Factors that Affect Arctic Lampeys’ Ascent Behavior on Fishway Weirs

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Abstract: We conducted laboratory experiments to clarify the weir designs suitable for Arctic lamprey (Lethenteron japonicum) ascent. Ascent experiments were conducted using three weir types (sharp-crested, inclined sharp-crested and broad-crested). The difference in water depth upstream and downstream of the weir and time period (daytime and night) were changed to determine their effects on ascent behavior. Our results indicated that the difference in water depth negatively and strongly affected ascent behavior and the weir type did not affect ascent behavior. No lamprey ascended the all types of fishway-weir when Δh was 24 cm. The inclined sharp-crested weir had a 45° incline upstream. However, it did not contribute to their ascent and gentler slope than 45° may be better for suitable weir design. The broad-crested weir served the attachment place for lamprey to suck by their mouth and was expected to be suitable for inherent ability of lamprey ascent. However, the ascent rate on the broad-crested weir was not better than the other two types. Additionally, video camera analysis revealed that lampreys attempted ascents more during the night than daytime. Our experiment result revealed unknown Arctic lamprey ascent behavior and can contribute to the conservation and modification in freshwater ecosystem.

Keywords: Arctic lampreys; Migration; Weir: Fishway; Conservation

1 Introduction

Lampeys are the most primitive group of vertebrates, with a suckermouth lacking jaws (Yamazaki and Goto, 2000). They are classified as Agnatha and have anadromous migration life cycle. During the larval period, their eyes are hidden under the skin and they have a funnel-shaped mouth. Arctic lamprey (Lethenteron japonicum) larvae burrow and stay in sediment of fine particles and organic matter in freshwater (Shirakawa et al., 2009; Arakawa and Yanai, 2017). The larval period lasts two to five years (Kataoka, 1985). The larvae feed on detritus and organic matter in sediment (Moore and Mallatt, 1980; Sutton and Bowen, 1994). The larvae metamorphose during autumn and winter. They then go to sea during May and June of the next year. Adult lampreys parasitize fishes including Osmeriformes, Clupeiformes and Trachiniformes in the sea and suck the blood of these fishes (Shink et al., 2019).

L. japonicum migrate across shallow-depth areas (less than 100 m deep) from the Sea of Japan to the northwestern Bering Sea (Potter and Hilliard, 1987; Orlov et al., 2014; Siwicke and Seitz, 2017). They migrate in the sea for about three years. Then, they ascend rivers from the late summer to the early spring. They overwinter near spawning areas (midstream) in the river. They spawn in spring and die after spawning.

Two genera and five species of lampreys, including L. japonicum, are distributed in Japan (Hubbs and Potter, 1971; Yamazaki and Goto, 2000). The population sizes and distribution ranges of these species have dramatically decreased mainly because of artificial disturbances (Renault, 1997). L. japonicum has been selected as a vulnerable species (that is, VU) by the Ministry of the Environment because of the rapid decrease of population size and distribution. L. japonicum has abundant fat and vitamins. Thus, this species has been used for fishery harvests (Murano et al., 2008, Arakawa and Yanai, 2018). However, the harvest is in danger of disappearance because of the rapid decrease of lamprey populations (Murano et al., 2008).

The main reasons causing the decrease of lampreys are (i) concrete-lining the shores of rivers (Sugiyama and Goto, 2002; Smith et al., 2011), (ii) artificial structures such as dams in rivers (Moser et al., 2002; Keefer et al., 2012) and (iii) degradation of water quality (Myllynen et al., 1997). Especially, artificial structure is critical because it restricts lampreys’ spawning area and habitat (Mateus et al., 2012).

Many dams have been constructed along the Columbia River. The fishways built next to the dams are designed for ascending salmon. Most Entosphenus tridentatus cannot ascend the fishways (Moser et al., 2002). In fishway with low efficiency of ascent rate by lamprey, it needs to design lamprey-specific passage structures additionally (Moser et al., 2006). Therefore, fishways suitable for E. tridentatus ascents have also been constructed (Moser et al., 2011; Pacific Lamprey Technical Workgroup, 2017). Similarly, fishways suitable L. japonicum ascents should be constructed in Japanese rivers. To design fishway accommodating passage by diverse fish communities, there is need to evaluate species-specific fish performance and behavior systematically (Keefer et al., 2010). However, the information on the ascent ability of L. japonicum is limited and the optimal design of fishways has not been identified.

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This study conducted laboratory experiment to identify the optimal fishway design and environmental conditions suitable for *L. japonicum* ascents.

2 Materials and methods

Three types of fishway-weirs were used in our study: (1) sharp-crested weir, (2) inclined sharp-crested weir, and (3) broad-crested weir (Figure 1). All weirs were 0.5 m wide and 0.3 m in perpendicular height. The inclined sharp-crested weir had a 45° incline upstream. All weirs were made using 24-mm-thick plywood. The uppers edges of the sharp-crested and inclined sharp-crested weirs had a 24-mm-radius curve. The broad-crested weir had a 10-cm horizontal region on the upper edge, a 100-mm-radius curve in the middle and a 20-cm vertical region at the lower end. All weirs and the bottom of flume were painted black using a synthetic resin paint (Kanpe Hapio Co., Ltd.) for us to see the lampreys’ ascent behavior. A net wall was set at 1 m upstream from the weir to prevent fish escaping. A net trap was set at 1 m downstream from the weir to catch the fish that ascended the weir.

Five lampreys with a standard length of 400–460 mm were used for the first experiment in 2015. These lampreys were captured using fish hooks in Omou, Yanagida, Noto-cho, Ishikawa Prefecture, in the middle reach of the Machino River. The lampreys were stocked in a water tank at 11–15°C for 2–3 weeks. Subsequently, they were used for the ascent experiments.

For the second experiment in 2017, five lampreys measuring 450–490 mm standard length were used. These lampreys were captured using a basket-shape net in Mogami River in Yamagata Prefecture. These lampreys were stocked in a water tank at the same temperature as the experimental temperature for 1 week. They were then used for the ascent experiments.

The ascent experiments are shown in Table 1. The three weir types were used. The difference in water depth upstream and downstream of the weir (Δh) was set at three different levels (11, 18 and 24 cm). The ascent experiments were conducted separately for daytime (9:00–17:00, for 8 hours) and night (19:00–5:00, for 10 hours). The lampreys were put in the downstream pool of the weir when the experiment started (9:00 or 19:00). Flow volume was constant at 5.3 L/s through all experiments. Critical water depth (hc) was calculated from the flow volume (Q: 5.3 L/s), width of weir (B: 0.5 m) and gravity acceleration (g: 9.8 m/s²). Critical velocity (Vc) at the overflow section of all weirs was calculated at 0.47 m/s as follows,

\[
h_c = \frac{3Q^2}{\sqrt{gB^2}} \quad (1)
\]

\[
V_c = \frac{Q}{h_cB} \quad (2)
\]

| No. | Experiment | Weir type           | Δh (cm) | Time period | Date    |
|-----|------------|---------------------|---------|-------------|---------|
| 1   | 1st        | sharp-crested       | 11      | Daytime     | 2015/4/26|
| 2   | 1st        | Night               |         |             | 2015/4/25|
| 3   | 2nd        | 18                  | Daytime | 2017/5/3    |
| 4   | 2nd        | Night               |         | 2017/5/4    |
| 5   | 1st        | 24                  | Daytime | 2015/4/27   |
| 6   | 1st        | Night               |         | 2015/4/26   |
| 7   | 1st        | inclined sharp-crested | 11    | Daytime     | 2015/4/23|
| 8   | 1st        | Night               |         | 2015/4/23   |
| 9   | 2nd        | 18                  | Daytime | 2017/5/8    |
| 10  | 2nd        | Night               |         | 2017/5/9    |
| 11  | 1st        | 24                  | Daytime | 2015/4/22   |
| 12  | 1st        | Night               |         | 2015/4/22   |
| 13  | 2nd        | broad-crested       | 11      | Daytime     | 2017/5/5  |
| 14  | 2nd        | Night               |         | 2017/5/5    |
| 15  | 2nd        | 18                  | Daytime | 2017/5/6    |
| 16  | 2nd        | Night               |         | 2017/5/6    |
| 17  | 2nd        | 24                  | Daytime | 2017/5/7    |
| 18  | 2nd        | Night               |         | 2017/5/7    |
The burst speed of *L. japonicum* has not been measured. However, Kemp *et al.*, (2011) reported that European river lamprey (*Lampetra fluviatilis*) classified in the same family to *L. japonicum* did not pass the weir when maximum velocities were as high as 1.66 m/s. In this experiment, it was presumed that the critical velocities of the weirs were lower than the burst speed of *L. japonicum*.

Lampreys’ ascent behavior was recorded using video camera. In the daytime experiments, HD video camera (Sony Co.,Ltd. type: HDR-GW66V) was used. The movie was recorded continuously for 8 hours. In the night experiments, interval movies were taken using a night-vision camera (BMC Software Inc., type: SG560P-8M) for 30 seconds per 15-minute interval, or using the other camera (CAMS Co. Ltd., type: LTL-5210B) for 60 seconds per 5-minute interval. Later, moves were extracted for 30 seconds per 15-minute interval. Then, the lampreys’ ascent behaviors were analyzed using these movies. Ascent challenge behavior was defined as the behavior when the lamprey’s head was thrust from the water surface toward the overflow area on weir. Successful ascent behavior was recorded when a lamprey went through the weir and non-successful ascent behavior when a lamprey failed to go through the weir. The frequency of ascent challenge behavior was calculated by summing the numbers of successful and non-successful ascent behavior. The successful ascent rate (%) was calculated as the frequency of successful ascent behavior divided by the frequency of ascent challenge behavior.

Water depths upstream and downstream of the weir, water temperature, dissolved oxygen level (DO), pH, and electric conductivity (EC) were measured when each experiment started and finished. Illumination was measured in 2-hour intervals only in the daytime experiments. Water depth was measured using a steel scale. Water temperature was measured using a digital thermometer (SATO KEIRYOKI MFG. Co. Ltd., type: SK-1260 with SK-S102T sensor), Portable meters (OM-51-2, Twin pH B-712, and Twin Cond B-173, HORIBA, Ltd.) were used to measure DO, pH, and EC. Discharge in the flume was measured using a point gauge when each experiment started and finished.

Regression analysis was conducted using a generalized linear mixed model to estimate the most suitable weir-shape and time period for lamprey ascents. A matrix comprising the numbers of successful and non-successful ascending individuals was used as a response variable. This matrix was made using R-software’s cbind-function according to Kubo (2012). The error distribution of the objective variable was assumed as a binomial. Weir type, Δ*h*, and time period were used as explanatory variables. Weir type and time period were defined as categorical variables and Δ*h* was defined as the numerical variable. The tolerance values of these explanatory variables were over 0.5 and above the criteria of Cohen *et al.*, (2003). Therefore, we considered multicollinearity among explanatory variables so weak that it could be ignored. However, chemical environmental variables (pH, DO and electric conductivity) and hydraulic variables (flow velocity and water depth) were not used as explanatory variables because multicollinearity among experimental variables was too strong (tolerance values were lower than 0.2) to conduct the analysis.

We made and examined all possible models. The model with the lowest AIC was defined as the best model. Following that, we calculated ΔAIC, which is the difference in AICs between a given model and the best model. ΔAIC < 2 indicated that the model was almost equivalent to the best model (Burnham and Anderson, 2002); these models were defined as candidate models. Additionally, ΔAIC can be used to compute the Akaike’s weights of each model, which is a measure of the likelihood that a model is the best one. We calculated the relative importance values (RI) of each explanatory variable using Akaike’s weight. The relative importance value is defined as the sum of the Akaike’s weights of the models including an explanatory variable. The RI value is between 0 and 1. It increases as the importance of the explanatory variable increases.

R 3.1.1 software (R Development Core Team, 2014) was used for all analyses. We used the glm function for logistic regression analysis, the tolerance function (Aoki, 2004) for calculating tolerance values and the dredge function from the MuMn package to make and select models.

3 Results

Lampreys successfully ascended all weirs when Δ*h* was 11 cm and the sharp-crested weir when Δ*h* was 18 cm (Figure 2). No lamprey succeeded to ascend the all weir when Δ*h* was 24 cm. The frequency of ascent challenge behavior taken using video cameras was shown in Figure 3. In this figure, the results of the experiments with 0% successful ascent rate (experiments 5, 6, 17 and 18) were compared because the number of lampreys that stayed in the downstream pool was constant in these experiments. In experiment 5 (daytime), lampreys were challenged in their ascent only twice between 10:15 and 10:45. In experiment 6 (night), the number of challenges continued and increased between 20:15 and 2:45. In experiment 17 (daytime), lampreys were challenged in their ascents only twice between 16:30 and 17:00. In experiment 18 (night), they were continuously challenged between 22:00 and 4:30. Therefore, they were challenged more frequently at night than daytime. The numbers of successful and non-successful ascending individuals and the means of standard lengths were shown in Table 2. Average length individuals ascended the sharp-crested and broad-
Figure 3: Frequency of ascent challenge behavior

crested weirs when $\Delta h$ was 11 cm. However, larger individuals ascended the inclined sharp-crested weir when $\Delta h$ was 11 cm and the sharp-crested weir when $\Delta h$ was 18 cm. The water temperature, water quality, and illumination were shown in Table 3. The water temperature was 13.1-18.7°C. The ranges of DO and pH were below the criteria of Japan Fisheries Resource Conservation Association (2005), so that water was safe enough for lampreys.

The results of regression analysis indicated that the difference in water depth upstream and downstream of the weir ($\Delta h$) was selected as an explanatory variable in the best model except weir type and time period to estimate the successful rates of ascended lamprey (Table 4). RI value of $\Delta h$ was 0.784 and much higher than time period (0.313) and weir type (0.156) (Table 5). From the regression coefficient of the best model, $\Delta h$ negatively affected the number of successful ascending individuals; Lampreys successfully ascended more when $\Delta h$ was smaller (Table 6).

Table 2: Population, mean length and standard deviation of migrated and non-migrated fish

| No. | Migrated fish | Not migrated fish |
|-----|---------------|-------------------|
|     | Population    | Average | SD | Population | Average | SD |
| 1   | 2             | 430     | 28 | 3          | 437     | 32 |
| 2   | 5             | 444     | 19 | 0          | -       | -  |
| 3   | 2             | 479     | 16 | 3          | 459     | 19 |
| 4   | 2             | 474     | 8  | 3          | 462     | 24 |
| 5   | 0             | -       | -  | 5          | 434     | 27 |
| 6   | 0             | -       | -  | 5          | 434     | 27 |
| 7   | 1             | 440     | 0  | 4          | 434     | 26 |
| 8   | 4             | 443     | 17 | 1          | 405     | 0  |
| 9   | 0             | -       | -  | 5          | 467     | 19 |
| 10  | 0             | -       | -  | 5          | 467     | 19 |
| 11  | 0             | -       | -  | 5          | 435     | 22 |
| 12  | 0             | -       | -  | 5          | 435     | 22 |
| 13  | 3             | 467     | 14 | 2          | 468     | 32 |
| 14  | 3             | 467     | 14 | 2          | 468     | 32 |
| 15  | 0             | -       | -  | 5          | 467     | 19 |
| 16  | 0             | -       | -  | 5          | 467     | 19 |
| 17  | 0             | -       | -  | 5          | 467     | 19 |
| 18  | 0             | -       | -  | 5          | 467     | 19 |

Table 3: Water temperature, water quality and mean illumination

| No. | Temperature ($^\circ$C) | DO (mg/L) | pH | EC (mS/cm) | Illumination (lux) |
|-----|-------------------------|-----------|----|------------|-------------------|
| 1   | 17.7                    | 7.22      | 7.7| 0.23       | 1,070             |
| 2   | 17.4                    | 7.69      | 7.7| 0.23       | N/A               |
| 3   | 17.7                    | 7.68      | 8.2| 0.28       | 970               |
| 4   | 18.8                    | 7.35      | 8.1| 0.28       | N/A               |
| 5   | 18.7                    | 7.48      | 7.9| 0.23       | 1,070             |
| 6   | 18.3                    | 7.41      | 7.8| 0.23       | N/A               |
| 7   | 15.8                    | 7.73      | 7.8| 0.23       | 1,088             |
| 8   | 16.6                    | 7.32      | 7.8| 0.23       | N/A               |
| 9   | 18.9                    | 7.55      | 8.0| 0.27       | 910               |
| 10  | 19.5                    | 7.41      | 8.0| 0.28       | N/A               |
| 11  | 13.1                    | 9.14      | 7.5| 0.23       | 1,098             |
| 12  | 14.6                    | 8.38      | 7.6| 0.23       | N/A               |
| 13  | 19.6                    | 7.39      | 8.2| 0.28       | 970               |
| 14  | 20.4                    | 7.21      | 8.2| 0.29       | N/A               |
| 15  | 20.1                    | 7.25      | 8.0| 0.28       | 830               |
| 16  | 19.6                    | 7.34      | 8.2| 0.29       | N/A               |
| 17  | 19.3                    | 7.81      | 8.0| 0.28       | 968               |
| 18  | 19.3                    | 7.76      | 8.1| 0.28       | N/A               |
Explanatory variable weight 0.452 0.00 Δ 0.784 p-value ΔAIC 0.625 RI 0.0143 1.531

et al. (2008) indicated that Pacific Lamprey ascended fishways with a 40° ramp more often than that with a 45° ramp. Additionally, Moser et al., (2002) indicated that Pacific Lampreys ascended fishways with a 40° ramp more often than that with a 45° ramp.

4 Discussion

Our results indicated that $\Delta h$ negatively and strongly affected the number of successful ascending individuals. Especially, no lamprey ascended when $\Delta h$ was 24 cm. These results suggest that weirs with lower $\Delta h$ are more suitable for lamprey ascents. Arctic Lampreys may have relatively low swimming and jumping ability and high $\Delta h$ may interfere with their ascents. Ichion et al., (2015) reported that Medaka (Orizias sp.) ascended fishways with 6 cm $\Delta h$ more often than those with 9 cm $\Delta h$. Medaka has small body and thus low swimming and jumping ability. Therefore, $\Delta h$ is likely to affect the successful ascent rate of species with low swimming ability, such as Arctic Lamprey and Medaka. In our experiment, we observed Arctic Lampreys propelled themselves forward by shaking the caudal fin in the pool when they challenged to ascent the weir (Figure 4). When $\Delta h$ was larger, they could not get enough driving force since their caudal fin did not reach to the pool sufficiently. To create optimal fishways for Arctic Lamprey, it is necessary to design step or $\Delta h$ smaller and modify the fishway structure.

Keefer et al., (2010) showed that vertical steps and sharp-edged corners in a fishway interfered with Pacific lamprey (Entosphenus tridentatus) ascents and stated that vertical steps should be removed or modified. In our experiment, inclined sharp-crested weir with a 45° ramp was used as the modification to vertical sharp-crested weir. However, our modification did not contribute to Arctic lamprey ascents because weir type did not affect ascents. Further study is needed to appropriately modify weir design. The weir with a gentler slope than 45° might be better. Indeed, Reinhardt et al., (2008) indicated that Pacific Lamprey ascended a fishway with an 18° ramp more often than that with a 45° ramp. Additionally, Moser et al., (2002) indicated that Pacific Lampeys ascended fishways with a 40° ramp more

5 Conclusions

Regression analysis indicated that $\Delta h$ negatively and strongly affected the number of successful ascending Arctic lampreys. Especially, no lamprey ascended when $\Delta h$ was 24 cm. The analysis also indicated that weir type (sharp-crested, inclined sharp-crest, and broad-crested weirs) did not affect lamprey passage. The slope weir had a 45° ramp and was expected to be suitable for inherent ability of lamprey ascent. However, the ascent rate on the broad-crested weir was not better than the other two types. It is reported that the burst and attach locomotion at flows with greater velocities is inefficient and lamprey passage is likely unsuccessful (Keefer et al., 2010; Kirk et al., 2016; Pacific Lamprey Technical Workgroup, 2017). In this experiment, broad-crested weid did not contribute to the increase of lamprey ascent rate since the critical velocity of the weir might be greater than the swimming speed to burst and attach for Arctic Lamprey. There is also a possibility that the swimming behavior differs in lamprey species. In future research, other shapes and settings should be tested to provide such an attachment place.
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