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ABSTRACT

Characteristics of a fish nest and a fish pool installed for conserving fish habitat in an agricultural drainage canal were evaluated in view of flow turbulence and fish energy expenditure. Three-dimensional instantaneous current velocities were observed at fifteen points in the canal seven times. The recorded data were used to compute the time-averaged velocities, turbulent kinetic energy, degree of turbulence, Reynolds shear stresses, and fish energy expenditure. Using the pairwise Mann-Whitney *U*-tests, it can be concluded that the fish nest has greater function of reducing turbulence than the fish pool and the control.

KEY WORDS: Fish nest, Fish pool, Habitat, Canal, Turbulence, Energy, Agriculture.

INTRODUCTION

Small-scale rehabilitation schemes for fish habitat conservation have been introduced to rivers and canals in Japan. In agricultural canals, eco-friendly physical structures like fish nest and fish pool have been installed with projects on modification of drainage, flood control, concrete lining, etc. However, lack of established scientific method for evaluating and designing fish habitat is a serious problem.

Evaluation methods of fish habitat such as IFIM (Instream Flow Incremental Methodology), HEP (Habitat Evaluation Procedure) and HSI (Habitat Suitability Index), etc. (e.g., Tharme, 2003; Yi et al., 2010; Maeda, 2013; Fukuda et al., 2015) could be used to design effective eco-friendly physical structures. These methods usually employed the time-averaged current velocity as a key environmental factors of fish habitat (Lacey et al., 2011), and the effect of turbulent flow on the fish behavior was not taken into account. Therefore, the currently-conducted designs of fish nest and fish pool in agricultural canals in Japan have payed less attention to the effect of flow turbulence on fish rheoreaction.

Recent laboratory experiments have, however, shown that flow turbulence significantly affects the behavior and energetics of fish (Pavlov et al., 2000; Liao, 2007; Enders et al., 2009). Influence of turbulence on fish behavior have been studied in the experimental channels, fishways, and spillways (e.g., Pavlov et al., 2000; Enders et al., 2009; Lupandin, 2005; Smith et al., 2005; Tritico and Cotel, 2010; Santos et al., 2014; Silva et al., 2012, 2015). Pavlov et al. (2000) revealed based on their successive studies that alternations in the turbulence intensity of flow cause significant changes in fish rheoreaction: in the threshold, cruise and maximum swimming speed, as well as in their swimming capacity. Silva et al. (2012) have provided insights on barbell swimming behavioral responses to turbulence by three submerged orifice arrangements in an experimental pool-type fishway. Reynolds shear stress appeared as one of the most important turbulence descriptors explaining fish transit time in the experiments.

This study aims at evaluating effectiveness of a fish nest and a fish pool installed in an agricultural drainage canal in Ibaraki Prefecture, Japan, using the equation of fish energy expenditure presented in Pavlov et al. (2000) and turbulent descriptors. Turbulent kinetic energy, degree of turbulence (or turbulent intensity), Reynolds shear stresses were estimated with data on instantaneous current velocities in the fish nest and fish pool. Water bodies in the target canal were categorized into five regions including control. Observed data in the corresponding five groups were supplied for statistical analysis to examine significant difference among the regions.

METHOD

Study Area

The study area is a pair of sections of agricultural drainage canal located in Ibaraki Prefecture, Japan. The canal conveys water issuing from paddy fields surrounding the canal to the Takahashi River which is one of the influent rivers of Lake Kasumigaura. In the downstream rehabilitated canal section, named 'Section 1', six artificial fish nests were installed by the local government as cavities on the sidewalls of the canal made by concrete in 2002 (see Fig. 1). The fish pool was also created by uniformly lowering the canal bed by 0.7m in Section 1, where fish can survive in the pool under extremely low discharge conditions in the canal. Section 1 is 3.9km upstream of the mouth of the Takahashi River. In contrast to Section 1, a control canal section without artificial fish nests and pool is selected, which is called 'Section 2'. Since Section 2 is located about 100m upstream of Section 1, hydraulic impact from the rehabilitation scheme in the downstream of Section 2 is negligible. These two canal sections have rectangular cross-sections in general, and the sidewalls are made by concrete.

Fig. 2 shows the side view of A-A' cross section indicated in Fig. 1. Sand settled on the canal bed within the fish nests because of rapid decrease of current velocity caused by the expansion of cross-sectional area in Section 1.

The bed of the fish pool consisted of artificially scattered gravel and sediment on them. Therefore its canal bed elevation was highly variable. In contrast, the canal bed of Section 2 had little sediment due to fast flow.

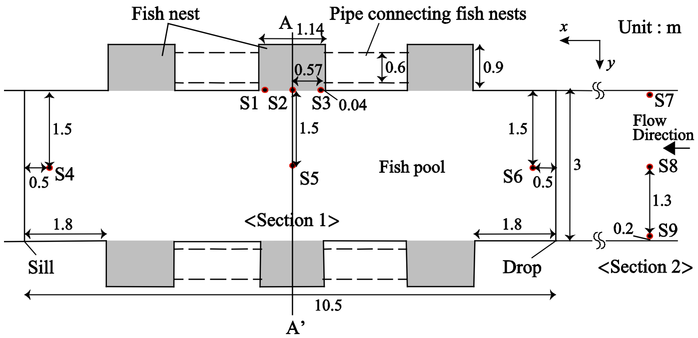

Fig. 1 Locations of fish nests, fish pool, and nine monitoring spots in Sections 1 and 2 (plane view)

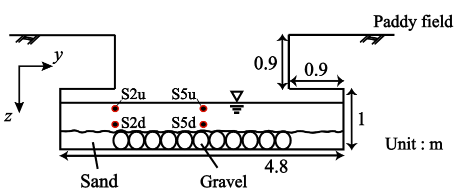

Fig. 2 Transversal A-A' cross section of the canal shown in Fig. 1 and vertical arrangements of upper and lower monitoring points at S2 and S5, (S2u, S2d) and (S5u, S5d)

Field Observations

Hydraulic observations were carried out seven times on the dates in 2014 and 2015. These were all sunny or cloudy days. Since the canal sections were surrounded by paddy fields, the stream was affected by agricultural practices in the fields. As shown in Fig. 1, nine and three monitoring spots S1-S6 and S7-S9 were set in Sections 1 and 2, respectively, for observing instantaneous current velocity and water depth for the seven days. The three-directional current velocities were measured at a frequency of 80Hz for a sampling period of 30 seconds at each monitoring point by electromagnetic current meter VP3500 (Kenek). The x component of the reference axis was lengthwise along the canal, the y component across the width of the canal and the z component the water depth (see Figs. 1 and 2).

Current velocities changed vertically even in the same monitoring spot. The vertical locations of some monitoring points depended on the local water depth at the spots. In order to monitor vertical difference in current velocity at S1-S6, points of 80% (i.e., near the canal bed, called "lower point" hereafter) and 20% (i.e., near the water surface, called "upper point" hereafter) of the local water depth from the water surface were chosen. Since water depth in Section 2 is shallow, points of 60% of the depth from the surface were selected at S7-S9 for the measurements. Locations of monitoring spots and points are depicted in Figs. 1 and 2.

The monitoring points were categorized into five groups, G1-G5. The groups G1 and G2 corresponded to upper and lower regions of fish nest, respectively, represented by the observed data at upper and lower points at spots S1-S3. The groups G3 and G4 were associated with upper and lower regions of fish pool, respectively, expressed by the observed data at upper and lower points at spots S4-S6. The remained group, G5, was the control related to spots S7-S9. The recorded data at the points were used to compute the turbulence descriptors and the energy expenditure defined below.

Turbulence Descriptors and Fish Energy Expenditure

The observed i-th instantaneous current velocity component $(i = 1, 2, \ldots, N)$ in the Cartesian coordinate (x, y, z), $\tilde{u}_i, \tilde{v}_i, \tilde{w}_i$, in space can be expressed as

$$\tilde{u}_i = U + u_i,\ \tilde{v}_i = V + v_i,\ \tilde{w}_i = W + w_i \tag{1}$$

where U, V, W = x, y, z components of time-averaged current velocity vector, respectively; u_i, v_i, w_i = fluctuating x, y, z components of i-th turbulent velocity vector, respectively; and N = number of recorded samples on instantaneous current velocity. Then turbulent kinetic energy (Silva et al, 2012) is computed by

$$\text{TKE} = \frac{1}{2}\left(\overline{u^2} + \overline{v^2} + \overline{w^2}\right) \tag{2}$$

where the term with over bar in Eq. 2 denotes the time-average of the related fluctuating variable.
The degree of turbulence (Pavlov et al., 2000), or often called as turbulent intensity, K, can be written as

$$K = \frac{\sigma}{V_0} \tag{3}$$

where σ = magnitude of pulsation standard vector, or standard deviation of instantaneous current velocity; and V_0 = magnitude of time-averaged current velocity. Since the degree of turbulence is the ratio of pulsation standard to time-averaged current velocity, it is useful in comparing spatial difference in magnitude of turbulence among the observation points.
Reynolds shear stresses, τ_{xy}, τ_{yz} and τ_{xz}, are defined for the plane of xy, xz and yz, respectively as

$$\tau_{xy} = -\rho\overline{uv},\quad \tau_{yz} = -\rho\overline{vw},\ \tau_{xz} = -\rho\overline{uw} \tag{4}$$

where ρ = water density; and u, v, w = fluctuating x, y, z components of turbulent velocity vector, respectively. The absolute values of the shear stresses reflect magnitude of velocity variation to a certain axis direction.
The energy spent by fish to overcome the water resistance in the turbulent flow in the canal can be mathematically expressed as (Pavlov et al., 2000)

$$\text{EE} = \frac{C\rho S V_0^3 T}{2}(1 + 3K^2) \quad (5)$$

where C = coefficient of drag force; S = projected area of the target fish to the time-averaged flow direction; and T = time. The energy expenditure, EE, at a point can be used as a measure for evaluating the value of the point as a fish habitat, because it is certain that the less energy expenditure (swimming cost) is, the more desirable it is for the fish. It is noteworthy that degree of turbulence, K, is appearing in Eq. 5 as well as the time-averaged water velocity, V_0, so that the turbulence-induced swimming costs can be quantified with this equation. In this study, by assuming the body shape of fish is slender, the drag coefficient, C, is estimated with diameter of the projected area (assumed a circle) of fish body and Reynolds number based on the fish total length (Azuma, 1993). A target coarse fish was gobiid *Tridentiger brevispinis* whose total length was 0.063m and body height was 0.01m captured in Section 1 on 22 May 2014.

The recorded data at the monitoring points were used to compute the time-averaged velocities, Reynolds number based on the total length of the fish, K, TKE, Reynolds shear stresses, and EE for 30 seconds. Using SPSS Statistics Ver. 22 (IBM), pairwise Mann-Whitney U-tests were conducted between the groups in G1-G5 to identify significant differences at the significance level $p < 0.05$ in each hydraulic variable mentioned above estimated with the 21 (= 3 spots × 7 days) samples.

RESULTS AND DISCUSSION

Observed stream discharge and water depth in the monitoring spots in the seven days ranged from 0.16 to 0.31 m^3/s and 0.13 to 0.54 m, respectively. Box-plots of the representative variables evaluated based on the observed data in the five groups are shown in Figs. 3-8. Larger current velocity and shear stresses are observed in the fish pool (G3 and G4) and the control (G5) (Figs. 3, 6,7).

It was found that V_0, TKE, $|\tau_{xy}|$, $|\tau_{xz}|$, and EE in the fish nest (G1 and G2) were all significantly smaller than those in G5. Additionally, the U-tests indicated no significant difference in EE and the turbulent descriptors between G1 and G2. Although K in the fish nest was larger than that in the control, EE in Fig. 8 in the fish nest was smaller due to the much influence of V_0 on EE compared with K. The median value of EE decreased from 0.027 J in G5 to 0.00030 J in G1 and 0.00010 J in G2. Therefore, it can be judged that the fish nest produced less turbulent regions in the agricultural canal successfully.

It was also illustrated that V_0 and EE in the fish pool were significantly reduced by comparing with those in G5. Thus, the fish pool were found effective to lessen the turbulence described with respect to those parameters. In contrast, no significant differences were detected in TKE, $|\tau_{xz}|$, and $|\tau_{xy}|$ between G4 and G5. This implies that the overall turbulent condition in the fish pool is fairly similar to that in the control section, compared with the fish nest. Larger vertical change of x-directional current velocity in the lower region of the fish pool, G4, shown in Fig. 7 is probably due to large roughness at the sites.

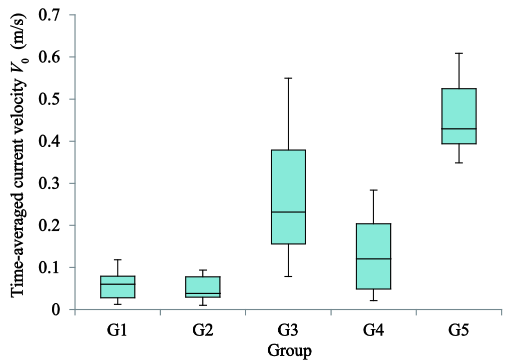

Fig. 3 Box plot of time-averaged current velocity

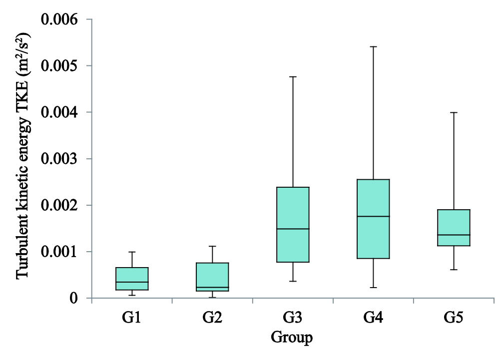

Fig. 4 Box plot of turbulent kinetic energy

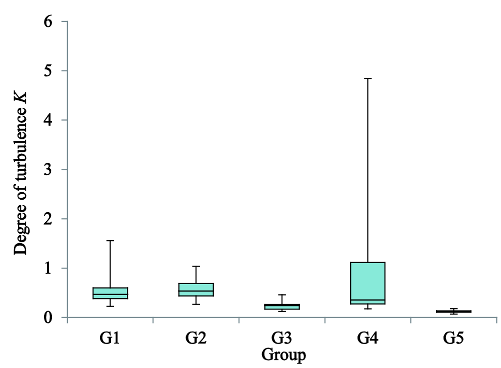

Fig. 5Box plot of degree of turbulence

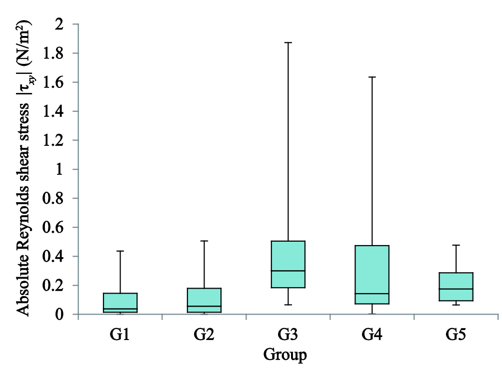

Fig. 6 Box plot of absolute Reynolds shear stress $|\tau_{xy}|$

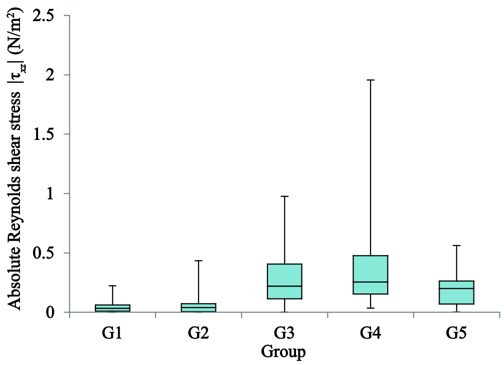

Fig. 7 Box plot of absolute Reynolds shear stress $|\tau_{xz}|$

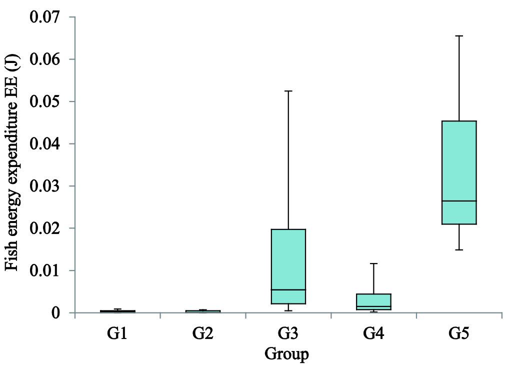

Fig. 8 Box plot of estimated fish energy expenditure

CONCLUSIONS

Both the fish nest and the fish pool have created flow regions with low fish energy expenditure in the agricultural drainage canal of interest. The fish nest provided less turbulent water regions than the fish pool in terms of lowered shear stresses and fish energy expenditure. From an ecohydraulic viewpoint, therefore, it could be concluded that introduction of fish nest to agricultural canals is more effective than fish pool for fish habitat conservation. Habitat selection by fish also depends on water quality, size-dependent choice of prey, and physiological state, such as hunger, of fish. Further research should, therefore, be conducted to evaluate effectiveness of fish nests and pools more comprehensively from various scientific viewpoints.

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