FIELD EXPERIMENT ON THE CRITICAL SWIMMING SPEED OF NATURAL FINGERLING SWEETFISH \((\text{Plecoglossus altivelis altivelis})\) DURING THE INITIAL PERIOD OF UPSTREAM RIVER MIGRATION

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The authors intend to clarify the swimming ability of the natural sweetfish \((\text{Plecoglossus altivelis altivelis})\) fingerlings during the initial period of its upstream river migration in the field. The critical swimming speed (CSS) of the natural sweetfish was measured in a small channel with a rectangular cross section under an average cross-sectional water flow velocity of 9 – 75 cm/s. The body length of the natural sweetfish fingerlings ranged from 5.9 cm to 9.9 cm (the mean body length was 7.5 cm, and the number of fishes was 50). The following results were obtained: (1) The CSS, measured for a duration of 60 min, ranged from 19 to 61 cm/s, and a positive correlation was observed between the CSS and the body length. A regression formula between the 60-min CSS and body length was obtained. (2) The ratio of the CSS and the body length was 3.1 – 8.0 (that is, the distance travelled per second based on the body length), and the mean ratio of the CSS and the body length was 4.7 times (the standard deviation was 1.1).

KeyWords : sweetfish (\text{Plecoglossus altivelis altivelis}), swimming ability, critical swimming speed, fishway

1. INTRODUCTION

Conservation of river habitat has become an important issue in Japan, particularly the habitats of diadromous fish species, such as the ayu sweetfish \((\text{Plecoglossus altivelis altivelis})\) and the masu salmon \((\text{Oncorhyncus masou masou})\), which must swim upstream in rivers to sustain Japan’s fishery resources. Cross-river structures, such as weirs and headworks, which are installed to enable water intake from the river, are provided with fishways that are hydrologically designed according to the swimming ability of the target fish species.

Cruising speed indicates the swimming capacity of fishes and is used to estimate the flow velocity at which they can rest in the fishway.\(^1\) It is defined as the maximum speed at which the fish can swim continuously for 60 min.\(^2\) Additionally, it is a useful index for preserving and maintaining the fish habitat in rivers. The cruising speed of fish inhabiting rivers has been studied by Brett et al.,\(^3\) Bainbridge,\(^4\) Tsukamoto and Kajiwara,\(^5\) and Suzuki.\(^6\) Although the cruising speed is proportional to (approximately 2 – 3 times) the standard body length (hereinafter “body length”),\(^7\) it may be greater depending on the fish species.\(^8\) Moreover, although it is known to be influ-
enced by water temperature, no clear differences in cruising speed have been reported for water temperatures above 11°C.5)

While designing the fishways for diadromous fish species, it is important to consider smaller fish species with lesser swimming ability.7) Therefore, in this study, we focused on a particular diadromous fish species (the pre-adult natural sweetfish (hereinafter referred to as “fingerling sweetfish”)) during the initial period of its upstream migration. The ayu sweetfish is an amphidromous fish from the salmon family with a body length of 7–8 cm during its upstream river migration period, which occurs between March and July (March to May in southern Japan and May to July in northern Japan).8) As noted, regional differences were observed during the upstream migration period of the sweetfish. To increase the number of fingerling sweetfish in rivers, it is necessary to increase the survival and growth of the populations that are migrating upstream, and therefore, guidelines have been provided for the release of artificial hatchlings to supplement the natural fish population.9)

The literature on the cruising speed of fingerling sweetfish includes a study conducted in a circular channel by Tsukamoto et al.9) In addition, experiments by Tsukamoto et al.10), aimed at increasing the effectiveness of the release of artificial hatchlings (provided by the National Federation of Inlandwater Fisheries Cooperatives) that were carried out at water temperatures ranging from 15.5 to 21.2°C; at documented cruising speeds of 5 to 15 cm/s and 50 to 70 cm/s at total lengths of 40 mm and 70 mm, respectively. Meanwhile, differences in the swimming capabilities of artificial hatchlings versus natural fingerling sweetfish were reported.12) It has also been reported that natural fingerling sweetfish exhibits regional genetic characteristics.9) Therefore, from the perspective of designing fishways and protecting the river’s fish habitat, we thought it would be beneficial to supplement previous findings by elucidating (from a scientific point of view) the cruising speed of natural fingerling sweetfish during their upstream migration period based on differences in regional characteristics for the development of future river habitats.

Brett13) defines the “critical swimming speed” (hereinafter, “CSS”) as a measure of the maximum sustained swimming speed over an extended period of time. In one experiment, the CSS was determined by gradually incrementing the flow velocity every 60 min until a point when the fish could no longer withstand the flow and were swept away by the current. Therefore, in this study, under the assumption that the CSS is the upper limit of the cruising speed, we decided to treat it as the cruising speed.14), 15)

Recent fish swimming experiments, such as those by Izumi et al.16), have adopted an experimental method that considers the natural motivation of the fish to swim by allowing the fish collected from the river to swim in on-site condition rather than under laboratory conditions. Following these examples, we conducted the swimming experiments on-site for the purpose of identifying the relationship between the body length and CSS of fingerling sweetfish during their initial period of the upstream migration and providing further corroboration regarding previous findings.

2. MATERIALS AND METHODS

(1) Fish used in experiments

We used fingerling sweetfish for conducting the experiment. It was collected from Ashino headworks, a weir located at 11 km from the mouth of the Iwaki River (a class A river in Aomori Prefecture). Fingerling sweetfish begin their upstream river migration from the downstream of this headworks during early May each year. Because the fingerling sweetfish required delicate handling, the migrating fish that had to be tested were collected immediately before starting each experiment. A total of 50 fingerling sweetfish were measured during the experiment (minimum and maximum body length 5.9–9.9 cm, mean body length 7.5 cm, standard deviation 0.8 cm) (Fig.1, Table 1). Each of the fish was subjected to not more than one swimming test.

(2) Time and place of the experiment and the equipment used

The swimming experiment was conducted on the left bank of the lower reaches of the Iwaki River at Ashino headworks. The experiment was conducted for a total of 15 times during mornings and afternoons in early- and mid-May in 2017 and 2018, (Table 1). The weather was clear or cloudy on the days of the experiment with an average water temperature between 10.6 and 18.0°C (Table 1).

A photograph and a schematic view of the experimental setup are depicted in Fig.2 and Fig.3, respectively. The experimental setup consisted of a manometer-equipped water tank with a spillway and rectifier (35 cm wide, 55 cm long, and 30 cm high) and a small
rectangular water channel made of clear acrylic (15 cm wide, 100 cm long, and 15 cm high) was installed along with a pedestal on a trestle assembled by scaffolding pipes (Fig.2). The gradient of the water channel was 1/90.

At the upstream end of the water channel, five transparent acrylic rectifier boards (0.2 cm thick and 3.0 cm long) were mounted vertically across the channel at regular intervals of 2.5 cm. At the terminal end of the water channel, a tilting gate was installed for adjusting the water depth. A partition net ([1]) of mesh size 5–7 mm was placed at the upstream end of the water channel. At the downstream end, a builder provided a constant supply of fresh river water to the water tank from the river by an underwater water channel. The water used for the experiment was supplied to the water tank from the river by an underwater water channel. At the downstream end, a builder provided a constant supply of fresh river water to the water tank from the river by an underwater water channel. At the downstream end, a builder provided a constant supply of fresh river water to the water tank from the river by an underwater water channel. At the downstream end, a builder provided a constant supply of fresh river water to the water tank from the river by an underwater water channel. At the downstream end, a builder provided a constant supply of fresh river water to the water tank from the river by an underwater water channel. (3) Methods and items tested

a) Swimming experiments

The flow velocity was set in the range of approximately 10–60 cm/s; the underwater pump supply, water tank level, and tilting gate were adjusted to produce a steady flow during the experiment. The average depth of the water in the swimming section was set to approximately 6–10 cm (a value more than twice the height of the fish), such that the fingerling sweetfish could swim without impediment.17)

For each experiment, a two-axis electromagnetic flow meter (ACM 250) with a sensor, of diameter of 5 mm was installed in the swimming section to monitor the flow velocity in the water channel. The test fish were placed into the swimming section with water flowing at a speed of approximately 10 cm/s, and they were allowed to accerate for several minutes. Then, the downstream tilting gate and the pump supply were adjusted to set the initial average cross-sec-

| Date & Ex. No. | Individual No. | Sample BL (cm) | Average flow velocity at the swimming stage (V_m)(cm/s) | Average T (°C) |
|---------------|----------------|--------------|------------------------------------------------------|--------------|
| 5/7/2017 Ind.1-1 | 6.5 | 33 | 39 | 10.6 |
| 5/8/2017 Ind.2-1 | 8.7 | 29 | 40 | 45 | 49* | 12.3 |
| Run.3 | Ind.3-1 | 6.9 | 28 | 37 | 46 | 50* |
| Run.4 | Ind.4-1 | 6.1 | 27 | 36 | 49* |
| Run.5 | Ind.5-1 | 7.4 | 25 | 34 | 43 | (49)** |
| Run.6 | Ind.6-1 | 7.2 | 22 | 42 | 16.0 |
| Run.7 | Ind.7-1 | 6.3 | 9 | 19 | 34 | 51 |
| Run.8 | Ind.8-1 | 6.3 | 14 | 29 | 36 | 17.2 |
| Run.9 | Ind.9-1 | 7.6 | 20 | 32 | 46 | 52 |
| Run.10 | Ind.10-1 | 7.5 | 28 | 41 | 13.7 |
| Run.11 | Ind.11-1 | 7.9 | 30 | 46 | 14.1 |
| Run.12 | Ind.12-1 | 7.2 | 28 | 49 | 12.5 |
| Run.13 | Ind.13-1 | 7.7 | 24 | 34 | 14.1 |
| Run.14 | Ind.14-1 | 7.6 | 21 | 33 | 39 | 47 |
| Run.15 | Ind.15-1 | 7.3 | 25 | 35 | 44 |
| * : Using Gate, ** : Cross sectional average flow velocity at [1]
during each swimming phase until the point of exhaustion when the test fish could no longer swim continuously and were swept away by the current. This point of exhaustion was defined as the point at which the fish were flushed from the downstream slits. In the first two experiments, run 1 and run 2, only one individual fish was tested. However, because we intended to increase the number of measurements per experiment, we attempted to conduct a preliminary experiment with multiple fish (approximately 5). The introduction of multiple fish did not affect the swimming behavior of the individual fish and therefore, we decided to use multiple fish in each experiment starting with run 3.

We positioned digital video cameras at the top and left bank side of the water channel to capture and record the swimming behavior and positions of the fish in the swimming section during each swimming stage. To measure the \( V_m \) during each swimming phase, we used the volumetric method to measure the flow velocity at the water discharge point at the end of the experimental apparatus (using the average value of the five measurements per run, excluding the maximum and minimum values). The \( V_m \) of the swimming section was obtained by dividing the measured flow velocity by the average water depth of the swimming section. Once the test fish were discharged from the swimming section, they were collected at the downstream of the tilting gate and their body lengths were measured. The \( V_m \) of the first swimming stage was 10 to 30 cm/s, and this value was then incremented by approximately 10 cm/s during each subsequent swimming stage. The * mark in Table 1 indicates the time when the insertion of the movable gate at point (B) caused an underflow downstream of the gate. In these cases, the \( V_m \) was obtained from the depth of the swimming position of the test fish.

b) Flow velocity measurements

To gain a better understanding of the flow velocities in the section where the test fish swam, we reproduced the hydraulic conditions of each swimming experiment in a laboratory (separately from the on-site swimming experiment), and then investigated the distribution of the cross-sectional flow velocities. We obtained the measurements using a small propeller flow meter (VO4100) with a diameter of 5 mm. The flow velocity measurement points were concentrated near the side walls and bottom of the water channel at three different transverse cross-sections of the swimming section (upstream, central, and downstream). We performed measurements at nine transverse-direction points and seven depth-direction points for a total of 63 measurement points.

(4) Method for calculating the critical swimming speed (CSS)

The 60-min CSS (\( V_{60\text{CSS}} \)) was calculated with respect to equation (1).\(^{13} \) Here, \( V_{\text{max}60} \) is the maximum flow velocity at which the fish were able to swim for 60 min; \( V_{\text{max}} \), which is greater than \( V_{\text{max}60} \), was the flow velocity at which the fish were swept away by the current before completing the experiment; \( T \) is the time (in seconds) at which the fish were swept away at the \( V_{\text{max}} \) flow velocity.

\[
60\text{-min CSS} = V_{\text{max}60} + (V_{\text{max}} - V_{\text{max}60}) \times T / 3,600 \tag{1}
\]

To calculate the CSS as shown in equation (1), we used the measurements of the flow velocity \( V \) (hereinafter referred to as the “representative flow velocity”) obtained with the small propeller flow meter after observing the swimming behavior (the method of calculating \( V \) is described later).

3. RESULTS and DISCUSSION

(1) Calculation of the representative flow velocity (\( V \)) during the swimming stage

Based on the behavioral observations of the test fish in the swimming section, the fingerling sweetfish were able to swim freely in the swimming section at
a $V_m$ of approximately 20 cm/s. When $V_m$ became faster than approximately 30 cm/s, there were cases of fish swimming near the bottom of the water channel (approximately 4 cm from the bottom) with their heads oriented upstream. During those times, the fish would align themselves vertically or horizontally, sometimes changing positions at arbitrary points. This swimming behavior was also observed in the critical swimming experiments with fingerling masu salmon (*Oncorhynchus masou masou*).15)

Because the fingerling sweetfish occasionally swam at the constriction point that was generated immediately downstream of the upstream partition net, we recorded the $V_m$ at the constriction point during those times (indicated by the ** in Table 1). An example of the shape of the water surface in this case is depicted in Fig.4. The swimming position of a fingerling sweetfish at the constriction point is depicted as point [1] in Fig.4. The shape of the water surface created by using the gate at swimming stage 5 of run 9 ($V_m=75$ cm/s) is depicted as point [2] in Fig.4. In this case, the fingerling sweetfish swam at an underflow position [2] downstream from the gate before being discharged after 11 s. In run 3 in Table 1, individual 3-2 was discharged during the third stage after 4 s of swimming. Immediately afterwards, the gate was inserted to increase the flow velocity in the fourth stage while individuals 3-3 and 3-4 continued swimming. In the second stage of run 6, individuals 6-2 and 6-3 were discharged similar to that of individual 7-3 in the 4th stage of run 7 after 3600 s.

An example of the constant velocity lines obtained from the flow velocity measurements is depicted in Fig.5. The figure was generated at a $V_m$ of 43 cm/s in the 3rd stage of run 5. It can be seen from Fig.5 that the flow velocities near the bottom, side walls, and corners of the water channel are slower than that in the middle of the flow area.

Therefore, while calculating the representative flow velocity $V$ of the fish used for calculating the CSS, we considered the average of the flow velocity values observed at the measuring points in the main swimming area during each swimming stage, rather than those at all the measuring points. In the cases where the test fish were swimming at the constriction point, we calculated the average flow velocity in the swimming area using the ratio of the $V_m$ in each experiment to the average velocity in the area where the fish were swimming.

As listed in Table 1, the $V_m$ at each swimming stage ranged from 9 to 75 cm/s. The representative flow velocity $V$ ranged from 9 to 67 cm/s (Table 2).

### (2) Critical swimming speed (CSS)

Table 2 summarizes the results of the swimming experiments on 50 fingerling sweetfish. The experiment numbers correspond to the experiment numbers in Table 1. Because the CSS is known to be influenced by water temperature, the water temperature at each swimming stage is also listed in Table 2. The number of swimming stages ranges from 2 to 5, and the average water temperature ranges from 10.6 to 18.5°C. The relationship between the $V_{60CSS}$ and body length; the average water temperature of each experiment divided into 1°C units; the swimming speed, which can be approximated as 3 times that of the body length are all depicted in Fig.6.

The $V_{60CSS}$ of the fingerling sweetfish tested in this experiment was between 19 and 61 cm/s. Although examination of the relationship between the $V_{60CSS}$ and the body length in Fig.6 shows individual variation, a positive correlation was observed in general. We obtained the regression formula $V_{60CSS} = 2.95$ BL + 12.74 (BL: body length, $R = 0.27$, $p = 0.055$). The correlation between CSS and average body length, with body lengths divided into classes of 1 cm is depicted in Fig.7. The standard error varies depending on the body length class; however, a positive correlation was observed, thus resulting in an experimental formula of $V_{60CSS} = 3.1$ BL + 9.9 (BL: body length, $R = 0.90$, $p < 0.05$). The CSS can also be expressed as a multiple of the body length (BL: cm). When the $V_{60CSS}$ is expressed as $V_{60CSS}$/BL, the speed ranges from 3.1 to 8.0 BL/s. At an average body length of 7.5 cm, $V_{60CSS}$/BL is 4.7 BL/s (standard deviation 1.1). The speed is therefore, greater than three times the
body length. An experiment by Suzuki [5] showed no clear difference in the endurance swimming speed (equivalent to cruising speed) of freshwater fish at water temperatures of 11°C or higher. As shown in Fig. 6, the water temperatures in our experiments were approximately 11 to 19°C, with no obvious variation in CSS due to changes in water temperature. This is consistent with previous findings regarding the effects of water temperature, which seems to have had little effect on the V₆₀CSS in this experiment.

We compared the natural sweetfish with a body length of 6 cm in this experiment to data on released artificial hatchlings. [11] The experiment on the artificial hatchlings used measurements of total length rather than body length. The relationship between total length and body length could be expressed as BL ≈ 0.92 TL (TL = total length). [3] We converted the data from Tsukamoto et al., from total length to body length and added it to Fig. 6. As shown in Fig. 6, the natural sweetfish of this experiment had a lower CSS than the artificial hatchlings. In another study, the cruising speed of sweetfish with an average total length of 6.6 cm (6.1 cm in body length) was reported to be 40 cm/s. [10] These experiments were conducted in different environments (some indoor and others outdoor), and we used different experimental setups, so that it is impossible to draw clear conclusions. However, it has been reported that natural sweetfish have lower sustained swimming capacity than artificial hatchlings owing to their smaller red muscles. [12]

Considering that the upstream river migration period begins not long after entering the river from the sea, the influence of the physiological differences in fish bodies is conceivable.

Meanwhile, swimming ability was found to vary depending on the fish species irrespective of the similarity of the swimming type and body length. [4] [18] There have been reports of cruising speeds of 5.1 BL/s for sockeye salmon (Oncorhynchus nerka nerka) with a body length of 6.9 cm [3] and 5.5 BL/s for fingerling masu salmon from artificial hatchlings with an average body length of 5.7 cm. [15] For the natural fingerling sweetfish of this experiment, the average body length was 7.4 cm, and the CSS was approximately 4.7 times the body length. These results were similar to those in the studies on the sockeye salmon [3] and fingerling masu salmon [13] mentioned above.

Based on these results, we are now in a position to estimate the flow velocity at which the fish can rest. This parameter could be used for preserving and maintaining the river habitat and for designing fishways that must be installed in the downstream where natural fingerling sweetfish begin their upstream migration in the Tohoku region of Japan. The V₆₀CSS is

### Table 2 Raw data of water temperature, representative flow velocity and swimming time, and calculation of 60-min CSS.

| Ex. No. | Swimming Stage | 60-min CSS |
|---------|----------------|------------|
| Ind.1   | Ave.1 | Temp.(°C) | 10.6 | 10.6 |
|         | Ave.2 | F(cm/s)   | 33    | 37 |
| Run.1   | Ave.3 | F(cm/s)   | 11.5  | 12.2 |
|         | Ave.4 | F(cm/s)   | 30    | 38 |
| Ind.2-1 | Ave.5 | F(cm/s)   | 3,600 | 3,600 |
|         | Ave.6 | F(cm/s)   | 30    | 42 |
| Ind.3-1 | Ave.7 | F(cm/s)   | 3,600 | 3,600 |
|         | Ave.8 | F(cm/s)   | 30    | 47 |
| Ind.4-1 | Ave.9 | F(cm/s)   | 3,600 | 3,600 |
|         | Ave.10| F(cm/s)   | 30    | 53 |

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Fig.6 Relation between the critical swimming speed (CSS) and the body length at each water temperature.

Fig.7 Relation between the average critical swimming speed (CSS) and the average body length of each class.

an indicator that represents a threshold value for the design of fishways. As a guideline, based on the empirical formula shown in Fig.6, the resting environment flow velocity for natural fingerling sweetfish with a body length of 6.0 to 9.0 cm should be set below 30 to 40 cm/s.

4. SUMMARY

To contribute toward the better design of fishways and conservation of river habitats, we investigated the CSS of a small diadromous fish species, specifically the natural fingerling sweetfish, by conducting swimming experiments in a small rectangular water channel erected on-site at the bank of the Iwaki river where the fish were collected. Consequently, we were able to obtain the following findings with respect to the 60-min critical swimming speed ($V_{60\text{CSS}}$) of the fingerling sweetfish.

1) The $V_{60\text{CSS}}$ at an average body length of 7.5 cm (5.9–9.9 cm, 50 individuals) measured at river water temperatures of 10.6–18.5 °C was between 19 and 61 cm/s. There was a significant positive relationship between the $V_{60\text{CSS}}$ and the body length, and a regression formula was obtained. The cruising speed of the natural fingerling sweetfish with a body length of 6 cm in this experiment was approximately 32 cm/s, which was slower than the data released on artificial hatchlings in previous experiments.

2) The velocity ($V_{60\text{CSS}}/BL$) expressed as the ratio of the 60-min CSS to the body length ratio ranged from 3.1 to 8.0 BL/s, with an average of 4.7 BL/s (standard deviation 1.1). The velocity expressed as $V_{60\text{CSS}}/BL$ was similar to the data obtained for different fish species, including fingerling masu salmon and fingerling coho salmon.

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