Ascent Behaviors of Nine-spined Sticklebacks in Orifices and on Overflow Weirs of Fishways

Kei Yamashita¹, Mitsunori Nakano², Shunsuke Chono³, Yoichi Fujihara⁴ and Eiji Ichion⁵

Abstract: Experiments on the ascent behaviors of nine-spined sticklebacks (Pungitius sp. 1) were conducted in a submerged orifice weir and on an overflow weir in an experimental flume. The ascent behaviors of the fish were identified using a high-speed camera to measure the ground speeds and ascent routes of sticklebacks. The flow velocities in and around the orifice and on and around the overflow weir were measured using a three-dimensional velocity meter and particle tracking velocimetry. Stickleback swimming speed in the ascent route was calculated based on ground speeds and flow velocities. In the experiments with the orifice weir, most sticklebacks passed the middle area of the orifice, where flow velocity was relatively slow. Conversely, in the experiments with the overflow weir, most sticklebacks passed over the weir, where flow velocity was relatively fast. In the experiments with the orifice and with the overflow weir, the swimming speeds of sticklebacks were 8–39 and 9–21 times their body lengths, respectively. The results indicate that many sticklebacks ascend in areas where flow velocities were faster than their burst speed, which is defined as 10 times their body lengths.

Keywords: High-speed camera; Submerged orifice; Overflow weir; Nine-spined stickleback; Burst speed

1 Introduction
There are 5,000–10,000 fishways in Japan, 90% of which are pool-type fishways comprising weirs and pools (Nakamura, 1995). Pool-type fishways have varying physical structures and some (e.g., ice harbor type fishway) have orifices in their weirs. An orifice is usually made for removing sediments accumulated in the pool and for the operation and maintenance of the fishway (MAFF, 2002). Izumi et al. (2003, 2006) reported that fish preferentially pass through weirs orifices to ascend the weirs.

Normal fish cruising speed is 2–3 body lengths per second (BL/s) and burst speed is approximately 10 BL/s (Tsukamoto and Kajiwara, 1973). The burst speeds of many species of freshwater fish have been identified (e.g., Izumi et al., 2009; Onitsuka et al., 2009). Knowledge of the cruising and burst speeds of conservation-target fish species is important for designing and constructing fishways. Normally, flow velocities in fishways are restricted to below the burst speed of target species (MAFF, 2002). However, Izumi et al. (2002) reported that Plecoglossus altivelis and Tribolodon hakonensis ascend fishway weirs faster than their burst speeds.

The nine-spined stickleback (Pungitius sp. 1) is a freshwater fish species classified as Gasterosteidae (Hosoya, 2013). Adult fish of this species are maximum 5–6 cm in body length (Miyagi et al., 1976). In Ishikawa Prefecture, the populations of this species have decreased, mainly because of the loss of spring water, concrete linings of agricultural ditches, degradation of water quality, and intercept of water connectivity (Hirai, 1992). This species was therefore assigned to the list of critically endangered species and rare wild species in Ishikawa Prefecture (Ishikawa Prefecture, 2014a; 2014b).

Fishways are used to maintain aquatic connectivity for fish migration. Setting fishways in agricultural ditches is important for the conservation of sticklebacks because agricultural ditches are the main habitat of sticklebacks in Japan today. However, it is unclear whether sticklebacks can ascend existing fishways. Moreover, the most suitable fishway design for sticklebacks has not been determined. In this study, we assessed the ascent of sticklebacks using a flume to identify the ascent speeds and routes of sticklebacks and to provide basic data for the design of fishways for this species.

2 Materials and methods
2.1 Experimental setup
An interior experimental flume in Ishikawa Prefectural University was used for our experiments. The width of the flume is 0.5 m. The two types of weirs (with orifice no overflow and without orifice overflow) were used (Figure 1). In the experiments of the orifice weir, water did not overflow the weir and passed through the orifice. In the experiments of the overflow weir, all water overflowed the weir. The weir with the orifice (orifice weir) was made using a plywood measuring 0.50 m wide, 0.50 m high, and 24 mm thick. The orifice was square with sides of 0.10 m. The orifice was made in the lower left of the weir to enable us to capture movies of the stickleback swimming. The overflow weir with no orifice (overflow weir) was made using the same plywood as the

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¹Company Staff, Hiro Photo Co., Ltd., 1st Floor, Chugin Mitaka Mansion, 4-16-8 Simorenjyaku Mitaka-ku, Tokyo 181-0013, Japan
²Research Assistant, Faculty of Bioresources and Environmental Sciences, Ishikawa Prefectural University, 1-308 Suematsu Nonoichi, Ishikawa 921-8836, Japan
³Lecturer, Faculty of Bioresources and Environmental Sciences, Ishikawa Prefectural University, 1-308 Suematsu Nonoichi, Ishikawa 921-8836, Japan
⁴Associate Professor, Faculty of Bioresources and Environmental Sciences, Ishikawa Prefectural University, 1-308 Suematsu Nonoichi, Ishikawa 921-8836, Japan
⁵Professor, Faculty of Bioresources and Environmental Sciences, Ishikawa Prefectural University, 1-308 Suematsu Nonoichi, Ishikawa 921-8836, Japan (Corresponding Author) E-mail: ichion@ishikawa-pu.ac.jp
orifice weir. The overflow weir was 0.50 m wide and 0.30 m high. Silicon was inserted in the spaces between the weir and the flume to prevent water leak. Partition nets were set 0.98 m upstream and downstream from the weir. The nets were 0.50 m wide, 0.30 m high and 24 mm thick. Two video cameras (Himawari GE60, Library Co., Ltd., 1000BASE-T, Gigabit Ethernet) were set around the flume (Figure 1). These cameras recorded the movies in the orifice weir or on the overflow weir during ascent experiments. The movies were recorded in AVI format.

2.2 Fish ascent experiment
The fish ascent experiments were conducted in 2010, 2011 (for the orifice weir), and 2012 (for the overflow weir). Four differences in water depth between the upstream and downstream areas of the weirs were set (0.02 m, 0.05 m, 0.07 m, and 0.10 m). The water depth in the upstream area of weir, that in the downstream area, and the difference of them hereinafter referred to as $H_1$, $H_0$, and $\Delta h$, respectively. Fish-ascent experiments were conducted using each level of $\Delta h$.

Ten to thirty sticklebacks were used for each experiment (Table 1). Their $BL$ was 2.4–6.7 cm. Sticklebacks used in our experiments were captured in agricultural ditches in Shikamachi, Hakui-gun, Ishikawa Prefecture, Japan (37°0 N, 136°4 E). The sticklebacks were preserved in a water tank. The larvae of Chironomidae were used for food for the sticklebacks in the tank. The preservation time of sticklebacks in the tank was restricted to be within 5 days. When the experiment started (9:00 a.m.), sticklebacks were released in the area between the weir and the downstream net. The ascent behaviors of sticklebacks were recorded using the video cameras. Sticklebacks that ascended the weir and reached the upstream area of the weir were captured using a hand net, and their body lengths were measured. Sticklebacks that ascended once were not re-used for other experiments. The experiments were finished when all sticklebacks had ascended or when 6 hours had passed (3:00 p.m.). Any sticklebacks that did not ascend the weir were captured and their body lengths were measured.

Water temperature ($T$), pH, electric conductivity (EC), dissolved oxygen concentration (DO), $H_1$, $H_0$, and flow velocity were measured. Water temperature, pH, EC, and DO were measured immediately after each experiment. A Thermo 1050 thermometer (IC Co., Ltd.) was used to measure water temperature, a pH meter (HORIBA Co., Ltd., Twin pH B-212) to measure pH, an EC meter (HORIBA Co., Ltd., Twin Cond B-173) to measure EC, a DO meter (HORIBA Co., Ltd., OM-51-2) to measure DO.

In the orifice weir, a three-dimensional velocity meter (KENEK Co., Ltd., VP-3000 and VPT-3-200-13P) was used to measure flow velocity in the orifice. The analytical region (Figure 2) was divided into cubic regions measuring 2.5 cm on each side. The flow velocities at the center of the cubic regions were measured for 10 seconds and averaged. In the overflow weir, the flow velocities above the weir were measured using a bead because we could not measure the flow velocity above weir with a velocity meter. The bead (polyethylene, specific gravity: 1.03) was flowed and the motion was recorded using the video camera. We calculated flow velocity using the movie. For the velocity measurement in and around the orifice weir, the analytical region was divided into cubic regions measuring 2.5 cm on each side. The average speed of the bead in each cube region was defined as the flow velocity in the water on weir.

![Figure 1: Schematic illustration of orifice and overflow weirs](image-url)
Table 1: Numbers and body lengths of fish used for experiments

| No. | Date      | Δh (cm) | Type of Weir | Number of fish | Mean BL (cm) |
|-----|-----------|---------|--------------|----------------|--------------|
| 1   | 2010/10/27| 2       | Orifice      | 10             | 3.2          |
| 2   | 2010/10/19| 5       | Orifice      | 10             | 3.0          |
| 3   | 2010/10/11| 7       | Orifice      | 10             | 2.7          |
| 4   | 2010/10/26| 10      | Orifice      | 10             | 3.3          |
| 5   | 2011/11/16| 2       | Orifice      | 25             | 3.5          |
| 6   | 2011/11/17| 5       | Orifice      | 26             | 3.7          |
| 7   | 2011/11/23| 7       | Orifice      | 24             | 3.8          |
| 8   | 2011/11/25| 10      | Orifice      | 30             | 4.0          |
| 9   | 2012/11/19| 2       | Overflow     | 26             | 3.9          |
| 10  | 2012/11/20| 5       | Overflow     | 27             | 4.0          |
| 11  | 2012/12/5 | 7       | Overflow     | 26             | 4.2          |
| 12  | 2012/12/6 | 10      | Overflow     | 28             | 4.1          |

2.3 Movie analyses of fish-ascent behavior

The movies were recorded using two video cameras connected with the computer on which CaptureEX (Library Co., Ltd.) was installed. The movies were then analyzed using both Move-Tr/2D and Move-Tr/3D (Library Co., Ltd.). We compared an already-known fixed point and the position of sticklebacks and calculated the positional coordinates \((x, y, z)\) and ground speeds \((V_g \_x, V_g \_y, V_g \_z)\) of sticklebacks every 1/30th of a second.

The ascent behavior of sticklebacks in the orifice weir was defined as the behavior from the time when the head of a stickleback entered an orifice to the time when the caudal fin passed through the orifice. In the overflow weir, the ascent behavior was defined as the behavior from the time when the head of a stickleback entered the 2.5-cm-downstream area from the weir to the time when the caudal fin passed through the weir. We identified the ascent speeds of sticklebacks according the above definitions. Ascent speed \((V)\) was calculated from the ground speed of stickleback \((V_g)\) and flow velocity \((v)\) in the ascent route every 1/30th of a second as follows.

\[
V_x = V_g - v_x \\
V_y = V_g - v_y \\
V_z = V_g - v_z \\
|V| = \sqrt{V_x^2 + V_y^2 + V_z^2} \\
|v| = \sqrt{v_x^2 + v_y^2 + v_z^2}
\]

Finally, average flow velocity \((\bar{v})\) and average swimming speed \((\bar{V})\) were computed by averaging all the above \(v\)s and \(V\)s in the ascent route, respectively. Then \(\bar{V}/BL\) were computed for all ascent behaviors.

3 Results and discussion

3.1 Physical and chemical conditions

\(H_0, H_1, \Delta h, T, \text{pH}, \text{EC}, \text{and DO}\) are shown in Table 2. In the orifice weir, \(T\) was 14.6–23.5°C, \(\text{pH}\) was 7.5–8.9, \(\text{EC}\) was 0.24–0.32 mS/cm, and \(\text{DO}\) was 6.2–8.1 mg/L. In the overflow weir, \(T\) was 12.1–15.2°C, \(\text{pH}\) was 8.6–8.9, \(\text{EC}\) was 0.22–0.26 mS/cm, and \(\text{DO}\) was 9.7–10.6 mg/L.

Table 2: Physical and chemical conditions during ascent experiments

| No. | \(H_0\) (cm) | \(H_1\) (cm) | Δh (cm) | \(T\) (℃) | pH  | EC  (mS/cm) | DO  (mg/L) |
|-----|-------------|-------------|---------|-----------|-----|-------------|-------------|
| 1   | 26.5        | 28.5        | 2.0     | 19.1      | 7.6 | 0.27        | 6.5         |
| 2   | 27.3        | 32.3        | 5.0     | 22.5      | 7.8 | 0.24        | 6.2         |
| 3   | 27.8        | 34.8        | 7.0     | 23.5      | 7.5 | 0.25        | 6.6         |
| 4   | 28.2        | 38.2        | 10.0    | 20.8      | 8.1 | 0.26        | 7.1         |
| 5   | 27.0        | 29.0        | 2.0     | 16.1      | 8.9 | 0.32        | 8.0         |
| 6   | 27.7        | 32.7        | 5.0     | 16.1      | 8.6 | 0.32        | 8.1         |
| 7   | 28.5        | 35.5        | 7.0     | 14.9      | 8.7 | 0.29        | 7.9         |
| 8   | 28.9        | 38.9        | 10.0    | 14.6      | 8.5 | 0.29        | 7.8         |
| 9   | 30.0        | 32.0        | 2.0     | 14.7      | 8.8 | 0.25        | 9.7         |
| 10  | 28.3        | 33.3        | 5.0     | 15.2      | 8.8 | 0.26        | 10.6        |
| 11  | 27.0        | 34.0        | 7.0     | 13.0      | 8.9 | 0.22        | 9.8         |
| 12  | 24.5        | 34.5        | 10.0    | 12.1      | 8.6 | 0.26        | 9.9         |

3.2 Fish ascent rate

The ascent rates and the mean body lengths of ascent and non-ascent fish are shown in Table 3. The ascent rates in the orifice weir in 2010 and 2011 were 30–100% and 20–60%, respectively; those in the overflow weir in 2012 were 0–42%. The ascent rate tended to be smaller as \(\Delta h\) was larger. The ascent rates in the orifice weir were larger than in the overflow weir. In almost all experiments, the average body length of ascent fish was larger than non-ascent fish.
Table 3: Ascent rates and mean body lengths of ascent and non-ascent fish

| No. | Δh (cm) | Type of Weir | Ascent rate (%) | Mean body length (cm) |
|-----|---------|--------------|-----------------|-----------------------|
| 1   | 2       | Orifice      | 100             | 3.2                   |
| 2   | 5       | Orifice      | 80              | 3.0                   |
| 3   | 7       | Orifice      | 40              | 2.9                   |
| 4   | 10      | Orifice      | 60              | 3.8                   |
| 5   | 2       | Orifice      | 60              | 3.0                   |
| 6   | 5       | Orifice      | 27              | 4.0                   |
| 7   | 7       | Orifice      | 25              | 4.2                   |
| 8   | 10      | Orifice      | 20              | 4.6                   |
| 9   | 2       | Overflow     | 42              | 3.7                   |
| 10  | 5       | Overflow     | 19              | 4.4                   |
| 11  | 7       | Overflow     | 0               | 4.4                   |
| 12  | 10      | Overflow     | 0               | 4.2                   |

3.3 Fish ascent speed

In the orifice weir, ascent time (t) was 0.07–1.40 s, $V_f$ was 0.20–1.03 m/s, $V_a$ was 0.24–1.14 m/s, and $V_a/BL$ was 7.80–38.95. Average $t$ was highest when $\Delta h$ was 10 cm. In the overflow weir, $t$ was 0.67–2.44 s, $V_f$ was 0.15–0.63 m/s, $V_a$ was 0.35–0.89 m/s, and $V_a/BL$ was 8.62–21.11. Average $t$ was highest when $\Delta h$ was 5 cm.

The relationship between $\Delta h$ and $V_a$ is shown in Figure 3. In both the orifice and overflow weirs, average $V_a$ was larger as $\Delta h$ increased. In the orifice weir, $V_a$ varied greatly in each $\Delta h$. However, in the overflow weir, $V_a$ varied slightly in each $\Delta h$.

The relationship between $BL$ and $V_a$, is shown in Figure 4. In the orifice weir, there was no correlation between $BL$ and $V_a$. In the overflow weir, although $R^2$ is 0.2909, the correlation between $BL$ and $V_a$ is uncertain because the $V_a$ of the data is concentrated around 0.40 m/s and 0.80 m/s. The lower scatter diagram in Figure 4 shows that only sticklebacks with body lengths over 4 cm ascended at a speed over 0.8 m/s.

Figure 3: Relationship between $\Delta h$ and $V_a$

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Figure 4: Relationship between $BL$ and $V_a$
was relatively fast and that of the marginal area was relatively slow (Figure 7). Sticklebacks with a slow $V_a$ passed through the marginal areas of the orifice. However, in the overflow weir, the ranges of $V_a$ for each $\Delta h$ were relatively small. This indicated that all the sticklebacks had almost the same $V_a$ when they ascended the overflow weir with the same $\Delta h$. This may be because that the overflow velocities above weirs were almost constant and relatively fast and all sticklebacks were forced to ascended in areas with high flow velocities.

Figure 5: Relationship between $V_f$ and $V_a$

Figure 6: Relationship between $BL$ and $V_a/BL$

Figure 7: Flow velocity distribution and swimming routes of fish in orifice
In the orifice weir, $V_o$ increased gradually and the difference of $V_o$ among $\Delta h$ was relatively small. However, in the overflow weir, $V_o$ increased greatly and differed to a relatively large degree among different $\Delta h$ values. Therefore, the orifice weir was determined to be more suitable for the ascent of sticklebacks than the overflow weir because the orifice provided a variety of flow velocities. In both the orifice and overflow weirs, sticklebacks ascended in response to $V_f$. This result is consistent with that of Izumi et al. (2006), who reported that fish burst speeds depended on flow velocity. Additionally, our results indicated that $V_o/BL$ was larger as $BL$ was smaller in the orifice weir. This tendency obviously appeared when $V_f$ was large.

The average $BL$ of the sticklebacks that ascended weirs was larger than that of sticklebacks that did not (Table 3). This suggests that the swimming ability of sticklebacks increased as the $BL$ increased. However, $V_o/BL$ was larger as $BL$ was smaller. This indicates that small sticklebacks could ascend at a similar speed as large sticklebacks for a short time.

### 3.4 Flow velocity and ascent route

The flow velocity distributions in the orifice and ascent routes of sticklebacks are shown in Figure 7. The flow velocities in the orifice varied: the flow velocity in the middle of the orifice was relatively fast and that of the marginal area was slow. When $\Delta h$ was 2 cm, sticklebacks passed through the center of the orifice. When $\Delta h$ was 5 and 7 cm, most sticklebacks passed in the area from the middle to the right (flume center) side of orifice. When $\Delta h$ was 10 cm, all sticklebacks passed through the area from the middle to the right side of orifice.

The flow velocity around overflow weir is shown in Figure 8. The flow velocity was highest where water fell into the downstream water surface after passing the weir and was lowest in the downstream area of the weir. The flow velocity was relatively low in upstream area of the weir and faster near the weir. From the flow velocity distribution in Figure 8, it is assumed that the flow regime was plunging flow (Rajaratnam et al., 1988) in both cases of $\Delta h=2$cm and 5cm. The ascent routes of sticklebacks in the overflow weir are shown in Figure 9. Sticklebacks swam around the bottom of the flume and approached the weir. Then, they swam parallel to the weir wall and passed through the overflow area. No sticklebacks ascended by jumping in the air.

In the orifice weir, the ascent behaviors of sticklebacks were classified into two types (A and B). The type A ascent was observed when sticklebacks swam from the immediately downstream in front of the orifice and passed it. The area in front of the orifice had a relatively high flow velocities. The type B ascent was observed when sticklebacks swam from the right (flume center) side and passed it. The area of the right (flume center) side had a relatively low flow velocity and the type B sticklebacks could ascend from this area. When $\Delta h$ was 10 cm, all sticklebacks used the type B ascent. Because the flow velocity in the orifice is not uniform and there was an area in which the flow velocity is low, it is thought that even the sticklebacks with low swimming ability could ascend through the orifice.
Contrary to the orifice weir, the ascent behavior of sticklebacks was simple in the overflow weir. Onitsuka et al. (2003) reported that *Opsariichthys platypus* jumped to ascend fishways when the overflow velocity exceeded the burst speed of this species. It is expected that fish can ascend the weir by jumping above the overflow where flow velocity is relatively high. Because all the sticklebacks used in our experiments did not jump, only the sticklebacks with higher swimming ability might be able to ascend the weir. Therefore, the orifice is more suitable for the ascent of sticklebacks than the overflow weir because sticklebacks normally have small bodies and low swimming ability.

4 Conclusion

We identified the ascent speeds and routes of sticklebacks when they ascended the orifice and the overflow weir using three-dimensional motion picture analysis. The results of our study indicated the following.

1. In the orifice weir, sticklebacks ascended with 0.24–1.07 m/s swimming speeds when $\Delta h$ was 2 cm; 0.33–1.13 m/s when $\Delta h$ was 5 cm; 0.32–1.14 m/s when $\Delta h$ was 7 cm; 0.50–1.09 m/s when $\Delta h$ was 10 cm. In the overflow weir, sticklebacks ascended with 0.35–0.47 m/s swimming speeds when $\Delta h$ was 2 cm and 0.78–0.89 m/s when $\Delta h$ was 5 cm. The ascent speeds for each $\Delta h$ of the orifice weir varied more greatly than for the overflow weir.

2. $V_o/BL$ was 7.80–38.95 in the orifice weir and 8.62–21.11 in the overflow weir. More than 80% of all sticklebacks ascended the weir at a swimming speed above 10 BL/s. In addition, $V_o/BL$ increased as $BL$ decreased.

3. $V_o$ was positively correlated with $V_f$ in both the orifice and overflow weirs.

4. In the orifice weir, most sticklebacks approached orifice from the right (flume center) side and passed in the area between the middle to the right (flume center) side of the flume where the flow velocities were relatively low. In the overflow weir, all sticklebacks swam vertically parallel to the weir wall and approached the overflow area where flow velocity was high and passed through it. No sticklebacks jumped when they ascended the overflow weir. The orifice is therefore more suitable for the ascent of sticklebacks because sticklebacks normally have small $BL$s and low swimming abilities.

5. Fishes in general have burst speeds equivalent to 10 $BL$/s and the burst speed is defined as the speed at which fish can swim for 1–5 seconds. However, sticklebacks swam at speeds more than 10 times their $BL$s and their ascent times were shorter than 1–5 seconds. Our results suggest that sticklebacks can ascend above their burst speeds if their ascent times are very short.

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References

[1] Hirai, K. (1992): Reduction of habitats of fresh-water fishes in Tetori fan, Ishikawa Prefecture, *Japan Sea Research Report*, 24, pp.49-62, (in Japanese).

[2] Hosoya, K. (2013): Fishes of Japan with pictorial keys to the species third edition. Tokai University Press, Japan, pp.606-607, (in Japanese).

[3] Ishikawa Prefecture (2014a): Red data book of Ishikawa Prefecture. https://www.pref-ishikawa.lg.jp/sizen/reddata/index.html, (in Japanese), (accessed 2019-12-31).

[4] Ishikawa Prefecture (2014b): Rare wild animal and plant species of Ishikawa Prefecture. https://www.pref-ishikawa.lg.jp/sizen/srdb/index.html, (in Japanese), (accessed 2019-12-31).

[5] Izumi, M., Takaya, D., Kudo, A., and Azuma, N. (2002): The ascending characteristics of fishes in the wall of ice-harbor type fishway of Akaishi –The number 2 headworks on the Akaishi River–, *Trans. of JSIDRE*, 70, pp.55-63, (in Japanese with English abstract).

[6] Izumi, M., Takaya, D., Kudo, A., and Azuma, N. (2003): Ascending route of fishes at a wall in ice-harbor type fishway of the Akaishi number 2 head-works, *Annual Journal of Hydraulic Engineering*, JSCE, 47, pp.763-768, (in Japanese with English abstract).

[7] Izumi, M., Ito, R., Yataya, K., and Azuma, N. (2006): Ascending fishes and hydraulic characteristics of the full-cross-sectional overflow stepped-pool type fishway in the Iwaki river diversion weir of the Iwaki River, *Trans. JSIDRE*, 74, pp.55-64, (in Japanese with English abstract).

[8] Izumi, M., Yamamoto, Y., Yataya, K., and Kamiyama, K. (2009): Burst speed of wild fishes under high-velocity flow conditions using stamina tunnel with natural guidance system in river, *Trans. JSIDRE*, 261, pp.73-82, (in Japanese with English abstract).

[9] MAFF (2002): Design guide of fishway in river headwork for better design, *The Japanese Society of Irrigation, Drainage and Rural Engineering*, Tokyo, p.184, (in Japanese).

[10] Miyaji, D., Kawanabe, H., and Mizuno, N. (1976): Colored illustration of the freshwater fishes of Japan. Hoikusha, Osaka, p.462, (in Japanese).

[11] Nakamura, S. (1995): Tales of fishway (Gyodou no hanashi). Sankaido publishing Co.,Ltd., Tokyo, p.225, (in Japanese).

[12] Onitsuka, K., Akiyama, J., and Yamaguti, H. (2003): Relationship between behaviors of jumping migration of Zakko platypus and hydraulic characteristics in pool-and-weir fishway, *Journal of Applied Mechanics*, 6, pp.983-990, (in Japanese with English abstract).

[13] Onitsuka, K., Akiyama, J., Yamamoto, A., Watanabe, T., and Waki, T. (2009): Study on burst speed of several fishes living in rivers, *Doboku Gakki Ronbunshuu B*, 63, pp.108-119, (in Japanese with English abstract).

[14] Rajaratnam, N., Katopodis, C. and Mainali, A. (1988): Plunging and streaming flows in pool and weir fishways, *ASCE Journal of Hydraulic Engineering*, *Suisan Doboku Gakkai Ronbunshuu B*, 74, pp.983-990, (in Japanese with English abstract).

[15] Tsukamoto, K., and Kajiwara, T. (1973): Swimming speed and ability of fish, *Suisan Doboku* 10, pp. 31-36, (in Japanese).

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