Conference Paper, Published Version

Tashiro, Takashi; Katsuno, Chiho; Tsujimoto, Tetsuro

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EFFECTS OF THE BEHAVIORS OF BENTHIC FISH *Pseudogobio esocinus* ON SUBSTRATUM ENVIRONMENT ON SAND RIVER

Takashi Tashiro[1], Chiho Katsuno[2] and Tetsuro Tsujimoto[3]

[1] Assistant Professor, Department of Civil Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan, e-mail: ttashiro@civil.nagoya-u.ac.jp
[2] Engineer, Nakamura Public Works Office, Greenification and Public Works Bureau, City of Nagoya
1-87 Katori-cho, Nakamura-ku, Nagoya, 453-0055, Japan, e-mail: katsunochiho@rd.city.nagoya.lg.jp
[3] Professor, Department of Civil Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan, e-mail: ttsujimoto@genv.nagoya-u.ac.jp

ABSTRACT

Pseudogobio esocinus is a common benthic fish in Japanese rivers, which has powerful effects on sand particle motions by its feeding and submerging in sand bed. In the present study, the indoor flume experiments with these fish were conducted to examine the preference of substratum condition for their staying and submerging, and furthermore to evaluate their impacts on pick up rate and step length of bed load particles which adapted to the conventional probability model for bedload developed by Einstein (1942).

The results of our experiments, especially in comparison of the pick up rates of bed load with the conventional hydraulic knowledge, have clarified that the population of *P. esocinus* fish could have increased 20-30 % of the effective dimensionless tractive force (τ_{*e}) with a certain degree of the density.

Keywords: *Pseudogobio esocinus, ecological rehabilitation, sand particle motion, pick-up rate, dimensionless tractive force, sand river*

1. INTRODUCTION

The benthic fish, *Pseudogobio esocinus* is often observed on sandy substratum in Japanese fluvial conditions. It usually feeds benthic organisms with sucking and exhaling sand particles and sometimes escapes with submerging in sandy substratum. Then, these specific behaviours have powerful effects on the sand particle motions. Jones et al. (1994) called such kinds of organisms “ecosystem engineers”, and they started to investigate these physical effects in fluvial ecosystems. There were some advanced works which clarified the physical effects of freshwater fishes on substratum environment (e.g. Statzner et al. 2003, Flecker and Taylor 2004 and Montgomery et al. 2006). Moore (2004) has categorized the works of ecosystem engineers from the viewpoints of these forms and functions. Although the behaviours of *P. esocinus* is considered to the “bioturbation” category according to Moore’s review, these effects on substratum environment has not been evaluated in the conventional studies. Furthermore, these relative works have been conducted mostly by ecological interests (in ecological fields), the mechanism has not been appropriately examined for predicting these effects in actual rivers with spacio-temporal various conditions.

Substratum environment in fluvial system depends on its flow and geomorphic regimes, especially on the frequency of local bed material movement. And such the substratum regime controls the primary production of benthic algal community which is the fundamental factor in fluvial ecosystem. Peterson (1996) indicated that the physical disturbance (e.g. bed material movement) could be the key control factor for ecological succession by illustrating the response of benthic algal communities to natural physical disturbance. Kitamura et al. (2000) examined the availability of rehabilitation for the degraded ecosystem with blooming macro algae, *Cladophora glomerata* on bed materials by controlling bedload transportation in laboratory experiment. Hence, the bioturbation due to *P. esocinus* behaviours also would need to be described from the viewpoint of the management of substratum environment.

The objectives of the present study are to clarify the preference of *P. esocinus* for substratum environment and to evaluate the effects of the fish behaviours on bedload transportation on sand bed rivers.

2. MATERIALS AND METHODS

The indoor flume experiments with these fish were conducted to examine the preference of substratum condition for their staying and submerging, and furthermore to evaluate their impacts on pick up rate and step length of bed load particles which adapted to the conventional model for bedload transport.

2.1 Fish sampling for laboratory experiment

The fish individuals employed in the laboratory experiment were caught in Japanese autumn season (Oct. and Nov. 07), and in some tributaries poured into the Kiso River located in Gifu prefecture, Japan, by using the electric shocker (Mod.12B, Smith Root Inc.). These fish were measured their body length and weight in the anesthetized condition with eugenol solution (~0.1% concentration). Figure 1 shows the distribution of total body length of the caught fish individuals.

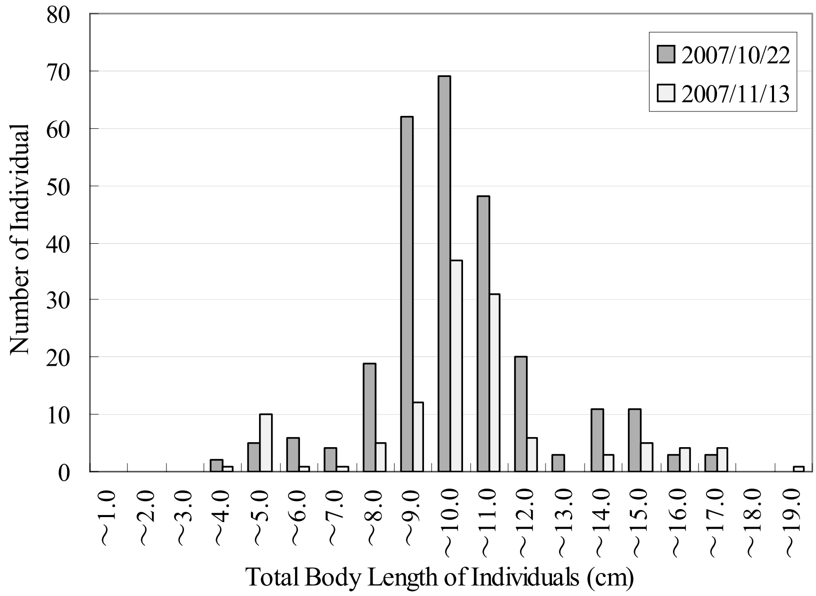

Figure 1 Size distribution of sampled *Pseudogobio esocinus* in Oct 22 and Nov 13 of 2007. These individuals were caught in the two experimental streams of ARRC and in the Shinsakai River located in Kakamigahara city, Gifu prefecture, the central region of Japan.

2.2 Experimental procedures

Figure 2 shows the experimental setup in laboratory flume located in Nagoya University, whereas Table 1 shows experimental conditions. We designed these conditions to

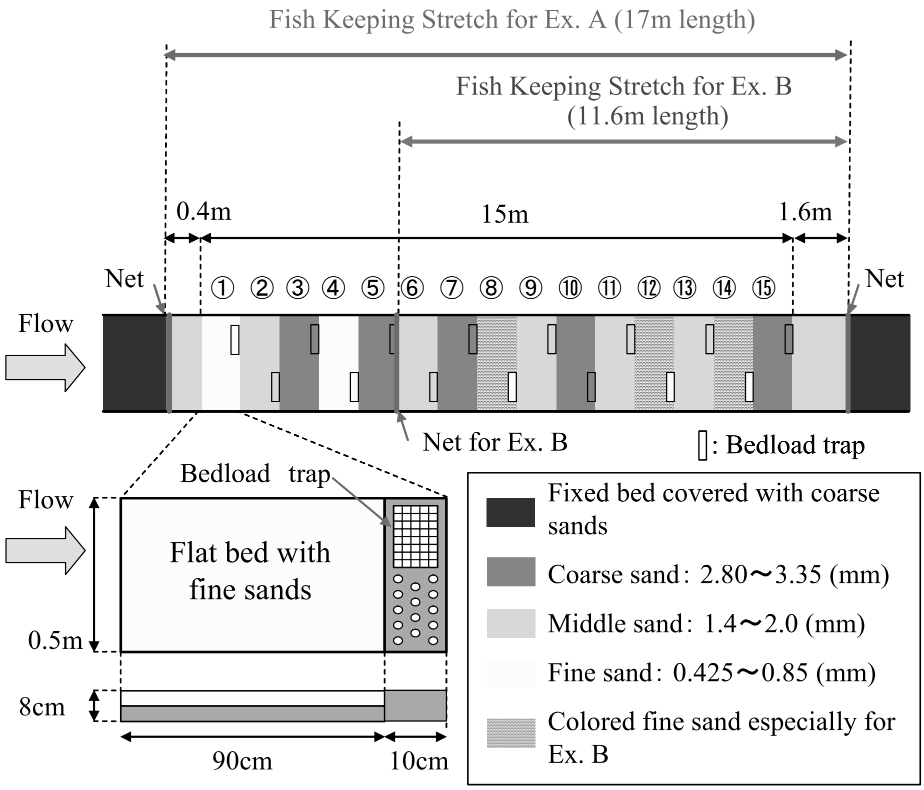

Figure 2 Schematic images of experimental setups in plan view. The two kinds of experiments "A" and "B" were distinctly designed in one laboratory flume which controlled inflow discharges. There were 15 units (3 substrate cases X 5 replications) for the measurements of bedload discharges and fish densities in the laboratory flume in the Ex. A. Whereas, the fine sand motions were observed on the shading substrate units covered with coloured sands in the Ex. B.

Table 1 Overview of the experimental conditions. The descriptions in "Num. of *P. esocinus*" column are as follows: the symbol in rear of "@" means the age of fish, whereas the front number shows the number of the fish of each age group.

Case			Discharge (l/s)		Num. of *P. esocinus* Indviduals	Exp. Date	Bedload Sampling	Water Temp. (℃)		Bed Surface Analyzing	
								max	min	Seg. No.	Color
A	Run-1	(1)	Q_2	8.3	$10@2^+$	2007/12/3-10	1^{st}, 2^{nd}, 4^{th}, 7^{th} day	15.4	14.7		
		(2)			$10@1^+$	2007/12/10-13	1^{st}, 2^{nd}, 3^{rd} day	15.4	14.6		
		(3)			$30@1^+$	2007/12/13-17	1^{st}, 2^{nd}, 4^{th} day	15.5	15.0		
	Run-2	(1)	Q_1	4.2	$10@2^+ + 20@1^+$	2007/12/17-22	1^{st}, 3^{rd}, 5^{th} day	14.6	14.1		
		(2)	Q_2	8.3	$10@2^+ + 18@1^+$	2007/12/22-25	1^{st}, 3^{rd}, 4^{th} day	14.3	13.8		
		(3)	Q_3	12.5		2007/12/25-26	daily	13.5	13.4		
B	Run-3	(1)	Q_2	8.3	$10@2^+ + 18@1^+$	2008/1/15-20	daily	11.8	10.8	8	Red
	Run-4	(1)	Q_2	8.3	$10@2^+ + 18@1^+$	2008/1/20-29	daily	12.0	10.3	8	Red
		(2)				2008/1/20-29	daily	12.0	10.3	12	Blue
		(3)				2008/1/20-26	daily	12.0	11.0	14	Black
		(4)				2008/1/26-29	daily	10.3	10.1	14	Black
	Run-5	(1)	-	11.1	$3@2^+ + 5@1^+$	2008/2/27-3/5	-	10.0	9.2	12	Blue
		(2)				2008/2/27-3/7	-	10.0	9.2	14	Black

examine the substrate preference of *P. escinus* individuals and the effects of their behaviours for sediment particle motions by controlling flow conditions and sizes and densities of the fish.

The locations of fish individuals were counted every 15 minutes with the oblique static images of six PC cameras (CMS-V20, Sanwa Supply Co., Ltd.), in order to estimate the fish density on each substrate condition. Whereas the sediment motions were investigated with the following two methods: one was the periodic measurements of trapped sand (bedload discharge) in all units (see Figure 2), the other was the periodic image analysis of coloured sand area (see the setup of Ex. B in Figure 2 and Table 1) with the plane static images of the above-mentioned cameras, for measuring the ratio of moved sand particles on each condition.

2.3 Modelling for bedload transportation

We employed two kinds of modelling for bedload transportation in these experiments. One is the empirical model only for estimating the equilibrium discharges for bedload transport. Hence, in the case of Run-2(3) where the shear stress exceeded the critical condition of fine sand motion, the empirical values for the fine sand discharges were calculated by using the Ashida and Michiue (1972) formula. The other is the probability model developed by Einstein (1942). He applied the probability of picking up sand particles from substratum and the step length of these sand particles in motion for evaluating the discharge of sand transport. The following equation (1) was described by him:

$$q_B = \frac{A_3}{A_2} p_s \Lambda d \tag{1}$$

where q_B means bedload discharge, p_s means the pick-up rate of sand particle from substratum, Λ means the step length of sand particle in motion and d means the diameter of sand particle. If the bedload discharge and the pick-up rate of sand particle are given in the equation (1), the step length of sand particle could be estimated as follows:

$$\Lambda = \lambda d = \frac{A_2 q_{B*}}{A_3 p_{s*}} \cong \frac{3}{2}\frac{q_{B*}}{p_{s*}} \tag{2}$$

where λ means the dimensionless step length of sand particle in motion.

3. RESULTS AND DISCUSSIONS

3.1 Substrate preferences of *Pseudogobio esocinus*

Figure 3 shows the temporal changes in the fish density on each substrate under the “Run-2” condition (see Table 1). The densities on fine substrate were relatively more than the other substrate conditions, even though the flow fields were changed and the fine sand particles were in motion under the Run-2 (3) condition. Although the submerging individuals could not be always counted only from the oblique images, we compensated them by direct observations. Because this tendency was not depended on the number and size distribution of fish individuals, it would be explained that *P. esocinus* preferred fine substrate to coarser substrate. These results are similar to the conventional findings reported by Hirano et al. (1984). They also indicated that the younger individuals occasionally submerged in coarser substrate because they needed more oxygen due to their high metabolic rate and selected relatively permeable conditions. This phenomenon was also observed in our experiment.

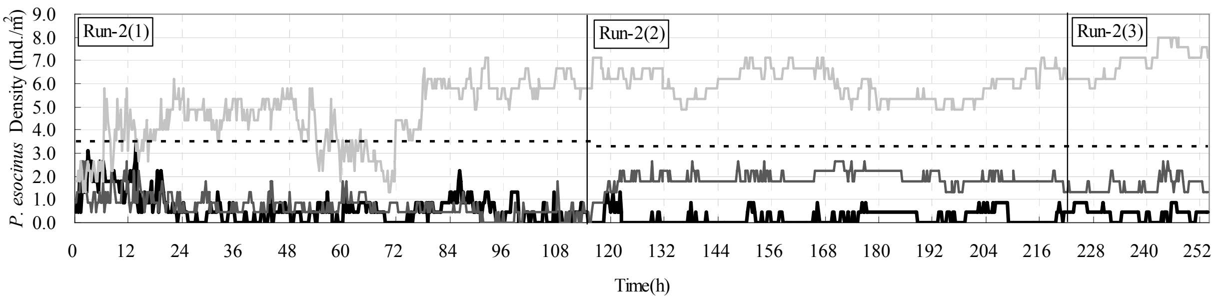

Figure 3 Temporal changes in the fish density on each substrate under the "Run-2" condition. The broken line shows the total averaged density, the reduced shade one shows the averaged density on fine sand substrate, the black one shows that on medium sand substrate and the bold one shows that on coarse sand substrate.

3.2 Physical effects of fish behaviours on bedload transport

Figure 4 shows that the observed bedload discharges influenced by fish behaviours. It was clarified that there was the positive correlation in relationship between the fish density and the bedload discharge. The higher densities increased the chances of digging up sand particles on each substrate, then could have more tractive force, and could accordingly cause the higher bedload discharges especially for fine sand particles. Furthermore, in the case of the Run-2(3) condition, the observed data plotted as black open circles were much higher than the broken line which showed the empirical value of fine sand discharge (Ashida and Michiue 1972). These results confirmed that the physical effects of fish behaviours on bedload transport were not only existed and were but also dependent on the size of sand particles and the fish density.

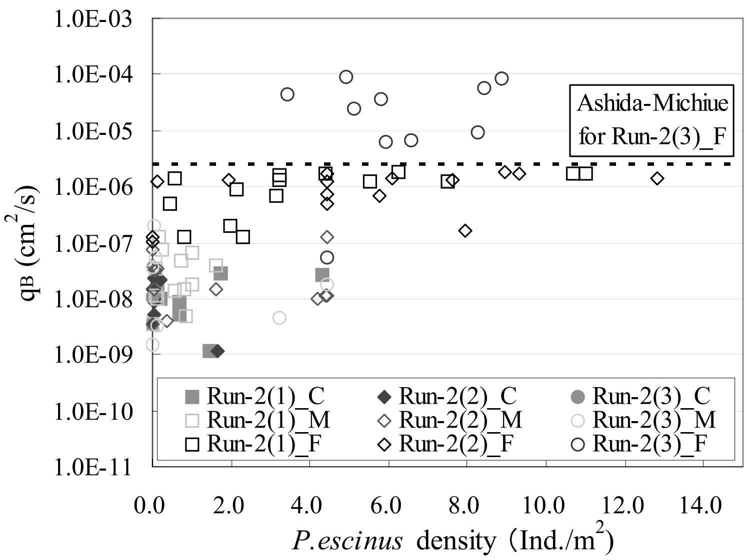

Figure 4 Relationship between the fish density and bedload discharge per unit width. Each plot means the results for the each substrate (C: coarse sand, M: medium sand and F: fine sand) under the "Run-2" condition.

3.3 Estimation of fish effects for sand particle motions

In the Ex. B condition (see Table 1), we observed the coloured area of substrate surface, in order to clarify the motion of fine sand particle due to the fish behaviours. Figure 5 shows that the temporal changes in the coloured area vary according to the number of fish and the substrate colour (red, blue or black). The substrate colour would control the density of fish, because the red substrate conditions were less frequently utilized than the other coloured substrate. Then, according to the Figure 5 relationships, the temporal changes in the ratio of coloured surface area, as it were, the ratio of number of moved sand particles could be estimated as the following differential equation (Eq. (3)) and its integration (Eq. (4)):

$$dA = -p_s A dt \tag{3}$$

$$\frac{A}{A_0} = \exp(-p_s t) \tag{4}$$

where the p_s means the pick-up rate of sand particles in motion (Einstein 1942). Hence, the pick-up rates in our experiment could be evaluated with the gradients of Figure 5. And we also could estimate the step length of these sand particles by using Eq. (2) (in his stochastic modelling for bedload transport) with measured bedload discharges in the Run-3 and -4 cases.

The both of Figure 6 show the relationship between the fish density and the pick-up rate or the step length of sand particles in motion. There was the positive correlation between the fish density and the pick-up rate of sand particles, whereas no correlation between the fish density and their step length. Consequently, these results provided that the presence of fish would control the chance of picking up from substrate surface, whereas would not effect on the step length of moving sand particles. It was suggested that the step length depended on the styles of fish behaviours such as staying, feeding and submerging.

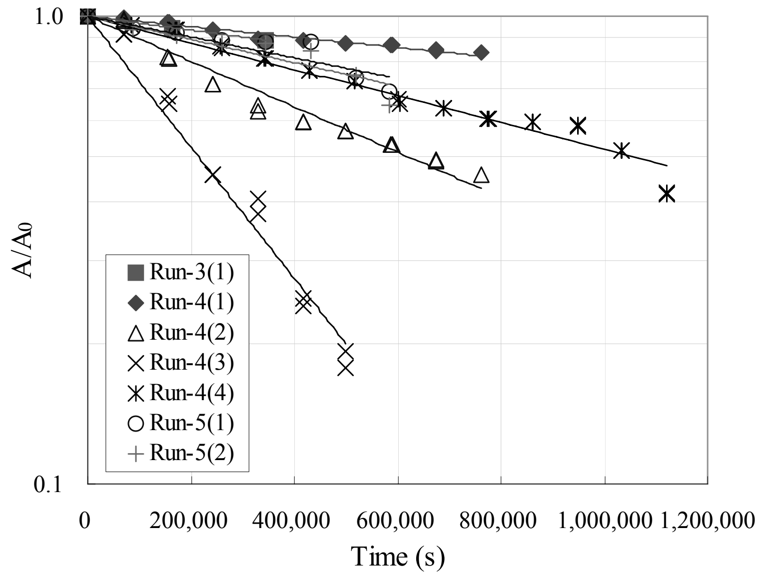

Figure 5 Temporal changes in the coloured sand area of substrate surface due to the fish behaviours. The vertical axis means the ratio of surface coloured area of each moment (A) to that of the initial condition (A_0).

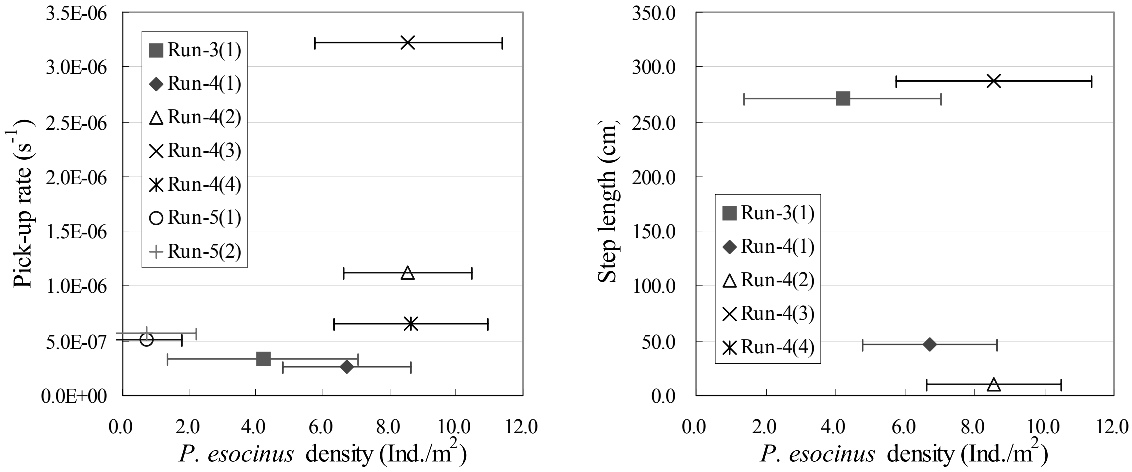

Figure 6 Relationship between the fish density and the pick-up rate (left-hand) / the step length (right-hand) of fine sand particles. Each horizontal plot shows the average of fish density, and the each horizontal error bar shows the standard deviation of fish density during the measuring period of the sand motion.

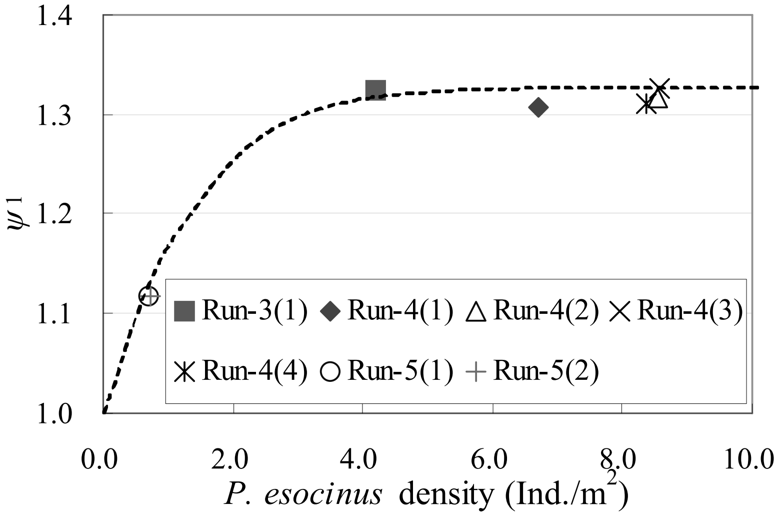

Figure 7 Relationship between the fish density and the increment ratio of dimensionless tractive force (ψ_1) for fine sands.

By the way, the empirical formula to estimate the pick-up rate of sand particles has been developed by Nakagawa and Tsujimoto (1975) as follows:

$$p_{s*} = 0.03\tau_{*e}(1 - 0.7\,\tau_{*c}/\tau_{*e})^3 \tag{5}$$

$$\tau_{*e} = \psi_1\tau_* \tag{6}$$

where ψ_1 means the coefficient of fish effects for the present study.

Therefore, the increment ratios of dimensionless tracitive force due to the fish behaviour could be evaluated by comparing of the observed pick-up rate (in the Run-3 and -4 cases of Ex. B) and the conventional hydraulic formula for the pick-up rates (Eq. (5)). Figure

7 shows the relationship between the fish density and the increment ratio of tractive force. These results confirmed that the population of *P. esocinus* could increase 20-30 % of the dimensionless tractive force with a certain degree of the density.

4. CONCLUSIONS

This study was conducted to examine the bioturbation effects of the *Pseudogobio esocinus* (fish) on bedload transport. By using indoor flume experiment, we conclude that the fish prefer fine sand particles (0.425-0.85mm) as substrate condition, the fish behaviours such as feeding and submerging in substrate have noted effects on bedload transport and the phenomenon of this bioturbation is described with stochastic modelling of sand particle motion. Especially, we clarified that the pick-up rates of sand particles were notably increased by the *P. esocinus* behaviours, and also the dimensionless tractive forces were increased up to 130 % with a certain degree of the density (4.0 inds./m^2).

ACKNOWLEDGMENTS

The Authors are thankful for the critical and the constructive comments given by Dr. Ikuko Morishita (from The Institute of Freshwater Biology), Dr. Shiro Sagawa and Dr. Yuichi Kayaba (which are from Aqua Restoration Research Center, Public Works Research Institute) in designing the field investigation and the laboratory experiment.

This study was performed through Special Coordination Funds for Promoting Science and Technology from the Ministry of Education, Culture, Sports, Science and Technology of the Japanese Government. And it was supported in part by the River Fund in charge of the Foundation of River and Watershed Environment Management (FOREM), Japan.

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