostly lentic plankton input (Table 3-3). Therefore the possibility can be proposed that foodwebs energy flow and nitrogen transport system in the dam tailwater ecosystem were significantly supported by lentic plankton derived from the dam reservoir.

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Table 3-1 Microscopic examination for S-FPOM source composition. Relative abundance of each category based on number of particles counted was calculated (a) and the abundance contributions of three sources (b) were recalculated according to their source origins (b). The values are mean abundance and standard deviation (S.D) in a total of 21 samples (*n* = 21).

(a) Relative abundance of each category

Category			Code	Relative abundance (%)	S.D (%)
Algae	Diatoms	*Asterionella formosa*	(1)	22.31	4.10
		Aulacoseria granulata	(2)	18.04	5.10
		Melosira varians	(3)	6.77	2.45
		Fragilaria crotonensis	(4)	6.36	0.93
		Tabellaria fenestrata	(5)	5.25	3.14
		Others	(6)	1.02	0.30
		Sub total		*59.75*	
	Chlorophytes	*Costerium aciculare*	(7)	12.24	1.76
		Staurastrum spp.	(8)	9.98	2.14
		Filamentous green algae	(9)	4.27	1.96
		Others	(10)	0.34	0.09
		Sub total		*26.83*	
	Blue green algae	*Anabaena* spp.	(11)	0.23	0.19
		Microcystis spp.	(12)	0.62	0.21
		Others	(13)	0.72	0.37
		Sub total		*1.57*	
	Flagellates	*Uroglena americana*	(14)	0.07	0.07
Animal	Zooplankton	Rotifers	(15)	0.31	0.15
		Cladoceran	(16)	0.76	0.43
		Others	(17)	0.00	0.00
	Insect fragment		(18)	0.21	0.15
	Sub total			*1.28*	
Terrestrial plant detritus			(19)	9.48	4.63
Macrophyte fragment			(20)	0.67	0.25
Moss tissue			(21)	0.39	0.19
Total				*100*	

Table 3-1 (Con't)

(b) Abundance contribution of three sources

Source origins		Code components	Abundance contribution
Dam originated lentic plankton	D_p	(1)+(2)+(4)+(7)+(8)+(11)+(12)+(15)+(16)	70.85 %
Autochthonous instream source	D_s	(3)+(5)+(9)+(21)	16.68 %
Allochthonous terrestrial source	D_t	(19)+(20)	10.15 %
Unknown source		(6)+(10)+(13)+(14)+(17)+(18)	2.37 %

Table 3-2 Stable isotope signatures, CN concentrations and C/N ratio of three possible POM sources and stable isotopic signatures of the four types of POMs.

	n	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	[C] %	[N]%	C/N
Source origins						
T.Leaf	3	-29.60±0.44	2.82±0.15	44.33	0.80	55.30
E.Algae	4	-20.41±2.61	6.83±0.93	37.25	3.61	10.40
L.Plankton	3	-28.32±0.10	12.96±0.15	23.12	4.42	5.25
POM type						
S-FPOM	21	-27.08±0.69	10.63±0.92			
S-CPOM	15	-26.58±2.11	6.54±2.10			
B-FPOM	7	-23.23±1.73	7.32±0.61			
B-CPOM	7	-23.52±1.99	7.24±1.08			

[C] and [N] mean the concentration of carbon and nitrogen, respectively.
where the concentration is the ratio of weight of carbon or nitrogen to the total weight of target sample.

Table 3-3 Comparisons of fractional contributions of POM source composition determined by standard linear mixing model and concentration-weighted model.

(unit: %)

	Standard model			Concentration-weighted model								
	(a) Biomass			(b) Biomass			(c) Carbon			(d) Nitrogen		
	$f_{B,p}$	$f_{B,s}$	$f_{B,t}$	$f_{B,p}$	$f_{B,s}$	$f_{B,t}$	$f_{C,p}$	$f_{C,s}$	$f_{C,t}$	$f_{N,p}$	$f_{N,s}$	$f_{N,t}$
S-FPOM	**70.1**	17.6	12.3	**47.0**	20.2	32.8	33.0	22.8	**44.2**	**67.7**	23.7	8.6
S-CPOM	25.1	29.3	**45.6**	5.0	35.5	**59.6**	2.2	32.8	**65.0**	8.8	**66.5**	24.6
B-FPOM	17.9	**66.8**	15.2	8.2	**69.4**	22.4	5.0	**68.6**	26.4	11.9	**82.2**	5.9
B-CPOM	18.5	**63.6**	17.9	7.6	**66.8**	25.6	4.6	**65.5**	29.9	11.3	**81.7**	7.0

The index of $f_{B,i}$, $f_{C,i}$ and $f_{N,i}$ represents fractionations of biomass, Carbon and Nitrogen, respectively, contributed to the POM by source *i*. Source *i* corresponds to lentic plankton (p), terrestrial plant (t) and instream algae (s) respectively.

Table 3-4 Values of autochthonous and allochthonous contributions estimated in various aquatic foodwebs studies.

Study material	Assumed sources	Autochthonous contribution (%)	Allochthonous contribution (%)	Reservoir origin Contribution (%)	Quantificati-on method	Habitat type	Study site	Reference
BPOM	Terrestrial plant periphyton	70.5 (open reach) 50.2 (shaded reach)	29.5 (open reach) 49.8 (shaded reach)		SLM*	Mountain stream	Kamo River, Japan	(Doi *et al.*, 2007)
Benthic invertebrates	Terrestrial leaf Epilithon	28-63	37-72		SLM*	Headwater stream	Ginzan Creek, Japan	(Watanabe *et al.*, 2008)
Crustacean zooplankton	Allochthonous POM phytoplankton		4 (min. summer) 38 (average) 89 (max. winter)	96 (max. summer) 62 (average) 11(min. winter)	SLM*	Lake	Loch Lake, UK	(Grey *et al.*, 2001)
Bacteria	Allochthonous DOC Autochthonous DOC	30-65	35-70		SLM*	Lake	Paul and Peter Lake, USA	(Kritzberg *et al.*, 2004)
Herbivores (Snail, shrimp)	Leaf litter, Allochthonous FPOM Periphyton, Cyanobacteria, Filamentous algae	41.3 (snail) 39.3 (shrimps)	58.7 (snail) 60.7 (shrimps)		SLM**	Headwater stream	TaiPoKau River, Hongkong	(Lau *et al.*, 2009)
S-FPOM B-FPOM	Lentic plankton, epilithic algae terrestrial plant	17.6 (S-FPOM) 66.8 (B-FPOM)	12.3 (S-FPOM) 15.2 (B-FPOM)	70.1 (S-FPOM) 17.9 (B-FPOM)	SLM	Dam tailwater stream	Uji River, Japan	Present study
Littoral zone consumers	Allochthonous POM Autochthonous POM	85	15		CWM†	Lake	Boomanjin Lake, Australia	(Hadwen and Bunn, 2004)
Secondary consumer (*Acroneuria* sp.)	Benthic algae, colloidal DOM, Terrestrial leaf litter, fine Algae, fine Detritus, Macrophytes	0-12 (algae) 62-74 (Fine algae)	0-20 (Terr. leaf) 0-24 (Fine detritus) 0-8 (Macrophytes)		CWM‡	Large river	Upper Mississippi River, USA	(Delong and Thorp, 2006)
S-FPOM	Lentic plankton, Epilithic algae, Terrestrial plant	20.2 (S-FPOM) 69.4 (B-FPOM)	32.8 (S-FPOM) 22.4 (B-FPOM)	47.0 (S-FPOM) 8.2 (B-FPOM)	CWM	Dam tailwater stream	Uji River, Japan	Present study

SLM: standard linear mixing model, CWM: concentration-weighted mixing model.
* Two source model based on SLM, ** Five source model based on SLM, † Two source model based on CWM, ‡ Six source mixing model based on CWM

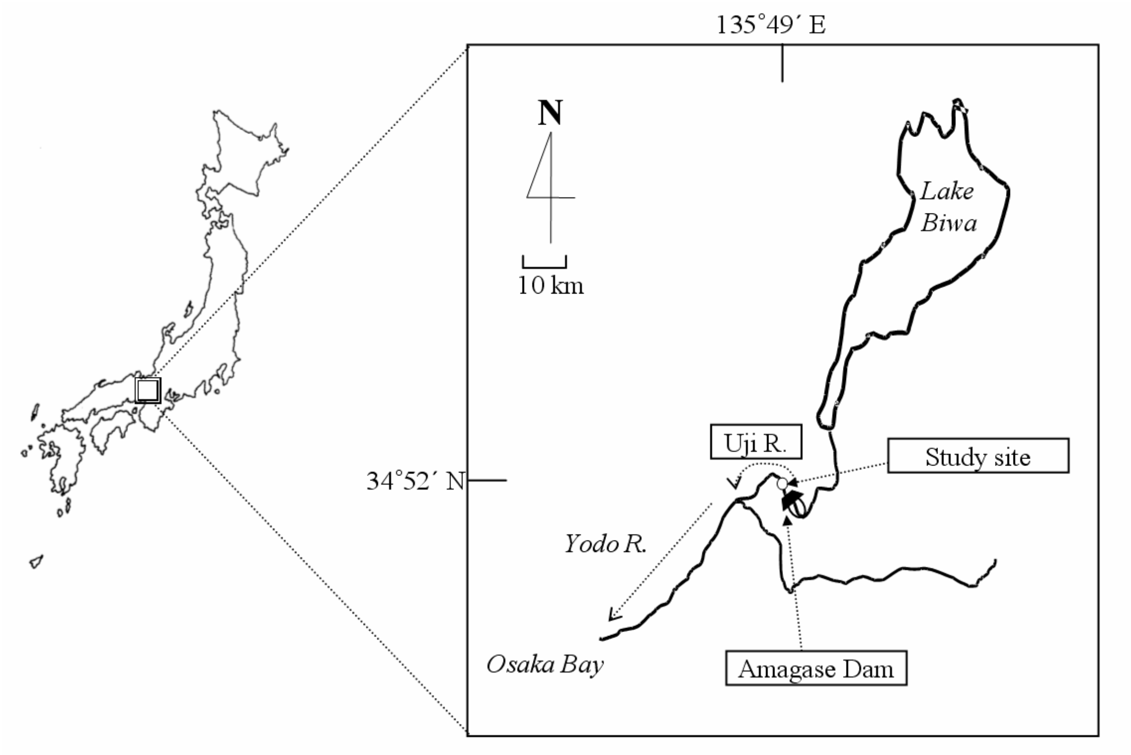
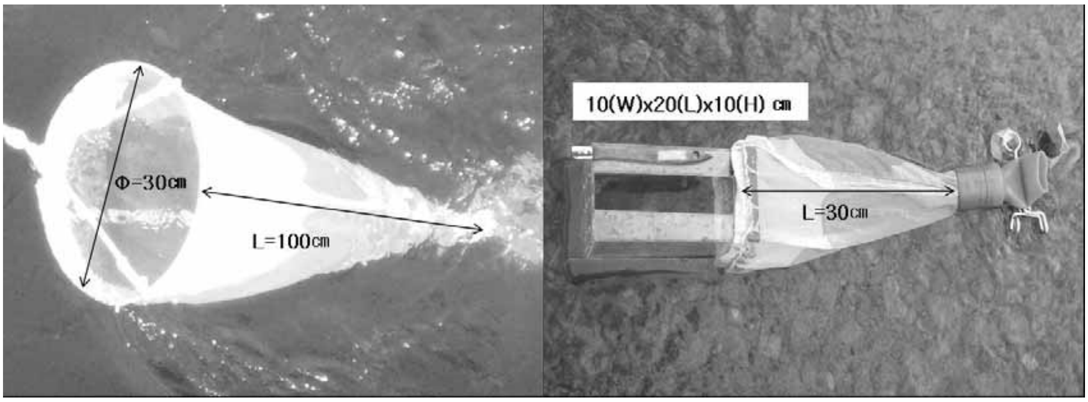
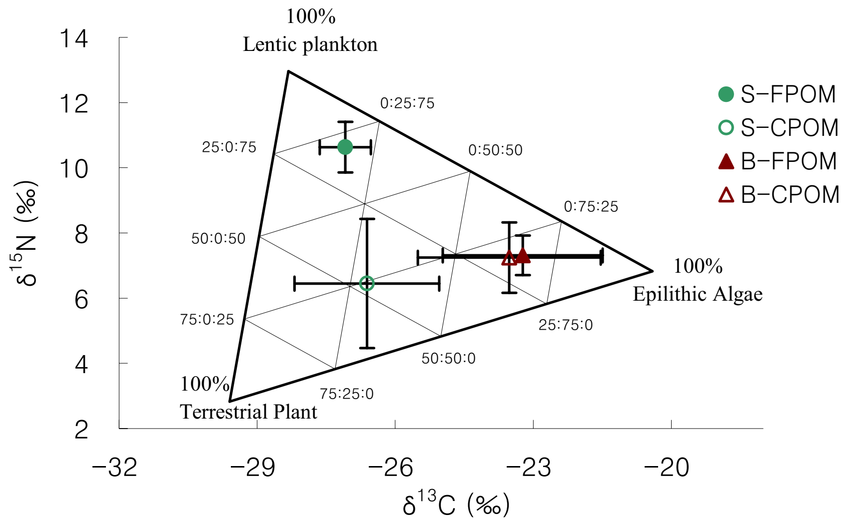


Fig.3-1 A map of study site in the Uji River located below the Amagase Dam in the Yodo River Basin, West-central of Japan.

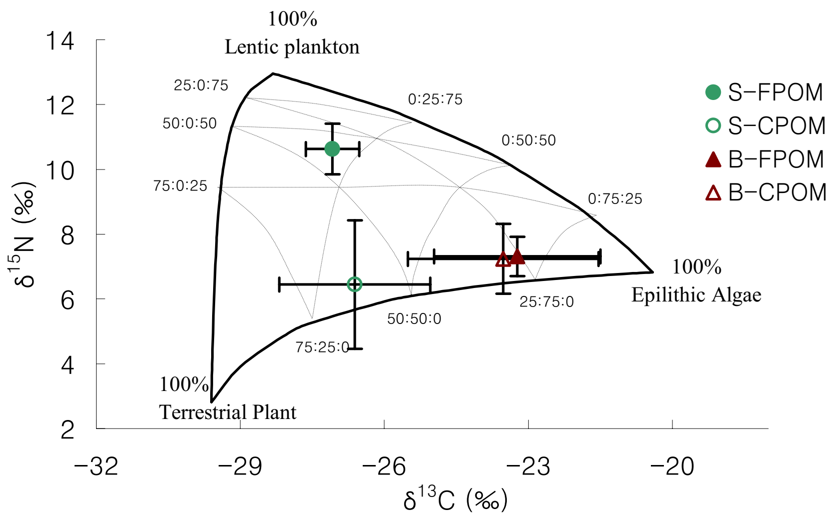


(a) (b)

Fig.3-2 Field view of SPOM sampler (a) and BPOM sampler (b). The upper part of BPOM sampler is open for soft brushing. SPOM was collected in active channel with relatively running water condition while BPOM was in channel boundary with relatively still water condition.

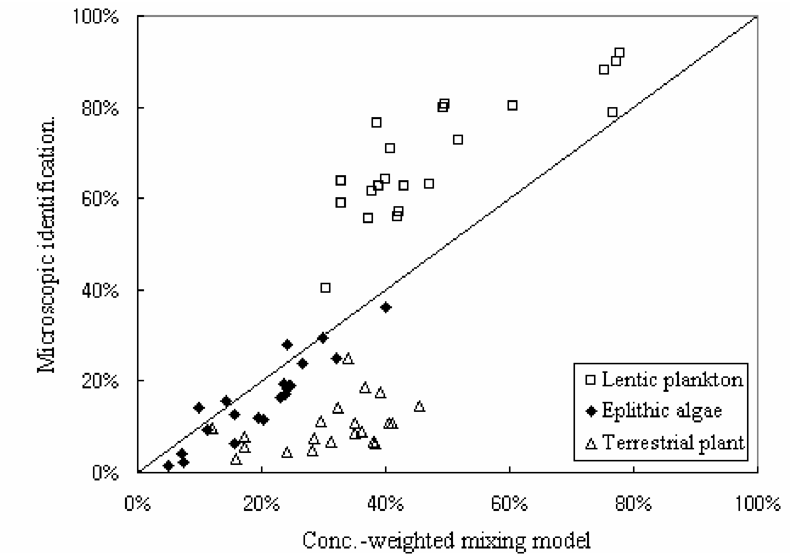


(a) SLM

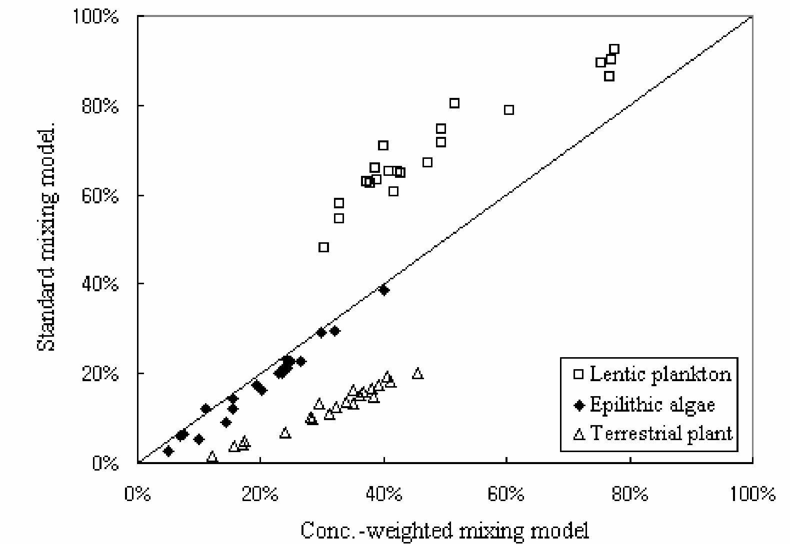


(b) CWM

Fig.3-3 Mixing triangles of a dam tailwater POM in stable isotope mixing model; (a) Standard linear model (SLM) showing a linear mixing triangle, (b) Concentration-weighted model (CWM) showing a non-linear mixing triangle. Values of ratios composed of three sources are in order of terrestrial plant : epilithic algae : lentic plankton.



(a) CWM vs ME



(b) CWM vs SLM

Fig.3-4 Comparisons of quantitative methods for relative contributions of dam tailwater POM sources; between microscope examination and concentration-weighted mixing model (CWM) (a), and between standard linear mixing model (SWM) and CWM (b). Both microscopic examination and standard model underestimated the terrestrial plant source but overestimated the lentic plankton source.

CHAPTER 4

Downstream changes in POM source composition and benthic communities in dam tailwaters in relation to channel geomorphology

4.1 INTRODUCTION

Knowledge on transport and deposition of particulate organic matter (POM) has been increasingly required for habitat management and restoration in lotic ecosystems because POM in running water plays a critical role in supporting heterotrophic food webs by providing energy resources and in structuring microhabitats for benthos communities. Although POM in a large river is generally derived from allochthonous terrestrial plant and autochthonous primary production being changed of its composition and size distribution (Vannote *et al.* 1980), tailwater ecosystems below dam reservoirs have been imposed to alter such SPOM dynamics due to being supplied large amount of lentic plankton as an independent food source and to increasing fine POM (FPOM, <1.0 mm) stock by settling of coarse POM (CPOM, >1.0mm) in the reservoirs (Angradi 1993; Kendall *et al.* 2001). Such alteration of SPOM composition by reservoir dams has been known as the discontinuity concept (Ward and Stanford 1983) also influencing the composition of functional feeding group of macro-invertebrate communities (Tanida and Takemon 1999; Monaghan *et al.* 2001). Some recent studies have showed the longitudinal changes of SPOM source composition in the dam tailwater channel (Angradi 1993; Vadeboncoeur 1994; Chen and Jia 2008). In addition, Ock and Takemon (2010) showed FPOM transport distance and deposition velocity are correlated well with hydraulic radius of a channel.

In a riffle and pool scale in dam tailwaters, however, longitudinal changing patterns of the SPOM source composition for FPOM transport distance and deposit velocity have never been investigated yet. In addition, subsequent effects of reach scale changes of S-FPOM source composition on the benthic communities was rarely reported in dam tailwater ecosystems. Development of stable isotopic analyses allows to identify origin of POM and application of mixing models using stable isotopic tracers through mass balance equations make it possible to quantify the source contribution to mixture (Fry 2006).

In the present study, we investigated the downstream changes of SPOM composition in relation to geomorphic features and benthic animals including filter-feeding mussels in the downstream below dam reservoirs. Relative contributions of terrestrial plant, instream algae and lentic plankton as SPOM source origins in riffle and pool structures were analyzed by the stable isotope mixing model.

4.2 METHODS

4.2.1 Site description

The study was carried out in the downstream reaches of about 1.6 km in length from the outlet of the Amagase Dam in the Uji River, the tributary of the Yodo River in west-central Japan (Fig.4-1a). Construction of the dam in 1964 resulted in degradation of the river bed in its tailwaters and exposed bedrock dominated in the study reaches. Seven sampling sites were established at the border area of two sets of riffle-pool (Fig.4-1 and Table 4-1).

4.2.2 Field Samplings

(a) SPOM and its potential sources

SPOM samples were collected using a POM net sampler with 100㎛ in mesh size and 30cm in diameter of flame size (Fig.3-2a and Photo 4-1) at each site in January 2009. For sampling of stable isotope analysis, the POM net was kept in the water for one to three minutes. Three replicates were collected at each site. Each S-FPOM samples was filtered in situ using the sieve of 1.0 ㎜ mesh size to separate it from S-CPOM. For quantifying S-FPOM concentration (the weight of S-FPOM per unit water volume), additional three replicates of samples were collected at each site. The current velocity in front of the net opening and elapsed sampling time were measured using a current-meter (CR-11, Cosmoriken) to estimate the volume of water filtered through the net sampler (Photo 4-1). S-FPOM concentration ($C_{S\text{-}FPOM}$) was calculated by Eq.4-1:

$$C_{S\text{-}FPOM}\ (\mu g/m^3) = \frac{Ash\ free\ dry\ weight\ \ of\ S\text{-}FPOM}{Volume\ of\ water\ filtered\ through\ the\ sampler} \qquad \text{(Eq.4-1)}$$

where the Ash free dry weight (AFDW), which is calculated as the weight of the dry weight (oven dried in 60℃ for 24 hours) minus the residual ash (combusted in 600℃ for 2 hours). As the same method, S-CPOM was also measured.

Terrestrial plant leaves, epilithic algae and lentic plankton were also collected as SPOM source origins. Detail informations on the sampling and procedures were described in the 3.2.2. Stable isotope values of carbon and nitrogen were analyzed. Relative contribution of each source to S-FPOM was estimated by means of the concentration-weighted three source mixing model using combined isotopes of carbon and nitrogen. Details in the stable isotope analysis and calculation of the relative contribution of each source using the concentration-weighted mixing model were described in the 3.2.4 to 3.2.5.

Using both the S-FPOM concentration and the biomass contribution of the three sources, the source-specific concentrations were estimated as Eq.4-2:

$$C_i\ (\mu g/m^3) = C_{S\text{-}FPOM} \times f_{B,i} \qquad \text{(Eq.4-2)}$$

where, C_i means the source-specific concentration from the source i. $f_{B,i}$ represents the biomass contribution to the S-FPOM by the source i. Source i corresponds to either lentic plankton (p), terrestrial plant (t) or epilithic algae (s).

(b) Filter-feeding mussel

Freshwater golden mussel, *Limnoperna fortunei*, which was dominant filter feeder in the reaches, was collected together with attaching stones at upper, middle and lower parts of each riffle. The stones surface was carefully to remove all the mussels into a bucket. All the collected mussels were preserved in 4% formalin solution and brought to the laboratory, fresh individuals having hard shells with soft tissues and dead ones having transparent empty shells without soft tissue were separately counted. Total weight of each type of shells was measured. The surface area of stones were measured using the following Eq.4-3 of Graham *et al.* (1988).

$$\textit{Surface Area} = 1.15\ (LW + WH + HL) \qquad \text{(Eq.4-3)}$$

where L, W and H are length, width and height of the stone respectively. It has been often applied due to its simplicity, accuracy and precision (Lam *et al.* 1992).

'Population density' of the mussels was calculated based on the number of living individuals and the stone surface area. 'Biomass' was similarly calculated as the ratios of the biomass of living shells to the unit surface area of the stone. In addition, 'death rate' of the mussel was calculated as the weight ratio of the dead individuals to the total ones.

(c) Aquatic animals

Benthic macro invertebrates and fishes were collected qualitatively at the Riffle1 (St1-St2), the Riffle2 (St3-St4) and the Glide (St5-St6) using a hand-net of 0.6x0.5mm mesh size. After collection of animal samples, specimens for stable isotope analysis were collected by handpicking in the field. The works took about one hour (25 min sampling and 35min sorting and picking) at the three sites with the same sampling effort. The benthic invertebrates were identified to the species or genus level. The animals were categorized not only into seven life form groups such as net-spinners, attachers, crawlers, case-bearers, gliders, swimmers and burrowers, but also into five functional feeding groups such as filterers, collector-gatherers, grazers, shredders and predators (Hatano *et al.* 2005; Takemon 2005). For stable isotope analysis, most of the samples were ground into a powder but small animal samples with less than 1 mg in dry weight were analyzed in bulk.

4.2.3 Measurements of bed elevation and flow velocity

Through the study reaches, the water depth and flow velocities (x, y and z directions) were measured by means of the ship-mounted ADCP (Acoustic doppler current profiler, RD Instrument, USA) system (Muto *et al.* 2006) in pool zones where the water depth exceed about 1m. A level and a portable current meter were used for the measurement in riffle zones where the ADCP measurement was not applicable (Photo 4-2). Measurements by the ADCP system were performed in cross sections with their intervals of about 50m distance. Bed elevation was calculated from the water depth and elevation of the base point in the bank. Three components of velocities were obtained in each cross section. In particular, cross sectional distribution of vertical velocity (w) was investigated for examination of a dominant vertical flow such as upwelling or downwelling (Fig.4-3) at each cross section.

4.3 RESULTS

4.3.1 Hydro-geomorphological characteristics

Longitudinal profiles of bed elevation and water slope of the studied reaches made it possible to differentiate their characteristics as two sets of riffle-pool, and one glide-pool (Fig.4-1). The two riffles had flows of high velocity with forming air-bubbles and steeper surface gradient, whereas the glide was composed of bedrock with gentle surface gradient (Table 4-1, Fig.4-1 and Photo 4-4). From the cross sectional profiles taken with 100m intervals, a various geomorphological parameters were calculated such as width, depth and hydraulic radius (Fig.4-2). Hydraulic radii (R_h) of the riffles (0.51 m at No. 53.1 and 0.53 m at No.52.5) were less than those of the pools (3.08 m at No.53.0 and 2.78 m at No.51.8) (Table 4-2).

In addition, predominant vertical flow was analyzed in each cross section and summarized in Table 4-6. In riffle sections whose depth is shallow (e.g., No.52.4 and 52.6), a downwelling was found. But the pools had various patterns according to the local characteristics. The Pool1 (St2-St3) showed more dominant in upwelling flows, whereas the Pool2 (St6-St7) was dominant of downwelling flows.

4.3.2 Stable isotope values of S-FPOM and its sources

As already explained in Chapter 3, in order to confirm source components to mixture and to quantify the relative contribution of each source by means of the three source mixing model, the coordination plot of three sources in two isotopes axes should form a triangle structure, and target mixtures should located within the mixing triangle (Peterson 1999; Phillips and Gregg 2003; Fry 2006). In our results, coordination plot in the $\delta^{13}C$ and $\delta^{15}N$ axes formed by the three sources of the tailwater S-FPOM satisfied the premises as depicted in Fig.4-4. As shown in Table 4-3, dam originated lentic phytoplankton dominated by diatom *Asterionella formosa* and *Aulacoseira granulata* resulted in depleted $\delta^{13}C$ and enriched $\delta^{15}N$ values with -28.32‰ and 12.96‰, respectively. Fallen leaves of terrestrial tree species with C3 photosynthesis pathway ranged both of depleted $\delta^{13}C$ and $\delta^{15}N$, while the epilithic algae dominated by green algae, *Mougeotia* sp. and *Ulothix zonata*, showed the most enriched $\delta^{13}C$ with a comparatively wide variation range of -20.41±2.61 ‰.

All of S-FPOM isotopic signatures were located within the mixing triangle and were close to lentic plankton source, the values of $\delta^{13}C$ ranged -28.05 to -26.30 ‰ (mean -27.08±0.69 ‰), and $\delta^{15}N$ ranged 9.63 to 11.86 ‰ (mean 10.63±0.92 ‰) (Table 4-3).

4.3.3 Relative contributions of the sources

It was found that during passing through the riffle zones, St1-St2 and St3-St4, isotopic plot of SPOM moved definitely to the right-down direction (Fig.4-5). By the concentration-weighted mixing model, the relative contributions of the three sources were estimated. As to biomass contribution of S-FPOM source composition (Table 4-4a), lentic plankton ($f_{B,p}$) was most abundant as much as 67.5% out of S-FPOM composition sources at St1, and decreased to 34.2% up to St4 and increased to 51.7% up to St7. The second most abundant contribution was the terrestrial plant source ($f_{B,t}$), which ranged 24.7 to 37.9% through the reaches. Although epilithic algae ($f_{B,s}$) appeared to be relatively small contribution (7.5-30.7%), it trended to increase gradually with downstream distance.

As to carbon contribution (Table 4-4b), the terrestrial plant accounted for the highest contribution from the St3 to St7 relative to the other sources. In case of nitrogen contribution (Table 4-4c), the lentic plankton was highest throughout all the sites accounting for 52.1-86.3%.

4.3.4 SPOM concentration and the source-specific concentration

The concentration of S-FPOM (349±77 ㎍AFDW/㎥) was significantly higher than that of S-CPOM (61±22 ㎍AFDW/㎥) as shown in Fig.4-7 ($p<0.001$, T-test). The concentration of S-FPOM was highest in the uppermost site near the Dam outlet and then longitudinally reduced to the downstream. In particular, it showed steeper reduction during passing St1-St2, St4-St5 and St6-St7 (Table 4-5a and Fig.4-7).

The concentration of lentic plankton, epilithic algae and terrestrial plant constituted to SPOM were calculated by the Eq.4-2. C_i showed a closely similar pattern with $f_{B,i}$. It was highest in the St1 and then longitudinally reduced to the downstream except the St5-St6 reach. In particular, it was found that C_t increased in the St2-St3 reach (Table 4-5b).

4.3.5 Population density and biomass of the filter feeding mussels

Population densities and biomass of the freshwater mussel, *L. fortunei*, varied greatly among sites from 0.02 to 1.22 shell/cm^2 and 0.01 to 0.31 g/cm^2, respectively. Both the density and biomass showed the highest values at the upper part of the riffle just below the dam and decreased longitudinally within a riffle zone and through the reaches (Fig.4-8). These downstream decreasing patterns fitted well to the exponential decay model. The longitudinal decreasing rate of the density (0.0027 m^{-1}) was not significantly different from that of the biomass (0.0028 m^{-1}). The rates of dead mussels appeared to be increased with the downstream distance (Fig. 4-9).

4.3.6 Longitudinal changes of benthic communities

A total of 14 taxa of benthic invertebrates were collected from two riffles and one glide site in the Uji River. All the sites showed low species richness: i.e., that of Riffle1, Riffle2 and Glide was 8, 10 and 7, respectively (Fig.4-11a and Appendix). However, life form and functional feeding groups were different among the three sites. In Riffle1, the relative abundance of the attachers was relatively higher than those of other life form types, on the other hand, the crawlers increased with downstream distance (Fig.4-11b). The results of functional feeding groups showed that Riffle1 consisted of only filterers (63%) and collector-gatherers (37%) and relative abundance of the filterers was the highest values among the sites (Fig.4-11c).

Fig.4-12 showed a changing pattern of the stable isotopic values of benthic invertebrates through the reaches. As a whole, the isotope values of the benthic animals were located between the lentic plankton source and the epilithic algal source. In addition, both $\delta^{13}C$ and $\delta^{15}N$ showed a longitudinally enriched pattern although the mean $\delta^{13}C$ and $\delta^{15}N$ was significantly different only between Riffle1 and the Glide ($p<0.05$, *t*-test). Among benthic animals, four common species which were found at all the three sites were selected and in the isotopic characteristics were investigated. As shown in Fig.4-13, overall the values of $\delta^{13}C$ of Hydropsychidae of a net-spinning filterer, *Limnoperna fortunei* of attaching filterer and both crawling collector-gatherers like *Crangonyx floridanus* and *Diamesa* sp. enriched with downstream distance.

4.4 DISCUSSIONS

4.4.1 Roles of riffle pool structures in S-FPOM dynamics in dam tailwater channel

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 the riffle zones, St1-St2 (Riffle 1) and

St3-St4 (Riffle 2), isotopic plot of S-FPOM moved distinctively to the right-down direction. $f_{B,p}$ decreased about 9.7% from 67.5 to 57.8% in Riffle 1 and 11.9% from 46.1 to 34.2% in Riffle 2. 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 by partially exposed bedrock (Table 4-4a and Fig.4-6a).

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% during passing the Pool1, whereas it decreased 7.0% in the Pool2 (Table 4-4a and Fig.4-6a). The changing pattern of the concentration of terrestrial plant (C_t) was similar to that of $f_{B,t}$ (Fig.4-6b). The reduction of $f_{B,t}$ and C_t in the Pool2 can reasonably attribute to dominance of the settling process of the terrestrial source, because pools with relatively low velocity and deep condition enable heavier particles to settle down into the bottom. It was generally supposed that fine particles of terrestrial plant leaves made of hard lignin tissues have much higher sinking velocity than those of plankton and algal particles.

However, the increase of both $f_{B,t}$ and C_t in the Pool1 can not be interpreted by the settling process in pools. Instead, it indicates possibility of supplying process of the terrestrial plant source in the reaches. The analysis on the vertical velocity (w) within the reach (No.52.95 to No.52.60 in Fig.4-3) can provide an interesting interpretation for explaining the pattern. From the velocity distributions, we decided which direction was predominant in each cross section (Table 4-6). It was found that the upwelling was dominant in the Pool1. The finding suggests that the terrestrial sources can be supplied from the bottom layer by the resuspension process in the pool.

4.4.2 Response of benthic communities to POM dynamics in the dam tailwater ecosystems

The non-indigenous mussel, *L. fortunei*, has been reported to cause a biofouling of natural and man-made structure by adhesion to the hard surface. In the study reaches, the mussels were abundant on the surface of stones (Photo 4-3). In order to evaluate the effect of riffle structure on the density of *L. fortunei*, we compared the decreasing rate of the relative density at upper, middle and lower part of the two riffles as well as through the entire study reaches, where the relative density means the ratio of density relative to the initial values at either the upper site of the riffles or the uppermost site of the whole reach (Fig.4-10). The decreasing rate of the relative density within each riffle was significantly higher than that in the whole reach. This indicates that the upper part of the riffles is a more suitable habitat for the mussel. The reason can be related to higher density of B-FPOM derived from S-FPOM at the upper part of riffles (Takemon *et al.* 2008). If this is true also in our study sites, the mussels inhabiting at the upper site of riffles have the benefit of abundant food supply. In addition, the decreasing pattern of relative contribution of lentic plankton to S-FPOM source composition may be a causal factor for a similar decreasing pattern in the mussel density because the mussel feeds on S-FPOM particularly on phytoplankton (Sylvester *et al.* 2005; Karatayev *et al.* 2007). This causal relationship was also supported by the downstream increasing pattern of the death rate of the mussel (Fig.4-9).

At the same time, a high density of the mussel can be a cause of high decreasing rate of the relative contribution of lentic plankton to S-FPOM source composition, since *L. fortunei* is known as an effective ecosystem engineer owing to its filtering ability as high as 125-350 ml ind^{-1} h^{-1} of filtration rate (Sylvester *et al.*

2005). Therefore, the reduction of the relative contribution of plankton in a riffle zone may also be attributed to the biological filter-feeding process by *L. fortunei* as well as the physical filtering process facilitated by riffle geomorphologic characteristics.

As to the benthic communities, it was found that the species richness was as low as 7 to 10 in the reaches. The life form composition was not enriched with downstream distance. Although Hatano et al (2005) showed that swimmers gradually increased within downstream reaches of 3 km in distance, whereas in the Uji River, burrowers and gliders as well as swimmers were not found in the Glide zone, probably due to a severe armoring effect without sand supply. In addition, the functional feeding groups leaned to the filterers, indicating their high dependence on lentic plankton as basal food resources (Fig.4-11). Fig.4-12 clearly showed the effect of FPOM source composition on benthic communities. As the relative contribution of lentic plankton reduced and instead of that of epilithic algae increased in S-FPOM and B-FPOM composition, the basal trophic sources of benthic communities shifted gradually from lentic plankton to epilithic algae (Fig.4-12). Interestingly, the similar patterns were found also in a single species feeding on S-FPOM (Fig.4-13). Particularly in the filter-feeding mussel of *L.fortunei* showed relatively high relation to changes in S-FPOM source composition compared with net-spinning caddisflies of Hydropsychidae (Fig.4-14). These results indicate that lentic plankton plays an important role as energy resources in dam tailwater foodweb systems and also downstream changes of its relative contribution to SPOM influence species richness, life forms and functional feeding groups in benthic communities.

4.4.3 Spatial sorting capacity of the SPOM sources by the riffle and pool structure

The results of contribution and concentration of the sources of S-FPOM indicated that although retention process of lentic plankton was dominant in the riffles, the reduction rate can be replenished by ephilitic algal production, due to relatively plentiful light radiation and dissolved oxygen (Fuller *et al.* 1986). The pool structure facilitates to deposit terrestrial detritus, which leads to increase the portion of lentic plankton. Based on the findings, source specific characteristics of POM dynamics can be conceptualized as Fig.4-15. The results showed that lentic plankton was the most abundant components in S-FPOM mixture in the reaches. Reduced biomass contribution of lentic plankton in riffles may be explained by both processes of physical filtering by substrate and biological filtering by the filter-feeding animals. While the increase of epilithic algae in riffle could be due to desorption from the stone surfaces by relatively high water velocity. On the other hand, the decrease of terrestrial fragment particles during passing the pools can attribute to settling down to the pool head and deposition to the pool tail, because of comparatively deep water depth and low velocity there. Such a conceptual model can provide an interesting implication that the riffle-pool sequence in a dam tailwater channel may play a role in sorting S-FPOM spatially according to its source origins.

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Table 4-1 Hydromorphological characteristics of downstream reaches of the Amagase Dam in the Uji River.

Reaches	Geo-morphologic features	Length (m)	Water surface velocity (m/s)	Water surface gradient (%)	Channel width (m)	Water depth (m)	Hydraulic Radius (m)	Predominant bed material	pH	DO (mg/L)	Water Tempe-rature (℃)	Conducti-vity (μs)
(1) St1-St2	Riffle 1	68	0.93	0.43	23.00	1.15	0.51	boulder	7.9	11.7	6.1	164.3
(2) St2-St3	Pool 1	509	0.47	0.08	40.54	2.92	2.34	gravel/sand	7.9	11.7	6.2	164.8
(3) St3-St4	Riffle 2	180	0.78	0.28	42.46	0.83	0.53	cobble/boulder	8.0	11.9	6.2	163.1
(4) St4-St5	Run	48	0.42	0.13	37.50	1.72	1.58	gravel	8.0	12.0	6.1	161.1
(5) St5-St6	Glide	63	0.7	0.05	44.43	1.37	0.89	bedrock	7.9	12.1	6.2	146.2
(6) St6-St7	Pool 2	730	0.33	0.02	57.94	3.05	2.65	gravel	7.8	12.0	6.4	155.2

The numbers of subreach correspond to those in Fig.4-1.

Table 4-2 Cross sectional characteristics with 100m distance intervals in the downstream reaches of the Amagase Dam in the Uji River

Site	Cross section No.	Distance from outlet (m)	Width (m)	Mean depth (m)	Maximum depth (m)	Sectional Area (m^2)	Wetted Perimeter (m)	Hydraulic radius, R_h (m)
	53.2	0	21.5	0.74	1.88	13.28	22.62	0.59
St1/St2	53.1	100	23.0	0.44	0.98	11.91	23.22	0.51
	53.0	200	30.4	2.44	5.10	102.22	33.18	3.08
	52.9	300	35.0	3.39	4.98	94.72	37.77	2.51
	52.8	400	35.9	1.94	4.50	105.31	37.93	2.78
	52.7	500	48.0	1.88	3.80	92.04	49.57	1.86
	52.6	600	53.4	1.14	2.45	79.24	53.25	1.49
St3	52.5	700	42.0	0.50	0.98	22.45	42.18	0.53
St4	52.4	800	42.9	1.30	4.00	70.12	44.27	1.58
	52.3	900	37.5	1.02	1.52	33.41	37.72	0.89
St5	52.2	1000	44.4	1.24	2.00	73.10	46.13	1.58
St6	52.1	1100	44.0	3.50	6.72	147.99	47.39	3.12
	52.0	1200	54.6	1.93	4.80	152.00	56.56	2.69
	51.9	1300	51.0	3.18	5.48	137.59	53.55	2.57
	51.8	1400	50.1	1.53	4.90	151.38	54.44	2.78
	51.7	1500	65.0	2.35	4.68	132.61	66.29	2.00
St7	51.6	1600	82.9	1.02	2.10	106.41	85.13	1.25
	Average		44.8	1.7	3.6	89.8	46.5	1.9

Table 4-3 Stable isotope ratios and elemental concentrations and C/N ratio of SPOM source origins and site-specific S-FPOM in the Uji River

	n	δ^{13}C (‰)	δ^{15}N (‰)	[C] %	[N]%	C/N
Source origins						
T.Leaf	3	-29.60±0.44	2.82±0.15	44.33	0.80	55.30
E.Algae	4	-20.41±2.61	6.83±0.93	37.25	3.61	10.40
L.Plankton	3	-28.32±0.10	12.96±0.15	23.12	4.42	5.25
S-FPOM						
St1	3	-28.05±0.14	11.86±0.63			
St2	3	-27.10±0.87	11.21±1.01			
St3	3	-27.49±0.38	10.67±0.27			
St4	3	-26.30±0.93	9.63±0.46			
St5	3	-26.85±0.09	9.96±0.32			
St6	3	-26.82±0.14	10.18±0.18			
St7	3	-26.96±0.38	10.87±1.07			

The values represent mean±standard deviation.

Table 4-4 Estimated relative contributions of S-FPOM source composition determined by the concentration-weighted mixing model using dual stable isotopes in the Uji River

(unit: %)

	Relative contribution								
	(a) Biomass			(b) Carbon			(c) Nitrogen		
	$f_{B,p}$	$f_{B,s}$	$f_{B,t}$	$f_{C,p}$	$f_{C,s}$	$f_{C,t}$	$f_{N,p}$	$f_{N,s}$	$f_{N,t}$
St1	**67.5**	7.5	25.0	**52.9**	9.5	37.6	**86.3**	7.8	5.8
St2	**57.8**	17.6	24.7	**43.3**	21.2	35.5	**75.4**	18.7	5.9
St3	**46.1**	16.6	37.3	31.9	18.5	**49.6**	**69.4**	20.4	10.2
St4	34.2	30.7	**35.1**	22.6	32.7	**44.6**	**52.1**	38.2	9.7
St5	37.5	24.6	**37.9**	25.0	26.4	**48.5**	**58.2**	31.1	10.7
St6	**40.8**	24.1	35.2	27.7	26.4	**45.9**	**61.0**	29.4	9.6
St7	**51.7**	20.2	28.2	37.4	23.5	**39.1**	**70.5**	22.5	7.0

The index of $f_{B,i}$, $f_{C,i}$ and $f_{N,i}$ represents fractionations of biomass, carbon and nitrogen respectively, contributed to the POM by source *i*. Source *i* corresponds to lentic plankton (p), terrestrial plant (t) and instream algae (s) respectively.

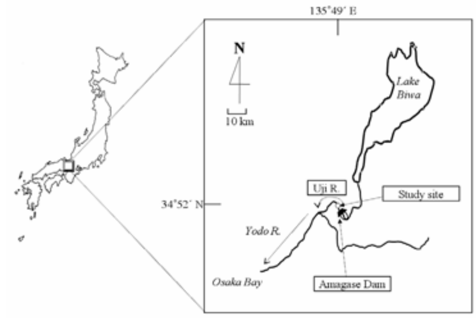
Table 4-5. Downstream changes on S-FPOM concentrations and the source-specific concentrations in the Uji River.

(unit: ㎍ AFDW /㎥)

	(a) S-FPOM concentration ($C_{S\text{-}FPOM}$)	(b) Source-specific concentrations		
		Lentic plankton (C_p)	*Epilithic algae* (C_s)	*Terrestrial plant* (C_t)
St1	479±82	323	36	120
St2	318±89	184	56	79
St3	358±64	165	59	134
St4	382±107	131	117	134
St5	284±76	107	70	108
St6	379±50	154	91	133
St7	243±17	126	49	69

Table 4-6 Vertical velocity (*w*) analysis in the cross sections in the Uji River. Positive and negative values in ⓐ toⓕ represent upwelling and downwelling of the flow (unit of *w* is cm/s)

sites	Section No.	Percentage contributions of each vertical velocity range (%)						Sum of negative and positive velocity groups (%)			Predominant vertical flow
		-30 to -5 ⓐ	-5 to -1 ⓑ	-1 to 0 ⓒ	0 to 1 ⓓ	1 to 5 ⓔ	5 to 30 ⓕ	Negativeⓖ (ⓐ+ⓑ+ⓒ)	Positiveⓗ (ⓓ+ⓔ+ⓕ)	difference ⓗ−ⓖ	
St2	53.00	33	17	4	5	15	27	54	46	**-8**	downwelling
	52.95	23	30	7	7	20	12	60	40	**-21**	downwelling
	52.90	18	19	6	6	22	29	43	57	**14**	upwelling
	52.85	9	29	11	11	29	10	49	51	**2**	upwelling
	52.80	8	26	9	11	32	14	43	57	**13**	upwelling
	52.75	10	26	10	12	30	12	46	54	**8**	upwelling
	52.70	8	32	12	10	29	9	52	48	**-4**	downwelling
	52.60	17	35	11	8	23	7	63	37	**-25**	downwelling
ST3	52.55-52.45	*Riffle zones- Too shallow to measure velocity by ADCP*						-	-	**-**	-
ST4	52.40	33	26	7	6	19	10	66	34	**-32**	downwelling
	52.35	10	22	6	8	31	23	38	62	**23**	upwelling
	52.30	25	33	9	6	16	12	66	34	**-33**	downwelling
ST5	52.25	39	27	7	4	11	12	73	27	**-45**	downwelling
	52.20	27	32	7	7	18	9	66	34	**-31**	downwelling
ST6	52.15	20	33	9	9	21	8	62	38	**-24**	downwelling
	52.10	13	22	8	9	30	17	43	57	**15**	upwelling
	52.05	10	31	11	10	29	8	53	47	**-5**	downwelling
	52.00	9	29	11	13	33	6	49	51	**2**	upwelling
	51.95	9	37	13	12	25	4	59	41	**-18**	downwelling
	51.90	21	35	10	8	18	7	66	34	**-32**	downwelling
	51.85	10	34	12	13	27	4	56	44	**-12**	downwelling
	51.80	5	33	14	14	32	2	51	49	**-3**	downwelling
	51.75	5	37	16	15	26	2	58	42	**-15**	downwelling
	51.70	7	31	13	14	28	6	52	48	**-4**	downwelling
ST7	51.65	8	31	9	16	30	7	48	52	**5**	upwelling
	51.60	6	36	10	13	30	5	53	47	**-5**	downwelling



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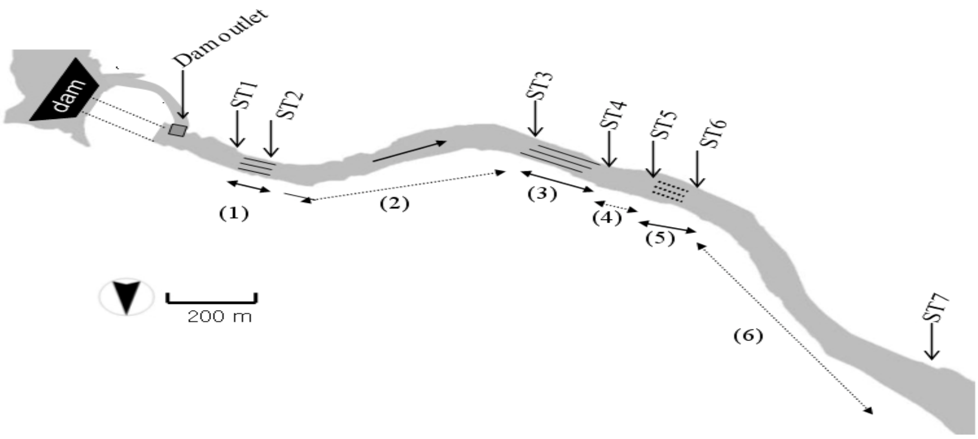

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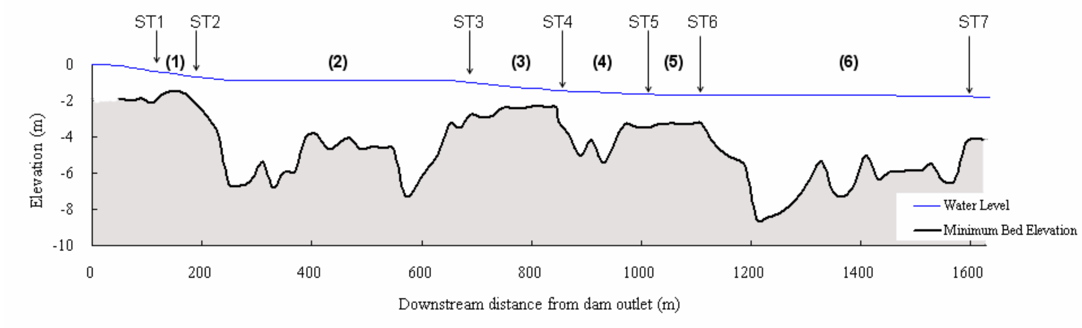
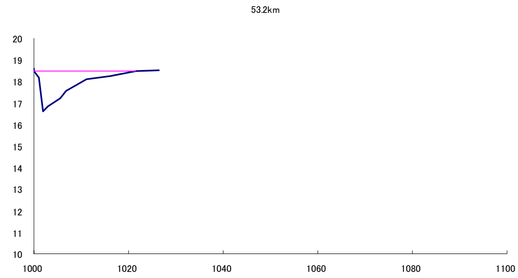


(c)

Fig.4-1 Maps of study sites in the downstream reaches of the Amagase Dam in the Uji River. (a) Location of the Uji River and the Amagase Dam, (b) A map of the sampling stations with riffle distribution. The solid and dotted lines represent riffle and glide, respectively. (c) Longitudinal profile of the lowest bed elevation and water level in the study reaches. A total of 6 reaches (1)-(6) were distinguished.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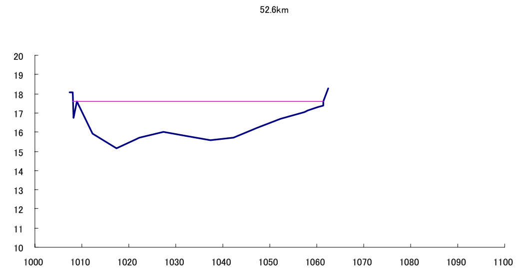
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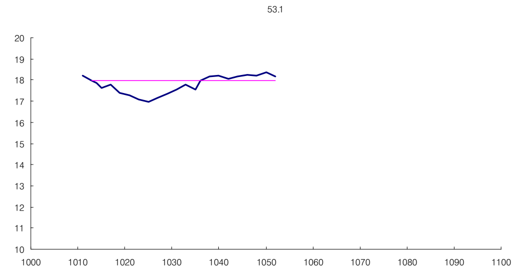
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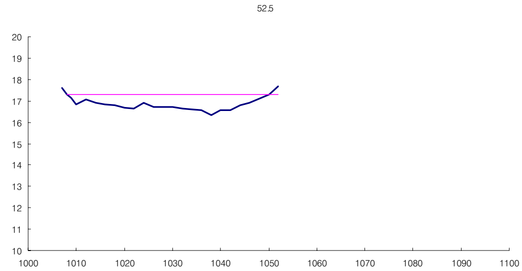
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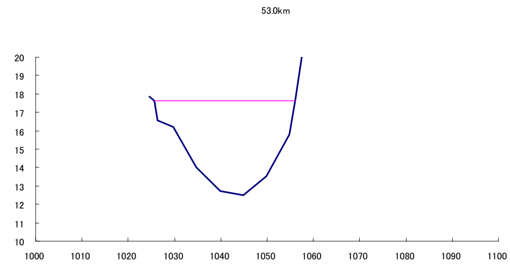
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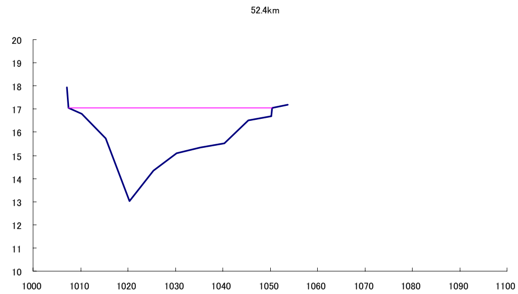
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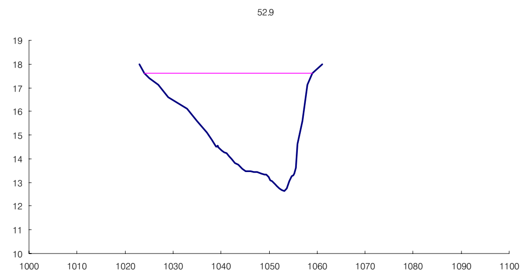
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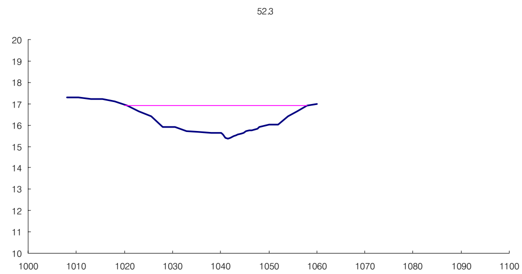
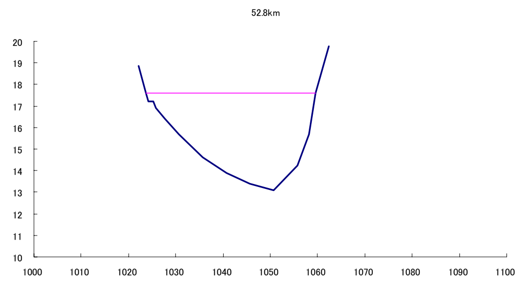
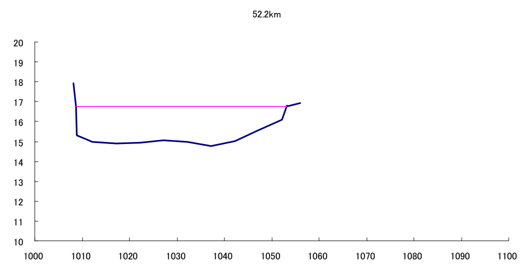
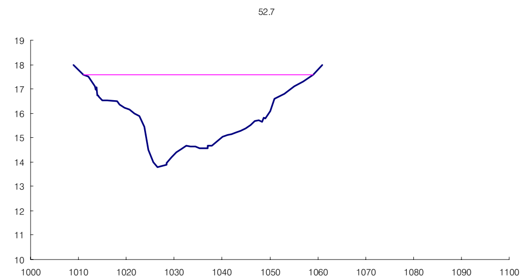
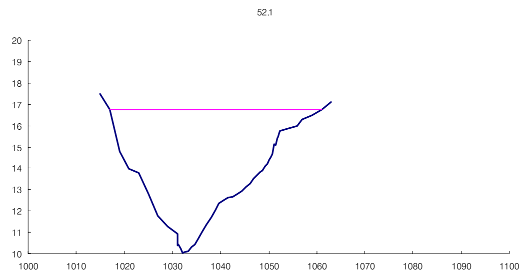
19 18 17 16 15 14 13 12 11 10
1000 1010 1020 1030 1040 1050 1060 1070 1080 1090 1100


52.3
20 19 18 17 16 15 14 13 12 11 10
1000 1010 1020 1030 1040 1050 1060 1070 1080 1090 1100


52.8km
20 19 18 17 16 15 14 13 12 11 10
1000 1010 1020 1030 1040 1050 1060 1070 1080 1090 1100


52.2km
20 19 18 17 16 15 14 13 12 11 10
1000 1010 1020 1030 1040 1050 1060 1070 1080 1090 1100


52.7
19 18 17 16 15 14 13 12 11 10
1000 1010 1020 1030 1040 1050 1060 1070 1080 1090 1100


52.1
20 19 18 17 16 15 14 13 12 11 10
1000 1010 1020 1030 1040 1050 1060 1070 1080 1090 1100

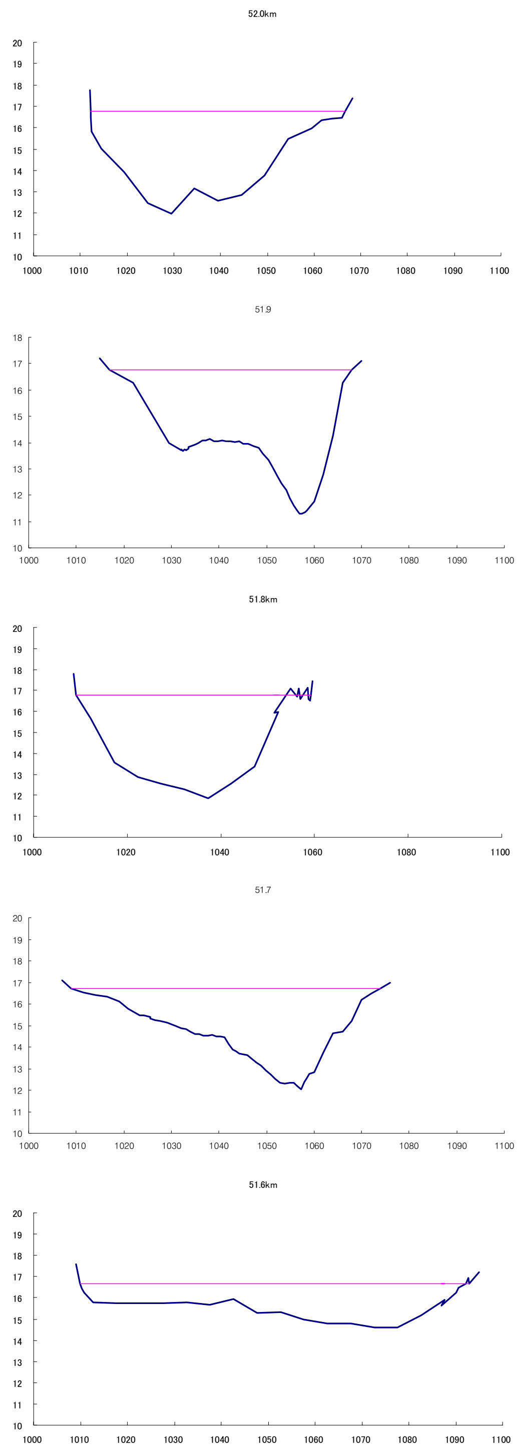
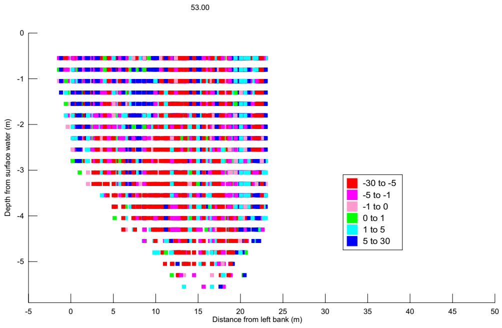
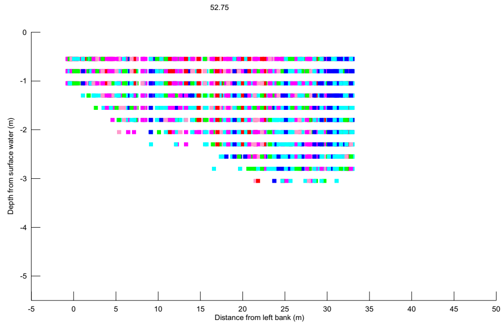
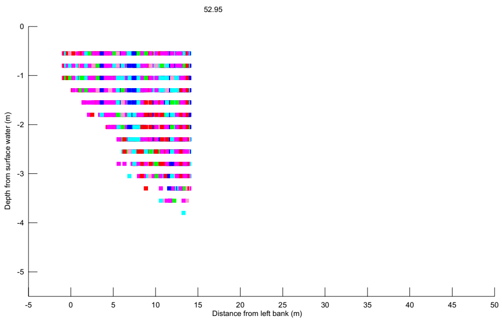
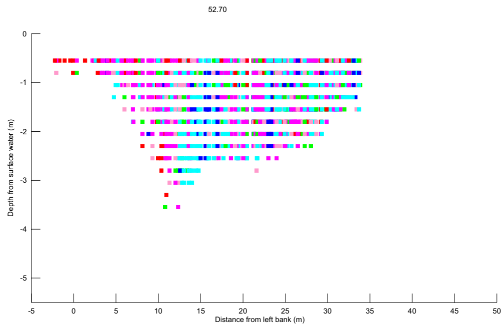


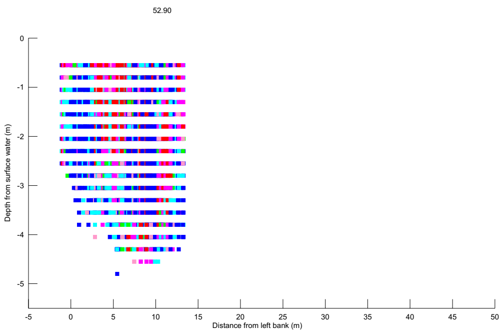
Fig.4-2 Cross sectional profiles with 100m distance interval in the Uji River. The corresponding location of the No. of cross sections to the reaches can be referred to Table 4-2.

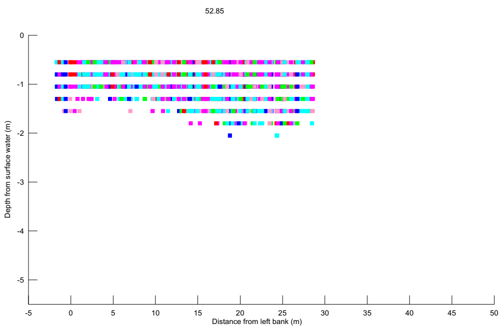

53.00
Depth from surface water (m)
Distance from left bank (m)
-30 to -5
-5 to -1
-1 to 0
0 to 1
1 to 5
5 to 30

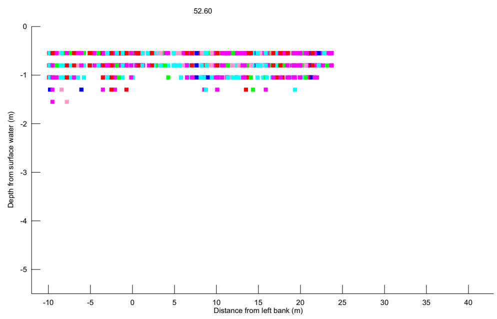

52.75
Depth from surface water (m)
Distance from left bank (m)

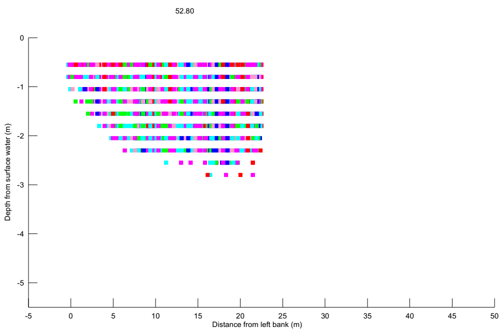

52.95
Depth from surface water (m)
Distance from left bank (m)

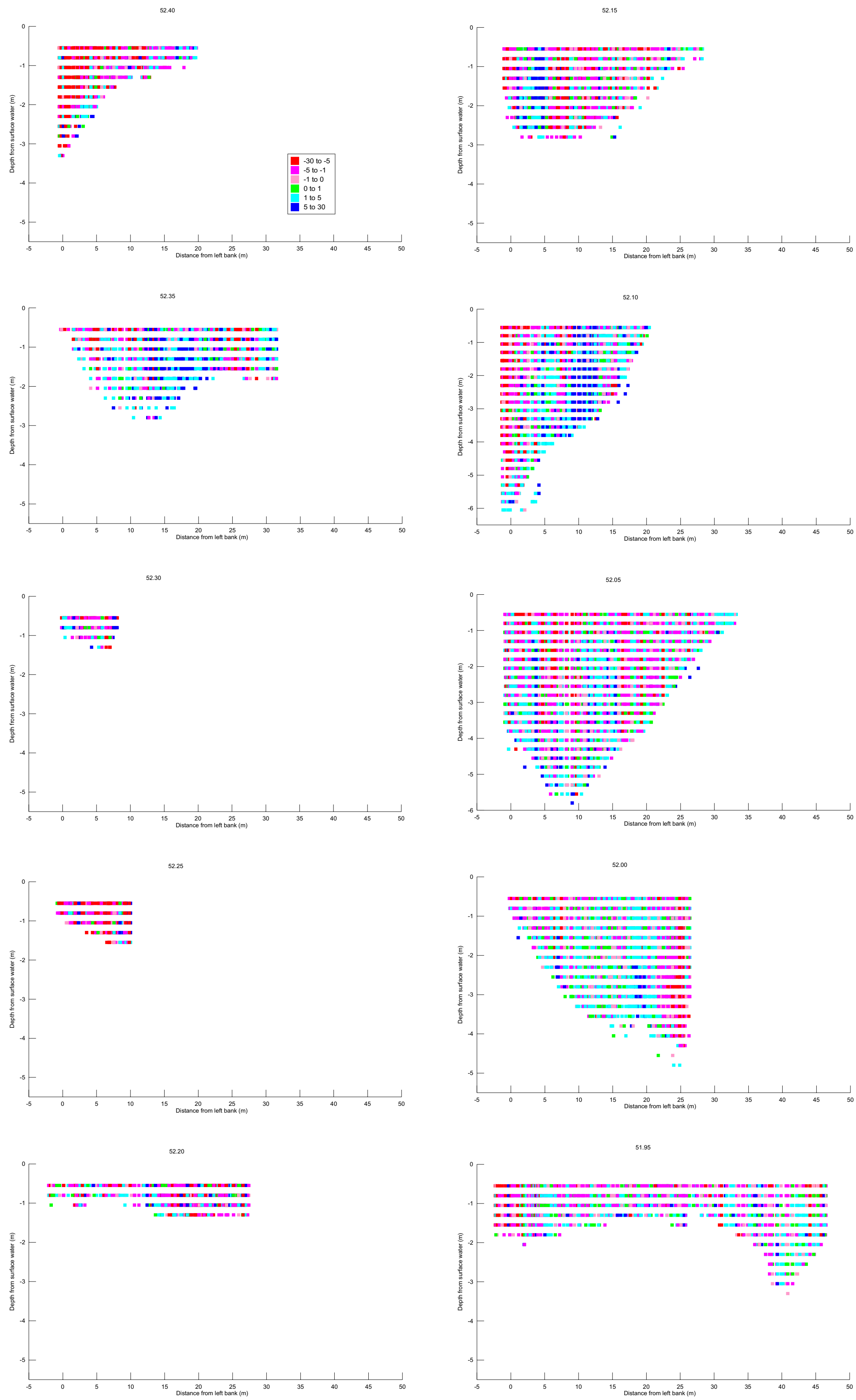

52.70
Depth from surface water (m)
Distance from left bank (m)


52.90
Depth from surface water (m)
Distance from left bank (m)


52.85
Depth from surface water (m)
Distance from left bank (m)


52.60
Depth from surface water (m)
Distance from left bank (m)


52.80
Depth from surface water (m)
Distance from left bank (m)


52.40
52.15
52.35
52.10
52.30
52.05
52.25
52.00
52.20
51.95
-30 to -5
-5 to -1
-1 to 0
0 to 1
1 to 5
5 to 30
Depth from surface water (m)
Distance from left bank (m)

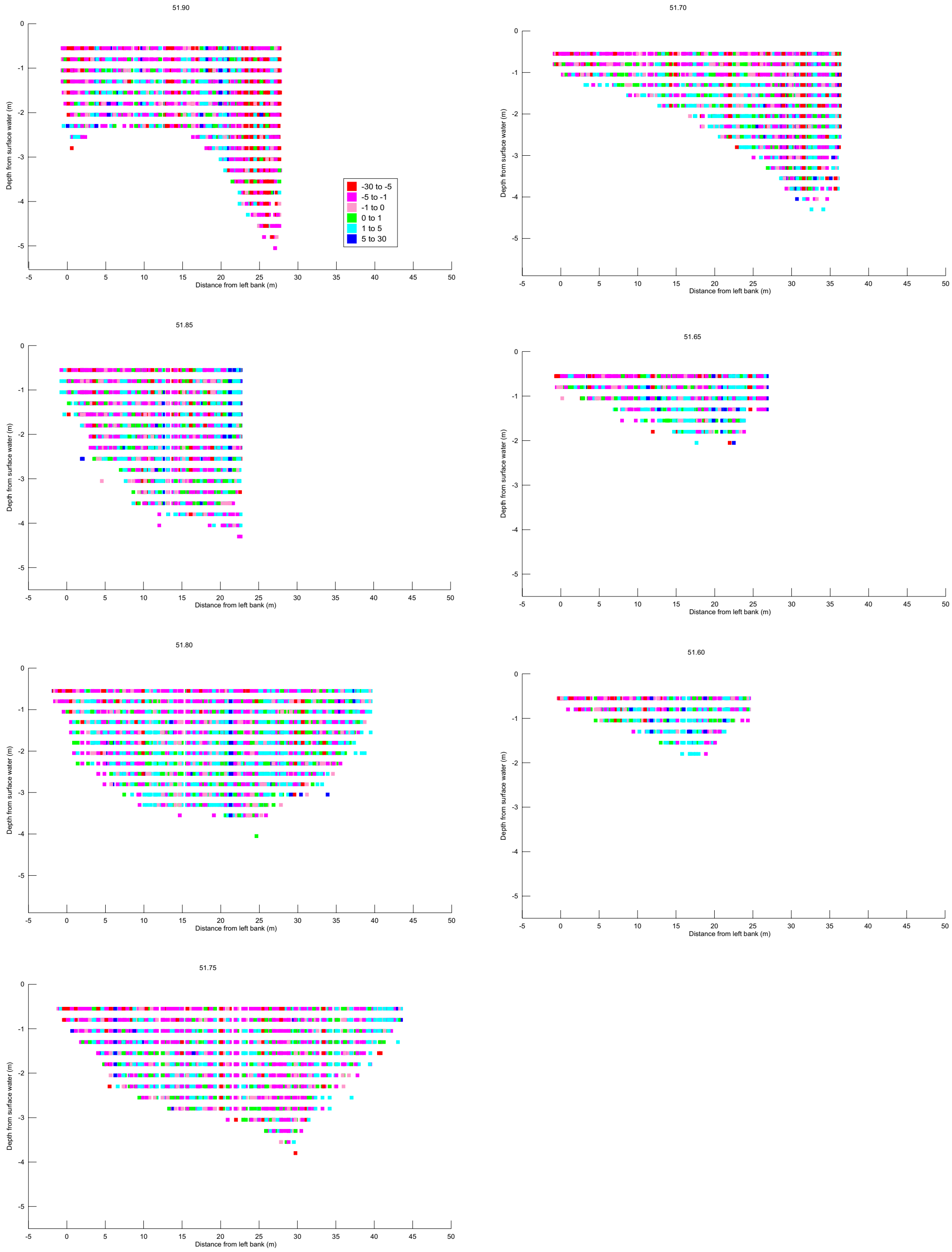


Fig.4-3 Cross sectional distribution of vertical velocity *w* (50m distance intervals) in the Uji River. The corresponding location of the No. of cross sections to the reaches can refer to Table 4-2. The unit of *w* is cm/s.

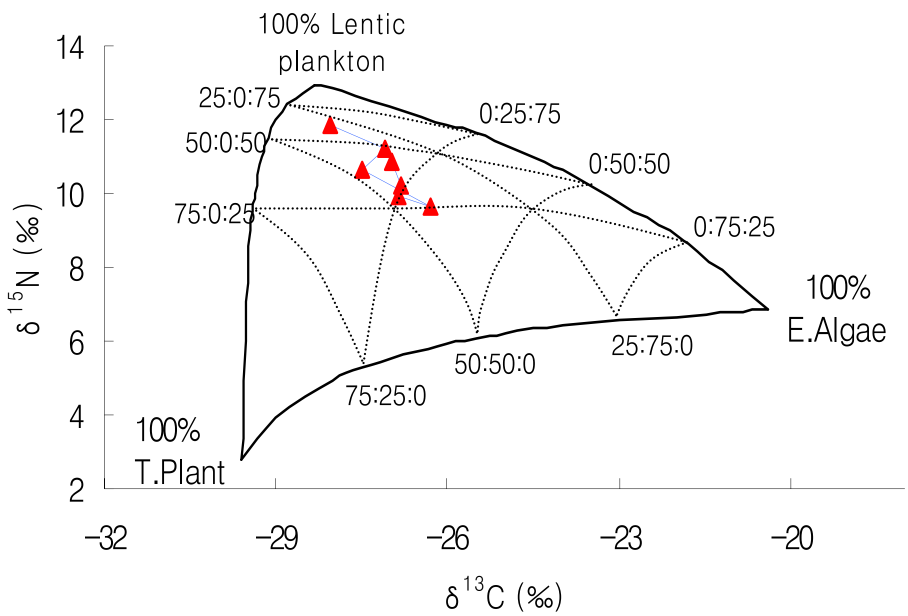


Fig.4-4 Spatial distribution of stable isotope ratios of S-FPOM surrounded by nonlinear mixing triangle from concentration-weighted multi-source mixing model in the Uji River. The values of ratios composed of three sources are in order of terrestrial plant : epilithic algae : lentic plankton.

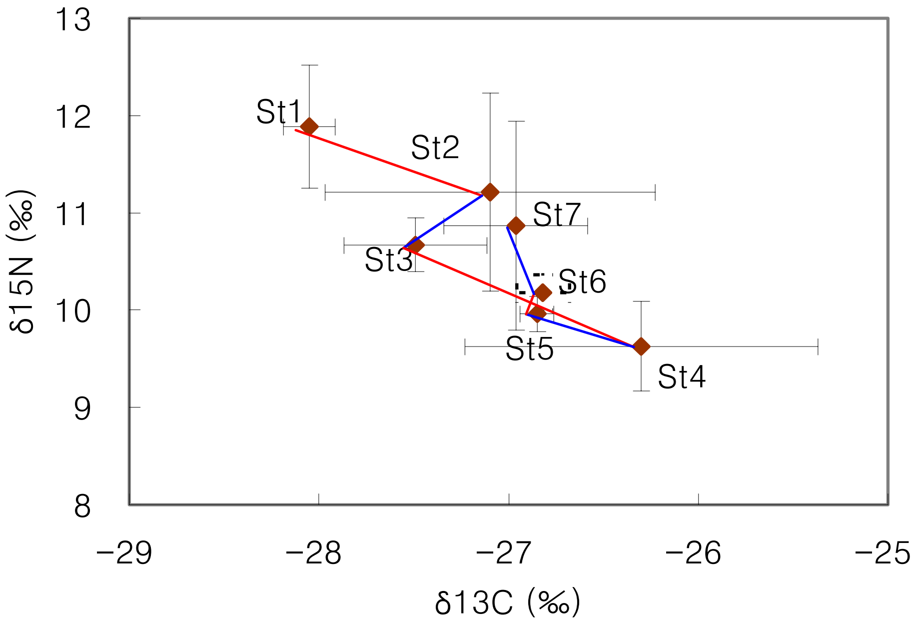
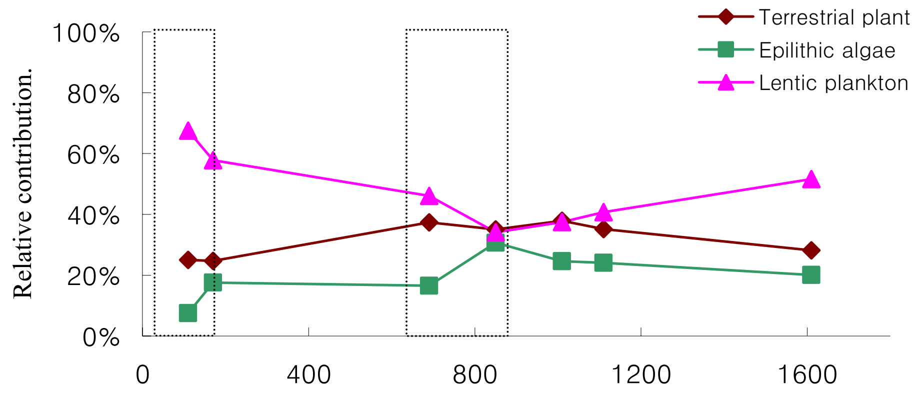
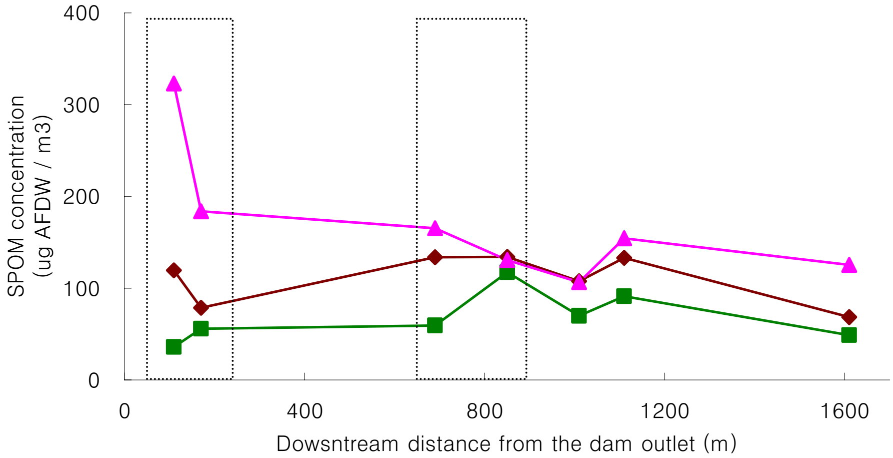


Fig.4-5 Spatial distribution of all of SPOM in $\delta^{13}C$ and $\delta^{15}N$ composite plot in the Uji River. Circle and error bar represent mean value and standard deviation respectively.



(a) Biomass contribution



(b) Concentration of the sources

Fig.4-6. Downstream changes of the biomass contributions and the concentrations of the three sources for S-FPOM in the Uji River. The dotted-rectangulars represents the riffle zones in the reaches

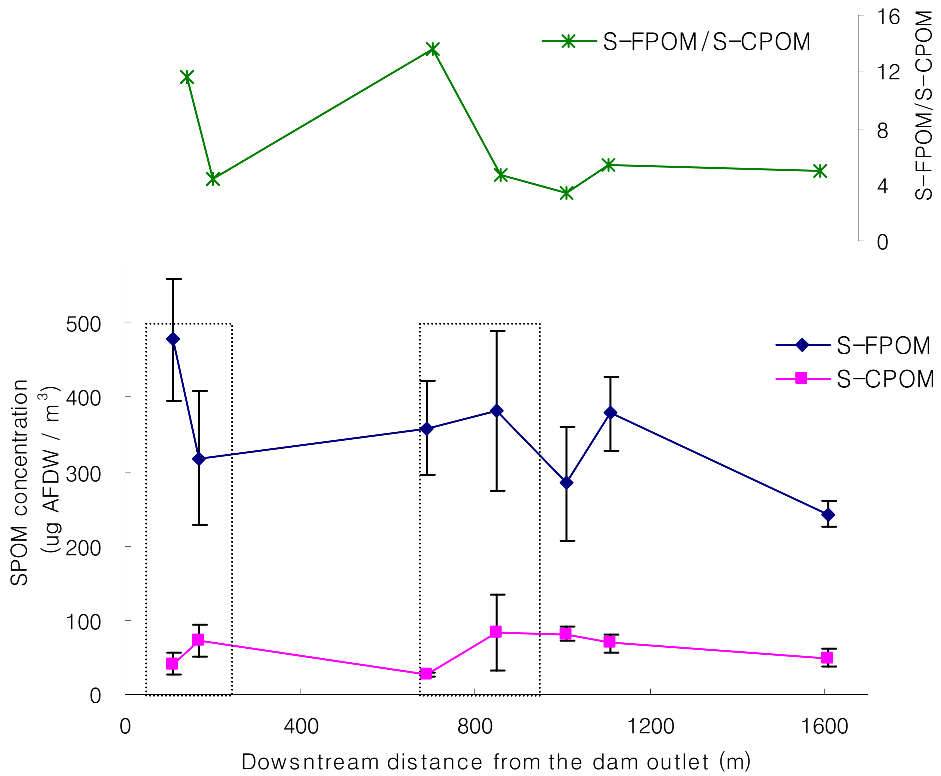


Fig.4-7 Comparison of the concentration changes between S-FPOM and S-CPOM in the Uji River. The dotted–rectangulars represents the riffle zones in the reaches. The concentration of S-FPOM was highest in the uppermost site and after that showed the reducing pattern as a whole, whereas that of S-CPOM increased in the riffles and decreased in the pools but showed no reducing pattern through the reaches. The ratio of S-FPOM to S-CPOM dropped quickly in the riffles, overall showing a reducing pattern.

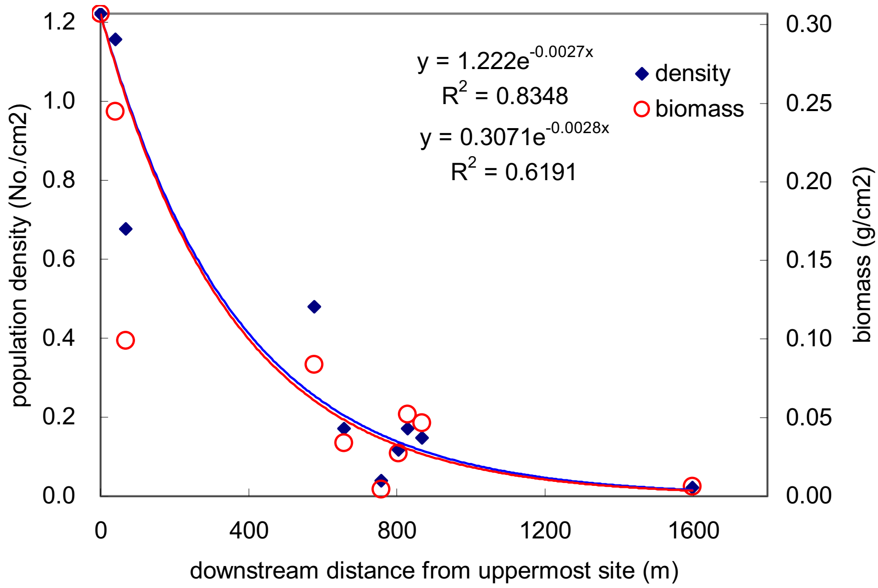


Fig.4-8 Downstream changing pattern in density and biomass of the freshwater golden mussel in the Uji River

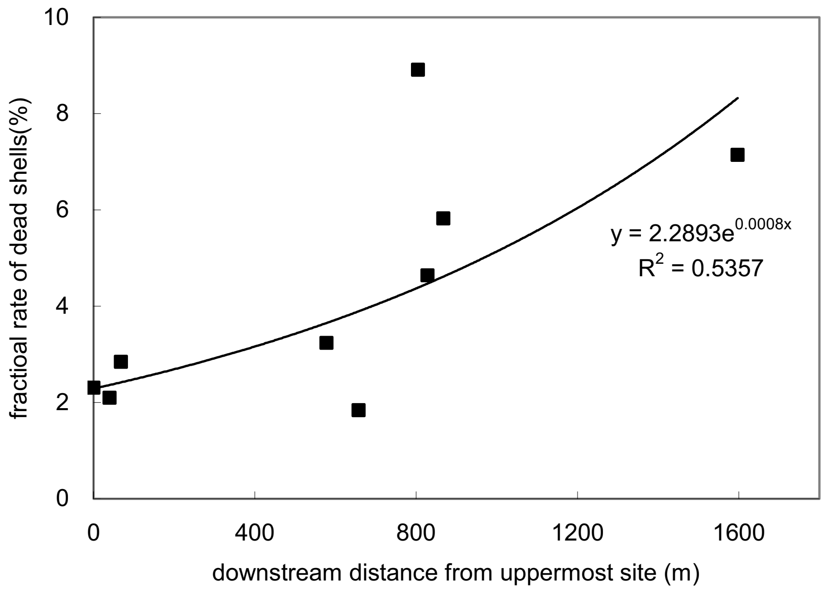


Fig.4-9 Downstream changes of death rate of the freshwater golden mussel in the Uji River. Death rate means the weight ratio of the dead shells to total.

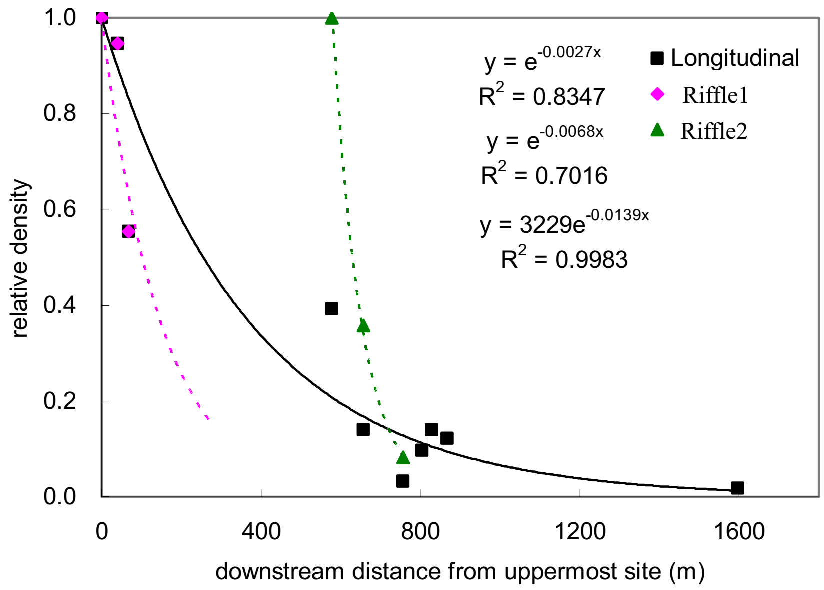


Fig.4-10 Comparison of longitudinal changes in the relative density of freshwater golden mussel within a riffle and through the reaches of the Amagase Dam in the Uji River

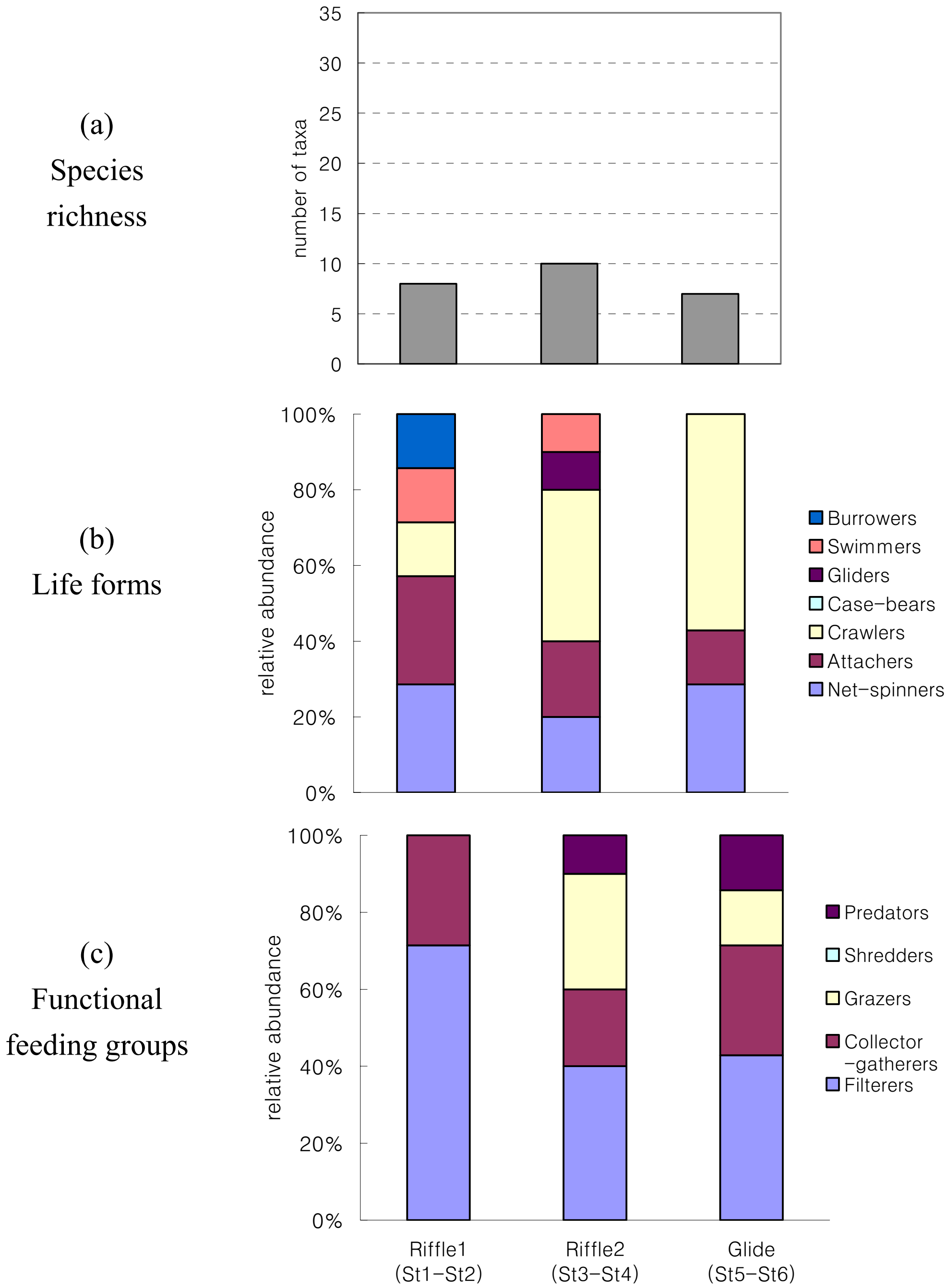


Fig.4-11 Longitudinal changes in species richness, life form and functional feeding group composition of benthos communities in the downstream reaches of the Amagase Dam in the Uji River

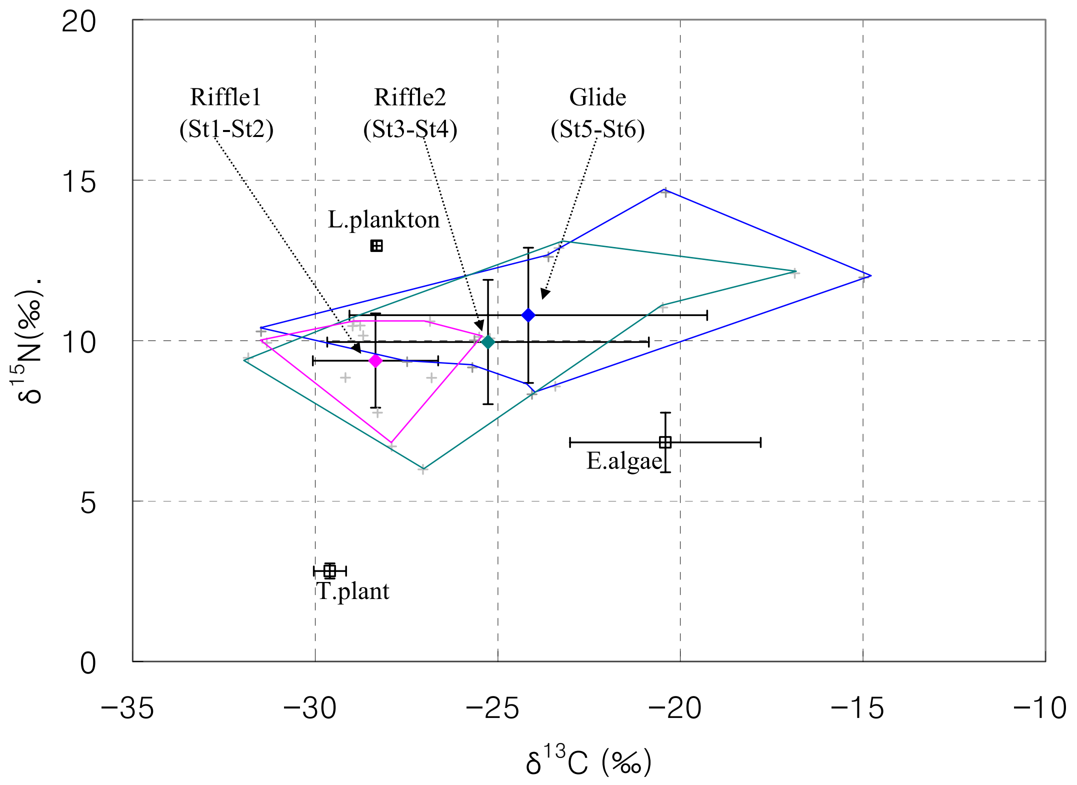


Fig.4-12 Longitudinal changes of stable isotopic values of benthic communities in the downstream reaches of the Amagase Dam in the Uji River

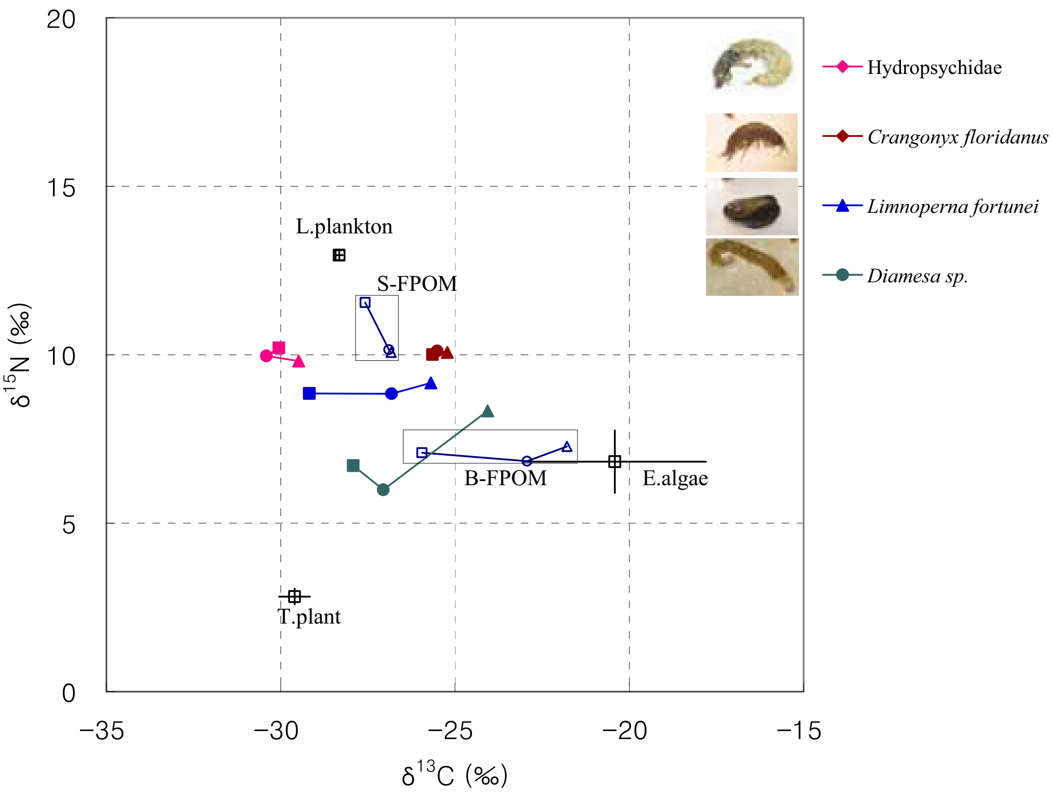


Fig.4-13 Longitudinal changes of stable isotopic values of four species of benthic invertebrates in the downstream reaches of the Amagase Dam in the Uji River. The closed square, circle and triangle in the figure represent Riffle1, Riffle2 and Glide, respectively.

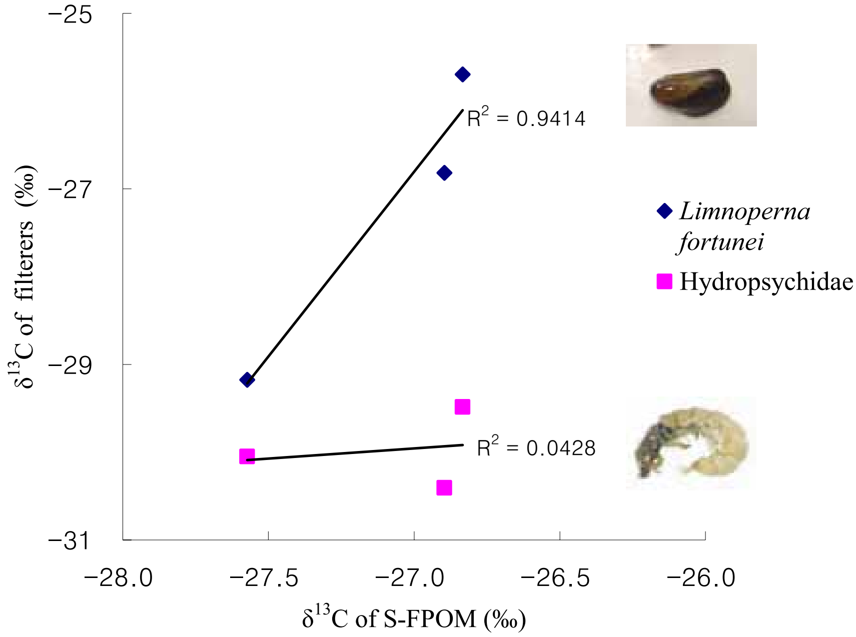


Fig.4-14 Relations of $\delta^{13}C$ of the two filterers to and $\delta^{13}C$ of S-FPOM at their sampling sites in the downstream reaches of the Amagase Dam in the Uji River

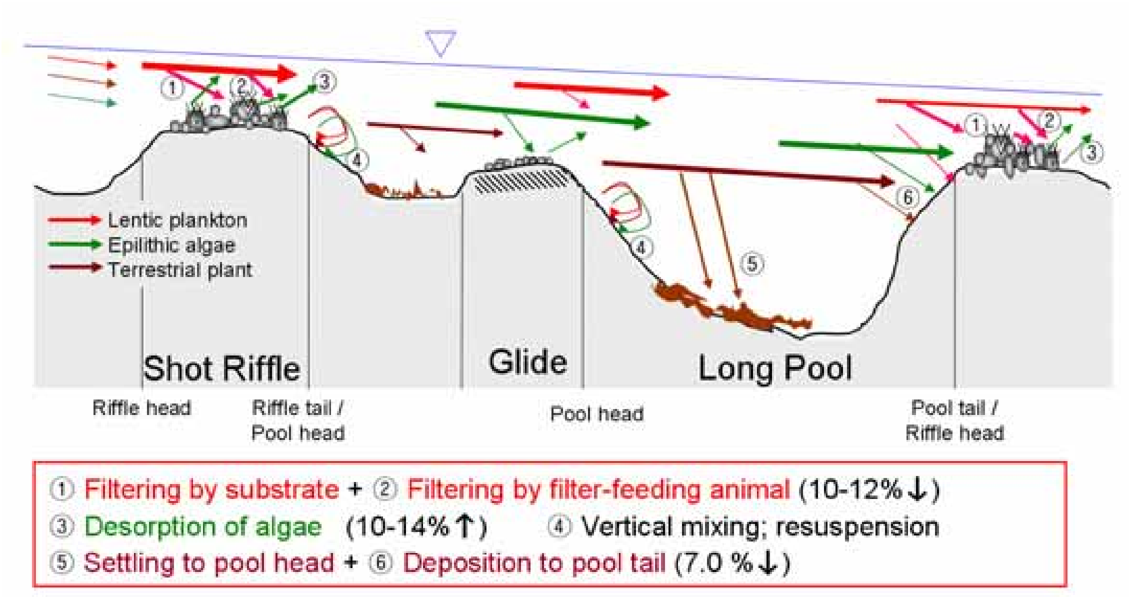
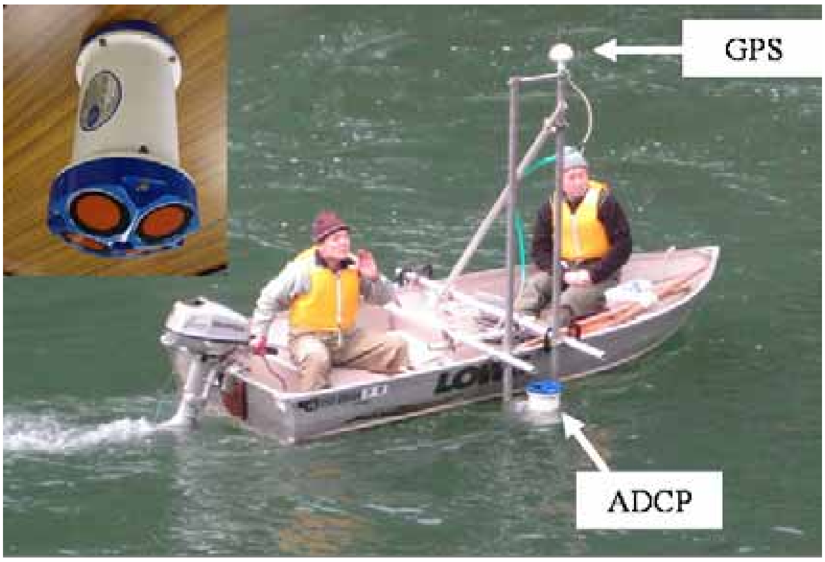
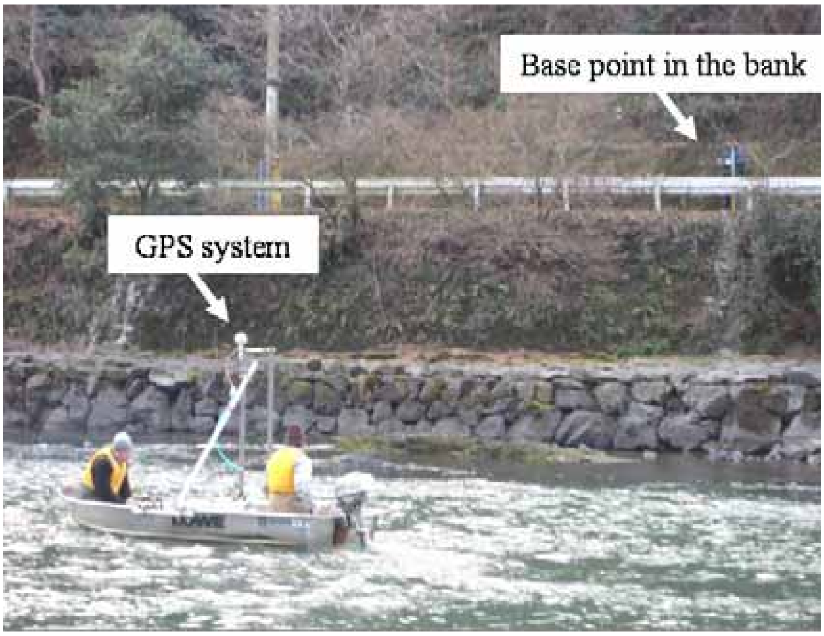


Fig.4-15 Conceptual scheme of SPOM dynamics in riffle and pool structures in the downstream reaches of the Amagase Dam in the Uji River

Photo 4-1 SPOM sampling using POM net in running waters in the Uji River. At the same time, flow velocity in front of net mouth and the duration time were measured for quantification of SPOM concentration.



(a) Ship-mounted ADCP set-up in the field.



(b) Bed elevation and flow velocity measurement by ship-mounted ADCP. The location by GPS system were calibrated using the data of base point in the bank

Photo 4-2 Field views of ADCP measurement in the Uji River

(a) St1

(b) St2

Photo 4-3 Comparison of the population density of freshwater golden mussel collected at upper (a) and lower (b) of Riffle1 in the Uji River. The stones were set upsides down: i.e., the mussels attached in high density on the underside of the stones

St1 boulder

St2 boulder

St3 gravel

St4 gravel

St5 bedrock

St6 bedrock

Photo 4-4 Coarsening bed materials within a quadrate (1.0 x 1.0 m). Bedrock was exposed in the St5 and St6.

CHAPTER 5

Effects of Sediment Replenishment on POM Retention Efficiency in Dam Tailwaters

5.1 INTRODUCTION

Rivers transport sediment from eroding upland to depositional downstream. If the continuity of sediment transport is interrupted by dams, the flow may become sediment-starved and give rise to various geomorphologic alterations such as riverbed degradation, coarsening of the bed material and costal shoreline erosion (Kondolf, 1997). Also some interdisciplinary studies for evaluating effects of river impoundment to the downstream revealed that maintaining the structural features in fluvial geomorphology and their dynamics over a range of spatial and temporal scale are responsible for sustaining the ecological integrity of rivers (Petts and Gurnell, 2005).

Recently geomorphological restoration efforts for connecting the sediment transport continuity have been employed for the ecological integrity in dam tailwater channel. For instance, in Japan, sediment replenishment, sediment bypass and flood-retention dam have allowed supplying upland sediment to downstream for achievement of various geomorphological and ecological objectives.

In the study, we tried to evaluate effects of sediment replenishment on POM dynamics in downstream reaches in the Nunome River, because sediment has been frequently supplied in the reaches by sediment replenishment. The procedures for selecting study sites and collecting POM samples were almost same with those conducted in the Uji River, which were described in Chapter 3 and Chapter 4. Therefore the comparative study between the Nunome River and the Uji River will make it possible to investigate how sediment transport influences retention efficiency of lentic plankton.

5.2 METHODS

5.2.1 Site description

The filed study was conducted in downstream reaches below the Nunome Dam in the Nunome River, a tributary of the Kizu River in Nara prefecture (34°42′ N, 135°58′ E) (Fig.5-1a). The concrete gravity dam with 72 m height and 17.3 million m^3 storage capacity was constructed in 1992 for flood control and water supply (JCOLD, 2008). Sampling works and measurements were conducted within about 1.0 km reaches from the dam outlet (Fig.5-1b).

Compared with the Uji River in Chapter 3 and 4, the reaches in the Nunome River were relatively small scale ones with a shallow and narrow channel. The reaches have 13m of the mean width and 0.5 m of the mean depth. Water surface gradient was on average 0.41% (Table 5-1). The flow discharge in the reaches is stably regulated by dam operation. The POM sampling were conducted on 7th February 2009, the recorded flow discharge during the samplings was 1.20 m^3/s.

Seven sites were established along the reaches taking into account of riffle and pool structures as shown in Fig.5-1c. The reaches were divided into three sets of riffle and pool sequences based on hydro-geomorphic properties as shown in Table 5-1.

5.2.2 Sediment replenishment

In the study sites in the Nunome River, frequent sediment replenishment works have been progressed since 2004. During the flooding season in which peak discharge out of the dam can be expected, about 100 to 500 m^3 of sediment have been supplied from St2 site (sediments deposit place) to the downstream. Sizes of the replenished sediment were ranged mostly from fine to coarse sand (0.075-0.85mm, D50≒0.4-0.5mm). Fig.5-2 gave temporal information about the date and volume of replenished according to annual water level changes measured at the Okugahara gauging station. The filed survey was conducted in February 2009, five months after the last replenishment of September 2008. Fig.5-3 showed the latest field views of the event conducted on October 2009. Approximately 500m^3 of sediment were transported to the downstream by 81m^3/s of the peak flow discharge.

5.2.3 Field sampling and measurements

Four types of POMs (S-FPOM, S-CPOM, B-FPOM and B-CPOM) were collected at each site. In particular, SPOM samples were collected three times at each site. Each sample was taken for approximately one to three minutes until not occurring in adverse flow in net sampler, which depends on flow velocity and particle concentration. BPOM samples were collected in stagnant place with comparatively low velocity. Collected both SPOM and BPOM samples were filtered *in situ* using 1.0 mm mesh sized sieve to separate fine POM from coarse POM.

Terrestrial plant leaves, epilithic algae and lentic phytoplankton were also collected as potential POM source origins. Hydraulic measurements including flow velocity, geomorphic measurement including cross sectional and longitudinal bed elevations, and biochemical measurements such as DO, pH, conductivity and water temperature were also investigated at each site. In particular, cross sectional profiles with 50m interval were surveyed using a level.

Benthic macro-meio invertebrates and fish were collected at the Riffle1 (St1-St2), the Riffle2 (St3-St4) and the Riffle3 (St5-St6) by the same methods and procedures with the Uji River (*refer to* 4.2.2-c). The species richness, life forms and functional feeding groups were investigated at each sampling site.

5.2.4 Stable isotope analysis and mixing model

Measuring of stable isotope ratios were followed the same procedures described in 3.2.4. The concentration weighted mixing model was used for quantification of POM source composition. Relative contribution of each source was calculated based on biomass, carbon and nitrogen. Detailed equations and processes can be referred in 3.2.5.

5.2.5 Determination of isotopic values of POM source origins

One importance for application of stable isotope mixing models is to determine the δ values of the end members distinctively and accurately. In case of POM source composition, if the isotopic values of each source origin are difficult to be differentiated distinctively due to complexity for isolating pure sample in field condition, an alternative method to infer isotopic values of source origin using those of herbivorous consumers assimilating the target source.

The stable isotopes of nitrogen and carbon provide powerful tools for estimating the trophic positions in food webs, because combined stable isotope ratios of carbon and nitrogen in herbivorous consumers are known to reflect the isotopic ratios of organic matter they have assimilated as long as the sources have distinct isotope signatures. Application of stable isotope techniques to quantify food web relations requires a priori estimates of the enrichment or depletion in $\delta^{13}C$ and $\delta^{15}N$ values between diet and its consumer (Vander Zanden and Rasmussen, 2001). This difference is known as 'trophic fractionation rate (hereafter $\Delta^{13}C$ and $\Delta^{15}N$)', and to be specific to the trophic level and consumer species. Generally carnivore had significantly higher $\Delta^{15}N$ values than herbivores. Therefore this method has been successfully used to examine food webs in various aquatic ecosystems (Hamilton *et al.*, 1992; Peterson, 1999; Post, 2002).

On the contrary, consumer's isotopic signatures could be used to infer those of diet (Finlay, 2001; Finlay *et al.*, 2002). In this study, we inferred isotopic values of epilithic algae and lentic plankton from those of epilithic algavores and plankivores respectively as following equations.

$$\delta^{13}C_{epilithic\_a\lg ae} = \delta^{13}C_{epilithic\_a\lg avore} - \Delta^{13}C \quad \text{(Eq.6-1)}$$

$$\delta^{15}N_{epilithic\_a\lg ae} = \delta^{15}N_{epilithic\_a\lg avore} - \Delta^{15}N \quad \text{(Eq.6-2)}$$

and

$$\delta^{13}C_{lentic\_plankton} = \delta^{13}C_{planktivore} - \Delta^{13}C \quad \text{(Eq.6-3)}$$

$$\delta^{15}N_{lentic\_plankton} = \delta^{15}N_{planktivore} - \Delta^{15}N \quad \text{(Eq.6-4)}$$

5.3 RESULTS

5.3.1 Hydro-geomorphological characteristics

The reaches were characterized as three sets of riffle-pool sequences according to their hydro-geomorphologic properties. From the cross sectional profiles of 50m downstream intervals (Fig.5-4), a various geomorphological parameters were calculated such as width, depth and Hydraulic radius (Table 5-2).

5.3.2 Determination of isotopic values for POM origin sources

Terrestrial plants in the basin were composed of mixed coniferous and broadleaf forest. Their isotopic values resulted in -29.34 ‰ of $\delta^{13}C$ and -2.58 ‰ of $\delta^{15}N$ (Table 5-2), which are correspondent to general observations found in temperate forests with C3 photosynthesis pathway. However C:N ratio was found to be 97.66 showing an extremely high value due to lower [N] than that of broadleaf measured in the Uji R..

Although special care was paid to take epilithic algae samples and lentic plankton samples, it was difficult to separate both pure algae because of lack of standing crop probably due to sediment replenishment effect and lentic plankton because of complexity of extraction by repetitive settling due to non distinctive sinking velocity among plankton and other seston particles. Alternatively, isotopic values of epilithic algae were inferred from that of algavores grazers such as gilled snail, *Semisulcopira reiniana*. In addition, the values of lentic plankton also were inferred from planktivores filter-feeder such as net-spinning caddisfly, *Macronema radiatum* and *Chematopsyche brevilineata* collected at the nearest site of dam outlet (Fig.5-5).

Although it is often assumed that $\Delta^{13}C$ and $\Delta^{15}N$ values of a consumer are enriched by +0.8‰ (DeNiro and Epstein, 1978) and +3.4‰ (Minagawa and Wada, 1984) over those of its diet respectively, Zaden and Rasmussen (2001) concentrated on estimating the rates in aquatic food web and furthermore showed separately the rates for carnivore and herbivores. They investigated that $\Delta^{15}N$ of the herbivores (+2.52‰) was lower than that of carnivores (+3.23‰) and $\Delta^{13}C$ of herbivores (-0.41‰) exhibited significantly lower fractionation than nonherbivores (+0.91‰). In this study, therefore, the trophic fractionation rates of Zaden and Rasmussen (2001) were applied as -0.41‰ of $\Delta^{13}C$ and +2.52‰ of $\Delta^{15}N$. As the results of them, epilithic algae appeared to be the most enriched -26.18‰ of $\delta^{13}C$ and 13.89‰ of $\delta^{15}N$. Lentic plankton resulted in the most depleted -36.39‰ of $\delta^{13}C$ and the most enriched 16.69‰ of $\delta^{15}N$ (Table 5-3).

Accordingly, feasible three sources of POM in the Nunome R. showed distinctive stable isotopic signatures, because the lentic plankton had the most depleted $\delta^{13}C$ and the most enriched $\delta^{15}N$ whereas the epilithic algae had the most enriched $\delta^{13}C$ and the terrestrial plant had the most depleted $\delta^{15}N$.

5.3.3 Stable isotope values and relative contribution among four types of POMs

Mean isotopic values of S-FPOM, S-BPOM, B-FPOM and B-CPOM collected in all sites were calculated (Table 5-4). S-FPOM had the most enriched $\delta^{15}N$ (-14.84‰) and the most depleted $\delta^{13}C$ (-30.97‰), while B-FPOM and B-CPOM showed together relatively depleted $\delta^{15}N$ and enriched $\delta^{13}C$ but showed large variation ranges in nitrogen relative to SPOMs. The isotopic values of S-CPOM were between those of S-FPOM and both BPOMs. As shown in Fig.5-6, all of them were located well within the nonlinear mixing triangle, but two curved lines connected to the terrestrial plant showed steeper angles than the other line due to comparatively high C:N ratio of the terrestrial plant ranged in 97.66 (Table 5-3). Based on the stable isotope mixing model, the mixing triangle structured by distinctive isotopic values of three sources and satisfactory surrounding target mixtures made it possible to quantify the relative contribution of each source (Table 5-6 and Fig.5-7).

As results of biomass contribution, S-FPOM comprised of the largest fraction of lentic plankton accounting for 47.2%, whereas S-CPOM, B-FPOM and B-CPOM had relatively higher terrestrial contribution than the other two sources. As to carbon contribution, although all types of POMs comprised of high fraction of terrestrial source over about 50%, carbon contribution of the lentic plankton in S-FPOM was relatively high when compared with the other POM types. Nitrogen contribution could differentiate SPOM and BPOM. Both SPOMs had higher contribution of the lentic plankton whereas both BPOMs had higher that of epilithic algae (Table 5-6 and Fig.5-7).

5.3.4 Downstream changes of relative contribution of S-FPOM

Mean isotopic values of site specific S-FPOM collected in the reaches were calculated (Table 5-5). The values of $\delta^{13}C$ were ranged -32.0 to -30.0 ‰ and interestingly it increases with downstream distance. The $\delta^{15}N$ ranging 14.4 to 15.4 roughly decrease with progressing downstream despite exceptive some reaches (Fig.5-8).

Based on the nonlinear mixing triangle depicted in Fig.5-9, the relative contribution in each site could be estimated (Table 5-7). The results of biomass contribution showed that lentic plankton was the highest fraction rather than the other two sources, moreover its fractional contribution reduced toward the downstream. In particular, the contributions of the lentic plankton were reduced during passing the riffle zones including St1-St2 (8.0%), St3-St4 (7.1%) and St5-St6 (6.8%), and the reduction difference was relatively large when compared with pool zones (see Fig.5-1). On the other hand, the contribution of terrestrial plant appeared to decrease during passing pool zones such as St2-St3 (24.1%), St4-St5 (2.3%) and St6-St7 (7.9%) even though different ranges (Table 5-7 and Fig.5-10a). But the contribution of instream algae showed a general increase in the pools and no trend in the riffles. It may attribute to local production and its detachment because much standing stock of epiphytic algae were attached on roots and stream of riparian reed in the St3 to the St4, whereas a standing stock of epilithic algae seems to be increased from the St5. As to carbon contribution, terrestrial plant constituted a major source in most sites (Fig.5-10b). While lentic plankton contributed the major parts of nitrogen contribution in the reach (Fig.5-10c).

5.3.5 Longitudinal changes of benthic communities

A total of 41 taxa of benthic invertebtrates were collected from the three riffle sites in the Nunome River. The species richness showed a downstream increasing pattern: i.e., that of Riffle1, Riffle2 and Riffle3 was 12, 20 and 31, respectively (Fig.5-11a and Appendix). Within 1.0 km reaches, the number of taxa at Riffle3 increased to about 2.5 times of that at Riffle1. Results of life form analysis showed that crawlers was the most abundant at all the three sites accounting for 30 to 46 %, and net-spinners showed a similar abundance among the sites. Unlike the Uji R., burrowers was frequently found at all sites, and was as subdominant species at Riffle2. In addition, swimmers also appeared at Riffle2 and Riffle3 (Fig.5-11b). Analysis on functional feeding groups resulted in less relative abundance of filterers ranging 15 to 22 %, which is only a quarter of that in the Uji R. Meanwhile, predators increased, and collector-gatherers and shredders decrased with the distance from the dam (Fig.5-11c).

Similar to the patterns in life forms and FFGs, the stable isotope values of benthic animals did not show any distinctive changing patterns in the reahces (Fig.5-12). The isotopic values of benthic animals located between those of lentic plankton and epilithic algae, but far from that of terrestrial plant.

The net-spinning filterers, Hydropsychidae, showed more enriched $\delta^{13}C$ and depleted $\delta^{15}N$ at downstream sites closing to the values of epilithic algae. In contrast, the stable isotopic signatures of Diamsinae, Chironomidae, *Asellus hilgendorifii* and *Tridentiger brevispinis* showed longitudinally a depleting patterns for $\delta^{13}C$ and an enriching pattern for $\delta^{15}N$ (Fig.5-13).

5.4. DISCUSSIONS

5.4.1 Contribution characteristics of size fractionated suspended and benthic POMs

Comparison of relative contributions showed that there were distinct difference of source origin composition between location types and size fractionation types. The biomass contribution of lentic plankton appeared to be more in the order S-FPOM(47.2%) ≫ S-CPOM(17.6%) > B-CPOM(7.4%) ≒ B-FPOM(6.4%) (Table 5-5). The result suggests that filter feeding invertebrates fed on S-FPOM may be susceptible to lentic plankton impacts because large amount of lentic plankton is transported downstream as suspended load.

The contribution characteristics of B-FPOM accounting for high contribution of terrestrial source (74.2%) were interestingly different from S-FPOM. It suggests that the shallow stagnant zone of BPOM and the flowing zone of SPOM can have trophically different foodweb structures even in the same cross section (*refer to* Fig.1-5). Although such contribution characteristics of S-FPOM and S-CPOM is closely consistent with the results in the Uji R. described in Chapter 3, those of B-FPOM and B-CPOM in the Nunome R. is significantly different from the pattern in the Uji R., where the contribution of epilithic algae was dominantly high in BPOM ($f_{B,s}$ was over 66%) relative to terrestrial plant (Table 3-4). Consequently, low contribution of epilithic algae in BPOM ($f_{B,s}$ was under 20%) can be an important effect of sediment replenishment on POM dynamics because the sediment replenishment can restrict epilithic algal production in downstream reaches and moreover the replenished sediment led to rub attached algae away from stone surfaces. The finding was supported by the result from Sakamoto et al (2005). They found the amount of organic matter of periphyton was reduced in 53.3% after a sediment replenishment in the downstream of the Managawa Dam.

5.4.2 Roles of riffle and pool structures in dam tailwater S-FPOM dynamics

As pointed out in 5.3.3, contribution changes of S-FPOM along the stream suggested that there were spatial trends according to riffle and pool structures. It was found that biomass contribution of the lentic plankton source decreased 6.8-8.0% during passing riffle structures, whereas that of the terrestrial plant source decreased 2.3-24.1% during passing pool structures (Table 5-7). Such findings can support the conceptual SPOM dynamics model which suggested from the results of the Uji R. in chapter 4. Reduced contribution of lentic plankton in the riffles may be attributed to physical filtering by substrate and biological filtering by filter-feeding animals. Also reduced contribution of allochthonous terrestrial source during passing pool could be due to settling down by comparatively deep depth and low velocity. These findings can provide an interesting implication that riffle-pool sequences in dam tailwater channels may play a role in spatially different contributions of S-FPOM according to its source origins.

Unlike the Uji R., however, a certain pattern of autochthonous epilithic algae in association with riffle and pool was difficult to be found. The contribution of epilithic algae, however, gradually increased with going downstream irrespective of riffle and pool, only after the sediment replenishment place near St2 (Fig.5-10a). It is supposed as one of replenishment effects on downstream POM dynamics.

5.4.3 Sediment replenishment effect on downstream POM dynamics: Comparison with the Uji River

Because there was unfortunately little information about POM dynamics before 2004 when sediment replenishment works were started in the Nunome R., evaluation of sediment replenishment effect on downstream POM dynamics is difficult by direct comparison of before and after in the same reaches. Instead, indirect evaluation may be possible by comparison with the results from other dam tailwater reaches without sediment replenishment records. In this section, therefore, we compared the POM dynamics characteristics between the Nunome R. and the Uji R. described in Chapters 3 and 4. As already mentioned in 5.4.1 and 5.4.2, some important effects of sediment replenishment on POM dynamics can be the low contribution of epilithic algal source and gradually increasing contribution of the terrestrial plant source in S-FPOM just after sediment supplement site.

Comparison of reduction pattern of lentic plankton contribution gave interesting information about retention efficiency of the downstream reaches with different geomorphological configuration (Fig.5-14). Mean transport distance (S_p) of lentic plankton, which calculated by longitudinal loss rate (k), was approximately 2 times shorter in Nunome R. (2.03km) than in the Uji R. (4.12km) as shown in Table 5-8 (Where the detailed information on calculating S_p and k can be referred to in 2.2.4). The result means that the downstream reaches of the Nunome R. has a retention efficiency of lentic plankton about 2 times higher than that of the Uji R., suggesting an important effect of sediment replenishment on downstream ecosystem.

From a geomorphological prospective, large amount of sediment artificially supplied by sediment replenishment will influence formation of the riffle and pool structures in the downstream reaches. By comparative analyses between the Nunome R.

and the Uji R., it was found that the Nunome R. had relatively long riffle and short pool, whereas the Uji R. had relatively short riffle and long pool. Such geomorphological difference was quantified by an index of riffle fraction, F_R (the ratio of the riffles distance to the total distance). The F_R in the Nunome R. and the Uji R. were 68.42% and 15.5% respectively. In addition, another morphological difference was the depth of riffle (h_R) and pool (h_p) structures (Table 5-8). The ratio of h_p/h_R in the Nunome R. (1.76) was much less than that in the Uji R. (3.30) probably because of the bed degradation effect continued since dam construction in the Uji R.

Subsequently increasing F_R and reducing h_p/h_R can lead to decrease the values of hydraulic radius (R_h). R_h of the Nunome R. was 0.34 m, which was 5.5 times lower than that of the Uji R. of 1.87m (Table 5-8). It was already found that a riffle structure has high retention efficacy of lentic plankton because of the finding that lentic plankton contribution was steeply reduced passing riffle structures (*see* 4.3.2 and 5.3.3).

It is supposed that sediment replenishment lengthens riffles and shortens pools likely as the Nunome R., and then it leads to decrease the mean transport distance of lentic plankton. While the Uji R., being affected by reduced sediment transport (in particular, bed load type) in the downstream of the Amagase Dam, has been degraded and bedrock has been exposed, it results in shorten riffles and lengthen deep pools and then leads to increase the mean transport distance of lentic plankton (Ock and Takemon, 2010). Therefore higher retention efficiency of lentic plankton in the Nunome R. can imply an important effect of the sediment replenishment for downstream ecosystem management.

5.4.4 Effect of sediment replenishment on benthic communities through POM dynamics

Comparing with the Uji R., the low relative abundance of both net-spinners and filters through the dowsntream reaches of the Nunome Dam, indicating a relatively low dependence on the lentic plankton. In particular, the burrowers having a habitat requirement for sand materials were frequently found throughout the sites, indicating an effect of the sediment replenishment work in this reach in the previous year (*see* Fig.5-2). Although overall longitudinal shifting patterns in basal diets were not found in the community level (Fig.5-12), those in the species level were comparatively distinct. The isotopic changes in Hydropsychidae reflected the source composition of S-FPOM, indicating their high dependence on lentic plankton. Whereas longitudinal changes in collector-gatherers such as Diamsinae, Chironomidae, *Asellus hilgendorifii* and benthic predator of *Tridentiger brevispinis* was similar to the pattern of B-FPOM (Fig.5-13), indicating their high dependence on B-FPOM.

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Table 5-1. Hydromorphological characteristics in the downstream reaches of the Nunome Dam in the Nunome River

Reaches	Geo-morphologic features	Length (m)	Water surface velocity (m/s)	Water surface gradient (%)	Channel width (m)	Water depth (m)	Hydraulic Radius (m)	Predominant bed material	pH	DO (mg/L)	Water Tempe-rature (℃)	Conducti-vity (µs)
(1) St1-St2	Riffle 1	300	0.41	0.48	11.71	0.41	0.29	gravel	7.5	11.53	6.7	122.8
(2) St2-St3	Pool 1	100	0.25	0.13	11.20	1.05	0.69	sand	7.45	11.52	6.8	123.5
(3) St3-St4	Riffle 2	50	0.69	0.69	7.20	0.56	0.41	sand	7.37	11.93	6.7	123.9
(4) St4-St5	Pool 2	100	0.41	0.11	9.75	0.84	0.56	sand	7.40	11.87	6.7	124.7
(5) St5-St6	Riffle 3	300	0.53	0.60	16.96	0.41	0.28	sand	7.42	11.66	6.7	125.0
(6) St6-St7	Pool 3	50	0.51	0.20	9.80	0.79	0.46	sand	7.29	11.66	6.5	124.2

The numbers of reaches correspond to those in Fig.5-1.

Table 5-2 Cross sectional characteristics measured by power level with 50m distance intervals in the downstream reaches of the Nunome Dam in the Nunome River.

Site	Cross section No.	Distance from outlet (m)	Width (m)	Mean depth (m)	Maximum depth (m)	Sectional Area (m^2)	Wetted Perimeter (m)	Hydraulic radius, R_h (m)
St1	Line0	50	14.0	0.33	0.71	9.86	24.55	0.40
	Line1	100	12.0	0.44	0.83	5.26	13.87	0.38
	Line2	150	21.7	0.31	0.65	6.40	22.40	0.29
	Line3	200	14.0	0.39	0.58	3.59	12.22	0.29
	Line4	250	5.0	0.13	0.15	0.82	7.02	0.12
	Line5	300	7.4	0.23	0.47	1.75	7.76	0.23
St2	Line6	350	7.9	0.30	0.43	2.29	7.58	0.30
	Line7	400	11.2	0.70	1.06	7.94	11.54	0.69
St3	Line8	450	7.0	0.39	0.58	2.79	7.19	0.39
St4	Line9	500	7.4	0.47	0.68	3.58	8.24	0.43
	Line10	550	9.8	0.54	0.86	5.82	10.41	0.56
St5	Line11	600	19.9	0.27	0.41	5.34	20.04	0.27
	Line12	650	18.1	0.28	0.39	5.32	18.19	0.29
	Line13	700	25.1	0.33	0.71	7.18	19.43	0.37
	Line14	750	14.9	0.21	0.36	2.63	12.17	0.22
	Line15	800	13.3	0.37	0.44	4.37	13.41	0.33
	Line16	850	16.4	0.24	0.40	3.36	16.47	0.20
St6	Line17	900	11.1	0.36	0.46	3.44	11.17	0.31
St7	Line18	950	9.8	0.57	0.68	4.63	10.05	0.46
	Average		12.94	0.36	0.57	4.55	13.35	0.34

Table 5-3 Estimated stable isotope signatures and elemental concentrations of POM source origins in the Nunome River.

	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	[C]	[N]	C/N	n
Terrestrial Plant	-29.34 ±0.24	-2.58±1.14	48.49%	0.50%	97.66	4
Epilithic Algae	-26.18 ±1.09*	13.89±0.23*	37.25%†	3.61%†	10.4†	6=3x2 (no. in bulk x no. of samples)
Lentic Plankton	-36.39±2.00**	16.69 ±3.74**	23.12%‡	4.20%‡	5.25‡	9=3x3 (no. in bulk x no. of samples)

The values of $\delta^{13}C$ and $\delta^{15}N$ are mean±standard deviation

* The values were inferred from algavores grazers

** The values were inferred from planktivores filter-feeders

The trophic fractionation rates for these herbivores in the study were used of -0.41‰ as $\Delta^{13}C$ and +2.52‰ as $\Delta^{15}N$ (Vander Zaden and Rasmussen 2001).

† The values were used from data of epilithic algae in Table 4-2

‡ The values were used from data of lentic plankton in Table 4-2

Table 5-4 Measured values of stable isotopic carbon and nitrogen of S-FPOM, S-CPOM, B-CPOM and B-FPOM in the Nunome River.

	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	n
S-FPOM	-30.97±0.78	14.84±0.36	21
S-CPOM	-29.80±1.07	12.20±1.50	15
B-FPOM	-29.06±0.82	9.90±2.81	6
B-CPOM	-29.24±1.04	9.52±4.14	6

The values are mean±standard deviation.

Table 5-5 Longitudinal changes of stable isotopic carbon and nitrogen of S-FPOM in the Nunome River.

	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	n
ST1	-32.02±0.20	15.40±0.78	3
ST2	-31.70±0.49	14.81±0.42	3
ST3	-31.15±0.16	15.26±0.65	3
ST4	-31.12±0.47	14.61±0.64	3
ST5	-30.77±0.21	14.41±1.15	3
ST6	-30.00±0.34	14.58±0.54	3
ST7	-30.00±0.19	14.84±0.62	3

The values are mean±standard deviation.

Table 5-6 Biomass, carbon and nitrogen contributions of S-FPOM, S-CPOM, B-FPOM and B-CPOM in the Nunome River.

(unit: %)

	(a) Biomass			(b) Carbon			(c) Nitrogen		
	$f_{B,p}$	$f_{B,s}$	$f_{B,t}$	$f_{C,p}$	$f_{C,s}$	$f_{C,t}$	$f_{N,p}$	$f_{N,s}$	$f_{N,t}$
S-FPOM	**47.2**	17.6	35.2	31.6	19.0	**49.4**	**71.0**	22.7	6.3
S-CPOM	21.4	13.1	**65.5**	11.9	11.7	**76.4**	**52.9**	27.9	19.3
B-FPOM	6.4	19.4	**74.2**	3.3	16.2	**80.5**	20.1	**52.3**	27.6
B-CPOM	7.9	14.6	**77.5**	4.1	12.1	**83.8**	26.6	**42.3**	31.1

The index of $f_{B,i}$, $f_{C,i}$ and $f_{N,i}$ represents fractionations of biomass, carbon and nitrogen, respectively, contributed to the POM by source *i*. Source *i* corresponds to lentic plankton (p), terrestrial plant (t) and instream algae (s) respectively.

Table 5-7 Spatial distribution of biomass, carbon and nitrogen contributions of S-FPOM source composition in the Nunome River.

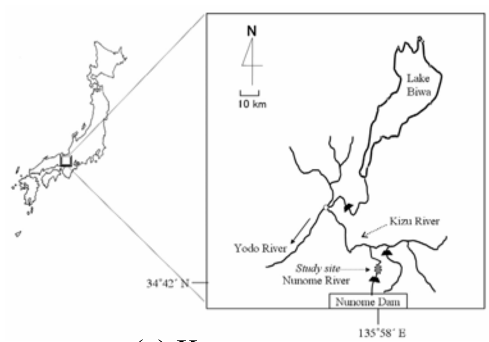
(unit: %)

S-FPOM	(a) Biomass			(b) Carbon			(c) Nitrogen		
	$f_{B,p}$	$f_{B,s}$	$f_{B,t}$	$f_{C,p}$	$f_{C,s}$	$f_{C,t}$	$f_{N,p}$	$f_{N,s}$	$f_{N,t}$
ST1	**59.9**	9.6	30.5	43.0	11.1	**45.9**	**83.5**	11.5	5.0
ST2	**51.9**	1.2	46.8	34.1	1.3	**64.6**	**88.7**	1.8	9.5
ST3	**53.2**	24.1	22.7	**38.1**	27.8	34.1	**69.5**	27.0	3.5
ST4	**46.1**	9.8	44.2	29.8	10.2	**60.0**	**77.2**	14.0	8.8
ST5	**44.5**	13.6	41.9	28.9	14.2	**56.9**	**72.7**	19.1	8.1
ST6	**37.7**	32.6	29.7	24.8	34.4	**40.8**	**54.5**	40.4	5.1
ST7	**40.8**	37.4	21.8	27.8	**41.0**	31.2	**54.0**	42.5	3.4

The index of $f_{B,i}$, $f_{C,i}$ and $f_{N,i}$ represents fractionations of biomass, Carbon and Nitrogen, respectively, contributed to the POM by source *i*. Source *i* corresponds to lentic plankton (p), terrestrial plant (t) and instream algae (s) respectively.

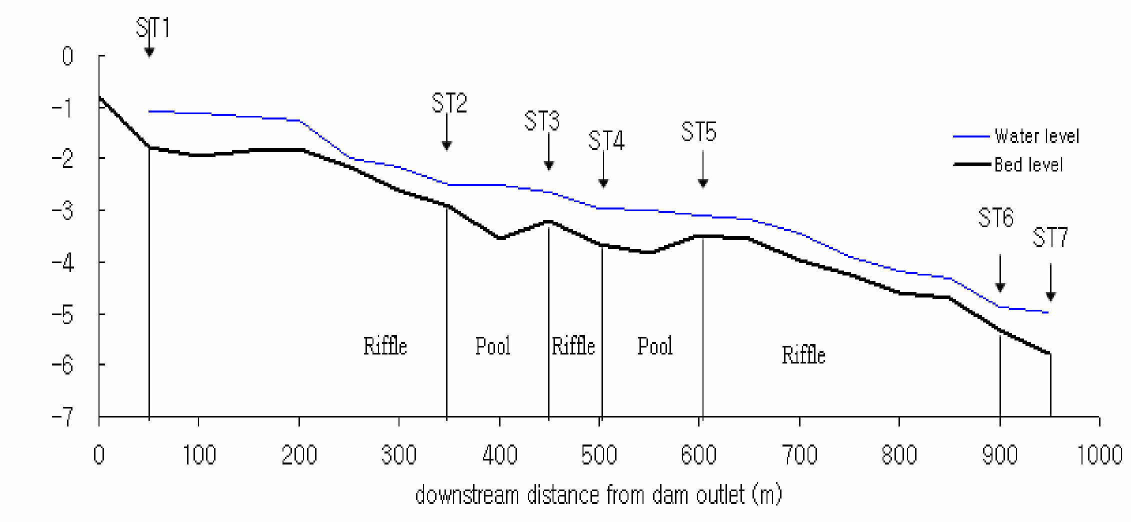
Table 5-8 Comparison of transport distance and hydro-geomorphological parameters between the Nunome River and the Uji River

	Transport distance	Slope		Depth				Hydraulic radius	Fraction of riffle	Mean velocity
		Water	Bed	Mean	Riffles	Pools				
	S_p (km)	I_w (%)	I_b (%)	h (m)	h_R (m)	h_P (m)	h_P/h_R	R_h (m)	F_R (%)	u (m/s)
Nunome River	**2.04**	0.45	0.44	0.56	0.34	0.61	**1.76**	**0.34**±0.13	**68.4**	0.47±0.15
Uji River	**4.12**	0.07	0.10	1.74	0.67	2.20	**3.30**	**1.87**±0.91	**15.5**	0.61±0.23



(a) Key map

(b) Plain profile



(c) Longitudinal profile

Fig.5-1 Map of study sites in the downstream reaches of the Nunome Dam in the Nunome River. Seven sites for samplings were established along riffles and pools of geomorphological features.

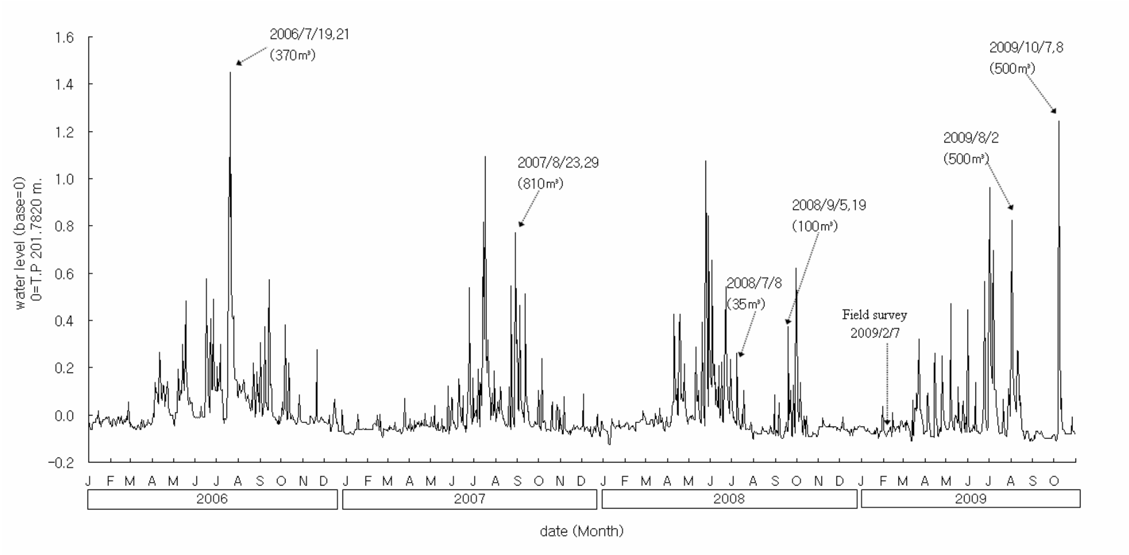


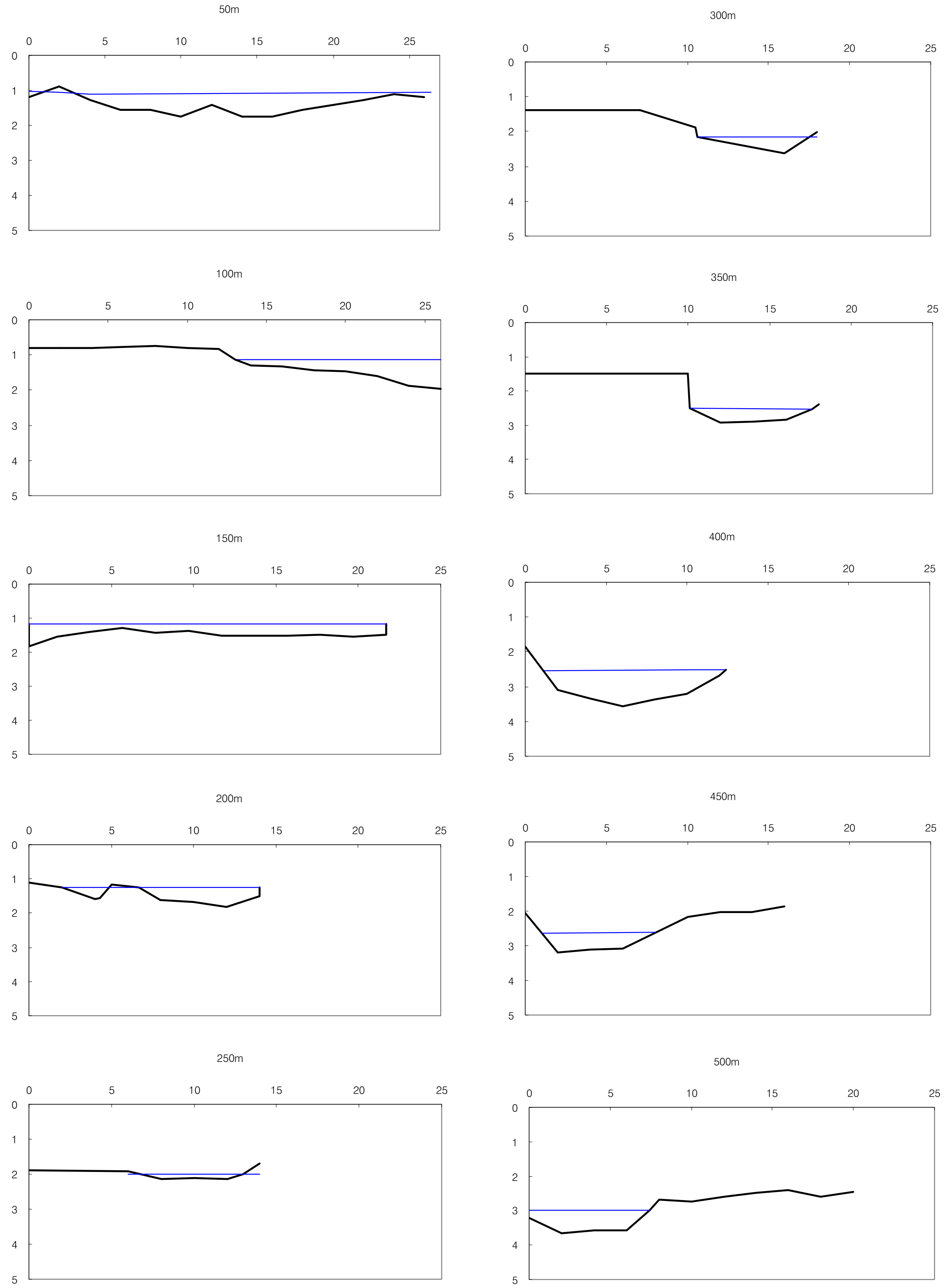
Fig.5-2 Temporal information about the date and volume of the replenished sediment since 2006 and filed survey in the Nunome River. The values below dates in the graph represent amount of supplied sediment in the day. The data of water level used was measured at the Okugahara gauging station.

(a) Before (2009/10/2)
sediment volume: 500 m^3

(b) Under replenishment (2009/10/8)
flow discharge: 81 m^3/s

(c) After (2009/10/14)

Fig.5-3 Field views of sediment replenishment in sediment deposit site (St.2) of the Nunome Dam in the Nunome River. About 500 m^3 of sediment was supplied from this point to the downstream reaches in 81 m^3/s of peak flow discharge.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0 1 2 3 4 5

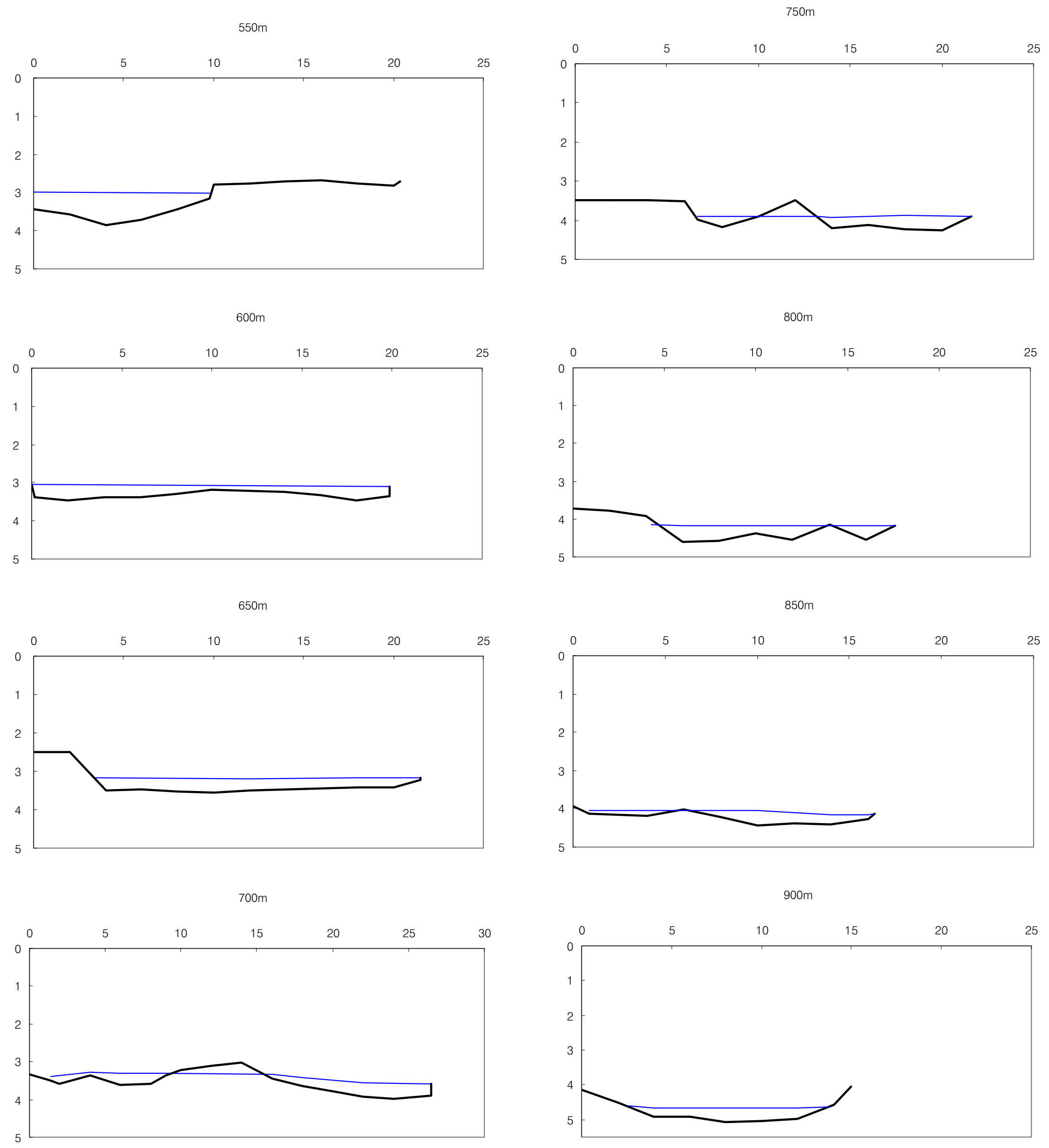


Fig.5-4 Cross sectional profiles measured by power level with 50m distance intervals in the downstream reaches of the Nunome Dam in the Nunome River. The length written in title represents the downstream distance from dam outlet. The axes units are meter.

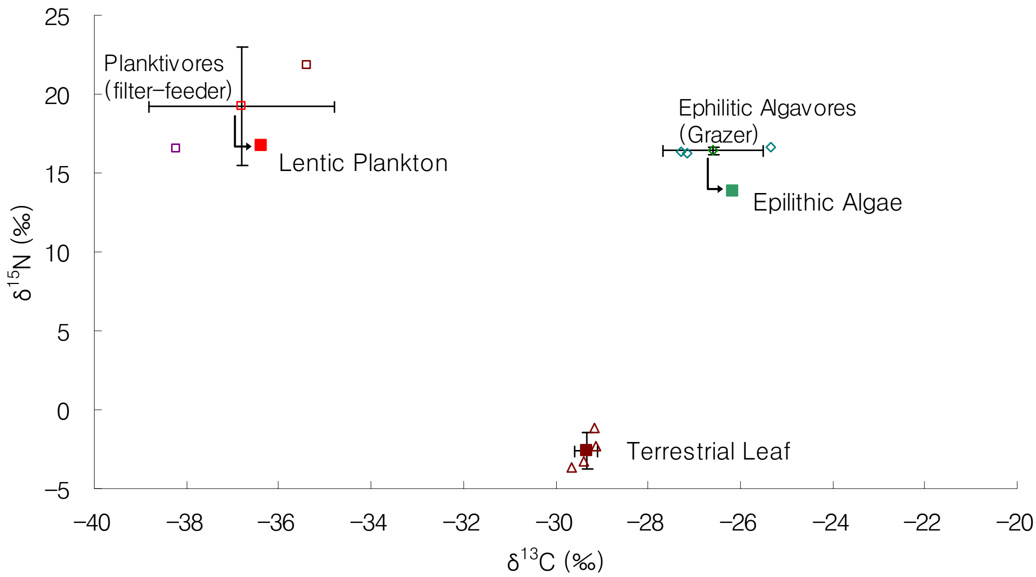


Fig.5-5 Estimation of stable isotope values of three source origins comprising of POM in the Nunome River. In this study, the values of lentic plankton and epilithic algae were derived from benthic marcro-invertebrates by means of assimilation fractionation rate of herbivores. The trophic fractionation rates for these herbivores were applied in -0.41‰ as $\Delta^{13}C$ and +2.52‰ as $\Delta^{15}N$ (Vander Zanden and Rasmussen 2001).

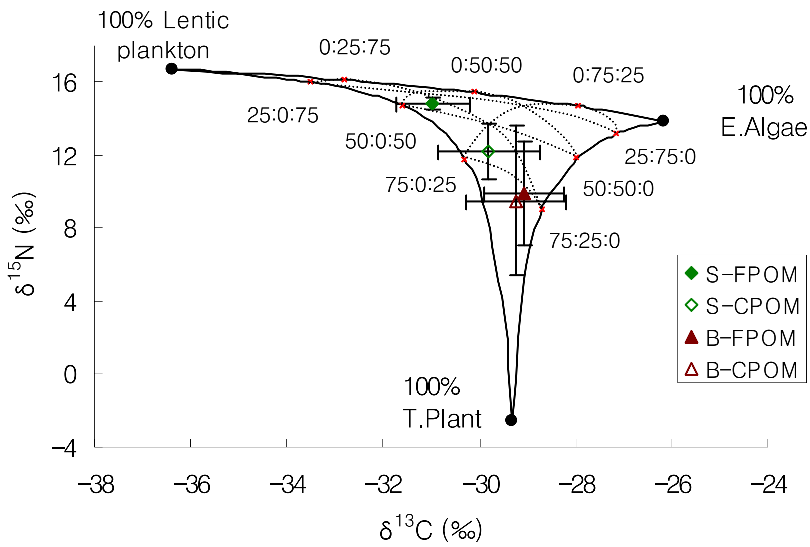


Fig.5-6 Mean stable isotope signatures of four types of POMs (S-FPOM, S-CPOM, B-CPOM and B-FPOM) and nonlinear mixing triangle in the Nunome River. The values of ratios composed of three sources are in order of terrestrial plant : epilithic algae : lentic plankton.

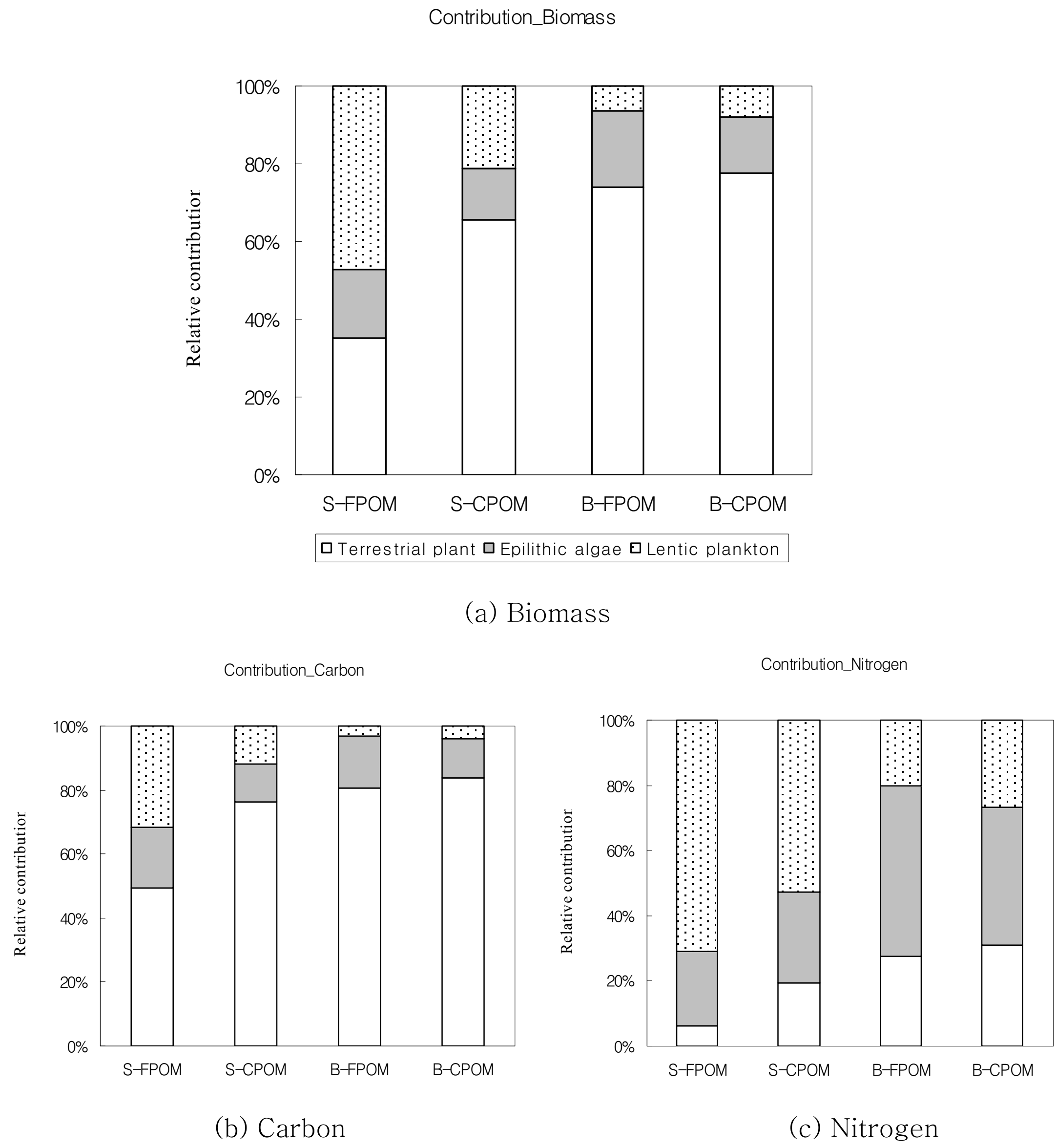


Fig.5-7 Comparisons of relative contributions of three POM source origins based on biomass (a), carbon (b) and nitrogen (c) among S-FPOM, S-CPOM, B-FPOM and B-CPOM in the Nunome River.

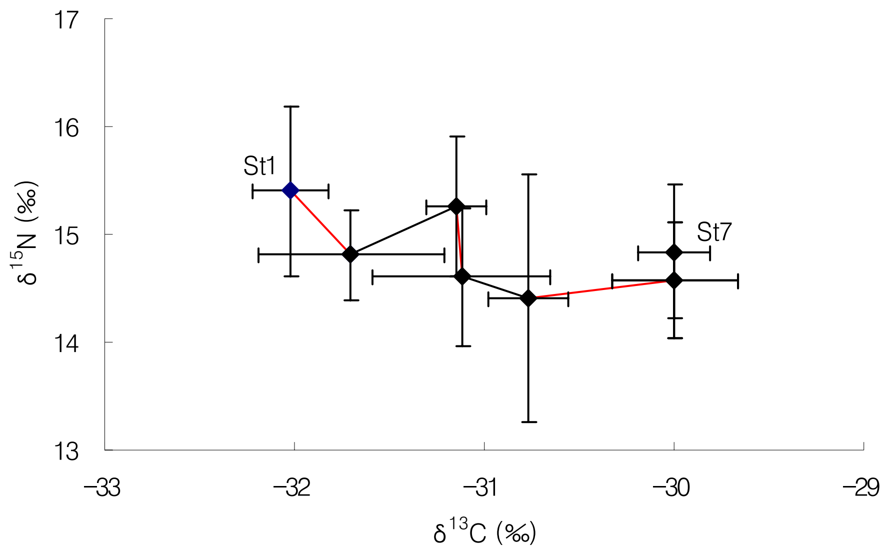


Fig.5-8 Spatial distribution of all S-FPOMs in dual isotope composite plots in the Nunome River. Closed circle and error bar represent mean value and standard deviation, respectively.

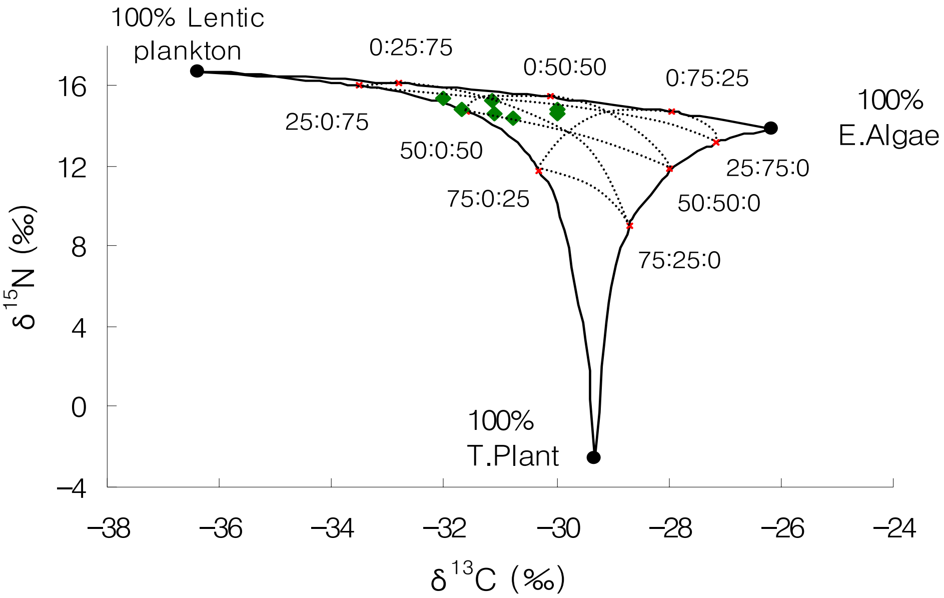
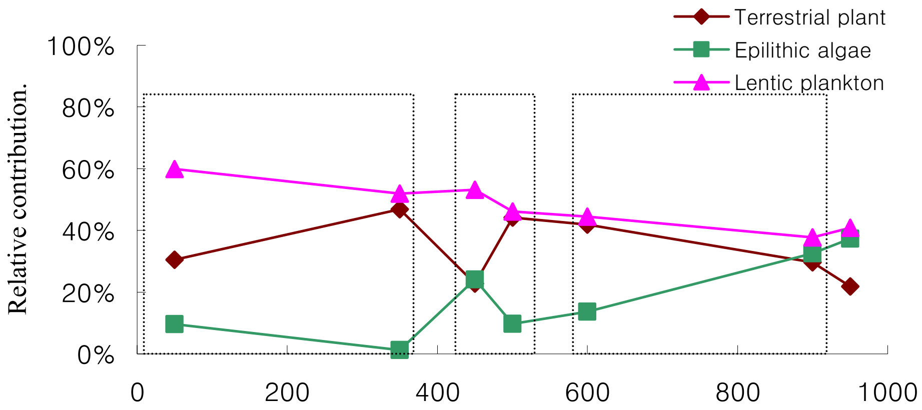
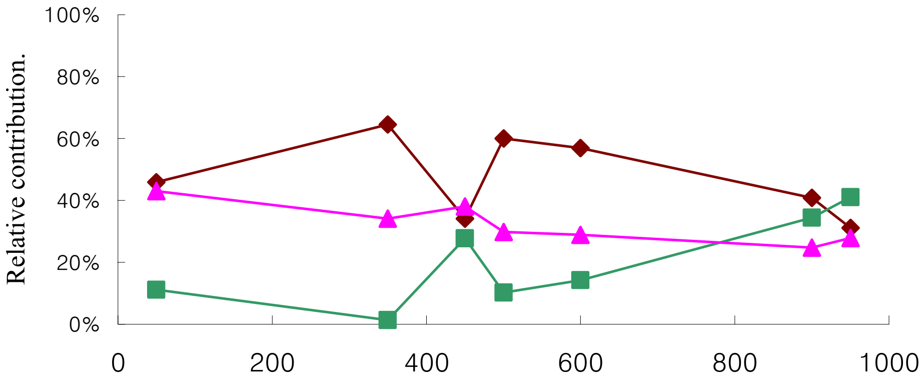


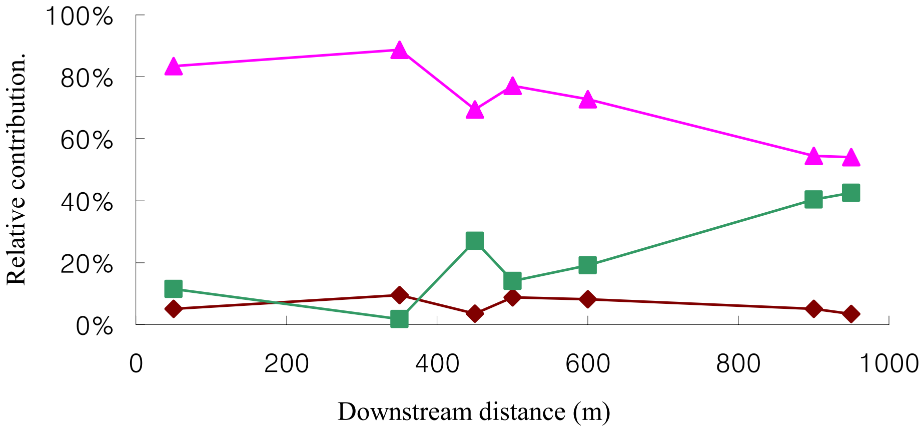
Fig.5-9 Spatial distribution of stable isotope ratios of S-FPOM surrounded by nonlinear mixing triangle derived from concentration-weighted multi-source mixing model in the Nunome River. The values of ratios composed of three sources are in order of terrestrial plant : epilithic algae : lentic plankton.



(a) Biomass contribution



(b) Carbon contribution



(c) Nitrogen contribution

Fig.5-10 Downstream changes of relative contributions of S-FPOM source origins based on biomass (a), carbon (b) and nitrogen (c) in the Nunome River. The dotted-boxes in the figure represent the riffle zones in the reaches.

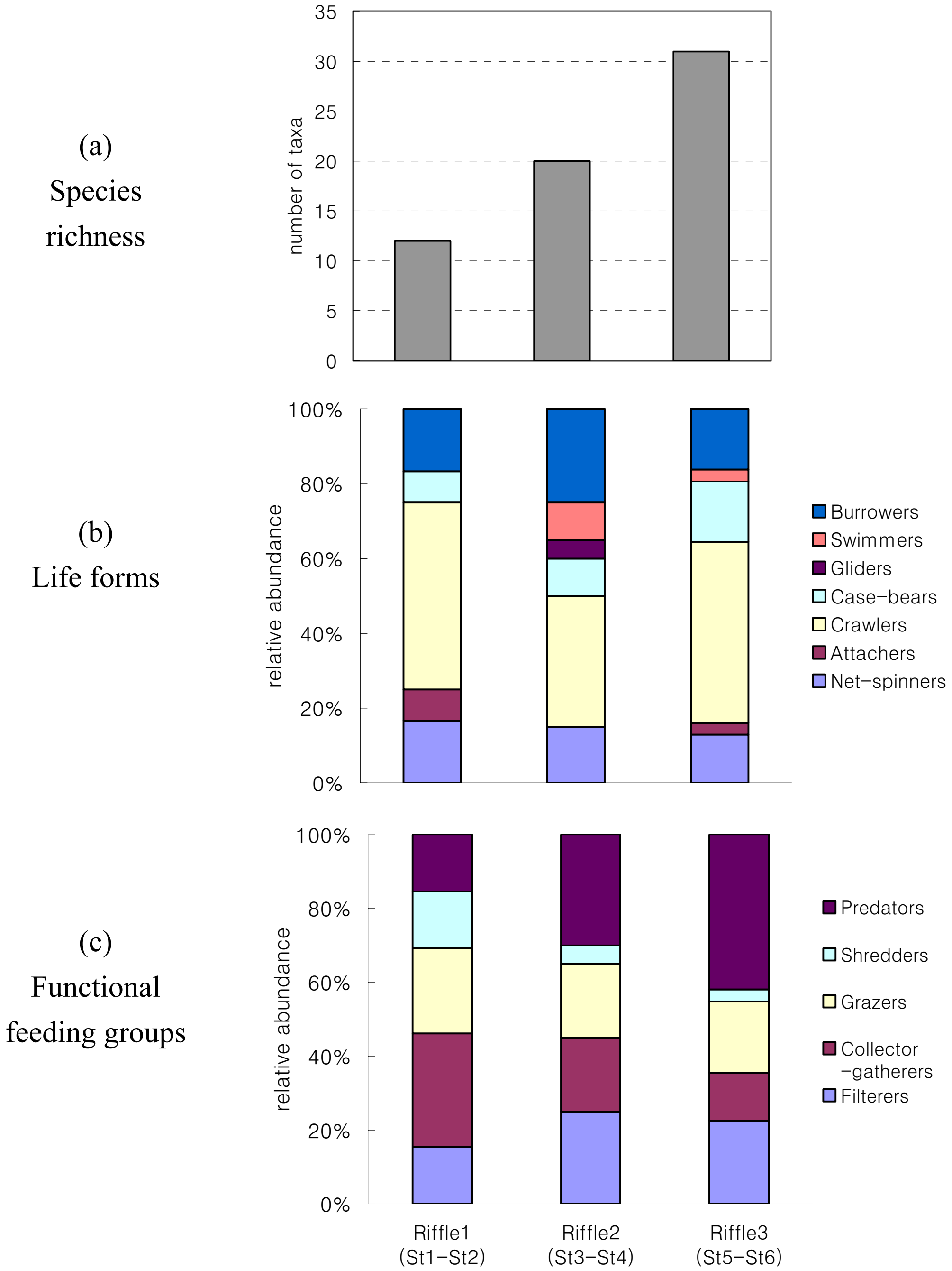


Fig.5-11 Longitudinal changes in species richness, life form and functional feeding group composition of benthos communities in the downstream reaches of the Nunome Dam in the Nunome River

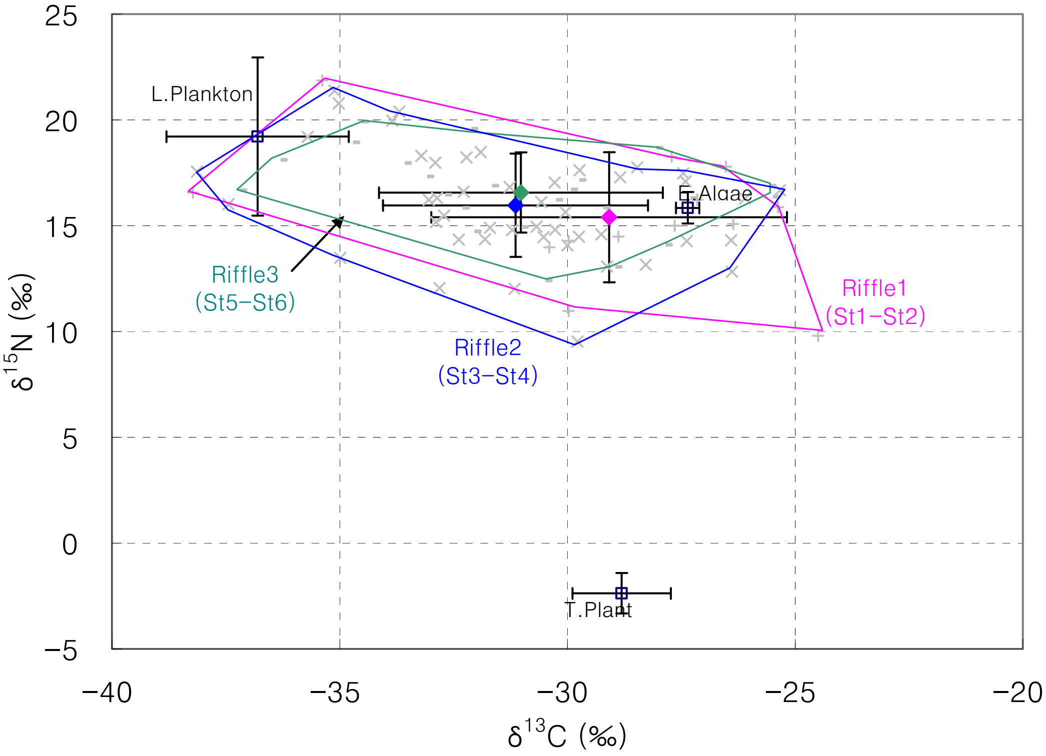


Fig.5-12 Longitudinal changes in stable isotopic values of overall benthic communities in the downstream reaches of the Nunome Dam in the Nunome River

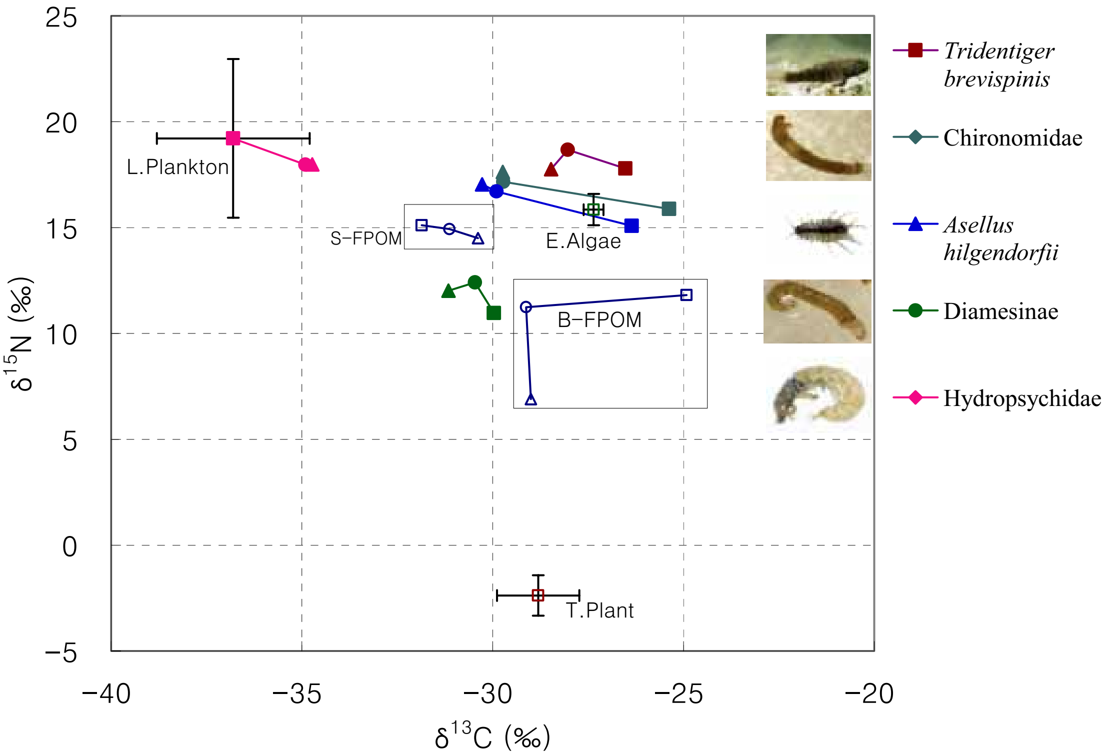


Fig.5-13 Longitudinal changes of stable isotopic values of aquatic animals in the Nunome River. The closed square, circle and triangle in the figure represent Riffle1, Riffle2 and Riffle3, respectively.

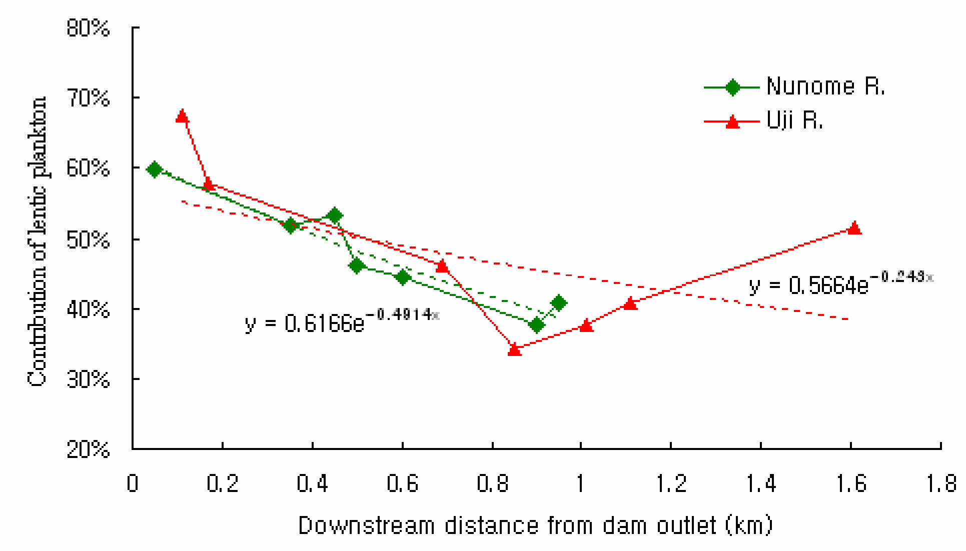


Fig.5-14 Comparison of reduction pattern of plankton contribution between the Nunome River and the Uji River

Appendix

Categorization of benthic invertebrates and fish by their life form and functional feeding types in the Uji R. and Nunome R.

Phylum	Class	Order	Family	Japanese name	Scienctific name	Life forms	FFGs	Food	Uji River Riffle1	Uji River Riffle2	Uji River Glide	Uji River *Total*	Nunome River Riffle1	Nunome River Riffle2	Nunome River Riffle3	Nunome River *Total*
軟体動物	腹足	吸腔	カワニナ	カワニナ	*Semisulcospira libertina*	CRL	GR	Algae		○	○	●			○	●
				チリメンカワニナ	*Semisulcospira reiniana*	CRL	GR	Algae					○			●
		基眼	サカマキガイ	サカマキガイ	*Physaacuta draparnaud*	CRL	GR	Algae					○			●
	二枚貝	マルスダレガイ	シジミ	マシジミ	*Corbicula leana*	BUR	FL	S-FPOM	○			●		○	○	●
		イガイ	イガイ	カワヒバリガイ	*Limnoperna fortunei*	ATC	FL	S-FPOM	○	○	○	●				
環形動物		ノビビル	イシビル	シマイシビル	*Erpobdella lineata*	CRL	PR	Animal		○		●				
節足動物	甲殻	ワラジムシ	ワラジムシ	ミズムシ	*Asellus hilgendorfii*	CRL	CG	B-FPOM					○	○	○	●
		十脚	サワガニ	サワガニ	*Geothelphusa dehaani*	CRL	PR	Animal							○	●
	ヒル	エビ	テナガエビ	テナガエビ	*Macrobrachium nipponense*	CRL	PR	Animal					○		○	●
				フロリダマミズヨコエビ	*Crangonyx floridanus*	CRL	CG	B-FPOM	○	○	○	●				
	昆虫	カゲロウ	カワカゲロウ	キイロカワカゲロウ	*Potamanthus formosus*	CRL	CG	B-FPOM							○	●
			モンカゲロウ	モンカゲロウ	*Ephemera strigata*	BUR	FL	S-FPOM						○	○	●
			マダラカゲロウ	シリナガマダラカゲロウ	*Acerella longicaudata*	CRL	PR	Animal						○	○	●
				オオクママダラカゲロウ	*Cincticostella okumai*	CRL	PR	Animal							○	●
				オオマダラカゲロウ	*Drunella basalis*	CRL	PR	Animal						○	○	●
				エラブタマダラカゲロウ	*Torleya japonica*	CRL	PR	Animal						○	○	●
				アカマダラカゲロウ	*Uracanthella rufa*	CRL	PR	Animal						○	○	●
			コカゲロウ	フタバコカゲロウ	*Baetiella japonica*	GLD	GR	Algae						○		●
				シロハラコカゲロウ	*Baetis thermicus*	SWM	GR	Algae	○			●			○	●
				コカゲロウ属	*Baetis* sp.	SWM	GR	Algae		○		●		○		●
			ヒラタカゲロウ	シロタニガワカゲロウ	*Ecdyonurus yoshidae*	GLD	GR	Algae		○		●				
			チラカゲロウ	チラカゲロウ属	*Isonychia* sp.	SWM	CG	B-FPOM						○		●
		トンボ	サナエトンボ	オナガサナエ	*Onychogomphus viridicostus*	BUR	PR	Animal							○	●
				コオニヤンマ	*Sieboldius albardae*	BUR	PR	Animal							○	●
		カワゲラ		オナシカワゲラ属	*Nemoura* sp.	CRL	SH	Litter					○			●
				フタツメカワゲラ	*Neoperla geniculata*	CRL	PR	Animal			○	●				
			アミメカワゲラ	フタスジミドリカワゲラモドキ	*Isoperla nipponica*	CRL	PR	Animal								
				ミドリカワゲラモドキ属	*Isoperla* sp.	CRL	PR	Animal						○	○	●
			ミジカオカワゲラ	ミジカオカワゲラ	*Taeniopterygidae*	CRL	PR	Animal							○	●
		トビケラ	シマトビケラ	コガタシマトビケラ	*Cheumatopsyche brevilinaeta*	NSP	FL	S-FPOM			○	●	○		○	●
				コガタシマトビケラ属	*Cheumatopsyche* sp.	NSP	FL	S-FPOM						○	○	●
				ナカハラシマトビケラ	*Hydropsyche setensis*	NSP	FL	S-FPOM	○	○		●		○	○	●
				オオシマトビケラ	*Macronema radiatum*	NSP	FL	S-FPOM	○	○	○	●	○	○	○	●
			ナガレトビケラ	ムナグロナガレトビケラ	*Rhyacophila nigrocephala*	CRL	PR	Animal						○	○	●
				トランスクィラナガレトビケラ	*Rhyacophila transquilla*	CRL	PR	Animal							○	●
			ニンギョウトビケラ	ニンギョウトビケラ属	*Goera* sp.	CBR	GR	Algae							○	●
			ヒゲナガトビケラ	アオヒゲナガレトビケラ	*Mystacides azurea*	CBR	CG	B-FPOM					○			●
			カクスイトビケラ	マルツツトビケラ属	*Micracema* sp.	CBR	GR	Algae						○	○	●
				マルバネトビケラ	*Phryganopsyche latipennis*	CBR	SH	Litter							○	●
				コエグリトビケラ	*Apatania insularis*	CBR	GR	Algae						○	○	●
			グマガトビケラ科	グマガトビケラ属	*Gumaga* sp.	CBR	GR	Algae							○	●
		ハエ	ガガンボ	ウスバヒメガガンボ属	*Antocha* sp.	ATC	GR	Algae					○			●
				ヤマトガガンボ属	*Tipula* sp.	BUR	SH	Litter					○	○		●
			ブユ	アシマダラブユ	Simuliidae	ATC	FL	S-FPOM	○	○		●			○	●
			ユスリカ	ヤマユスリカ属	*Diamesa* sp.	CRL	CG	B-FPOM	○	○	○	●	○		○	●
				ユスリカ亜科	Chironominae	BUR	CG	B-FPOM					○	○	○	●
				アカムシユスリカ	*Tokunagayusurika akamusi*	BUR	CG	B-FPOM						○		●
脊索動物	条鰭	スズキ	ハゼ	ヌマチチブ	*Tridentiger brevispinis*	SWM	PR	Animal					○	○	○	●
			サンフイツシユ	オオクチバス	*Micropterus salmoides*	SWM	PR	Animal			○	●				
		コイ	コイ	カワムツ	*Zacco temminckii*	SWM	PR	Animal						○	○	●
				オイカワ	*Zacco platypus*	SWM	PR	Animal						○	○	●
					Species richness of bentic communities				8	10	7	*14*	12	20	31	*41*
					Species richness of aquatic communities (including fish)				8	10	8	*15*	13	23	34	*44*

Life forms	
NSP	Net-spinners
ATC	Attachers
CRL	Crawlers
CBR	Case-bears
GLD	Gliders
SWM	Swimmers
BUR	Burrowers

Fuctional feeding groups	
FL	Filterers
CG	gatherers
GR	Grazers
SH	Shredders
PR	Predators

CHAPTER 6

Experimental Study on FPOM Deposition in relation to Channel Geomorphology

6.1 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 by conditioning microhabitats for benthic animals such as macro invertebrates and fish.

Spatial distribution of FPOM has been often considered in a 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 the variation in reach scale is interestingly 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 retention efficiency of the riverbed will benefit to enhance rive ecosystem functions.

We focused on the FPOM dynamics in the downstream below dam reservoir. The POM source composition in the dam tailwater ecosystem has been considered to be different from natural river ecosystem. The supply of large amount of lentic plankton derived from dam reservoir outflows alters the balance of FPOM dynamics and it often results in a thick accumulation of epilithon on the riverbed. Moreover the changes of geomorphologic features derived from riverbed degradation and bed material armoring by reduced sediment load is expected to affect the transport and deposition processes of FPOM. Consequently, for habitat management and restoration in dam tailwater ecosystem, it is essential to evaluate and predict how concentration and source composition of FPOM are spatially distributed according to river geomorphological characteristics in a reach scale channel. In Chapter 2, the mean transport distance and field deposition velocity were estimated by tracing lentic plankton in four different tailwater channels for assessment of the retention efficiency, and the results 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 2010). These indicate that deposition densities of suspended FPOM may be influenced by reach scale geomorphological features.

In Chapter 4 and Chapter 5, transport and deposition of lentic plankton and terrestrial plant were found to be changed dynamically even in a riffle and pool scale with distinctly different characteristics, although those of the epilithic algae were various according to a local algal production which is highly affected by the length and depth of riffles and pools. Based on these findings, the present study focuses on clarifying deposition processes (*see* Fig.1-5) according to source materials with different settling velocity (i.e., lentic plankton and terrestrial plant) by means of an experimental study. When compared with the filed studies, the experimental study not only enables a constant discharge to sustain for preventing the errors from a discharge variation, but also can exclude the inputs of source materials from outside of the reaches. Moreover the exclusion of the effects of biological filtration and application to various experiential bed conditions with interests can be important merits of the experimental study.

This present study aims to investigate how, where and how much will different source materials of FPOM be deposited to riverbed by influenced from channel geomorphology. A series of hydraulic experiments were conducted using two types of pine pollen as FPOM analogue under two forms of channel morphology. To test the pine pollens as FPOM analogues under dam tailwater channels is one of the purposes of this study. The spatial distribution of the deposition density of the pollens was analyzed in relation to the bed elevation, velocity distribution.

6.2 EXPERIMENT SET-UP

Experimental procedures from the setup of the flume to the measurements were described in the following sections and were summarized in Photo 6-1.

6.2.1 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, Kyoto University. For this experiment, the channel slope was adjusted to be 1/200. The detailed experimental set-up was depicted in Fig.6-1.

A weir model made of 11.7 cm height wooden pieces was placed at the end of the movable bed zone, which had 8.5 cm set-up thickness made of silica sand with 1.56 mm of mean diameter. Two types of bed configurations were produced by changing the height of the weir. In this study, 'CASE Initial' was an equilibrium bed configuration with the initial weir shape, i.e., no removal type, under a stable discharge. 'CASE 1' was an equilibrium bed configuration under the same discharge condition, but removing the head of the weir 3 cm (1/4 falling) from the Case Initial. Detailed experimental conditions are given in Table 6-1.

When channel morphology reached an equilibrium condition, the two types of pine pollen prepared in 1L bottles were uniformly released into the flowing water at uppermost site of the flume. Flow discharge kept constant until the pollens were enough to be deposited on the bed. The remaining pollens in water not deposited on the bed were trapped using the wide net with 20㎛ mesh size equipped at the mouth of flume in order to prevent them from recirculation.

6.2.2 Measurements

The origin of the measurement area for the analysis was set in Fig.6-1. The x, y and z axes start from the beginning of the movable bed of the flume to upward, the left wall of the flume to the rightward and bottom of the flume to the surface-ward, respectively.

Water levels were longitudinally measured at the centre of the flume using a pointer gauge.

Bed elevations were measured from 0 to 680 cm in x axis by means of a laser range finder. Δz which is defined as a difference between elevation of a point and the mean elevation of the cross section was calculated. A positive Δz means that elevation of the point is higher than the mean elevation in the cross section, whereas a negative one means lower. And the relative Δz ($\Delta z/\Delta z_{max}$) means the standardized value to the largest Δz designated as 1.0. In addition, 'aspect' defined as the direction of slope faces were analyzed by ArcGIS software (ESRI ®, version 9) using a bed elevation contour map derived by Surfer software (Golden software Inc, version 8). The index of aspect is generally measured clockwise in degrees from 0° (due north) to 360° (again due north), and that of slope is percentage of run to rise where 100% is corresponding to 45° degree. In the present study, the relations between the aspect and shapes of the slopes in bed elevation were shown in Fig.6-2. For Instance, the west of aspect is corresponding to a forwarding slope which shows longitudinally decreasing gradient of the slope and the north is a rightwarding slope which laterally decreasing gradient with a right direction.

Surface flow velocities, *u* (longitudinal) and *v* (lateral) were measured by means of the particle image velocimetry (PIV) method. Divergence *divV* is calculated by the following Eq.6-1. In this study, we assumed that the positive value of the *divV* we observed in surface water corresponds to an upwelling of the flow and the negative is a downwelling.

$$divV = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \qquad \text{(Eq.6-1)}$$

6.2.3 Channel Morphology and hydraulics

(1) Case Initial

As shown in Fig.6-3a, the bed configuration of 'CASE Initial' was morphologically characterized by 'damming pool and inflow channel'. A damming pool was formed up to approximately 4 m distance from the weir location (x=0), and in the upstream area of the damming pool, an asymmetrical inflow channel was produced as the backwater effect from the weir reduced. In particular, a sediment front with relatively high elevation was outstandingly built between the damming pool and the inflow channel.

The aspects were different among the damming pool, front area and inflow channel. While the front area was abundant of west and east sides because of the hill occurrence. In the inflow channel, although it showed various aspects, the north was abundant in a higher sites but the south was abundant in lower sites (Fig.6-3b).

The longitudinal velocity *u* showed a distinct difference between the damming pool and the inflow channel. *u* was highest in the inflow channel and then decreased with going to the damming pool. In particular, the backwater effect was occurred near the front area. The lateral velocity *v* was almost 0 in the whole channel (Fig.6-3c). The flow divergence, *divV*, also did not show an obvious difference as a whole but only showed the local convergence near X= 40 and 400 locations (Fig.6-3d)

(2) Case 1

A bed configuration of 'Case 1' was morphologically characterized as 'alternate bar and thalweg areas' (Fig.6-4a). As the damming pool which was formed in the Case initial was disappeared, the alternate bar structures were newly created. In the present study, the configuration was morphologically divided into two groups: the first is 'bars' area, which has a positive Δz with relatively high lateral elevation. The second is 'thalweg' area, which has a negative Δz with relatively low lateral elevation. As a whole despite a few local variations, the two groups were divided by about 8 to 8.2 cm of the bed elevation. In result, the large three bars were produced and the riffle and pool structures were located in the thalweg area along the channel.

Aspects of bed slope faces were variously distributed compared with the Case Initial. Generally the north sides were located at the highest area in the bars and at the lowest area in the thalweg. The middle of bar and thalweg had south sides, but the boundary area between the bar and thalweg varied in aspects including northeast, northwest, southeast and east (Fig.6-4b).

u was distinctively higher than in Case Initial. And in general, the u in the thalweg showed relatively higher than that in the bars. *v* showed almost 0 as a whole, but increased a little near the highest areas of bars and at the right wall neat the weir (Fig.6-4c). Compared with the Case Initial, the distribution of the *divV* showed various patterns (Fig.6-4d).

6.2.4 FPOM Analogue: Two types of pine pollen

Some studies for investigating riverine FPOM transport in the field experiment have used lentic diatom, Lycopodium spores, leaves particle, radioactive ^{14}C labeled seston, fluorescently labeled yeast and corn pollen (Georgian *et al.* 2003) as FPOM tracer or analogues particles.

In this hydraulic model experiment, pine pollen was used because of its merits as suspended FPOM analogue; it has two types in water, floating type buoyant in water and sinking type falling to the bottom. In a natural condition, most of pine pollen is buoyant in water due to air bladders (Fig.6-5a). However, we made it possible to transform the floating type into the sinking one (Fig.6-5b) without alteration of shape and size by removal of inside air through washing out an oily outer layer using chemical surfactant. We measured the size and sinking velocity of the pollen particle in laboratory. The mean particle size in water was 72.9±10.2 ㎛ at long axis and 42.8±4.9 ㎛ at short axis (n=50). The settling velocity of sinking type particle was 3.32±0.15 m/h in 26.2℃ in a room temperature.

6.2.5 Sample collection and identification

When most of water was drained sufficiently from the experimental bed, spot samples of deposited pollen particles were collected at a lattice section at about 1.5 cm depth from the bed surface collected with bed material using a core sampler whose diameter is 4.6cm (Fig.6-6a). Four samples with equal intervals (generally at Y= 10, 20, 30 and 40 cm) were taken in each lateral line. The lateral lines and total numbers of samples were determined according to bar structures in river channel morphology (Fig.6-6b).

The collected samples were wet-sieved using a 250 ㎛ meshed sieve to separate the pollen grains from bed material particles. The separated pollens were put in 5ml bottles with distilled water filling it up and then the bottles were preserved in a refrigerator prior to the analyses.

A quantitative analysis was performed using a microscope under x100 magnification. After shaking fully each bottle for making the pollen grains distribute uniformly, the 20㎕ drop was put on a slide glass using a micropipette for a microscopic examination. Two types of pine pollen particles were identified, and total number of each type was counted for three times per one sample. The pollen deposition density, ρ_{dep}, was estimated with the total numbers of pollen particles in consideration of the are of the core sampler and the dilution rate (20㎕ for examination to 5㎖ of total volume) as the following equation.

$$\rho_{dep}\text{-}F \text{ or } \rho_{dep}\text{-}S \text{ (grains/cm}^2\text{)} = \textit{Number of pollen particles deposited in bed / Unit area} \quad \text{(Eq.6-2)}$$

where ρ_{dep}-F and ρ_{dep}-S are the floating and the sinking pollen density deposited to the bed, respectively. And the relative ρ_{dep} ($\rho_{dep}/\rho_{dep\_\max}$) means the standardized value to the largest ρ_{dep} designated as 1.0.

6.2.6 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 test was used to test relationship between ρ_{dep} and several factors such as u, v, Δz and $divV$. The multiple regression analysis was applied for explaining the pattern of ρ_{dep} in relation to significant factors. The statistical analyses were conducted by SPSS software (version 11.0).

6.3 RESULTS

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

In a total of 56 samples in 14 lines, the deposition densities of the pollens (ρ_{dep}-F and ρ_{dep}-S) were calculated. The results of ρ_{dep}-F and ρ_{dep}-S in the damming pool, the front and the inflow channel were separately obtained and they were overlaid with the bed elevation and the surface flow velocity contours as depicted in Fig.6-7.

(1) Relation to bed elevation

There was a significant difference among the elevations in the damming pool, the front and the inflow channel (Fig.6-8). The bed elevations were in the order; the damming pool < front < inflow channel (ANOVA, $p<0.001$). The ρ_{dep}-S was higher about 35% in the damming pool (302 grains/cm^2) than in the inflow channel (196 grains/cm^2) ($p<0.05$), while the ρ_{dep}-F did not show a significant difference between the damming pool and the inflow channel. On the other hands, in the damming pool, the ρ_{dep}-S was significantly higher than ρ_{dep}-F ($p<0.001$) (Fig.6-8).

Distribution of ρ_{dep}-F was mostly flat without consideration of the lateral elevation difference Δz, whereas ρ_{dep}-S in the damming pool was distributed in high values near $\Delta z=0$ range not in larger $|\Delta z|$ (Fig.6-9). In order to examine the falling process in detail in relation to channel morphology, relationship between ρ_{dep} and Δz was analyzed. Fig.6-13 showed the relation of the aspect and the ρ_{dep}.

(2) Relation to surface flow velocity

As mentioned before, the velocity u was obviously different among the damming pool, boundary and the inflow channel. The ρ_{dep}-F showed no significant correlation with u and was not significantly different among the three spatial areas (Fig.6-10a). However the ρ_{dep}-S was significantly higher in the damming pool (301.87±230.07 grains/cm^2) than in inflow channel (196.42±80.75 grains/cm^2) ($p<0.01$), and ρ_{dep}-S

showed weak negative correlation with *u* (r=-0.22, p=0.12) (Fig.6-10b), suggesting the sinking pollens are more deposited as a flow is slower.

Because the velocity *v* or *divV* showed little variation in the whole channel, the significant relations with ρ_{dep}-*F* or ρ_{dep}-*S* were not appeared (Fig.6-11 and Fig.6-12)

6.3.2 Distribution of ρ_{dep} in CASE 1; Alternate bar and thalweg area

In a total of 64 samples in 16 lines, the deposition densities of the pollens (ρ_{dep}-*F* and ρ_{dep}-*S*) were calculated. According to channel morphology characterized as alternate bar structure, all sampling sites were grouped into the bar or the thalweg. The results of ρ_{dep} were overlaid with the bed elevation contour and surface flow velocity contour as depicted in Fig.6-14.

(1) Relation to bed elevation

In both bar and thalweg, a significant difference between ρ_{dep}-*F* and ρ_{dep}-*S* was not found (p>0.05, t-test) (Fig. 6-15). On the other hand, the ρ_{dep}-*F* was significantly higher in the bar (186.48±153.61 grains/cm^2, n=27) than in thalweg (83.49±65.12 grains/cm^2, n=34) (p<0.01, t-test) (Fig.6-15a). However, the ρ_{dep}-*S* did not show any significant difference between bar (151.94±110.60 grains/cm^2) and thalweg (108.56±106.36 grains/cm^2) (Fig.6-15b). In addition, ρ_{dep}-*F* showed a negative correlation with the bed elevation in the bar, but not in thalweg (Fig.6-15a). ρ_{dep}-*S* showed a negative correlation with the bed elevation both in the bar and thalweg (Fig.6-15b). The similar negative correlation of Δz with ρ_{dep}-*S* was shown in Fig.6-16b, but no relation with ρ_{dep}-*F* was depicted in Fig.6-16a. As results of the aspect analysis (Fig.6-16), ρ_{dep}-*F* and ρ_{dep}-S were significantly abundant in the north (rightward slope), south (leftward slope) and northeast (Right-backward slope) aspects in the bars, whereas in the northwest (right-forward slope) and southeast (left-backward slope) in the thalweg ($p<0.05$, ANOVA test).

(2) Relation to surface flow velocity

In the bars, both of ρ_{dep}-F and ρ_{dep}-S did not show any correlation with u. In the thalweg, the ρ_{dep}-F was negatively correlated with u ($r=-0.40$, $p<0.05$) (Fig.6-17a), and ρ_{dep}-S showed weak negative correlation with u ($r=-0.30$, $p<0.1$) (Fig.6-17b). In addition, ρ_{dep}-S was highest at near $v=0$, but decreased as $|v|$ increased (Fig.6-18b). As to the relation with $divV$, although both ρ_{dep}-F and ρ_{dep}-S did not show significant correlation with $divV$ in both of bar and thalweg, they increased as $divV$ was near 0 as a whole (Fig.6-19).

6.4. DISCUSSIONS

6.4.1 Pine pollen as FPOM analogue in dam tailwater ecosystem

In mountain streams, since most of POM entering to the streams is primarily in the form of allochthonous CPOM, leaves and woody debris from surrounding terrestrial forests, most FPOM transportable to the 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 a single type tracer with a similar settling velocity such as leaves particle, radioactive ^{14}C labeled seston, corn pollen (Georgian *et al.* 2003).

On the other hand in the downstream of dam reservoirs, since large amount of lentic plankton inputted from the upstream reservoir contributes highly to FPOM composition, for example accounting for about 50% in the Uji River and Nunome River (referred to Chapter 3 and 5), it is highly required to trace each source separately for understanding accurately the FPOM dynamics in dam tailwater channels. 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 for using pine pollens as a FPOM analogue is highly important for development of the experimental study on FPOM dynamics by followings reasons; the floating pine pollen buoyant in still water can be represented as lentic plankton drifting mainly in surface water. The sinking pine pollen can be regarded as allochthonous sources such as tree leave and detritus particles because of its settling velocity of 3.32 m/h, which is intermediate of natural FPOM (5.58 m/h) comprised of 72% vascular plant and 12% inorganic particles (Cushing *et al.* 1993) and corn pollen (1.12 m/h) (Miller and Georgian 1992).

In addition, pine pollen is easy to identify using a 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. In this sense, it may be meaningful as the first time research to apply pine pollen for FPOM dynamics experiment as a tracer or analogue.

6.4.2 Relation of bed geomorphology to deposition process of FPOM according to settling velocity of source materials

The mean transport distance (S_p) is reflecting various field conditions, because the value was estimated using the longitudinal loss rate (k) which was based on field data measured empirically. S_p can be compared with predictions of a model that assumed the pine pollen settled at a velocity in the running water equal to its settling velocity. Thus, the predicted transport distance (S_w) is calculated if we know a depth (d), velocity (u) and settling velocity of pollens (V_{set}) by following equation (Miller and Georgian 1992);

$$S_w = \left(d / V_{set}\right) \times u \qquad \text{(Eq.6-3)}$$

In the present study, the values of d, u and V_{set} of the sinking type of pine pollen are 4.18 cm, 39.0 cm/s and 3.32 m/h, respectively (*see* 6.2.1 and 6.2.4). Therefore, the S_w of the sinking pollen in this study was calculated as 17.71 m, indicating that the sinking pollen can transport to 17.71m if without internal retention processes in this experimental condition. In particular, from this predicted model, the floating pollen ($V_{set} = 0$) can not be settled to the bed till the last. As the results of the experiments, however, the floating pollens as well as the sinking ones were deposited to the bed even within 11 m of the channel, suggesting that the any internal retention processes including hydraulic and geomorphological effects were influenced in the pollen deposition.

(1) Influence of damming pool structure on FPOM deposition

Mechanism of a FPOM deposition is generally composed of falling process by settling velocity, physical filtering by bed material and biological filtering by organisms. Through the results of CASE Initial, it was found that the sinking pollens were more deposited with reducing u in the damming pool. This indicates that the deposition process of the terrestrial particles in a damming pool can be highly influenced by the falling process. However, the deposition density of floating pollens (ρ_{dep}-F) was small in the damming pool irrespective of indices related with flow velocity such as u, v and *divV*. This indicates that lentic plankton may be difficult to deposit or trap in the damming pool.

From these findings, we can draw an important implication that damming pool structures can play a role in sorting FPOM component according to their sources origins. Since most of lentic plankton will drift to the downward without deposition like the floating pollen, terrestrial leaves and wood particles will remains in riverbed by the falling process like the sinking pollen. This highly corresponds to the results from the field measurements in the Uji R. and the Nunome R. (*refer to* Chapter 4 and Chapter 5). Also an empirical fact by Takemon *et al.*(2008) can support the implication that benthic FPOM in backwater reach above a check dam comprised of higher portion of allochthonous origin upto 70%.

(2) Influence of alternate bar structure on FPOM deposition

From the results of Case 1, we found that large amount of the floating pollen could be deposited to whole reaches, particularly in the bars, unlike the result of Case Initial. It means that any processes for making the floating pollens deposit were existed in the conditions. Significant high ρ_{dep}-F in the bars relative to in thalweg and the negative correlation between ρ_{dep}-F and the bed elevation in the bars mean that the floating pollens can be deposited more to the high elevation area but not to the highest point, indicating that the physical filtering process by bed elevation will strongly influence the deposition of the floating pollens compared with the falling process (*refer to* Fig.1-5). As mentioned above, the falling process can not be explained for the deposition of the floating pollens whose settling velocity is near zero. Although the v and *divV* were analyzed as factors for explaining the filtering process, they showed no significant correlation with ρ_{dep}-*F*. It is probably why the *v* and *divV* which are derived from only surface velocities could not reflected the cross sectional velocities such as downwelling and upwelling (*refer to* Fig.4-3).

The deposition pattern of sinking pollens in the bars was similar with ρ_{dep}-*F*. The ρ_{dep}-*S* was negatively correlated with the elevation and even with Δz, indicating that the deposition of the sinking pollens in the bars can also be influenced by the physical filtering process and the filtering can highly occur in slope areas on the bars instead of the highest elevation. As to the deposition of the sinking pollens in the thalweg, ρ_{dep}-*S* were found to be high under low *u* and near *v*=0, indicating that the falling process can be dominant factor.

From perspectives of alternate bar structures in dam tailwater ecosystems, lentic plankton corresponding to the floating pollens can be deposited more in bar slopes rather than the thalweg by physical process. And terrestrial plant corresponding to the sinking pollens will be deposited in bar area by physical filtering and in the thalweg area by falling process.

6.4.3 FPOM deposition patterns in the alternate bar structures: implication from the aspect analysis

As results of the aspect analysis of the Case 1 (Fig.6-20), the north, south and northeast in the bars had significantly higher ρ_{dep}-*F* and ρ_{dep}-S than the other aspects. The aspects were corresponding to the rightward, leftward and right-backward in the bar slopes, respectively. In addition, in the thalweg, the ρ_{dep}-*F* and ρ_{dep}-S were found to be significantly higher in the northwest and southeast, which are corresponding to the right-forward and left-backward slope in the thalweg slopes, respectively.

When the aspects of bed slopes are visually applied in the alternate bar structures (Fig.6-21), the locations with significantly higher ρ_{dep}-F and ρ_{dep}-S are corresponding to the head and middle in the bar area, and the intermediate between the two opposite bars in the thalweg. This finding is interestingly supported by the filed study of Takemon *et al.* (2003). They measured the densities of benthic POM from head to tail of the sandbar located in the Kizu River and showed the density of B-FPOM was significantly higher in the order of bar head≫bar middle>bar tail.

Although many researches including the previous chapters focused on the velocity, depth and elevation, the present result highlights the aspects of bed slopes as important controlling factors for increasing the retention efficiency of the reaches-scaled channels. From an application prospective in a dam tailwater channel, much of lentic plankton will be more deposited by physical filtering process in the head and middle of bars than in the tail, indicating that more laterally undulating riverbed has much higher retention efficiency in the channels.

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Table 6-1 Details of experimental conditions. All hydraulic conditions between the Case Initial and Case 1were same during the experiments, except of the weir height located in the end of movable bed. The bed configuration of Case 1 was produced from that of Case Initial by lowering the weir height form 11.7 cm to 8.5 cm.

	Case Initial	Case 1
Weir height	11.7 cm	8.5 cm
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	

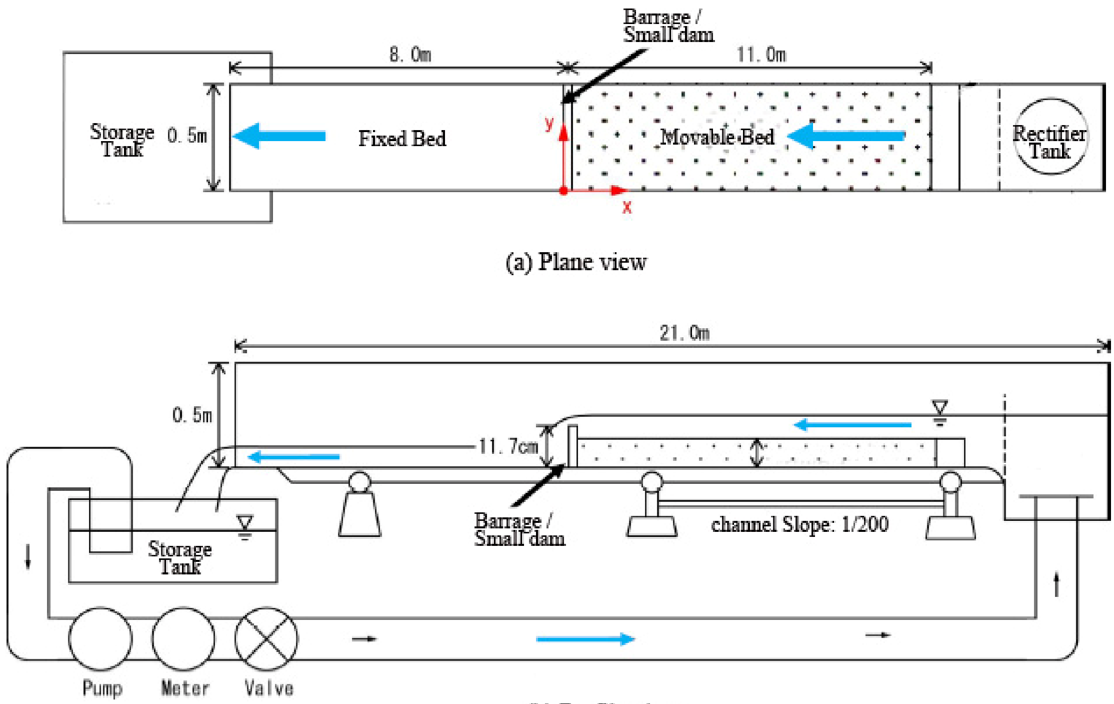


Fig. 6-1 Experimental setup diagram. The straight experimental flume is 0.5x 0.5x 21m. The flume consisted of a fixed bed zone without bed material and a movable bed zone covered by 8.5 cm thickness of silica sand. The origin of measurements area starts from the beginning of the movable bed. Two types of pine pollens were uniformly released into the flowing water at the uppermost site of the flume. Flow discharge kept constant until the pollens were enough to be deposited on the bed. The remaining pollens in water not deposited on the bed were trapped at the mouth of flume to prevent them from recirculation.

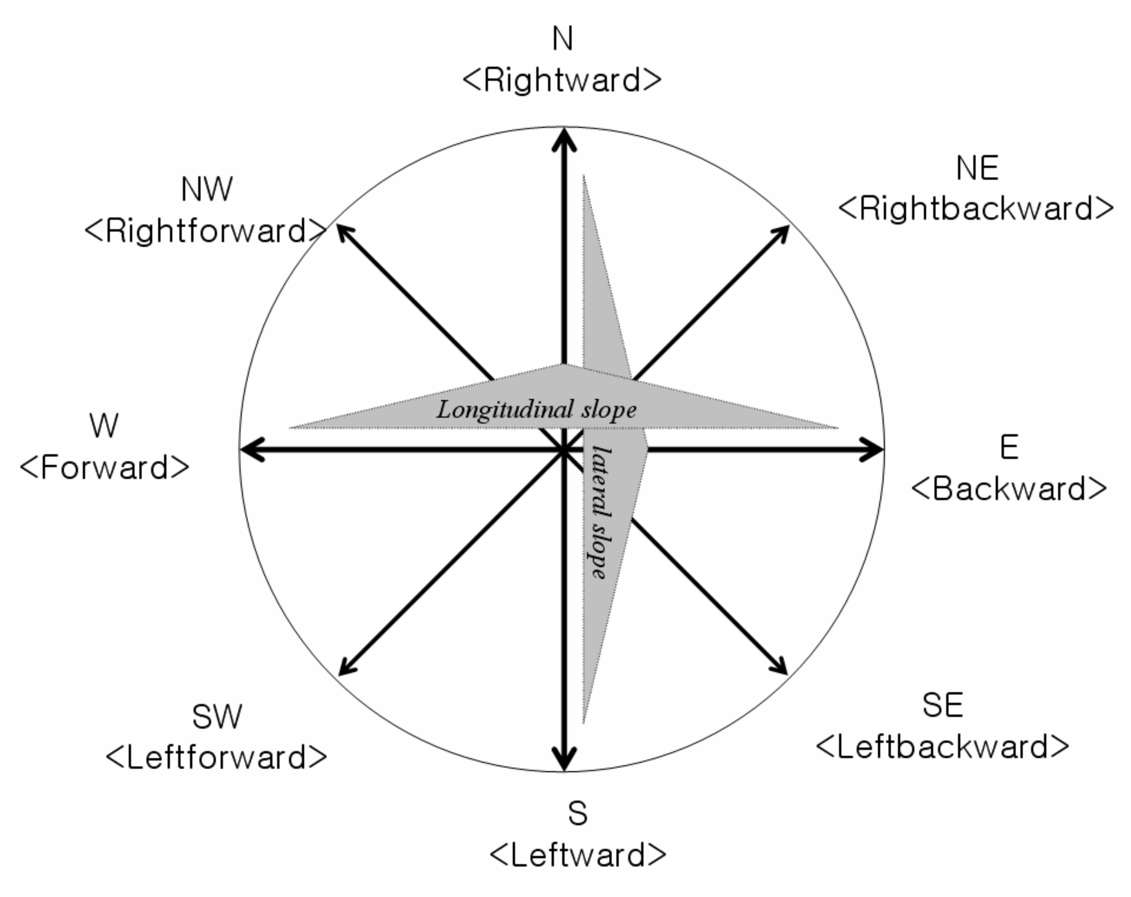
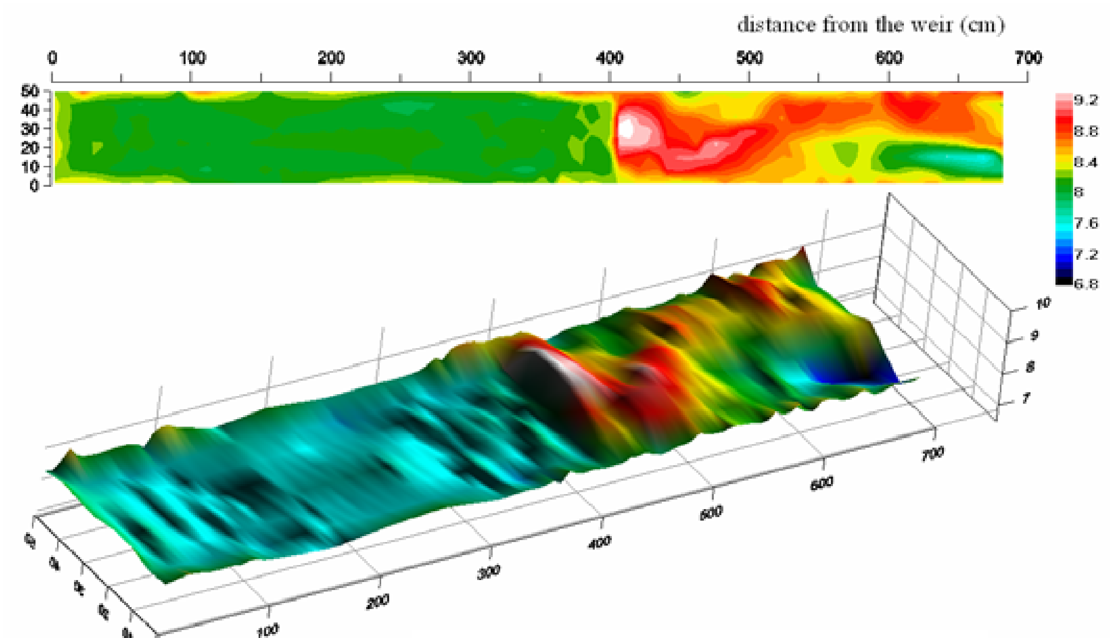
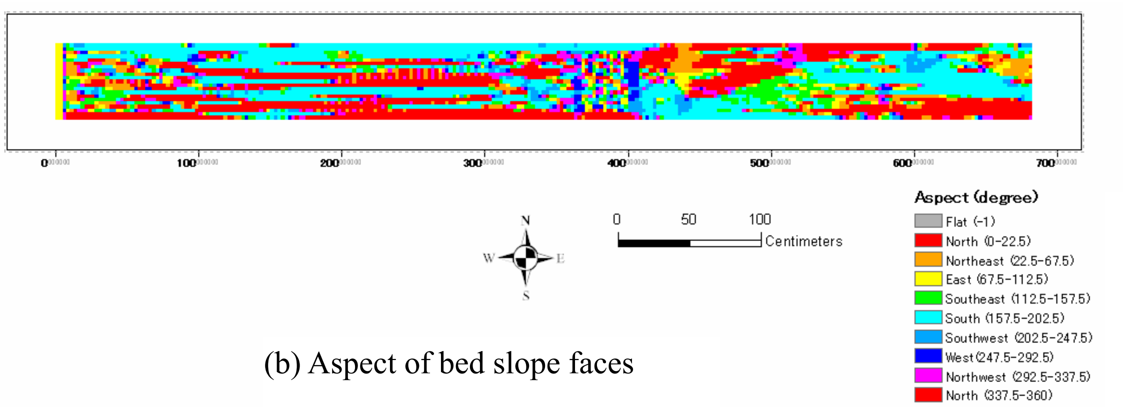


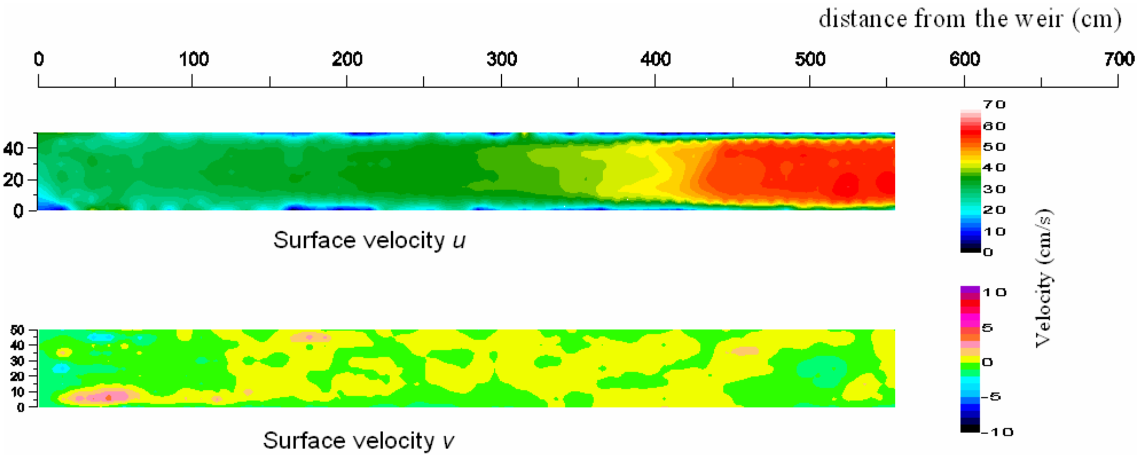
Fig.6-2 Relation between aspects of slope faces and shapes of the slopes in bed elevation. For example, the west of aspect is corresponding to a forwarding slope which shows longitudinally decreasing gradient of the slope. The north is a rightwarding slope which laterally decreasing gradient with a right direction.



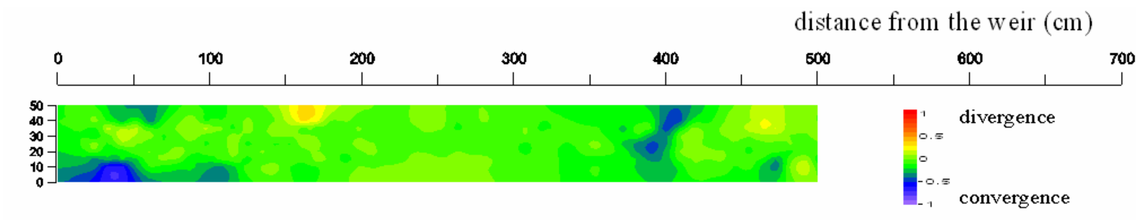
(a) Bed elevation and configuration



(b) Aspect of bed slope faces

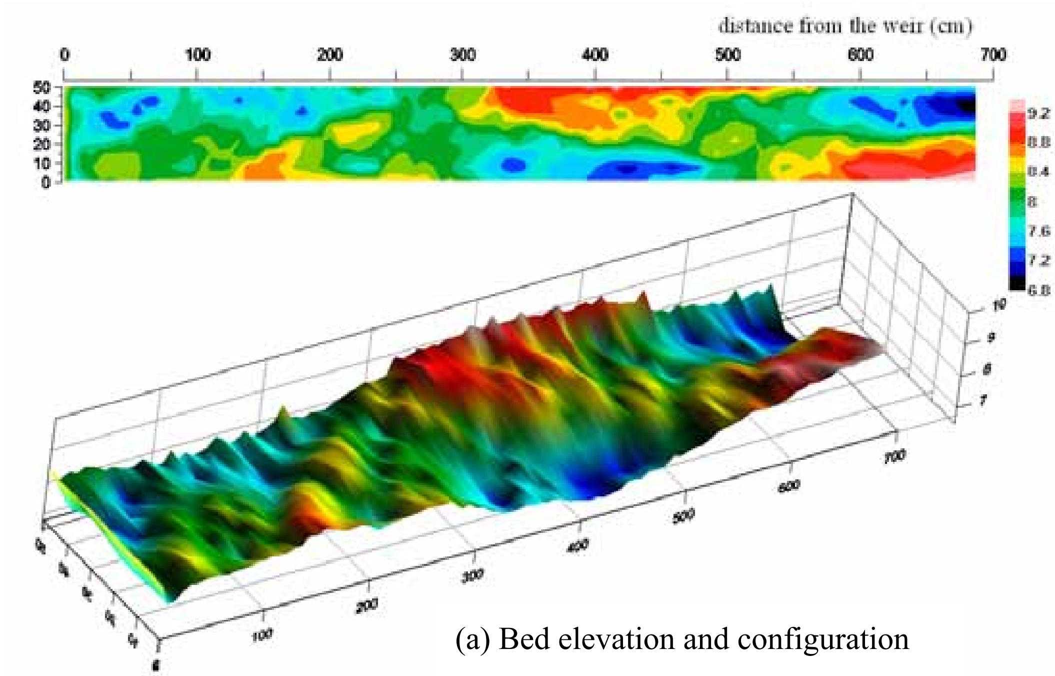


(c) Longitudinal velocity u and lateral velocity v

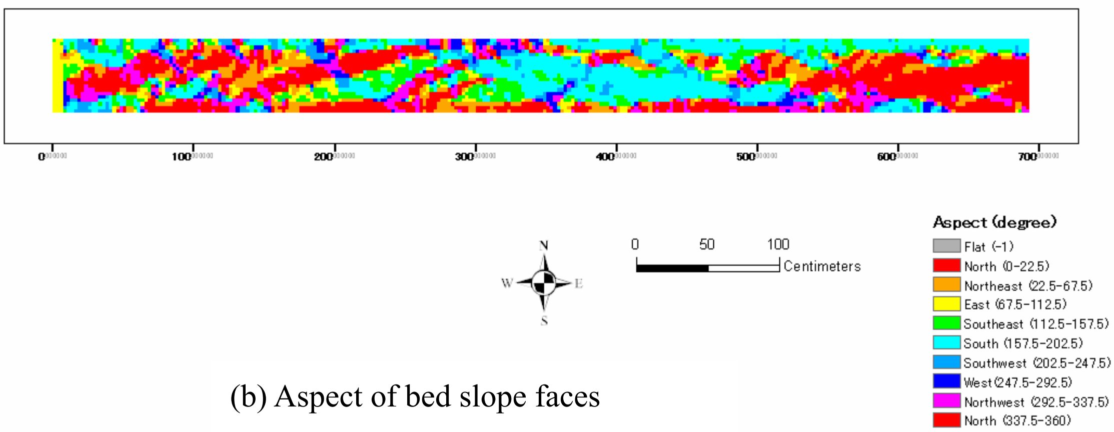


(d) Flow divergence $divV$

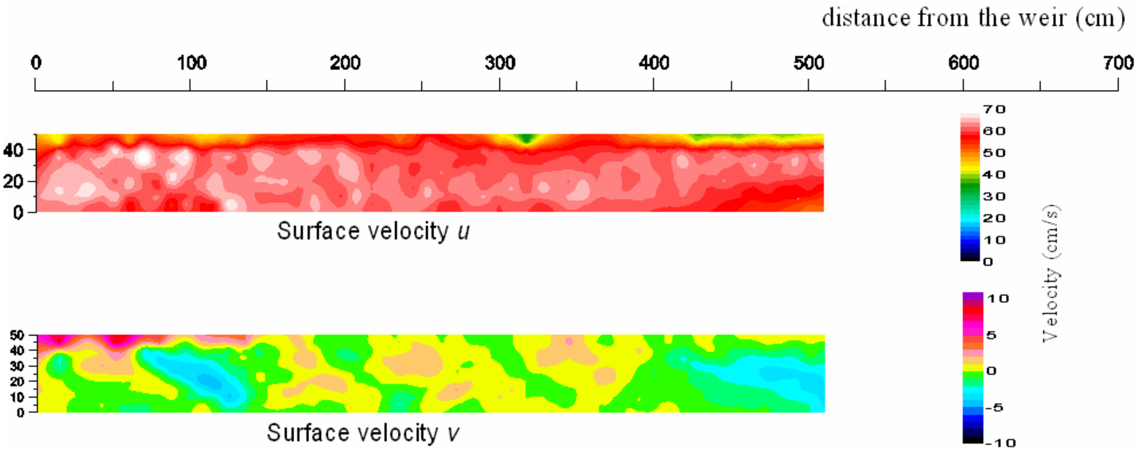
Fig.6-3 Channel morphology and surface velocities in the Case Initial: the damming pool structure.



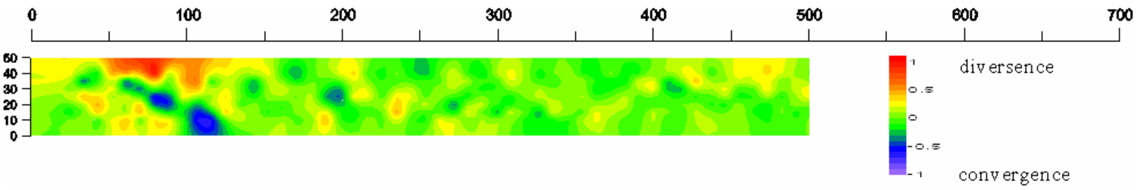
(a) Bed elevation and configuration



(b) Aspect of bed slope faces

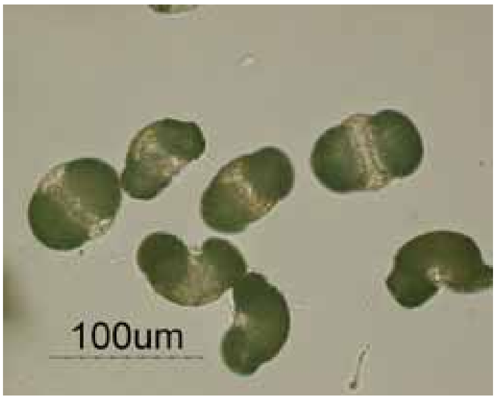


(c) Longitudinal velocity *u* and lateral velocity *v*

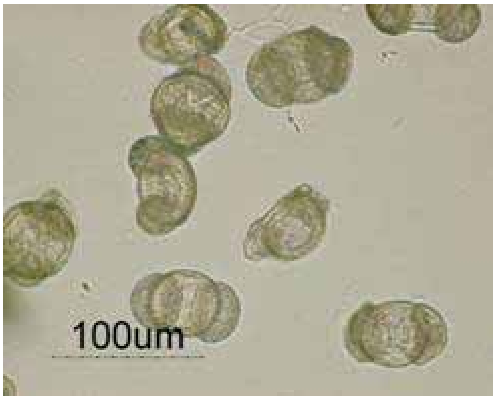


(d) Flow divergence

Fig.6-4 Channel morphology and surface velocity in the Case 1: the alternate bar structure.

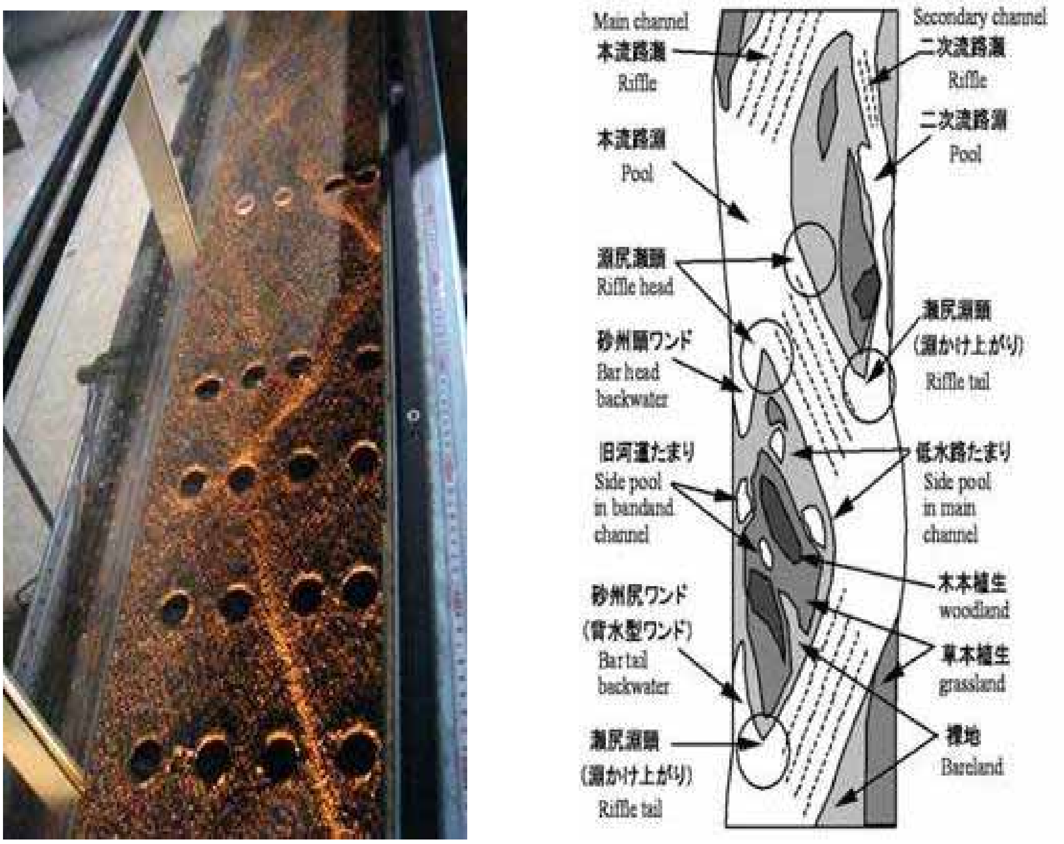


(a) Floating type



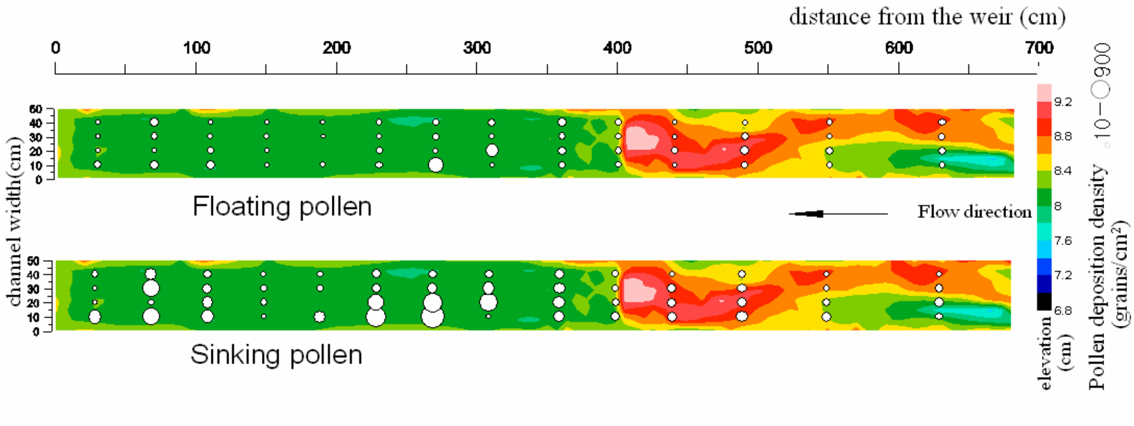
(b) Sinking type

Fig.6-5 Shape comparison of two types of pine pollen grains by optical microscopy. The floating pollens are easily identified by air bladders like Mickey Mouse cap appearance.

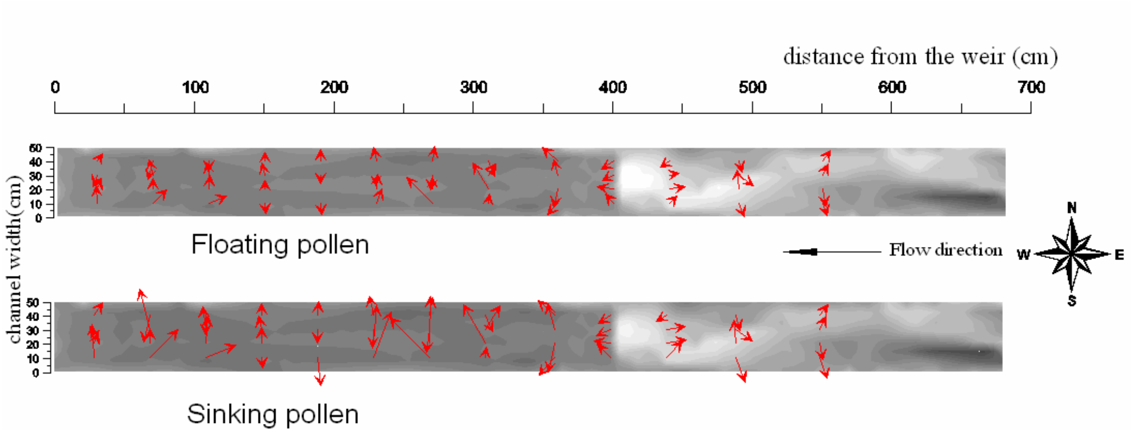


(a) (b)

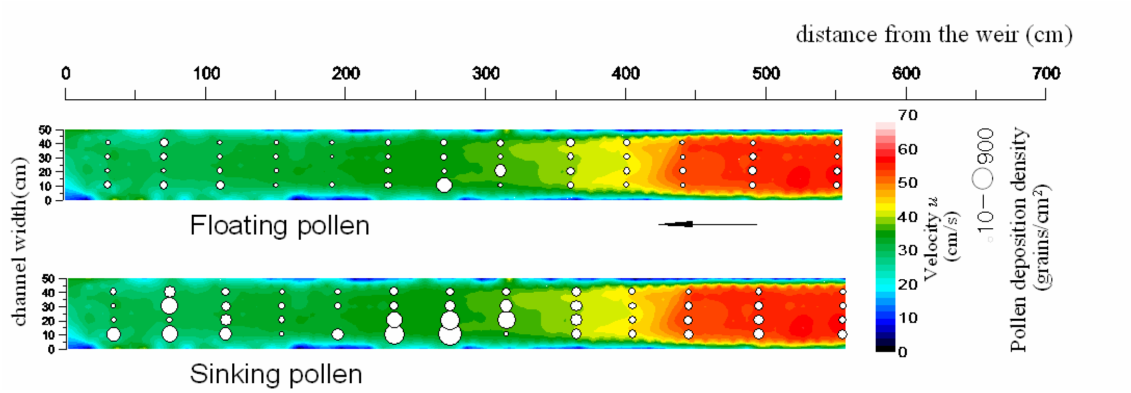
Fig.6-6 Collecting Samples of deposited pollens using spot sampling in lattice section(a) in consideration of sandbar habitat structure(b) referred from Takemon (2007)



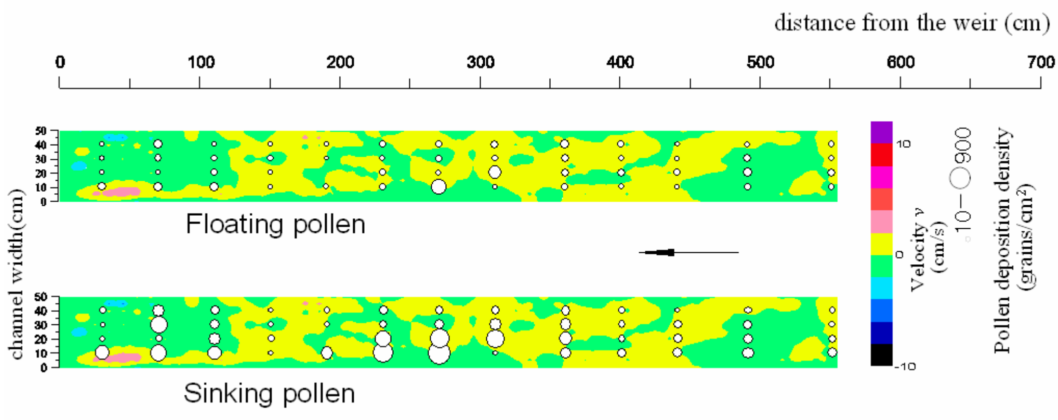
(a) Bed elevation



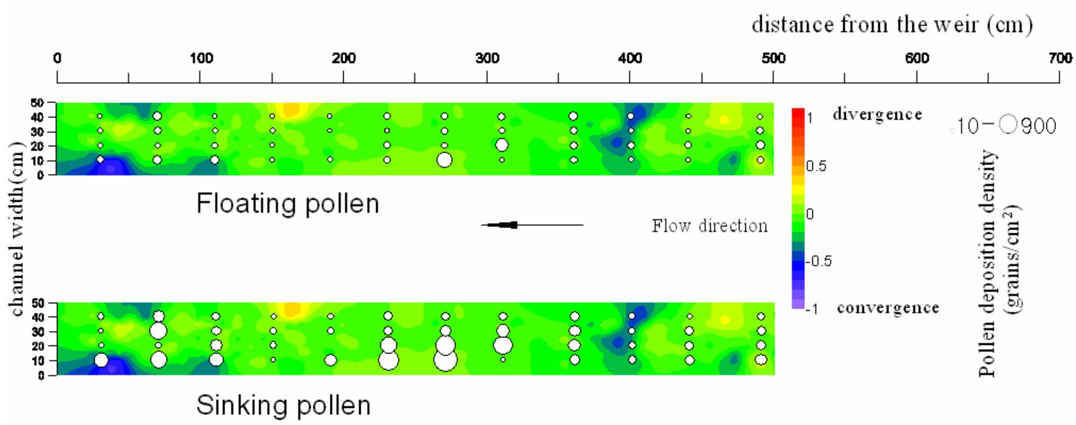
(b) Aspect of bed slope faces. The length of arrow is in proportion to the pollen deposition density.



(c) Longitudinal velocity u

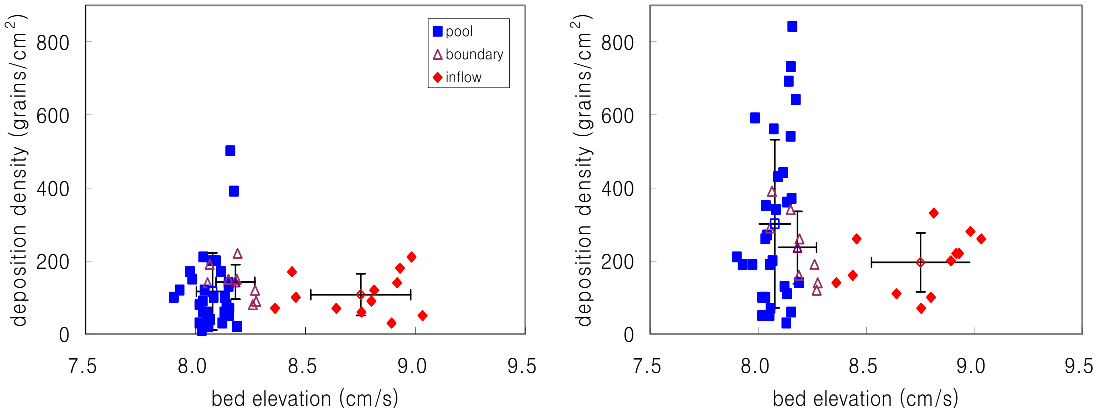


(d) Lateral velocity *v*



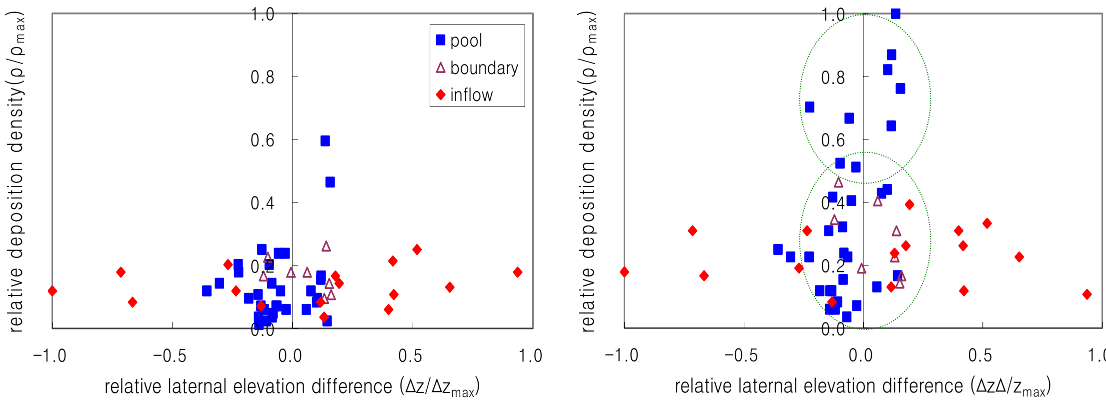
(e) Divergence of flow, *divV*

Fig.6-7 Distribution of pollen density deposited on experimental channel bed shown with bed elevation and flow velocity in Case Initial. The numbers of samples for (a) and (c) were n=55 on 14 lateral lines and n=51 on 13 lateral lines respectively.



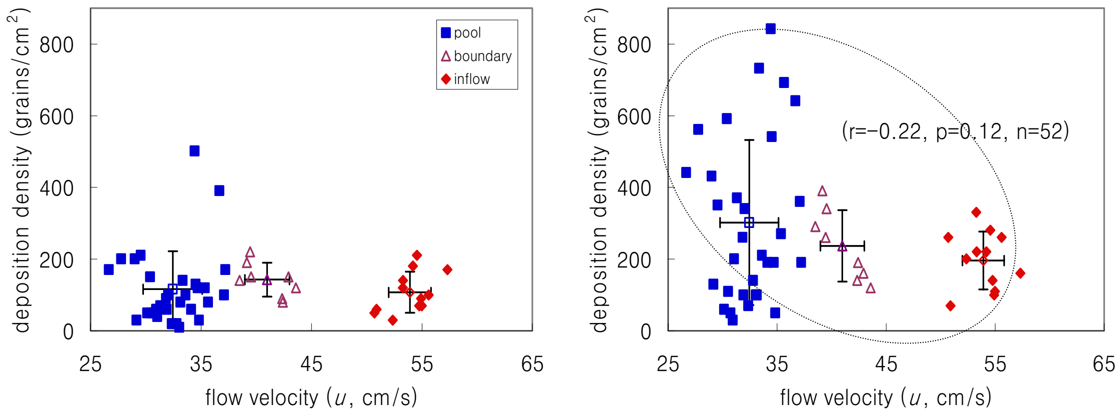
(a) Floating pollen (b) Sinking pollen

Fig.6-8 Relationship between ρ_{dep} and bed elevation in Case Initial



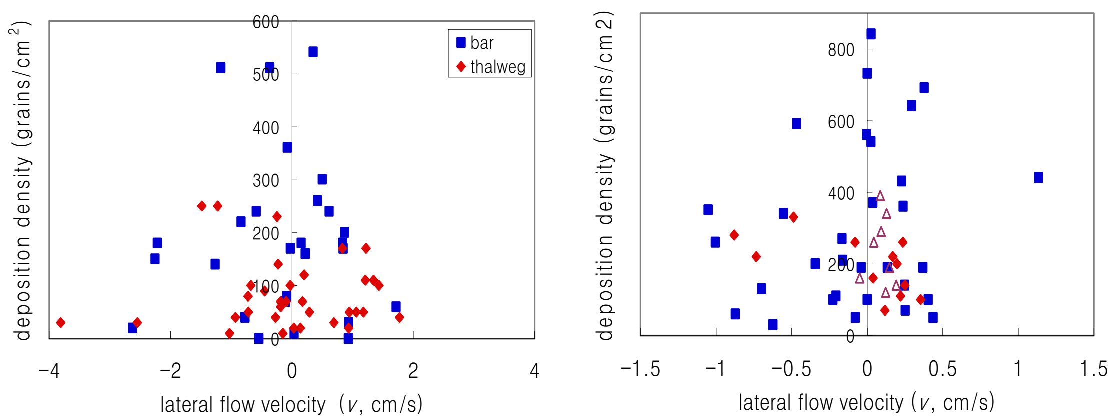
(a) Floating pollen (b) Sinking pollen

Fig.6-9 Relationship between the relative ρ_{dep} and the relative Δz in Case Initial



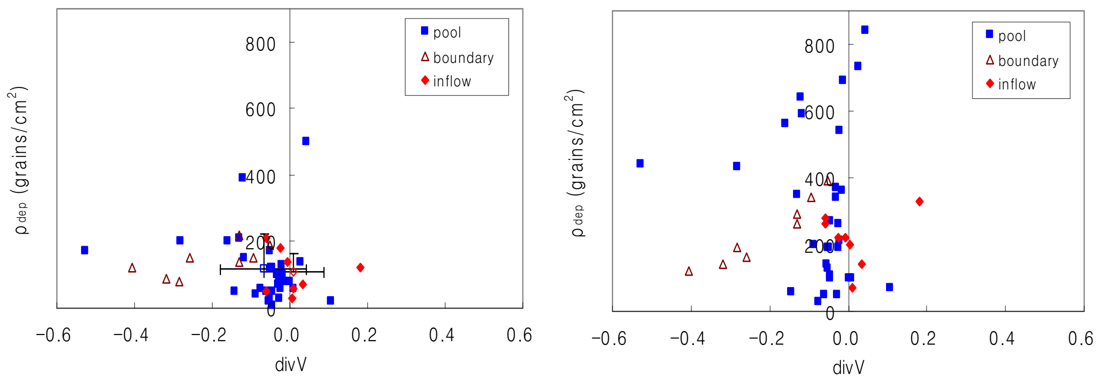
(a) Floating pollen (b) Sinking pollen

Fig.6-10 Relationship between ρ_{dep} and u in Case Initial



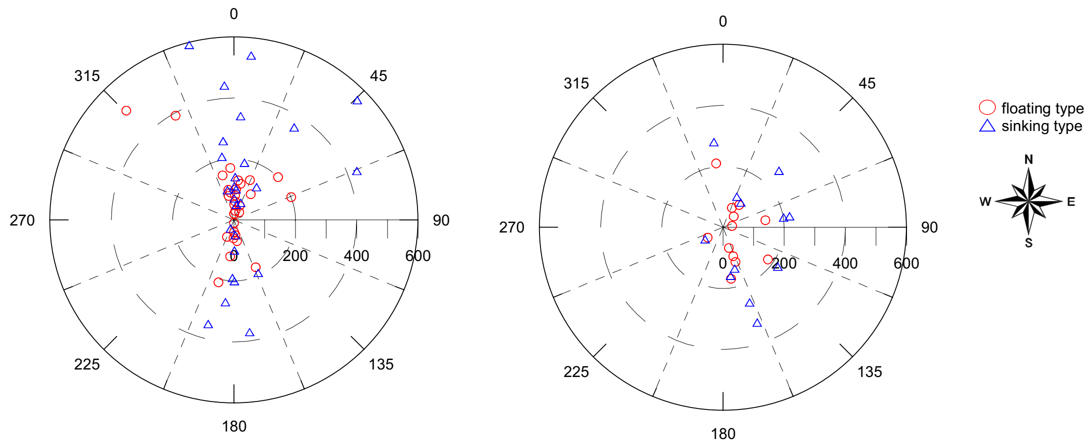
(a) Floating pollen (b) Sinking pollen

Fig.6-11 Relationship between ρ_{dep} and v in Case Initial



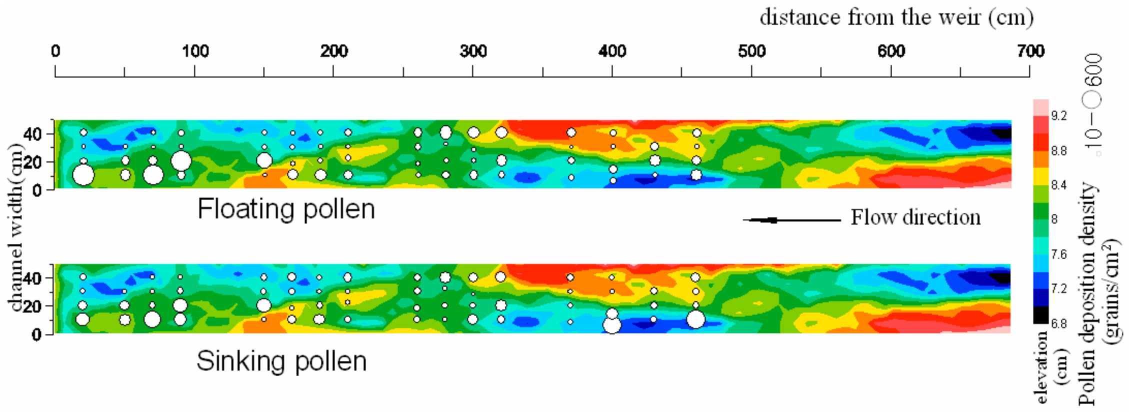
(a) Floating pollen (b) Sinking pollen

Fig.6-12 Relationship between ρ_{dep} and $divV$ in Case Initial

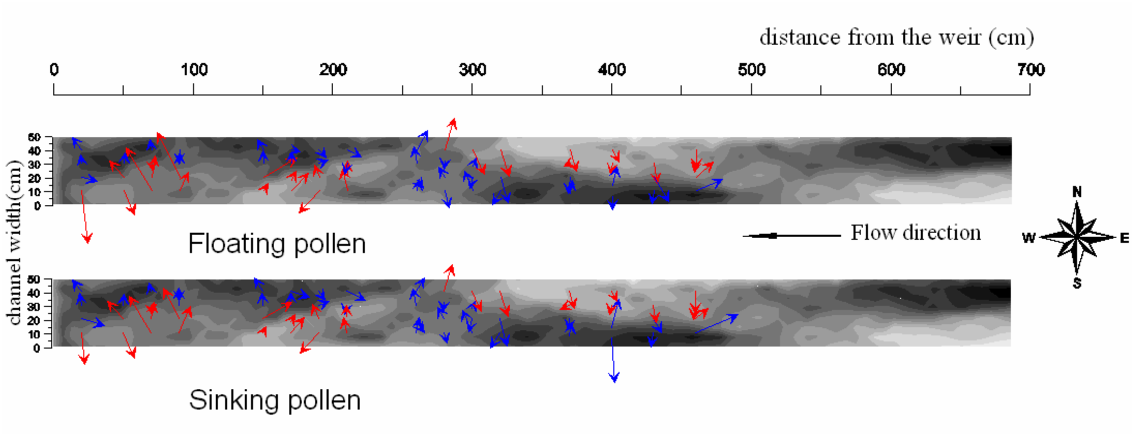


(a) Damming pool (b) Inflow channel

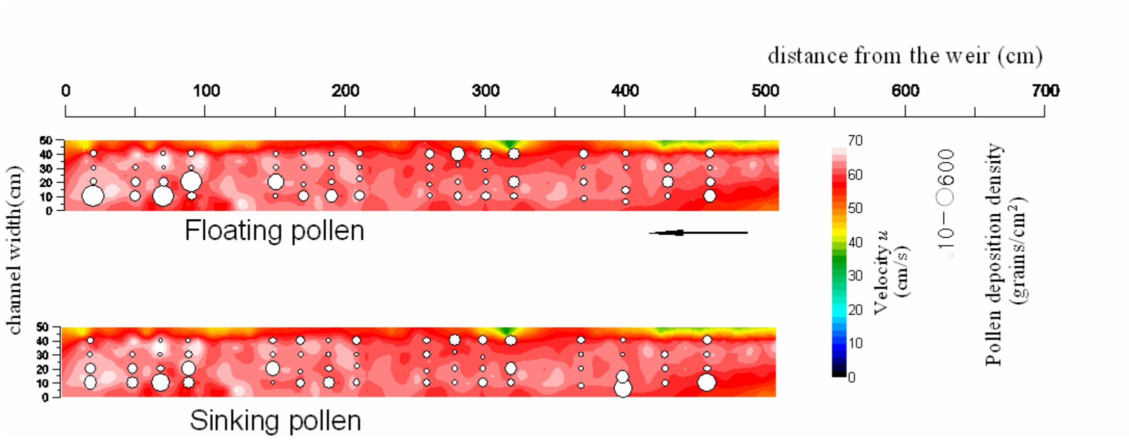
Fig.6-13 Relationship between ρ_{dep} and aspect of bed slope in Case Initial



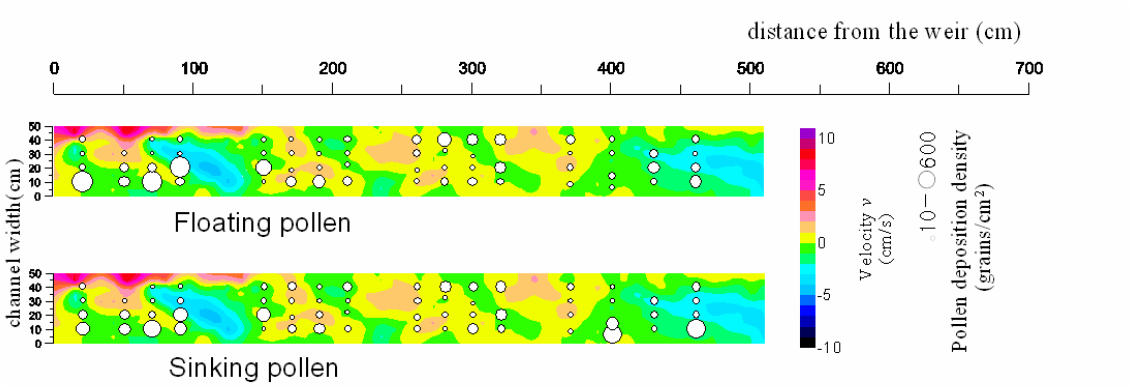
(a) Bed elevation



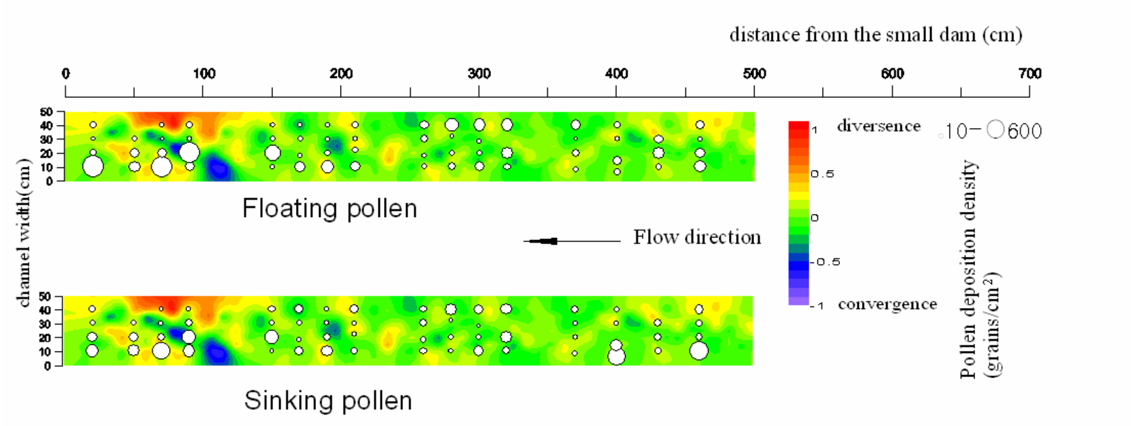
(b) Aspect of the bed slope faces. Red arrow is in bar and blue in thalweg. The length of arrow is in proportion to the pollen deposition density



(c) Longitudinal velocity u

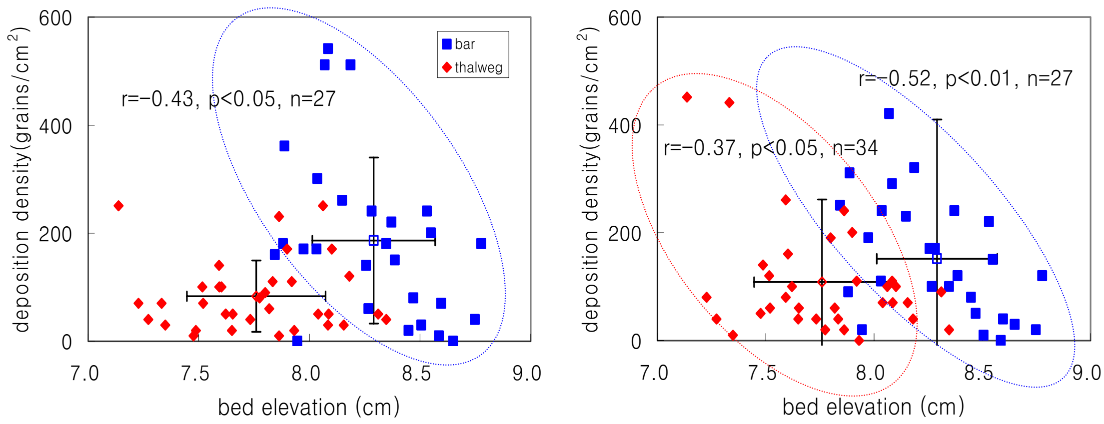


(d) Lateral velocity *v*



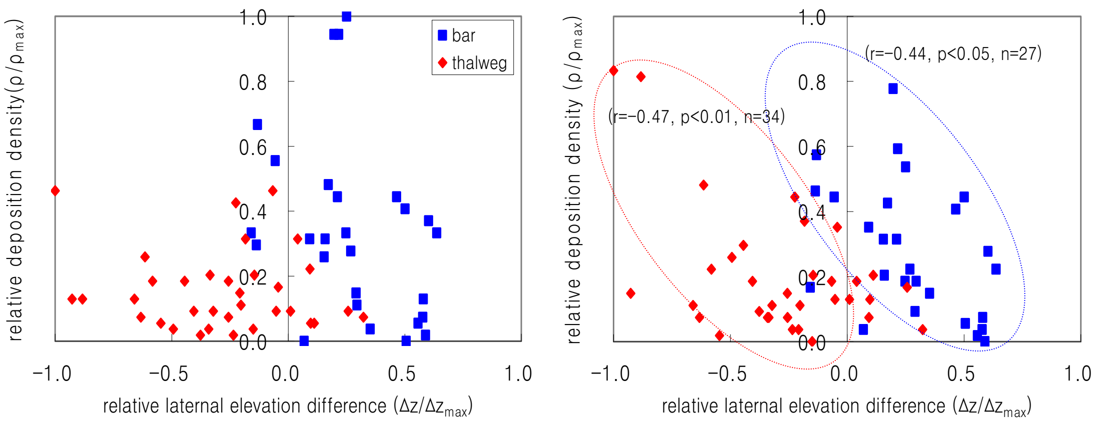
(e) Divergence of flow *divV*

Fig.6-14 Distribution of pollen density deposited on experimental channel bed shown with bed elevation contour and flow velocity in the Case 1. The numbers of samples are n=62 on 16 lateral lines.



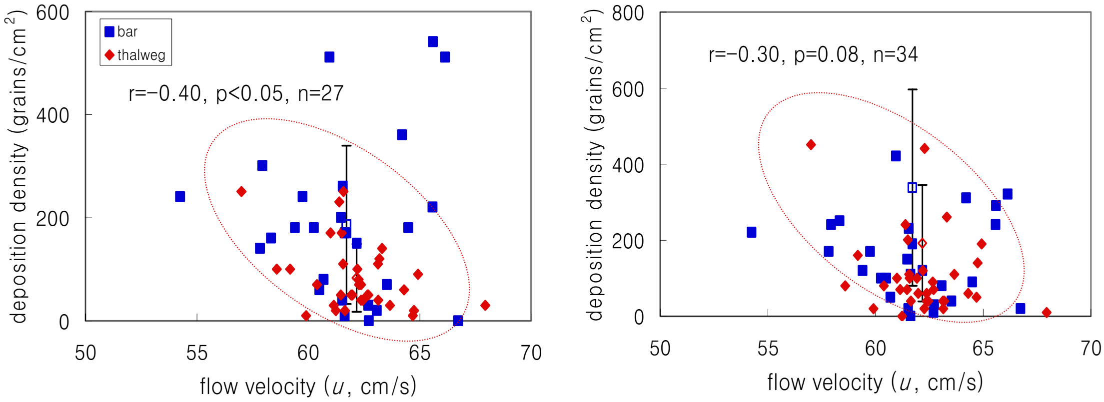
(a) Floating pollen (b) Sinking pollen

Fig.6-15 Relationship between ρ_{dep} and bed elevation in Case 1



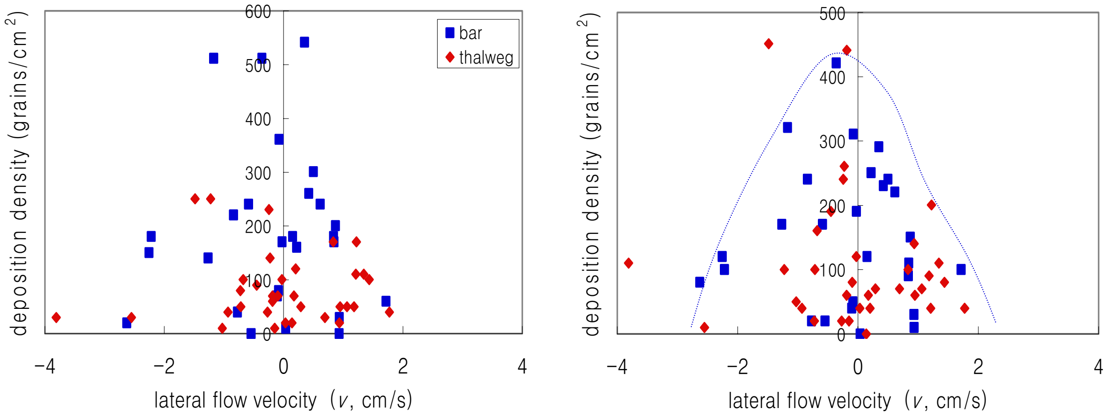
(a) Floating pollen (b) Sinking pollen

Fig.6-16 Relationship between the relative ρ_{dep} and the relativeΔz in Case 1



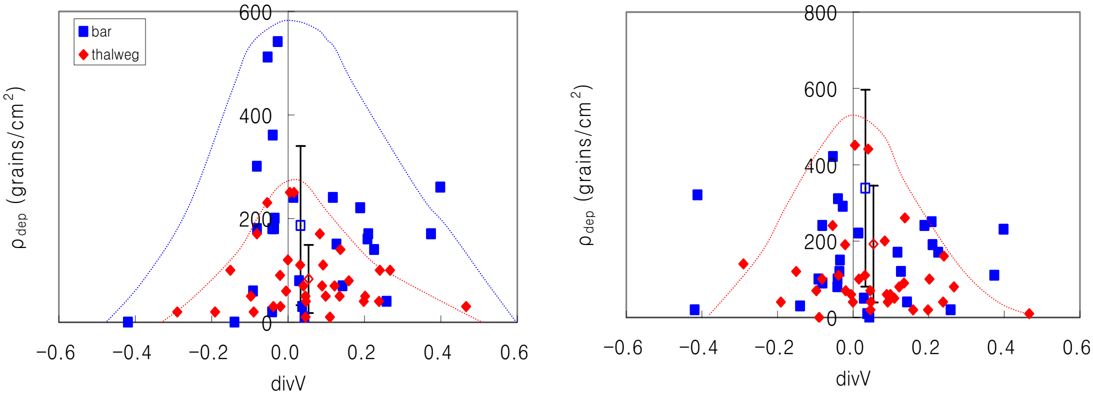
(a) Floating pollen (b) Sinking pollen

Fig.6-17 Relationship between ρ_{dep} and u in Case 1.



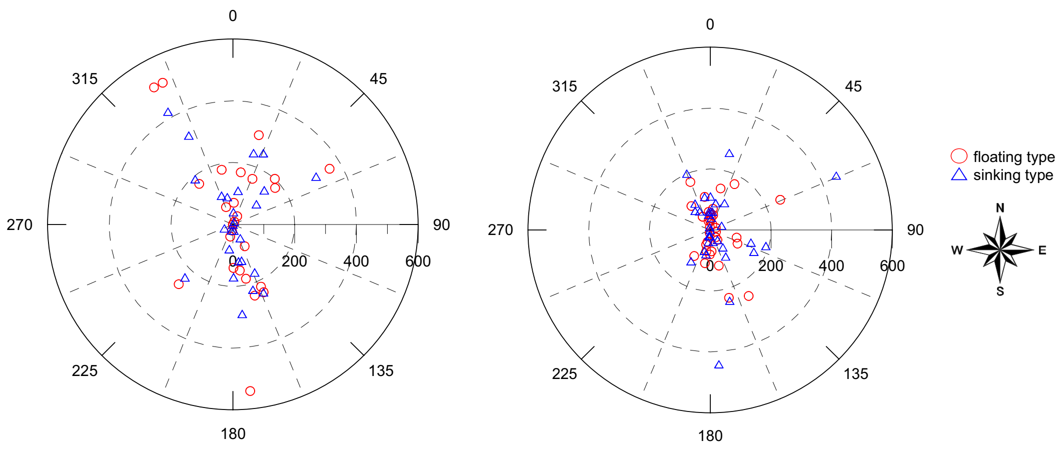
(a) Floating pollen (b) Sinking pollen

Fig.6-18 Relationship between ρ_{dep} and v in Case 1.



(a) Floating pollen (b) Sinking pollen

Fig.6-19 Relationship between ρ_{dep} and $divV$ in Case 1.



(a) Bars (b) Thalweg

Fig.6-20 Relationship between ρ_{dep} and aspect of bed slope in Case 1

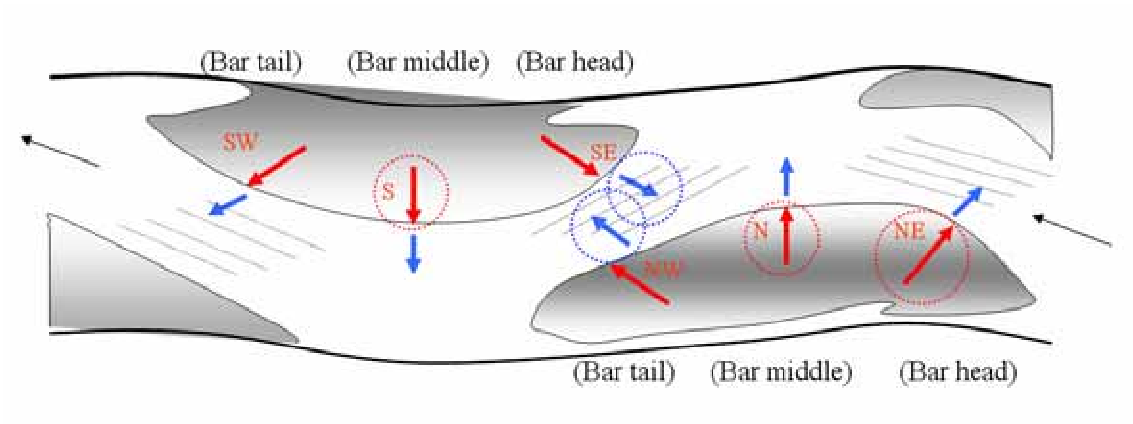
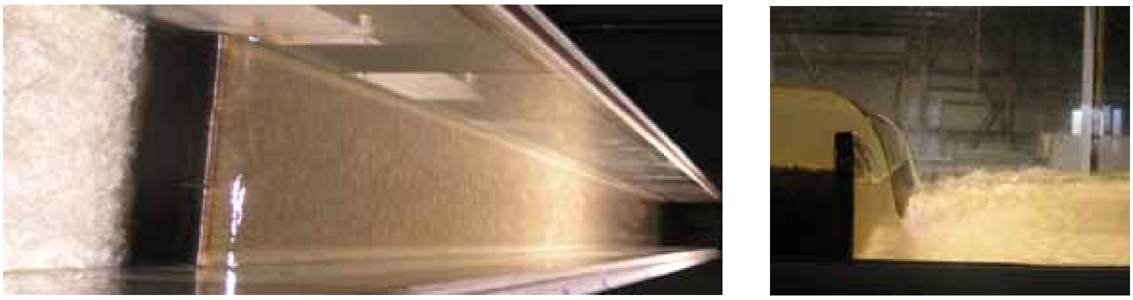


Fig.6-21 Experimental distinction of high ρ_{dep} sites in the bar and thalweg areas by results of aspect analysis of bed slopes in the Case 1. In the bar area, ρ_{dep} at the rightward (N), rightbackward (NE) and leftward (S) were significantly higher than the other aspects, whereas in the thalweg area, ρ_{dep} at the rightforward (NW) and leftforward (SE) were higher.

(a) Experimental flume (21m x 50cm x 50cm) at the Ujigawa Open Laboratory of the Kyoto University.



(b) Formation of experimental bed configuration (left) and flow in the vicinity of the weir model (right, 50cm x 11.5cm x 2.0cm).

(c) Production of bed configuration; Case Initial (left) and Case 1 (right)

(d) Measurement of flow velocity (left), water level (middle) and bed elevation (right)

(e) Preparation of two types of pollen (left), release of the pollens at upper of the flume (middle) and collection of transported pollens after deposition to the experimental bed (right)

(f) Spot sampling of the deposited pollens (left) and separation of the pollens from bed materials by wet sieving technique (middle) and identification and quantitative analysis of each sample using a microscope (right)

Photo 6-1 Procedures of the experiment

CHAPTER 7

Summary, Synthesis and Conclusions and Recommendations

7.1. CHAPTER SUMMARY

CHAPTER 2

1. The study aims to show the relations of FPOM retention efficiency to channel morphology in dam tailwaters. S-FPOM samples were collected in tailwaters of two river channels below reservoir dams and two artificial canals connected from Lake Biwa.
2. Using lentic plankters as a tracer of S-FPOM, the mean transport distance, S_p, by calculating downstream reduction ratios of lentic tracer plankters and the field deposition velocity, v_{dep}, were estimated as indicator of retention efficiency.
3. The longest S_p (19.2 km) and the shortest one (2.2 km) were recorded in the deep canal and shallow canal, respectively, showing a positive correlation with hydraulic radius of the channels. The values of v_{dep} were 4.7-6.4 times higher in

river channels than those of artificial canals (Table 2-2). These results indicate that increasing complexity of bed morphology can minimize S_p, whereas bed degradation and armored bed materials may lead to increased S_p.

4. Advantages of lentic plankters as tracers for estimating distance ranges of reservoir dam impacts on river ecosystems were also discussed.

CHAPTER 3

1. The study aims not only to evaluate the suitability of three methods to quantification of tailwater POM sources composition, which is assumed to comprised of lentic plankton, allochthonous terrestrial plant, autochthonous epilithic algae, but also to investigate a variation of the three sources contribution among S-FPOM, S-CPOM, B-FPOM and B-CPOM. A microscopic examination (ME) and two stable isotope mixing models (SLM and CWM) combined $\delta^{13}C$-$\delta^{15}N$ estimated the relative contribution of the three sources and then their results were compared.
2. The comparative analysis among the three methods showed that the concentrated-weighted mixing model (CWM) should be applied when the masses and concentrations among the sources of POM are distinctively different. Both ME and standard linear mixing model (SLM) underestimated the contribution of the terrestrial plant and overestimated that of the lentic plankton (Fig.3-4).
3. The biomass contribution of lentic plankton was in order S-FPOM ≫ B-FPOM ≒ B-CPOM > S-CPOM. In addition, it showed a high reliance of S-FPOM on the lentic plankton accounting for 47.0% while a high contribution of epilithic

algae to B-FPOM accounting for 69.4%. In addition, it was found that the lentic plankton takes a majority of nitrogen supply, whereas the terrestrial plant of carbon supply in S-FPOM composition (Table 3-3).

4. The results indicate that a flowing zone which were mainly supplied from S-FPOM and a stagnant zone which were from B-FPOM even the same cross section may show trophically separated foodwebs systems. Particularly, filter-feeding invertebrates feeding on lentic plankton as their energy resources can be more susceptible to quantity and quality of lentic plankton from dam reservoirs.

CHAPTER 4

1. Downstream changes in SPOM source composition and their response of filter-feeding mussel were investigated in the downstream with subsequent riffle-pool structures in the Uji River. The relative contribution and the field concentration of each source were quantified by means of the three source mixing model using dual stable isotopes of carbon and nitrogen.
2. The concentration of S-FPOM was measured to be 5.7 times higher than that of S-CPOM (Fig.4-7), indicating one of the dam reservoirs impacts on size fractionation of SPOM due to settling down of most of S-CPOM to reservoir bottom.
3. The high contribution of the lentic plankton was found accounting for 51-88% of S-FPOM, and the exponential reduction model fitted well to the downstream decreasing of the constitution of the lentic plankton (Fig.4-6).
4. Interestingly, contributions of the lentic plankton was reduced more steeply and that of epilithic algae increased during passing riffles, whereas that of the

terrestrial plant was reduced during passing long pools. It indicates that the riffles function as trapping of large amount of lentic plankton and detachment of epilithic algae, whereas the pools make the terrestrial plant fall to the bottom. Consequently, the subsequent riffle and pool structures can play a role in sorting spatially according to its source origins (Fig.4-15).

5. The population density and biomass of freshwater golden mussel, *Limnoperna fortunei*, showed similar exponential reductions in riffles (Fig.4-8 and Fig.4-10). And the death rates of the mussels result in increase with downstream distance (Fig.4-9). These findings suggest that the spatial distribution of the filter-feeding mussel can be highly dependent on the changes of lentic plankton contribution.

CHAPTER 5

1. The geomorphological management has been increasingly required management of channel geomorphology for the restoration of the tailwater ecosystem. As a case study for the purpose, the sediment replenishment was employed in the downstream reaches of the Nunome Dam. The field sampling, measurement and analytical procedures were almost similar with those in the Uji River in Chapters 4 and 5. By comparative study between the Nunome R. and the Uji R., the influences of sediment replenishment on downstream POM dynamics were evaluated.
2. The contribution of lentic plankton was in the order S-FPOM > S-CPOM ≫ B-CPOM ≒ B-FPOM (Table 5-5). In the S-FPOM. When compared with the result of the Uji R., the contributions of the epilithic algae were relatively low in the four types of POMs.

3. The contribution of lentic plankton was reduced with downstream distance, but was more steeply reduced during passing the riffles. The contribution of the terrestrial plant was reduced during passing the pools (Fig.5-10), which as largely similar with downstream reduction pattern of the Uji R.
4. Comparative study showed that the mean transport distance (S_p) of lentic plankton in the Nunome R. was 2 times shorter (2.03km) than in the Uji R. (4.12km), indicating much higher trapping efficiency of the Nunome R. (Table 5-8).
5. From a geomorphological prospective, the Nunome R. had relatively long riffle and short pool, whereas the Uji R. had relatively short riffle and long pool. The F_R (the percentage ratio of the riffles to the total distance) in the Nunome R. and the Uji R. were 68.42% and 15.5% respectively. Subsequently increasing F_R can lead to decrease the values of hydraulic radius (R_h) (Table 5-8). It is supposed that sediment replenishment lengthens riffles and shortens pools likely as the Nunome R., and then it leads to decrease the mean transport distance of lentic plankton. Therefore higher trapping efficiency of lentic plankton in the Nunome R. can imply an important effect of the sediment replenishment for downstream ecosystem management.

CHAPTER 6

1. The experimental study on deposition of FPOM in relation to channel morphology was conducted. Using two types, the floating and the sinking, of pine pollen as tracers of the lentic plankton and the terrestrial plant respectively, the deposition density of floating pollen(ρ_{dep}-F) and sinking pollen(ρ_{dep}-S) were

calculated. Experimental bed configurations were applied for the damming pool and the alternate bars.

2. Various hydro-morphological parameters such as the bed elevation, lateral elevation difference, aspect, slope, flow velocity u and v, divergence were measured and calculated.
3. In the damming pool, the ρ_{dep}-S was significantly higher than ρ_{dep}-F, and was negatively correlated with u. In addition, higher deposition was found to be in the aspects with lateral slope. Although ρ_{dep}-F showed no significant correlation with u, ρ_{dep}-S showed weak negative correlation with u. It indicates that the deposition characteristics of sinking pollens are different from the floating pollen in the damming pool. In addition, the sinking pollen can be easy to deposit in comparatively low elevation and velocity conditions (Fig.6-8~13).
4. In the alternate bars and thalweg structures, ρ_{dep}-F was higher than in the damming pool, and there were no significant difference between ρ_{dep}-F and ρ_{dep}-S. In addition, the ρ_{dep}-F was significantly higher in the bar than in thalweg, whereas the ρ_{dep}-S did not show any significant difference between bar and thalweg. It indicates that the bars had higher retention efficiency of the lentic plankton, especially in the head and middle of bar area, which was resulted from the aspect analysis. And ρ_{dep}-S showed a negative correlation with the bed elevation and Δz both in the thalweg, indicating that terrestrial leaves and wood particles can be deposited in the thalweg (Fig.6-15~20).
5. Consequently, 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.

7.2 SYNTHESIS AND CONCLUSIONS

7.2.1 Development of tracers for quantification of tailwater POM dynamics

As described in introduction, some objectives of the study are the development and application of tracers for quantification of POM dynamics. In the study, three types of tracers were successfully used and applied.

First, using ‘lentic plankters’ produced in dam reservoirs, the mean transport distance and the filed deposition velocity of dam tailwater FPOM were well estimated. The tracing of lentic plankton as dam tailwater FPOM tracer is appropriate to overcome the river scale restriction which the previous artificial materials such as corn pollen and radioactive labeled seston was only applicable to small headwaters. Moreover tracing lentic plankton has an advantage of no consideration of dispersion process.

Second, ‘natural stable isotopes ratios’, in particular combined $\delta^{13}C$ and $\delta^{15}N$, were used to identify a dam tailwater POM according to its source origins. Moreover the concentration-weighted three source mixing model based on $\delta^{13}C$ and $\delta^{15}N$ made it possible to trace their composition change along downstream reaches.

Finally, using ‘pine pollen’ was as long as the author’s survey for the first time research as analogue of dam tailwater FPOM in the experimental study conducted in a straight flume. The pollens has two types in water by different settling velocity, a floating type buoyant in water and a sinking type falling to bottom. Although in natural condition, most of pine pollen is drifted in water as floating type due to air bladders, in the study, a sinking type could be transformed from floating type without change of shape and size. In this sense, the application of two types pine pollen can have important implication as FPOM tracer in the dam tailwater reaches, because a floating pine pollen can be represented as lentic plankton drifting mainly in surface water, and a sinking pine pollen can function as terrestrial plant particles with relatively high settling velocity.

7.2.2 Quantification of retention efficiency for lentic plankton and POM source composition in the downstream reaches of dam reservoirs

Quantification of FPOM dynamics is methodologically important in stream ecology for explanation and prediction of material cycling and energy flows in heterotrophic foodwebs system. Using the three types of tracers mentioned previously, the source composition of S-FPOM, S-CPOM, B-FPOM and B-CPOM can be quantified.

Retention efficiency for lentic plankton were quantified by estimation of the mean transport distance (S_p) in Chapter 2, 4 and 5 and the field deposition velocity (v_{dep}) in Chapter 2. POM source composition can be investigated by estimation of relative contributions of three source origins by means of the microscopic examination and two stable isotope mixing models. It was found that the concentration-weighted model (CWM) can reflect the true values in dam tailwater ecosystems, whereas the microscope examination (ME) and the standard linear model (SLM) underestimated the contribution of the terrestrial plant and overestimated that of lentic plankton.

7.2.3 Comparison of POM dynamics characteristics between the Nunome River and the Uji River

As shown in Fig.7-1, when compared with the five rivers without upstream dams, S-FPOM of the five dam tailwaters had more depleted $\delta^{13}C$ and enriched $\delta^{15}N$. The isotopic characteristics attributes to a high contribution of lentic plankton to S-FPOM composition in dam tailwaters. In particular, the Nunome R. and the Uji R. showed much more enriched $\delta^{15}N_{S\text{-}FPOM}$ relative to other dam tailwaters. It indicates that the dam reservoirs in the Nunome R. and Uji R. have been highly influenced by loads of anthropogenic nutrients or contaminants from the upper basins, because nitrogen isotopes were used as an indicators of anthropogenic activities of the basin (Costa *et al.*, 1992; Lake *et al.*, 2001). Therefore, increasing the retention efficiency for lentic plankton by geomorphological restoration of riverbed can be critical to recover and to enhance ecological functions in dam tailwaters.

Fig.7-2 compared the nonlinear mixing triangles and the isotopic values of the four types of POMs between the Nunome R. and the Uji R.. Although the isotope values of the terrestrial plant were similar between the two rivers, the other endmembers showed the distinctive differences. Overall the more enriched $\delta^{13}C$ and more depleted $\delta^{15}N$ were found in the Uji R.

Table 7-1 provides insights on energy resources of foodwebs in the two tailwater reaches. The S-FPOM which is diet for filter-feeders comprised of largely the lentic plankton ($f_{B,p}$= 47.2 and 47.0%) in both the Nunome R. and the Uji R.. However, compositions of B-FPOM which is diet for collector-gatherers were different between the two rivers. The B-FPOM of the Nunome R. comprised of mainly terrestrial plant ($f_{B,t}$=74.2), whereas the Uji R. was mainly epilithic algae ($F_{B,s}$=69.4%). Subsequently, the nitrogen stock of S-FPOM was supplied from mainly lentic plankton ($f_{N,p}$) and carbon was from terrestrial plant ($f_{C,t}$) in the two rivers. However, in case of carbon stock of the B-FPOM, the Nunome R. was supplied from mostly the terrestrial plant whereas the Uji R. from epilithic algae. Consequently, the relatively less contributions of epilithic algae in the Nunome R. can be supposed of an important effect of sediment replenishment.

7.2.4 Significant hydro-geo-morphological factors to influence retention efficiency for lentic plankton

Throughout the present researches, relation of the hydraulic radius (R_h) to the mean transport distance (S_p) which was used as an indicator of retention efficiency in the study was investigated. Even though the physical characteristics such as discharge, velocity and depth were varied among the four channels in Chapter 2, the riffles in the Uji R. in Chapter 4 and the riffles in the Nunome R. in Chapter 5, overall the S_p had a weak positive regression with R_h (Fig.7-3) (R^2=0.41, p=0.06). It indicates that the lentic plankton deposition can increase with reducing R_h . The research of Speaker et al (1984) was closely related to the result, they showed the retention rate of POM were greater with higher ratios of wetted perimeter to channel cross sectional area.

On the other hand, the relationship between S_p and more diverse parameters such R_h, longitudinal velocity (u), water gradient (I_w), width (B), depth (H) and B/H were examined. The reaches where data used were the riffles and some pools showing positive S_p in the Nunome R. and the Uji R. By multiple regression analysis, three parameters such as hydraulic radius, velocity and water gradient can predict 84% of variability in S_p despite of different characteristics of the reaches using following regression model (Eq.7-1) ($p<0.05$) (Fig.7-4).

$$S_p \text{ (km)} = -0.237\, R_h - 4.365\, u - 1.961\, I_w + 5.054 \qquad \text{(Eq.7-1)}$$

The result provides applicable implication that the hydro-morphological optimization of the three parameters can increase the retention efficiency for lentic plankton.

7.2.5 Roles of channel geomorphologic features in SPOM dynamics: Spatial sorting capacity of SPOM according to source origins

It was interestingly found that even reach scale distance, SPOM source composition or concentration could be dynamically changed being strongly affected riffle and pool structure.

In the Chapter 4 and Chapter 5, longitudinal changing pattern of relative contribution of S-FPOM composition were investigated in the Uji R. and the Nunome R. where the both rivers had subsequent riffle and pool structures in the reaches, however, from a geomorphological prospective, the Nunome R. had relatively long riffles and short-shallow pools, whereas the Uji R. had relatively short riffles and long-deep pools. The differences of the geomorphologic features could cause different retention processes and extends of S-FPOM composition according to source origins.

In the Uji R., during passing shot riffles, the contribution of lentic plankton was reduced and that of epilithic algae increased. However, during passing long pools, the contribution of terrestrial plant either increased in the first pool probably due to resuspension by dominant upwelling flows or decreased in the second pool. The findings indicate that riffles have high retention capacity of lentic plankton by both physical and biological filtering processes, moreover long pools, if without upwelling, have tendency to trap the terrestrial plant particles by falling process (Fig.7-5a).

In the Nunome R., 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 a general increase in the short pools and no trend in the long riffles. The tendencies both in reducing lentic plankton in riffles and in reducing terrestrial plant in pools were similar to the results of the Uji R. However, the instream algae is difficult to explain in association with riffle and pool. It may attribute to local production and its desorption because much standing stock of epiphytic algae was attached on roots and stream of riparian reed in the end of riffle 1 to the head of pool 2, whereas a standing stock of epilithic algae was increased from the riffle3. The findings indicate that long riffles tend to remove lentic plankton, and even short pools can trap the terrestrial plant particles (Fig.7-5b).

The results from experimental study in Chapter 6 also provided an importance of channel geomorphology for S-FPOM deposition processes. In the Case Initial which was characterized as damming pool structure, it was found that ρ_{dep}-S was significantly higher than ρ_{dep}-F and was negatively correlated with u. It can support the finding that the pools have high retention efficiency of terrestrial plant particles. In the Case 1 which was characterized as alternate bars and thalweg structures, the ρ_{dep}-F was significantly higher in the bar than in thalweg, whereas the ρ_{dep}-S did not show any significant difference between bar and thalweg. It indicates that the bar area had higher retention efficiency of the lentic plankton and terrestrial plant particles will be deposited in the thalweg area.

Based on overall results in the study, the geomorphic features such as riffle and pool structures and the damming pool condition can spatially sort or distribute FPOM particles separately according to its source origins. Subsequently, it will make the reaches higher heterogeneity of feeding space for stream biota and it may lead to increase in habitat diversity even in the reach scale channel.

7.2.6 Response of benthic communities to POM dynamics in dam tailwater ecosystems

(1) Density, biomass and death rate of Filter feeding mussels

It was supposed that quality and quantity of the suspended fine food materials give higher influence on the filter feeding invertebrates fed on S-FPOM than other functional feeding groups. The population density and biomass of freshwater golden mussel, *Limnoperna fortunei*, showed similar exponential reductions in the riffles. And the death rates of the mussels result in increase with the downstream distance. These findings suggest that the spatial distribution of the filter-feeding mussel can be highly relying on the changes of lentic plankton contribution. Also it contributes the reduction of lentic plankton in the riffles by the biological filtration of high density of filter feeding mussel vice versa (Welker and Walz, 1998; Monaghan *et al.*, 2001).

(2) Longitudinal changes of CN isotopic signatures of filter-feeders

In Chapter 4 and Chapter 5, the isotopic changes of the benthic filter-feeders such as Bivalves, Hydrpsychidae and Simuliidae were found to be highly similar patterns with those of the S-FPOM in the Uji R. and the Nunome R. In particular, the longitudinal changes of $\delta^{13}C$ in the freshwater golden mussel were more highly correlated with that in Hydrpsychidae, indicating that the mussels is more sensitive to the source composition changes of S-FPOM than Hydrpsychidae probably due to a selective feeding to phytoplankton of the mussels (Baker *et al.*, 1998). These findings indicate that the downstream changes of relative contribution of the lentic plankton can make shift the food quality and quantity of the filter-feeding animals from phytoplankton to epilithic algae.

(3) Life form and functional feeding group of benthic invertebrates

Species composition and community pattern of benthic invertebrates have been used as biological indicators for river environmental assessment such as water quality (Gaufin, 1973; Lenat, 1988), river health (Norris and Thoms, 1999) and environmental monitoring (Hodkinson and Jackson, 2005). In the present study, characteristics of life forms and functional feeding groups (FFGs) of benthic communities in the Uji R. and Nunome R. reflected the responses of benthic communities to dam impacts as well as sediment replenishment work conducted for their mitigation. As already mentioned on the geomorphological characteristics of the two rivers, the riverbed in the Uji R. was degraded and even bedrock are exposed in the downstream reaches of the Amagase Dam. As to the size fractionation of SPOM, the concentration of S-FPOM was 3-5 times higher than that of S-CPOM (Fig.4-7), which is one of important characteristics of POM dynamics in dam tailwater ecosystem. In the S-FPOM composition, the lentic plankton was most abundant accounting for 47.2% of relative contribution (Table 7-1). These characteristics of geomorphology and POM dynamics resulted in the following responses of benthic invertebrates; In the life forms, high relative abundance of the net-spinners and attachers, whereas low abundance of the burrowers due to lack of sand as their habitat matrix. In the FFGs, the filterers fed on S-FPOM and the collecting gatherers fed on B-FPOM were most abundant accounting for 48% and 25%, respectively. However, the shredders fed on coarse litters were not found in the reaches (Fig.7-6).

On the other hand, in the Nunome R. large amount of sediment were replenished for geomorphological restoration. The species richness in the Nunome R. higher than in the Uji R. and its increasing pattern with the downstream distance may be positive responses of the benthos community to the sediment replenishment works. In addition, the composition of the relative abundance was characterized by a low relative of the net spinners and attachers comparing with the Uji.R. Instead, the burrowers were much more abundant accounting for 19% of the total. The composition of FFGs with relatively balanced abundance among the five groups also indicates more healthy state of the Nunome R. in comparison with the Uji R (Fig.7-6).

7.2.7 Needs of sediment management for ecological improvement in dam tailwater ecosystem

In Chapter 2, the mean transport distance was highest in the Deep Canal and it was positively correlated with hydraulic radius, in addition the field deposition velocity of canals was observed in much lower than those in river channels. It indicates that simplified shapes of the tailwater channel by dam impacts such as bed degradation, loss of pool-riffle structures and loss of bar structure lead to decrease the retention capacity of the reaches. The results of Chapters 4 to 6 stressed the importance of diverse geomorphologic features for improving balance of POM dynamics and benthic communities. Therefore, for sustaining and enhancing the ecosystem health of dam tailwaters, it is increasingly required to maintain, restoring and even creating fluvial geomorphological features and their dynamics over a range of spatial and temporal scales by sediment management in dam tailwater channels.

7.3 Recommendations: channel geomorphological management for increasing retention efficiency

The findings and results derived from the field studies and physical experimental were synthetically analyzed and constitute a dam tailwater POM dynamics model combined with geomorphological parameters, which can serve as persuadable theoretical and applicable tool for planning, assessment and monitoring in several downstream sediment management. In this section, some conceptual designs are presented for increasing the retention efficiency for channel geomorphological management in order to restore or improve a tailwater ecosystem health.

- **Design of Riffles**

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 (refer to Table 5-8). 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 and gradient appeared to be highest retention efficiency ($\Delta f_{B,p}$/m) (Table 7-2). Thus several numbers of short riffles is more efficient than one long riffle (Fig.7-7).

In addition, since it is supposed that vertically downwelling flow leads to increase a filtering capacity of the riffles, the steep and rapid riffles with a high water slope (I_w) to activate downwelling flow are more efficient than the flat and slow ones (Fig.7-8). However, as 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.

- **Design of Pools**

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 (Fig.7-9). In particular, if an appropriate structure of pools were restored or created, sustainable management is required not to progress the river bed degradation.

- **Design of Bars**

The results from Chapter 6 suggest that a head and middle area of bars will have higher deposition density of lentic plankton. Therefore if bar area is fixed or same condition, the expanding of bar head and middle areas is more efficient than that of bar tail, because it will increase the contact area with suspended POM.

In addition, the results of aspect analysis in the alternated bar structure show that the direction of bar slopes and an arrangement of bars also important factors to influence the retention efficiency (*See* Fig.6-21). High deposition density of lentic plankton in the head and middle of bars than in the tail of bars indicate that more laterally undulating riverbed will have much higher retention efficiency in the channels.

- **Design of Cross sections**

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 from Chapter 2, 4 and 6. 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.7-10).

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Table 7-1 Comparison of biomass, carbon and nitrogen contributions to POM composition between the Nunome River and the Uji River

(unit: %)

		(a) Biomass			(b) Carbon			(c) Nitrogen		
		$f_{B,p}$	$f_{B,s}$	$f_{B,t}$	$f_{C,p}$	$f_{C,s}$	$f_{C,t}$	$f_{N,p}$	$f_{N,s}$	$f_{N,t}$
Nunome R. (Chap.5)	S-FPOM	**47.2**	17.6	35.2	31.6	19.0	**49.4**	**71.0**	22.7	6.3
	S-CPOM	21.4	13.1	**65.5**	11.9	11.7	**76.4**	**52.9**	27.9	19.3
	B-FPOM	6.4	19.4	**74.2**	3.3	16.2	**80.5**	20.1	**52.3**	27.6
	B-CPOM	7.9	14.6	**77.5**	4.1	12.1	**83.8**	26.6	**42.3**	31.1
Uji R. (Chap.3)	S-FPOM	**47.0**	20.2	32.8	33.0	22.8	**44.2**	**67.7**	23.7	8.6
	S-CPOM	5.0	35.5	**59.6**	2.2	32.8	**65.0**	8.8	**66.5**	24.6
	B-FPOM	8.2	**69.4**	22.4	5.0	**68.6**	26.4	11.9	**82.2**	5.9
	B-CPOM	7.6	**66.8**	25.6	4.6	**65.5**	29.9	11.3	**81.7**	7.0

The data used were from Table 5-6 and Table 3-3.
The index of $f_{B,i}$, $f_{C,i}$ and $f_{N,i}$ represents fractionations of biomass, carbon and nitrogen, respectively, contributed to the POM by source *i*. Source *i* corresponds to lentic plankton (p), terrestrial plant (t) and instream algae (s) respectively.

Table 7-2 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**
Nunome R. (Chap.5)	(1) St1-St2	Riffle 1	300	0.41	0.48	8.0	0.03
	(3) St3-St4	Riffle 2	**50**	0.69	0.69	7.1	**0.14**
	(5) St5-St6	Riffle 3	300	0.53	0.60	6.8	0.02
Uji R. (Chap.4)	(1) St1-St2	Riffle 1	**68**	0.93	0.43	9.7	**0.14**
	(3) St3-St4	Riffle 2	180	0.78	0.28	11.9	0.07

*$\Delta f_{B,p}$: 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 unit distance of $f_{B,p}$ in the riffle

The data of the Nunome R. were from Table 5-1 and Table 5-7, and the Uji R. from Table 4-1 and Table 4-4.

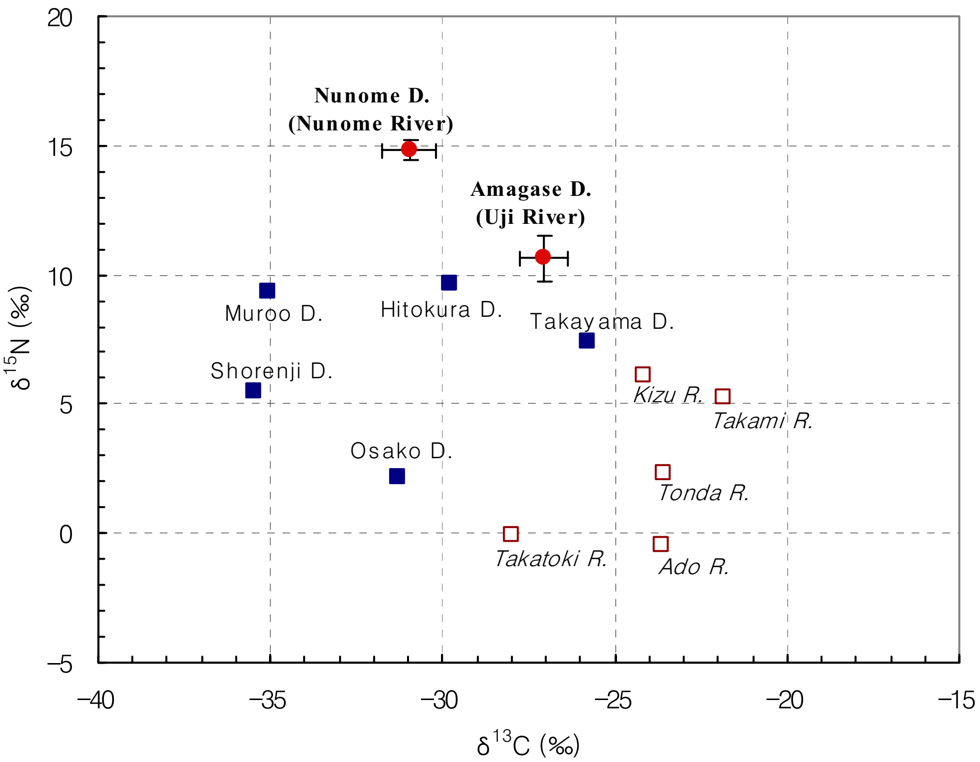


Fig.7-1 Comparison of $\delta^{13}C$ and $\delta^{15}N$ of S-FPOM among Nunome River, Uji River, five tailwaters of dams (shade squares) and five rivers without upstream dams (open squares). The isotope data used as those of reference sites were sourced from Takemon (unpublished data, sampling in the 7-8th March 2005). The SPOM samples of the five tailwaters were collected possible near the dam outlets.

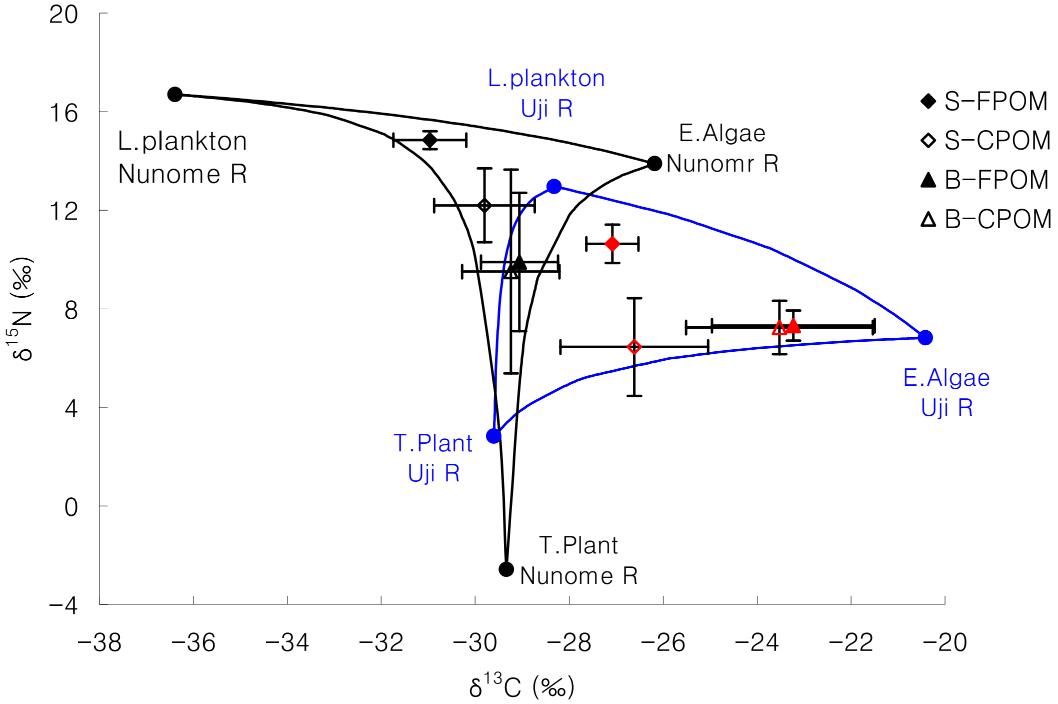


Fig.7-2 Comparison of various POM types and mixing triangles between the Nunome River (green) and the Uji River (red).

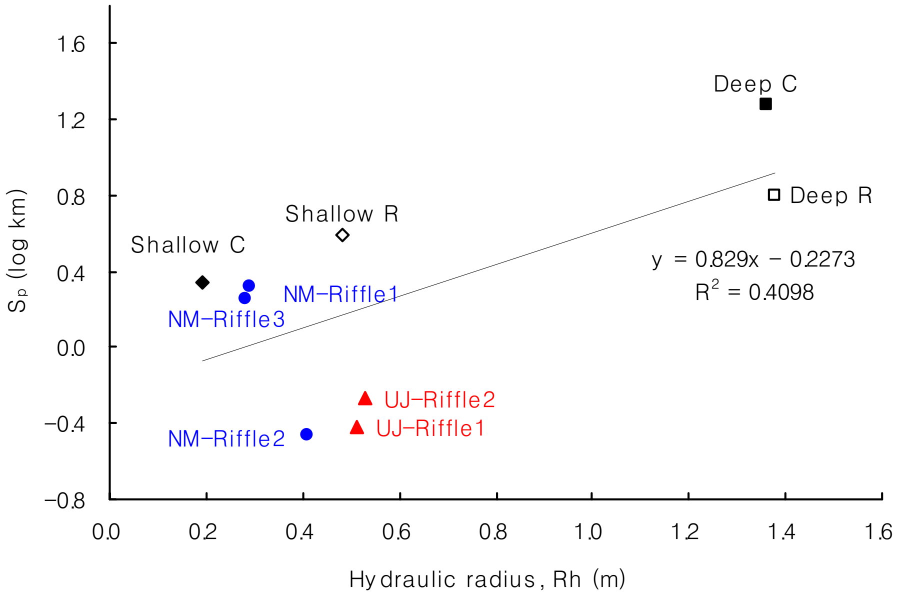


Fig.7-3 Relationship between Rh and Sp in all of sites in the study. The Sp values of grey symbols were estimated by tracer lentic plankton (*refer to* Chapter 2) whereas red and blue symbols by stable isotope mixing model (*refer to* Chapter 4 and 5). UJ and NM mean Uji River and Nunome River, respectively. (n=9, p=0.06)

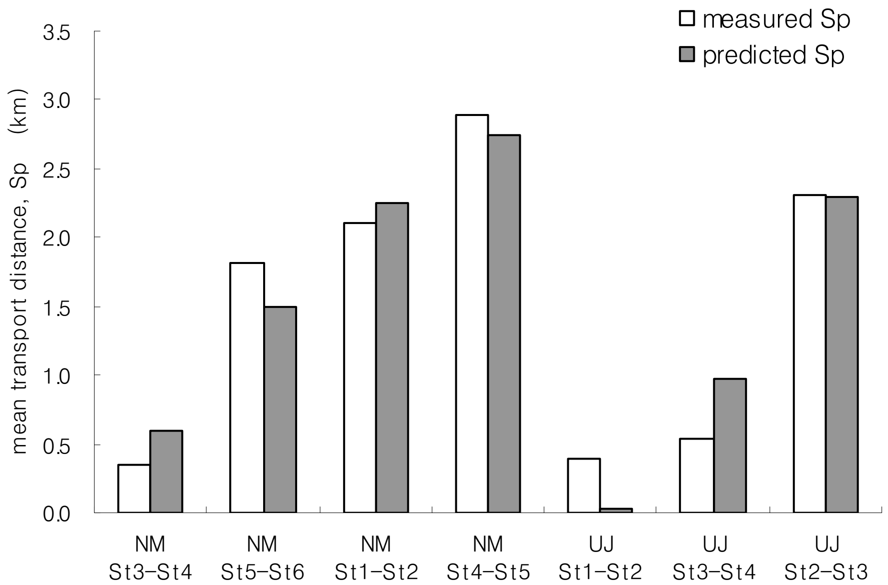
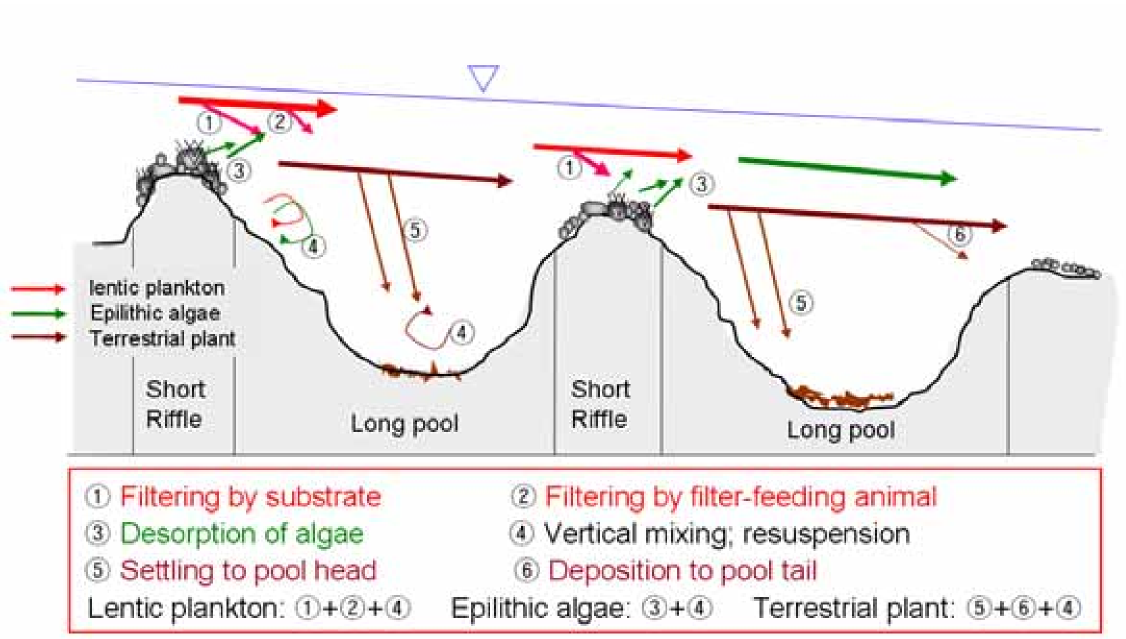


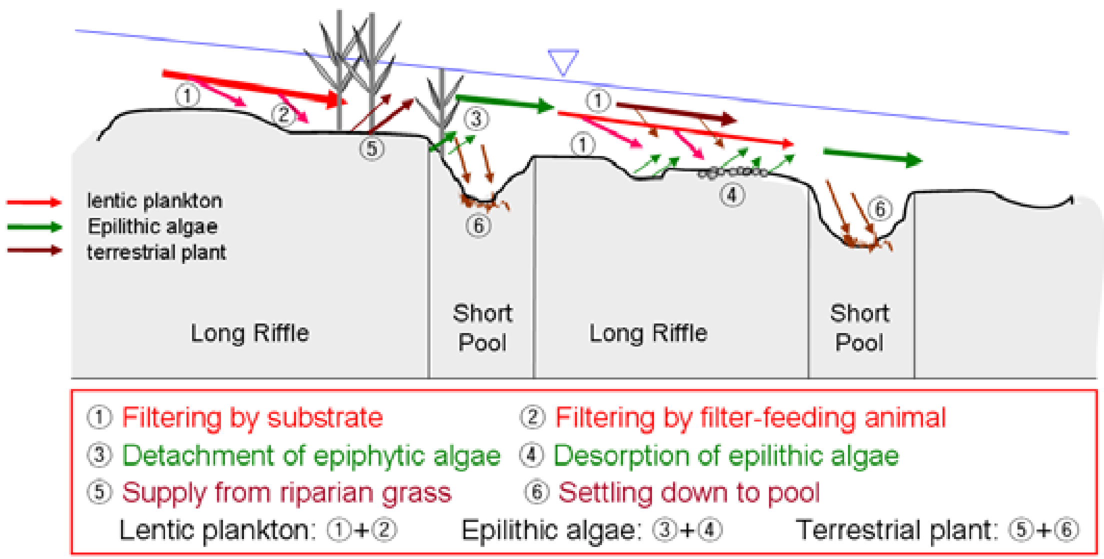
Fig.7-4 Comparison of measured Sp with predicted Sp by multiple regression analysis.

S_P (km) = $-0.237R_h - 4.365u - 1.961I_w + 5.054$ (R^2=0.836, $p<0.05$).

R_h, u and I_w mean the hydraulic radius, velocity and water gradient respectively. NM and UJ represent the Nunome River and the Uji River, respectively.



(a) Example of the Uji River: Short riffles and long-deep pools



(b) Example of the Nunome River: Long riffles and short-shallow pools

Fig.7-5 Conceptual scheme of S-FPOM dynamics in relation to riffle and pool structures

(a) Species richness

(b) Life forms

(c) Functional feeding groups

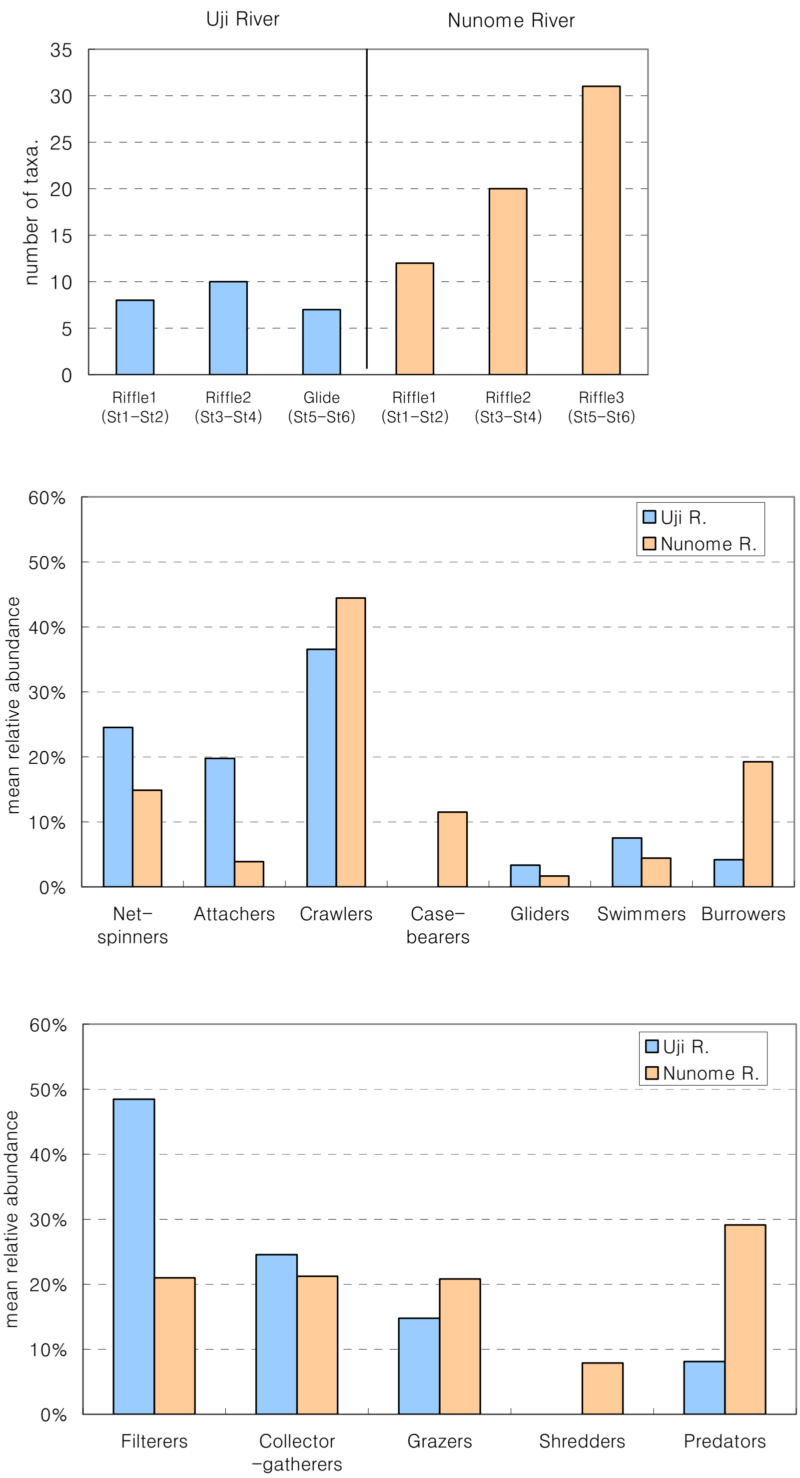
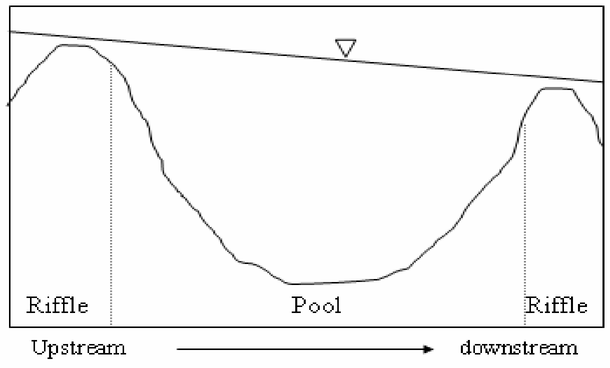
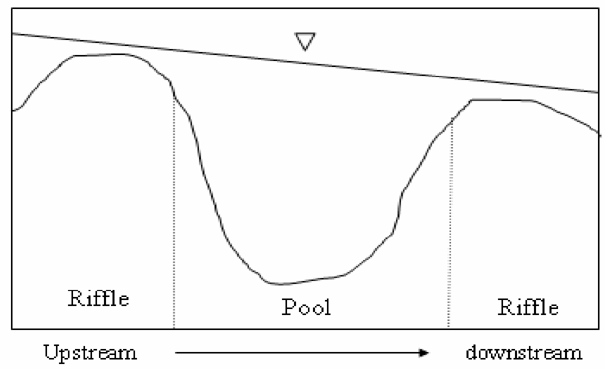


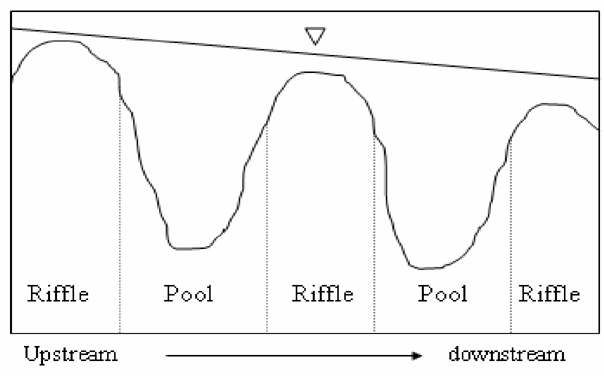
Fig.7-6 Comparisons of species richness (a) and life forms (b) and functional feeding groups (c) of benthos communities between Uji River and Nunome River. The units of (b) and (c) are the mean values of relative abundances of all the sites in each river



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

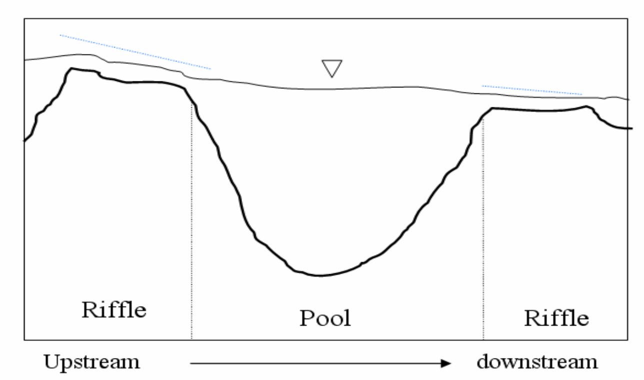


(b) F_R=(3+3)/10=0.6



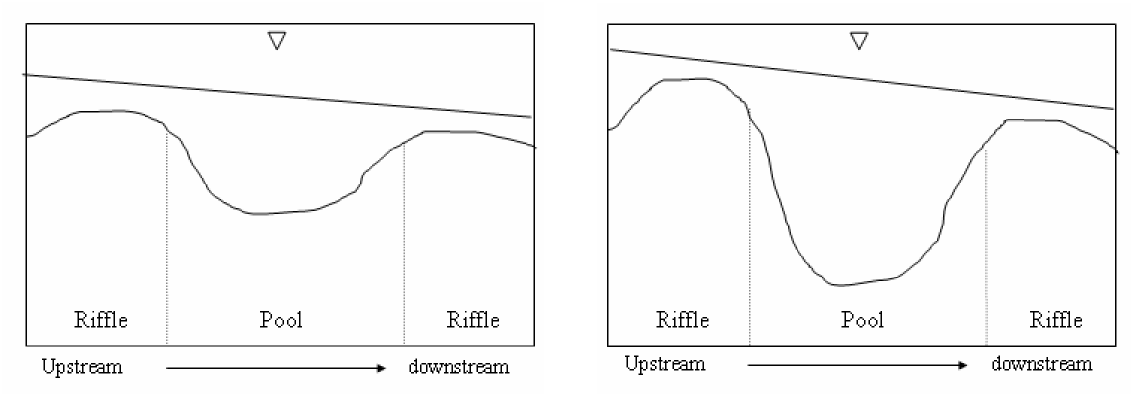
(c) F_R=(2+2+2)/10=0.6

Fig.7-7 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).



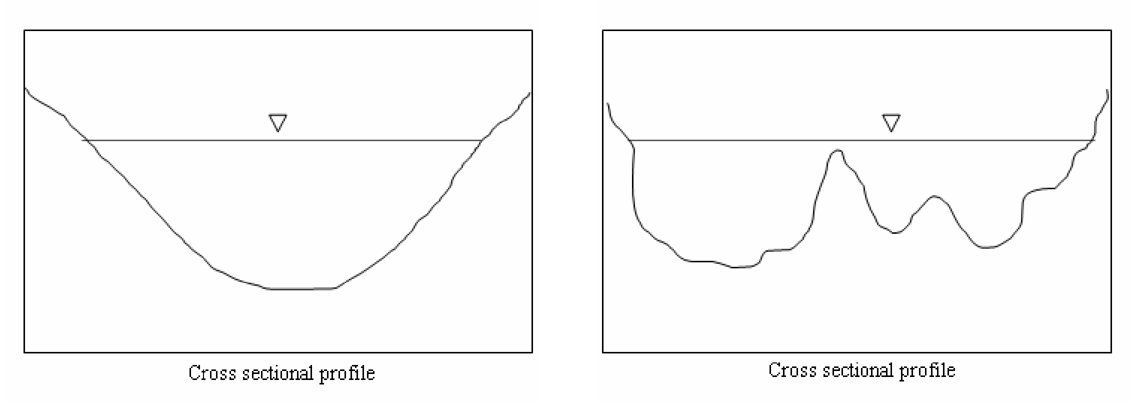
high I_w (left) and low I_w (right)

Fig.7-8 Management of the water slope (I_w) of riffles for increasing retention efficiency. High I_w is efficient for retention for lentic plankton



(a) low h_P/h_R (b) high h_P/h_R

Fig.7-9 Management of the depth of pools for increasing retention efficiency. High h_P/h_R is efficient for retention for terrestrial plant source



(a) high R_h (b) low R_h

Fig.7-10 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

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PAPERS BASED ON THIS THESIS

This manuscript of Ph.D. Thesis includes the contents of the following published and accepted journal and conference papers:

1. 玉基英, 竹門康弘 (2007). 京都市疏水における琵琶湖由来のプランクトンの流下距離の推定. *応用生態工学会11回大会*. 名古屋: 201-204

2. 玉基英, 竹門康弘, 武藤裕則 (2009). ダム下流河川の粒状有機物の動態における河道地形の役割. *応用生態工学会13回大会*. 埼玉: 65-66

3. Ock G, Takemon Y, Yamomoto K, Ichise S (2008). Effect of channel morphology on FPOM transport distance based on dam originated plankters as tracer. *55th Annual meeting of Ecological Society of Japan*. Hukuoka

4. Ock G, Takemon Y (2008). Changes in SPOM composition in reservoir tailwaters interpreted by stable isotopic signatures. *6th Annual Joint Seminar between Korea and Japan on Ecology and Civil Engineering*. Jinju, Korea: 17-18.

5. Ock G, Takemon Y (2008). Downstream changes in SPOM sources composition below dams based on stable isotope mixing model. *12th Annual meeting of Ecology and Civil Engineering*. Hukuoka

6. Ock G, Takemon Y (2008). Estimation of the transport distance of suspended particulate organic matter measured by lake originated plankters in tailwaters. *5th AOGS (Asia Oceania Geoscience Society) Conference*. Busan, Korea: HS25-A003

7. Ock G, Takemon Y (2008) Relation of channel morphology to FPOM transport distance in tailwaters. *Annuals of Disas Prev Res Inst, Kyoto Univ.* 51:815-828

8. Ock G, Takemon Y (2009) Downstream changes in source composition of particulate organic matter in dm tailwaters in relation to channel geomorphology and benthos communities. *33rd IAHR (International Association of Hydro-Environment Engineering and Research) Congress*, Vancouver, Canada: 3672-3679.

9. Ock G, Takemon Y, Kanda K, Muto Y, Zhang H, Nambu Y, Samoto Y, Nakagawa H (2009) Experimental study on deposition of fine particulate organic matter affected by river channel morphology. *Annuals of Disas Prev Res Inst, Kyoto Univ*. 52:913-922.

10. Ock G, Takemon Y, Muto Y (2009). Dam impacts on POM dynamics and its ecological response in dam tailwater channel. *7th Annual Joint Seminar between Korea and Japan on Ecology and Civil engineering*. Saitama: 207-208.

11. Ock G, Takemon Y (2010) Estimation of transport distance of fine particulate organic matter in relation to channel morphology in tailwaters of the Lake Biwa and reservoir dams. *Landscape and Ecological Engineering* DOI: 10.1007/s11355-11009-10099-y.

12. Ock G, Takemon Y, Muto Y, Sumi T (2010) Roles of riffle and pool structure for increasing retention of lentic plankton in dam tailwater reaches. Accepted in *8th International Symposium on Ecohydraulics*. Seoul, Korea.

VITA

Giyoung OCK received the following degrees: B.A. in Faculty of the Agriculture and Life sciences from Seoul National University, Seoul, Korea (1997); M.S. in Graduate School of the Environmental Planning and Management from Seoul National University, Seoul, Korea (1999); and Ph.D. in Graduate School of the Urban and Environmental Engineering from Kyoto University, Kyoto, Japan (2010).