Doctoral Dissertation

MODELING OF FISH PREFERENCE FOR DESIGNING RIVER WORKS TO FACILITATE MIGRATION

魚がのぼりやすい河川工作物を設計するための魚の選好性のモデリング

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2015.3

ABSTRACT

Migration of fishes from downstream to upstream or vice versa takes place for the purpose of food, spawning and so on. Barriers across rivers often have negative impacts on natural fish populations and, along with other factors, may contribute to the diminished abundance, disappearance or even extinction of species. To minimize the severe impact on the river ecosystem, fish passage is installed. The general principle of fish passage is to attract fish that move up the river to a specific location in the river downstream of the obstruction so as to induce them actively, or even make them passively, pass upstream by opening a waterway or by trapping them in a tank and transferring them upstream. In Japan, the pool and weir fishways are intended mainly to provide passage upstream for ayu (*Plecoglossus Altivelis Altivelis*). Ayu is an amphidromous species and is the most important commercial fish in Japan.

The design of a fish passage, the effectiveness of which is closely linked to the water velocities and flow patterns, should take into account the behavior of the target species. The most important factor in designing fish passage is the easiness to find the entrance of fish passage. Water currents are believed to play an important role in guiding or directing fish on their migrations. Thus the water velocities in the pass must be compatible with their swimming capacity and behavior. A large water level difference between pools, excessive aeration or turbulence, large eddies or low flow velocities can act as a barrier for fish. In addition to hydraulic factors, fish are sensitive to other environmental parameters (sound, air bubble, level of dissolved oxygen, temperature, noise, light, etc.), which can have a deterrent effect.

This study is divided into two parts. In the first part, I determine approach to entrance of fish passage. In this part I select sound and rheotaxis as controlling parameters because sounds are believed to elicit changes in the behavior of fish and the movement of fish in response to current (rheotaxis) has been treated as a priori driving force that can determine swimming direction. In this research, I determine preference of rheotaxis and sound based on laboratory experiments, and build a model to determine fish migration path.

In the second part, I evaluate a fish passage itself. Recently, stone embedded fish passage (SEF) is getting popularity in some areas of Japan as an inexpensive small-scale river restoration works. I select Fushino River SEF because the efficiency of the SEF has not been evaluated and the design parameters of it are not clear enough yet. In this research, I evaluate the condition of Fushino River SEF whether ayu can rest at pools and swim through channels or not based on preference of adult and Juvenile Ayu.

In rheotaxis experiment, I conducted pair comparison of Ayu distribution between upper and lower section of a test watercourse using several velocity conditions (10, 30, 40 cm/s for Juvenile and 20, 30, 50, 70, 90 cm/s for adult). Through these experiments, I revealed that ayu shows positive rheotaxis under 30 cm/s and 40 cm/s for juveniles, and 50 cm/s for adults.

Sound experiments were conducted by using a watercourse at the end of which an underwater speaker was installed. I emitted sound from speaker with different sound pressure level. Sound source were pure tone (100 Hz, 200 Hz, 400 Hz and 800 Hz), white noise, a recorded sound at a weir in Fushino River, and a recorded sound at a fish ladder in Misumi River. The result showed juvenile and adult ayu avoid pure sound of 100 Hz and the recorded sound at the Fushino River weir, but they prefer pure sound of 200 Hz and the recorded sound at the fish ladder.

Based on above findings, I define a procedure to calculate preference of rheotaxis and sound then build them into our fish behavior simulation model on GIS software. The model could successfully reproduce observed fish migration behavior in the actual river.

For evaluating Fushino River SEF, I reproduced the condition of the SEF in laboratory, which consists of a pool and a channel. Based on experimental results using various discharge, channel slope, channel length, and pool size, I develop decision tree to estimate the passability of a pair of channel and pool. Then I propose an equation to estimate whole SEF combining the estimation result of the decision tree. Lastly I verify the equation through field experiments. The equation could show a framework of SEF estimation.

Key words: Ayu, preference, rheotaxis, sound, SEF

要旨

魚類の遡上や降下などの回遊行動は、産卵や摂餌のために行われる。回遊行動を妨げるような障壁は、多くの場合天然魚の個体数に負の影響を持ち、他の要因と相まって、生物量の減少や、種の絶滅をもたらす恐れすらある。河川生態系への深刻な影響を最小限に抑えるために設置される人工構造物として、魚道がある。魚道の原理には、魚類を能動的、あるいは受動的に障害物を迂回する水路に誘導したり、魚をタンクなどに捕捉して強制的に障害物上に移送したりするなどがある。日本では、最も重要な淡水域での商業魚であるアユ（*Plecoglossus Altivelis Altivelis*）を対象魚として、プールと堰を組み合わせた階段式魚道が主に用いられている。

魚道の設計の有効性は、対象種の行動特性に応じた流速と流れのパターンに密接に関係している。魚道の設計で最も重要な要素は、魚道の入口の発見の容易さである。流れのパターンは魚の移動方向を定めるために重要な役割を果たすと考えられている。また魚道内の流速は魚の遊泳能力や行動特性と整合していなければならない。大きな水位差や過度の曝気、乱流や大規模な渦、さらには低すぎる流速さえ、魚には障壁として機能することがある。水力学的要因に加えて、魚は音、溶存酸素、温度、水中音、光などの他の環境パラメータにも敏感であり、これらが魚の行動を制御することもある。

本研究は 2 つパートからなる。最初のパートでは、魚道入口への魚の接近経路の評価法を取り扱う。魚の接近経路を定める重要な要因として、本研究では音と走流性をとりあげる。魚道入口の落水音などの水中音は、魚が魚道入口を発見するために重要な役割を果たしていると考えられている。また、魚の走流性は魚の遊泳方向を決定する主要な駆動力と考えられている。本研究では、走流性と水中音に対する選好性を室内実験に基づいて定量化し、魚の移動経路を決定するモデルを作成する。２つ目のパートでは、魚道そのものの通過容易性を評価する。近年山口県などいくつかの地域で、安価な小規模河川再生事業として粗石を埋め込んだ魚道（粗石付き斜路）が人気を得ている。しかし、粗石付き斜路の設計条件は明確とは言えない。本研究では、椹野川粗石付き斜路をモデルとして、魚がプールで休息でき、水路を突進速度で通過できる条件を研究室実験により評価した。

走流性の実験ではまず、稚魚では 10、30、40cm/s、成魚では 20、30、50、70、90cm/s の速度条件下で実験水路の上流部と下流部の間でアユ分布の一対比較を行い、稚魚では 30～

40cm/s、成魚では50cm/sの時、アユは強い走流性を示すことを明らかにした。

水中音の実験は、一端に水中スピーカーが設置された水路を用いて行った。スピーカーからは、純音（100 Hz, 200 Hz, 400 Hz, 800 Hz）、ホワイトノイズ、槵野川の堰で録音された音、三隅川の魚道で録音された音を種々の音圧レベルで放音し、水路内のアユの分布を記録した。その結果、稚魚、成魚とも100 Hzの純音と槵野川の堰で録音された音を忌避する一方、200 Hz純音と魚道で録音された音を選好することが明らかになった。

以上の知見を元に、GISソフトウェア上に魚群行動シミュレーションモデルを作成した。このモデルは実際の河川における魚類の移動挙動観察を再現することに成功した。

槵野川粗石付き斜路の評価にあたっては、実験室に代表的なプールとチャネルの模型を作成した。流量、チャネル勾配、チャネル長、プールサイズを種々変更して実験を行い、一対のプールとチャネルの組み合わせを魚が通過できる条件を表す決定木を作成した。この決定木を用いて槵野川粗石付き斜路全体の評価式を提案し、その評価値と魚の遡上実験結果を比較することで、評価式が槵野川粗石付き斜路の評価に使用可能であることを示した。

ACKNOWLEGEMENTS

I am indebted to a lot of people to success this dissertation and would like to spend this space to express my gratefulness to my academic advisors, family and friends for invaluable support.

I am respectful and appreciative to my academic advisor, Prof. MASAHIKO SEKINE for his guidance, expert suggestion, and warm encouragement during my stay in Japan.

My sincere gratitude is also expressed to Asst. Prof. ARIYO KANNO, who gave many advises to improve my research.

I am also indebted to Prof. T. IMAI, Assoc. Prof. K. YAMAMOTO, Prof. T. HIGUCHI, for their expert and meaningful advices as well as their kind attention in many aspect.

I would like to acknowledge to The Indonesia Education Ministry for financial support through the DIKTI scholarship.

My deepest gratitude to T. YAMAMOTO, SUN XIAOFENG, H. YAMASITA, H. KANEMOTO, KATSUBE, TSUKADA, T. TABE, N. OKAMURA, J. WEI, L.V. TUAN, V. T. HUY, K. EVI, H. RIYANTO, P. KANTHIMA, A. RIFAI, Y.P. DEVIA, W. R. YUSA, W. SUWANNASING, GIRIJA, LOC, ASHRAF and other friend for sharing ideas, knowledge, literature and colour life in Japan.

Finally, I would like to express my heartfelt gratitude to my big family especially for my lovely husband SYAHBUDIN for his love, support, patience and understanding, my two angels (RIZKI and KEIKO) for their love and patience, my parents for their immeasurable long distance support and love, my sister and my brother for their love and support.

Rina Febrina
October 2014

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CHAPTER 1
INTRODUCTION

1.1 General

Upstream or downstream fish migration takes place for purposes such as food, spawning and other. Barriers across rivers often have negative impacts on natural fish populations and, along with other factors, may contribute to the diminished abundance, disappearance or even extinction of species. Dams are threatening many aquatic species, as well as in other continents where even far less is known about the biology, behavior, fishery and population dynamics of the fish species concerned.

In recent years, there is increasing concern that fisheries and the associated livelihoods are being threatened as a consequence of dam construction. To minimize the severe impact on the river ecosystem, fish passage is installed. The general principle of fish passage is to attract fish that move up the river to a specific location in the river downstream of the obstruction so as to induce them actively, or even make them passively, pass upstream by opening a waterway or by trapping them in a tank and transferring them upstream. The design of a fish passage, the effectiveness of which is closely linked to the water velocities and flow patterns, should take into account the behavior of the target species. Thus the water velocities in the passage must be compatible with their swimming capacity and behavior. A large water level difference between pools, excessive aeration or turbulence, large eddies or low flow velocities can act as a barrier for fish. The most important factor in the design of fish passage is the easiness way to finding the entrance of fish passage. In addition to hydraulic factors, fish are sensitive to other environmental parameters (sound, air bubble, level of dissolved oxygen, temperature, noise, light, odour, etc.), which can have a deterrent effect. In designing facilities for migratory fish, I need to concerns with the swimming ability, direction, and trigger ascending behavior of the migrant to pass through the fish passage. The movement of fish in response to current (rheotaxis) has been treated as a priori driving force that can determine swimming direction and sounds are believed to elicit changes in the behavior of fish (Yan et al., 2010). Rheotaxis and sound can be used to attract fish to find the entrance of fish passage.

In Japan, the pool and weir fish passage are intended mainly to provide passage upstream for ayu (*Plecoglossus Altivelis Altivelis*). Ayu is an *amphidromous* species and is the most important commercial fish in Japan (Ishida, 1976). However, these traditional fish passages have sometimes been degraded because of river bed degradation or other problems and many of them require restoration. Recently, the stone embedded fish passage (SEF) is getting popularity in some areas of Japan as an inexpensive small-scale river restoration works. Fushino River SEF is one of such works intended to improve or substitute existing pool and weir fish passage (Project Team "Mizube no Kowaza", 2007).

1.2 Objectives

The aim of this research was to designing river works to facilitate fish migration based on modeling preference. In order to reach the aim, this study was divided into two stages these are:

1. To determine the approach to gap section. In this stage, I selected rheotaxis and sound to attract fish to find the entrance of fish passage based on preference. The objective of this stage is to determine preference and weight of rheotaxis and

underwater sound based on laboratory experiment then validate them through field experiment and model it.

2. To evaluate gap section. In this stage, I build a simple model applicable in designing SEF stage to estimate the passability of SEF for Ayu using preference information on velocity, depth, and air bubble. Then verify the model through field experiments in Fushino River SEF.

1.3 Structure of This Study

This thesis comprises of six chapters. Chapter 1 explains the background, the significance and the objectives of this study. Chapter 2 presents a literature review on ecology of ayu, the effect of water quality on ayu, sound and hearing in fish, rheotaxis, air bubble, fish passage, formulation of preference and decision tree. I choose ayu as experimental animal because ayu is a migratory fish and an important fish in Japanese commercial fishing industry. Chapter 3 describes about the movement of fish in response to current (rheotaxis) has been treated as a prior driving force to determine swimming direction based on preference. Chapter 4 describes about preference model on underwater to find an entrance of fish passage so that fish can determine migration path in the river. Chapter 5 describes about evaluation on passability of stones embedded fish passage based on preference. Chapter 6 is conclusions and future work.

1.4 References

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CHAPTER 2
LITERATURE REVIEW

2.1 Ecology of Ayu

Ayu is a migratory fish that migrates between the sea and river over the course of its life. Ayu begins its life at a spawning spot in the downstream area of a river where there is loose rock and sufficient water flow. A single female is surrounded by numerous males, which issue sperm to match the timing of the female's egg release. The fertilized eggs, which are adhesive and can stick to stones in the river bed, then hatch after about 1–2 weeks. Mostly, they hatch between 17:00 to 20:00 in the evening (Nagao, K., 1978).

Ayu larvae cannot swim, so they are transported from the river mouth to the sea by water flow. Because the salt cells used for regulating osmotic pressure are formed after hatching, the larvae are physiologically able to survive in the marine environment. Several days after hatching, larvae can be found in the shallow surf zone where many waves break from the costal shore. After spending a certain period of time here, it is likely that they move to deeper waters. Indeed, the ecology of Ayu in the ocean is not fully understood. It is known that around the beginning of the year, sub-adults measuring 3-cm long and with transparent bodies, called Shirasu Ayu, will gather in low flow areas, such as harbors and bays. During their life at sea, they eat phytoplankton and zooplankton such as rotifers. At 4-cm long, the fish develop teeth and can start to eat large zooplankton (Nagao, K., 1978).

After spending the first half of their life in the sea, the fish travel upstream during spring when the sea and river water temperatures are similar (early March to early May, with a peak in April). The optimum water temperature here is 13–16°C. Ayu migrating upstream usually measure 7–8 cm, and the fish travel upstream in order of growth. Initially, the fish consume an omnivorous diet, but then shift to grazing algae (such as blue green algae) and diatoms attached to the stones when the water becomes warm. This dietary shift is accompanied by changes in their dentition to comb teeth, which are suitable for eating algae growing on stones. Indeed, by studying tooth marks on river stones, it is possible to estimate the size and number of Ayu (Nagao. K., 1978).

Ayu will disperse gradually in flocks during the upstream migration. They graze algae from stones and maintain territories. Ayu will defend their territories, which measure approximately one square meter, by relentlessly attacking any intruders; a behavior that is exploited by bait fishermen. The behavior of territoriality is not exclusive to Ayu, but is also found in other river fish, such as Bouzuhaze and Oikawa (Nagao. K., 1978).

During autumn, when daylight hours and water temperatures decrease, Ayu start to become mature for spawning. Their territoriality diminishes, and they begin to gradually move downstream. The males, which mature quickly, gather in a spawning area. The females attain final maturity at a pool near the spawning area where they then go to spawn (Nagao. K., 1978).

The Ayu lifecycle lasts 1 year, and animals die after spawning. But in rare cases, individuals that were immature during the breeding season, and not able to participate in spawning, can live until the following year (Nagao. K., 1978).

2.2 The Effect of Water Quality on Ayu

The lowest turbidity to mortality in a 48-hour period has been observed to be 740 mg/l in larvae and 2420 mg/l in juveniles. The LC50 of juveniles is 4360 mg/l in a 24-hour period and 4160 mg/l in 48 hours. In addition, the turbidity threshold concentration is 13–25 mg/l for causing food intake inhibition in fish measuring 74.4 ± 0.6 mm (body length), 22 mg/l for causing avoidance of muddy water in 59–72 mm fish, and 31 mg/l for causing decrease of upstream rate in 53.3–89.2 mm fish (Fujiwara. K., 1997). Additional studies have shown that the turbidity threshold concentration is 15 mg/l for avoidance of muddy water in 70–90 mm fish, and 30–50mg/l for causing decrease of upstream rate in 90–114 mm fish (Serene. H., 1983). It has also been found that the habitable water quality (SS) of Ayu is below 35 mg/l (Watanabe. A., 1993).

With respect to water temperature, it was reported that Ayu of 70–90mm body length will display avoidance behavior when water temperature is more than 5°C lower than historic water temperature. Further, it is known that Ayu inhabit environments where water temperatures are below 20°C (Watanabe. A., 1993).

A study by Mitsumasa et al. (1983) has shown that optimum growth in the species occurs at 20°C, followed by 15°C and then 10°C. In their study, Ayu were taken from downstream areas; 48 fish (10~15cm) were given the choice of swimming to three tanks with water temperatures of 12, 17 and 19°C, respectively. They found that Ayu avoided the 12°C tank and preferred the 17°C tank over the 22°C tank. The results showed that Ayu do not display avoidance behavior when water temperatures increase. However, when the water temperature decreases by 1°C, avoidance behavior was seen across the 16–19°C range. At 17°C, 18°C and 19°C, avoidance behavior was observed by a 0.2°C reduction in water temperature (Mitsumasa et al., 1983).

For farming Ayu, the suitable water temperature range is 13–25°C, with optimal growth occurring at 18–23°C. In addition, 48-hour median lethal concentration of ammonia is 1.18 ppm and of nitrite nitrogen is 2.8 ppm. The pH over the same 48-hour period is 8.2. The saturation of dissolved oxygen is optimal when more than 40% and critical at less than 20% when mortality begins to occur (Kenzo. S., 1996).

It is said for Ayu, the highest rates of food intake and growth occur at 20–25°C water temperature, the optimum temperature for digestive enzymes is 27°C, and the greatest aggression occurs at 23–27°C (Kenzo. S., 1996).

2.3 Sound and Hearing in Fish

2. 3.1 Characteristic of sound

There are two components to sound propagation through water: particle displacement and sound pressure. Particle displacement is the to-and-fro movement (on the order of nanometers) of water molecules and is a vector quantity, whereas sound pressure is the oscillatory change in pressure above and below hydrostatic pressure and is scalar quantity acting in all directions.

In a free sound field without physical obstructions to sound transmission, and with an advancing wave front that is essentially a plane surface, particle velocity (the first derivative of particle displacement) is proportional to sound pressure in the following manner:

$$v = p/\rho c \qquad (1)$$

where v = particle velocity,
p = sound pressure,
ρ = the density of the medium, and
c = the propagation velocity.

The product ρc is the acoustic impedance of the medium. However, sound levels are not usually expressed as particle velocity; rather the logarithmic decibel (dB) scale of sound pressure level (SPL) is used because a great range of sound levels are found in nature:

$$\text{SPL (dB)} = 20\log (p / p0) \qquad (2)$$

where p is the pressure level of the sound in μ Pa and $p0$ is the reference pressure level. Sound pressure levels above water are referenced to 20 μ Pa, while underwater they are referenced to 1 μ Pa.

2. 3. 2 Physiology of hearing

Fish hearing in general is different from that of terrestrial organisms. Most fish hear with a primitive version of the terrestrial inner ear (located in the skull of fish) and with the lateral line that runs the length of each side of the fish and is often extensively routed on the head. The inner ear and the lateral line system are called the acoustic lateralis system. The inner ear does not have a cochlea as in terrestrial vertebrates; rather there are three symmetrically paired structures with associated bony otoliths: the lagena, sacculus, and utriculus. The lagena and sacculus are directly involved with hearing, whereas the utriculus is mainly for three dimensional orientations (Platt and Popper 1981). The mechanism for hearing is the differential displacement of high density otoliths relative to the low density bodies of fish, resulting in bending of sensory hair cells that lines the lagena and sacculus. This mechanical stimulus is then converted to electrical stimuli in the hair cell body and sent to the brain for processing.

2.3.3 The various sound pressure level on the behavior of fish

Characteristics of underwater sound vary with the location in water (5) reviewed underwater sound pressure in relation to various sound sources and approximated auditory thresholds of fishes, they are:

1. Hearing threshold: minimum perceived sound pressure level sound to fish. Maximum sensitivity of the special fish good sensitivity: 60 ~ 80 dB, marine fish common poor sensitivity: 90 ~ 110 dB.
2. Attract level: This is a strength of the comfortable sound for fish, sound pressure level coming to drop in to see sound source direction if sound of interest. In general, the 110 ~ 130 dB.
3. Treat level: sound pressure level or dive in deep fish surprised, indicating the reaction away from the sound source. In general, the 140 ~ 160 dB.
4. Damage level: sound pressure level that causes damage, rupture of internal organs of fish. Related to the impulse and energy flux density of the sound, but the measure of sound pressure damage occurs in water drilling blasting, 220 dB or more.

2.4 Rheotaxis

Rheotropism is a term used to cover all the reactions that a fish might make in response to a current of water, either directly as a response to water flowing over the body surface or indirectly as a response to the visual, tactile or inertial stimuli resulting from the displacement of fish in space (Harden and Jones, 1968; Arnold, 1974). The rheotropic response is composed of an orientational and a kinetic component; fish generally turn to head into a current and adjust their swimming speeds in response to the rate of the current.

Rheotaxis devided tobe 2:

1. Positive rheotaxis (face into an oncoming current).
2. Negative rheotaxis (avoid currents).

2.5 Air Bubble

The river water flow from upstream to downstream cause the flow rate. Flow rate, water depth, channel width and slope will cause air bubbles. The result of air bubbles will affect the ability of fish to swim upstream. Actually, if the air bubbles in small amounts will increase the amount of oxygen dissolved in water, and creates favorable conditions for fish. However, the mixing of air bubbles with a high concentration will reduce the density of water, and reduce the ability of fish to swim; the current became much distorted, and can inhibit the fish to move.

2.6 Fishway

Fishway is a structure on or around artificial and natural barriers (such as dams, locks and waterfalls) to facilitate diadromous fishes natural migration. Most fishways enable fish to pass around the barriers by swimming and leaping up a series of relatively low steps (hence the term *ladder*) into the waters on the other side. Fishways usually consist of a sloping channel partitioned by weirs, baffles, or vanes with openings for fish to swim through. The in-channel devices act hydraulically together to produce flow conditions that fish can navigate. Several types of fishways have been developed and are usually distinguished by the arrangement of in-channel devices. There are five main types of fishways:

1. Pool and weir
2. Baffle fishway (Denil, Larinier, Alaskan Steeppass, or other baffle configuration)
3. Fish elevator
4. Rock-ramp fishway
5. Vertical-slot fish passage

Excavated channels utilizing rocks, sills or weirs are also used as fishways. The different physical and hydraulic characteristics of each fishway type may make them suitable for some fish species and not suitable for others. An effective fishway attracts fish readily and allows them to enter, pass through, and exit safely with minimum cost to the fish in time and energy. The use of nature-like fishways as a viable fish passage alternative is becoming more accepted around the world. Many examples of these nature-mimicking structures now exist in countries throughout Europe, as well as Australia, Canada and Japan. The design philosophy for these fishways is simple, ecologically minded, and aims to achieve a good fit with the specific riverine environment they are constructed in.

In the design of a fishway, important factors to be considered include the hydraulic characteristics of the fishway type, as well as the swimming performance and behaviour of the species of fish to be passed. Biological and hydraulic criteria for designing fishways vary with species and sizes of fish. Fishway efficiency depends on attraction, as well as safe and speedy transport of fish. Attracting fish to the fishway entrance is critical and depends on species behavior and motivation. Commonly, flows and appropriate water velocities at the entrance are used for fish attraction. Experience with the target species is usually the best guide for designing fishway entrances.

2.7 Formulation of preference

Authors have formulated preference of fish on environmental factors through laboratory experiments based on pair comparison using a U-shaped experimental watercourse (Sekine et al., 1997), and the formula have been validated through several researches (Sekine et al., 2001, Karim et al., 2003, Sekine et al., 2004, Fukuda and Hiramatsu, 2008, Sekine et al., 2009). The formula is described as below:

$$P^{*} = \prod\nolimits_{j=1}^{J} \left(P_j\right)^{\frac{W_j}{W_{\max}}} \tag{3}$$

$$W_{\max} = \begin{cases} \max_{J \in V} \left(W_j\right) & V \neq \phi \\ \infty & V = \phi \end{cases} \tag{4}$$

$$V = \left\{ j \middle| \left(\exists i, i`\right)\left(P_{j,i} \neq P_{j,i}\right) \right\} \tag{5}$$

Where P^{*} is overall preference, P_j is preference for environmental condition j, W_j is weight of environmental condition j, W_{max} is maximum weight among weight sets, V, that had different preference levels in surrounding water body, ϕ represents the null set, $\exists$ is an existential quantifier, and i represents a segmented location of water body. This formula has an important advantage that environmental preference and its weight can be determined separately. Consequently, a new environmental factor can be added or removed without affecting other environmental factors. Thus we employ this formula to newly add the sound preference on already existing preference information. By use this equation, preference of velocity, bubble, turbulence, and shade were determine.

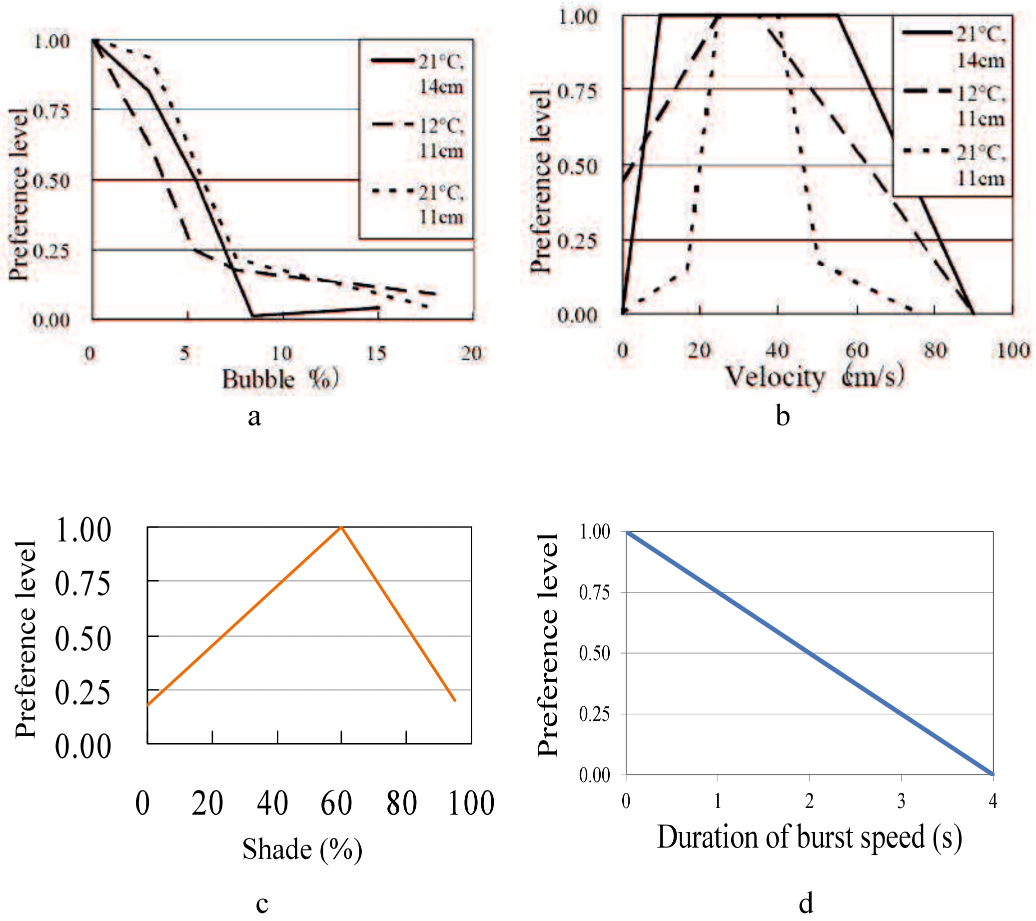

Fig. 2.1 Preference curve. (a) Air bubble (Sekine et al., 2004); (b) velocity (Sekine et al., 2004); (c) shade (Noguchi et al., 2007); (d) duration of burst speed (Sekine et al., 2009).

To calculate weight, assume, for example, that we testing two environmental factor j (j = {rheotaxis, illumination}), were included in the calculation of the values for the weights. The ratio of fish distribution between the upper and lower sections, R, was:

$$R = \frac{D_{Up}}{D_{Low}} = \frac{P_{r(Up)}^{\frac{W_r}{W_{max}}} \; P_{ill(Up)}^{\frac{W_{ill}}{W_{max}}}}{P_{r(Low)}^{\frac{W_r}{W_{max}}} \; P_{ill\,(Low)}^{\frac{W_{ill}}{W_{max}}}} \tag{6}$$

Where D_{Up} was the upstream distribution, D_{Down} was the downstream distribution, P_r

was the rheotaxis preference, P_{ill} was the illumination preference, W_r was the rheotaxis weight, W_{ill} was the illumination weight, and $W_{\max}$ was the maximum weight value used for each environmental factor.

When $P_{r(Up)}$ does not equal $P_{r(Low)}$ and $P_{ill(Up)}$ does not equal $P_{ill(Low)}$, then V becomes {rheotaxis, illumination} (from Eq. (3)) and $W_{\max}$ is W_r or W_{ill} (from Eq. (2)). Although, we cannot know explicitly whether $W_{\max}$ is W_r or W_{ill}, we can obtain these values recursively. If we assume that $W_{\max}$ is W_r , Eq. (4) becomes:

$$R = \frac{D_{Up}}{D_{Down}} = \frac{P_{r(Up)}^{\frac{W_r}{W_r}} P_{ill(Up)}^{\frac{W_{ill}}{W_r}}}{P_{r(Down)}^{\frac{W_r}{W_r}} P_{ill\,(Down)}^{\frac{W_{ill}}{W_r}}} \tag{5}$$

$$\frac{W_{ill}}{W_r} = In\left(R\frac{P_{r(Up)}}{P_{r(Low)}}\right) \div In\left(\frac{P_{ill(Up)}}{P_{ill(Low)}}\right) \tag{6}$$

The various values for $P_{j,i}$ were defined from the single environmental factor experiment, and R was obtained from the composite experiment, so the value of $\frac{W_{ill}}{W_r}$ could be estimated. When the value of $\frac{W_{ill}}{W_r}$ is between 0 and 1, the values of W_{ill} and W_r are determined because there is no meaning in the absolute value of W_j, but the relative relationship among W_j `s is essential (Eq. (1)). When $\frac{W_{ill}}{W_r}$ >1, then $W_{ill} > W_r$, which contradicts the assumption that $W_{\max}$ is W_r. In this case, we can accept the assumption that $W_{\max}$ is W_{ill}, and Eq. (1) becomes:

$$\mathrm{R} = \frac{D_{Up}}{D_{Low}} = \frac{P_{r(Up)}^{\frac{W_r}{W_{ill}}} \, P_{ill(Up)}^{\frac{W_{ill}}{W_{ill}}}}{P_{r(Down)}^{\frac{W_r}{W_{ill}}} \, P_{ill\,(Down)}^{\frac{W_{ill}}{W_{ill}}}} \qquad (7)$$

$$\frac{W_r}{W_{ill}} = In\left(R\,\frac{P_{ill(Up)}}{P_{ill(Low)}} \right) \div In\left(\frac{P_{r(Up)}}{P_{r(Low)}} \right) \qquad (8)$$

2.8 Decision tree

A decision tree is a flowchart-like structure in which internal node represents test on an attribute, each branch represents outcome of test and each leaf node represents class label (decision taken after computing all attributes). A path from root to leaf represents classification rules. In decision analysis a decision tree and the closely related influence diagram is used as a visual and analytical decision support tool, where the expected values (or expected utility) of competing alternatives are calculated.

A decision tree consists of 3 types of nodes:

1. Decision nodes - commonly represented by squares
2. Chance nodes - represented by circles
3. End nodes - represented by triangles

Decision trees are commonly used in operations research, specifically in decision analysis, to help identify a strategy most likely to reach a goal. If in practice decisions have to be taken online with no recall under incomplete knowledge, a decision tree should be paralleled by a probability model as a best choice model or online selection model algorithm. Another use of decision trees is as a descriptive means for calculating conditional probabilities. Decision trees, influence diagrams, utility functions, and other decision analysis tools and methods are taught to undergraduate students in schools of business, health economics, and public health, and are examples of operations research or management science methods. Decision tree technique for making decisions in the presence of uncertainty is really quite simple, and can be applied to many different uncertain situations (Hullet D. T., 2006). Among decision support tools, decision trees (and influence diagrams) have several advantages. Decision trees:

- Are simple to understand and interpret. People are able to understand decision tree models after a brief explanation.
- Have value even with little hard data. Important insights can be generated based on experts describing a situation (its alternatives, probabilities, and costs) and their preferences for outcomes.
- Possible scenarios can be added
- Worst, best and expected values can be determined for different scenarios
- Use a white box model. If a given result is provided by a model.
- Can be combined with other decision techniques.

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CHAPTER 3
PREFERENCE MODEL OF RHEOTAXIS AS A PRIOR DRIVING FORCE TO DETERMINE SWIMMING DIRECTION

3.1 Introduction

Fish exhibit rheotropic behavior in response to water currents. They respond directly, to water flowing over the body surface, or indirectly, as a response to the visual, tactile, or inertial stimuli that result from displacement in space (Harden and Jones, 1968; Arnold, 1974). The rheotropic response consists of an orientational and a kinetic component. For example, fish generally turn to head into a current and adjust their swimming speeds in response to flow rate. Environmental factors that affect the orientational and kinetic components of rheotropism have an important role in migration (Arnold, 1974; Dodson and Young, 1977).

A core problem for the study of rheotaxis is the effect of current orientation on fish behavior patterns. Modeling behavior to determine if virtual fish can swim up a virtual river is a promising technique for determining the barriers to fish migration. However, rheotaxis has been treated as an a priori driving force in most fish migration modeling research. Because rheotaxis is one of the most important factors that determine swimming direction, it should be expressed from the viewpoint of preference. In this paper, I try to determined preferences for rheotaxis based on laboratory experiments using adult and juvenile ayu (*Plecoglossus altivelis altivelis*) and the present study involves observations under different light conditions. I then confirmed the formula through field experiments. I choose ayu as a model because it is a migratory species and is the most important commercial amphidromous fish in Japan (Ishida, 1976). This research consisted of three experiments. First, I performed paired comparisons with varying illumination levels. Second, I observed ayu distribution under a uniform illumination of 11000 lux and variable velocity conditions (10, 30, and 40 cm/s for juvenile fish; 20, 30, 50, 70, and 90 cm/s for adult fish). Last, I observed ayu distribution in the upper section at 11000 lux and in the lower section at 4000 lux, with the same velocity conditions used in the second experiment.

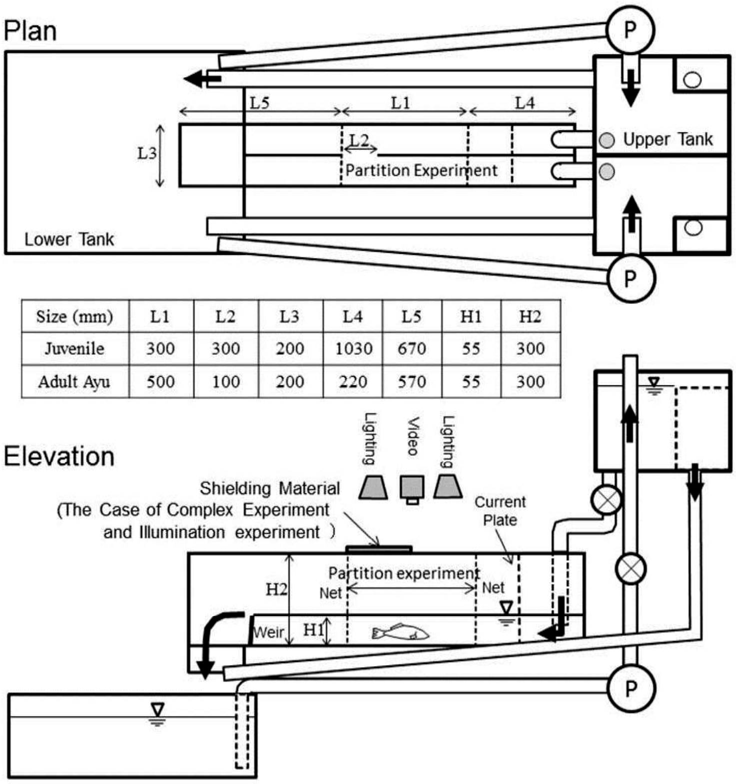
3.2 Materials and methods

3.2.1 Experimental animals

Juvenile (7±1 cm) and adult ayu (16±1 cm) I purchased from the Fushinogawa River Fishing Cooperative. I maintained the fish in a large tank (150 cm long × 60 cm width × 80 cm height) under recirculated, temperature-controlled conditions (21±1°C) with supplemental aeration. I fed them once per day, after experiments were completed, or at 1500 h on the days they were not included in an experiment (0.5 g/fish, *Kawazakana no esa*, Kyorin Co., Japan)

3.2.2 Experimental set-up

To determine rheotactic responses, juvenile and adult ayu were placed in similar experimental apparatus and water flow set-ups (Fig. 3-1). The watercourse for juvenile fish was 30 cm long × 20 cm wide × 30 cm high and was 50 cm long × 20 cm wide × 30 cm high for the adults. It was made of transparent acrylic and was surrounded by gray curtains to minimize the effect of visual stimuli. Two halogen lights were installed above the watercourse to maintain light conditions at approximately 11000 lux. In the downstream section, the illumination intensity was varied by changing the shielding material, which consisted of a transparent plastic wrap, cheesecloth, and a black plastic sheet. By varying and overlaying these materials, eight levels of illumination intensity (500–11000 lux) were created (Table 3-1).



Size (mm)	L1	L2	L3	L4	L5	H1	H2
Juvenile	300	300	200	1030	670	55	300
Adult Ayu	500	100	200	220	570	55	300

Fig. 3-1 Experimental apparatus

Table 3-1
Shielding materials and surface illumination conditions in the rheotaxis experiments.

Shielding material	Illumination (lx)	Example
Without shielding	11000	Full daylight (not direct sun)
A transparent wrap	9500	
One white cheesecloth	8000	
One black cheesecloth	6000	cloudy
Two black cheesecloth	4000	Boxing ring
Two black cheesecloth + one white cheesecloth	3000	Baseball infield of night game
Three black cheesecloth	2000	Convenience store
A black plastic sheet	500	Office lighting

3.2.3 Experimental method

Experiments I performed between 09:00 to 19:00 to control for the effects of diurnal variability in behavior (Yang et al., 2001). For each test, three fish at a time (i.e., three replicates) were randomly selected from the stock tank and placed in the watercourse to acclimate for 10 min (water temperature = 21±1°C). After testing was completed, fish were moved to a different tank to avoid using them in multiple experiments in 1 day. Fish distribution in the tank was recorded every 10 s with a video camera (SONY SR-60) placed above the watercourse.

For the illumination experiments, the velocity was kept at 10 cm/s without shielding material during the initial 10-min acclimation period. After acclimation, the shielding material was placed in the lower section, the velocity set to 0 cm/s, and the light was turned on for a second (5 min) acclimation period. After the 5-min acclimation to light conditions, fish distribution was recorded for 10 min.

Rheotaxis experiments and combined condition experiments were performed together. I exposed juvenile ayu to three velocity conditions (10, 30, and 40 cm/s) and exposed adult ayu to five velocity conditions (20, 30, 50, 70, and 90 cm/s). Illumination was a constant 11000 lux. During the first 10-min acclimation period, the velocity was maintained at the intended value. After the 10-min period, fish distribution was recorded for 10 min. At the end of the 10-min observation period, the shielding material was placed around the lower section to create 4000 lux illumination, fish were acclimated for 5 min, and then the distribution was recorded for 10 min.

3.3 Theory

3.3.1 The formulation method of preference

Fish orientation preference in a specific environment has been previously described by an equation (Tanaka and Shoten, 2006) and using laboratory experiments with a U-shaped experimental watercourse (Sekine et al., 2004).

$$P^{*} = \prod_{j=1}^{J} \left(P_j\right)^{\frac{W_j}{W_{\max}}} \tag{1}$$

$$W_{\max} = \begin{cases} \max_{J \in V}\left(W_j\right) & V \neq \phi \\ \infty & V = \phi \end{cases} \tag{2}$$

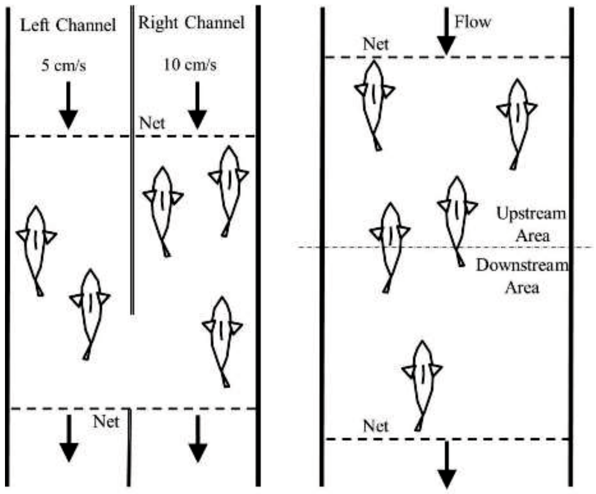
$$V = \left\{ j \middle| \left(\exists i, i'\right)\left(P_{j,i} \neq P_{j,i}\right) \right\} \tag{3}$$

Where P^{*} is an overall preference, P_j is a preference for an environmental condition, j, W_j is a weight for the environmental condition, j, W_{max} is the maximum weight among the weight sets, V, with different levels of preference in the surrounding water body, ϕ represents the null set, $\exists$ is an existential quantifier, and i represents a segmented location of an water body.

To determine fish preference for flow rate, I set up two parallel flows with two different flow rates (Fig. 3-2a). These flows Ire partly connected so that fish could choose a side to swim in. I then observed the distribution ratio of the fish in the left and right side ($D_{right} + D_{left} = 1$), and

$$\frac{D_{left}}{D_{right}} = \frac{P_{v,left}}{P_{v,right}} \tag{4}$$

where D_{left} is the fish distribution ratio at the left side of the watercourse, D_{right} is the distribution ratio of fish at the right side of the watercourse, $P_{v,left}$ is the flow rate preference on the left side, and $P_{v,right}$ is the flow rate preference on the right side.



(a) (b)

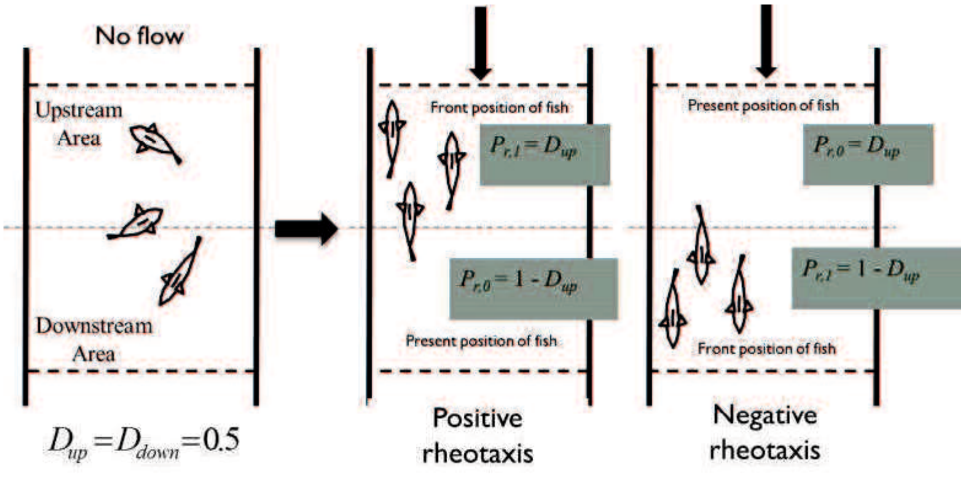
Fig. 3-2 The channel concept. (a) u-shaped waterway; (b) rheotaxis experiment

By observation, I can know the relative relationship between P_v and the flow rates at the left and right sides of the channel (Fig. 3-2a). For example, if there is a fixed constant flow rate value at the right channel, and the experiment is repeated by changing only the flow rate at the left channel, a functional form of P_v can be determined. However, it cannot be calculated when D is zero. When D was zero, I used 0.01 and 0.99. In addition, P has only a relative meaning in Eqs. (1) – (3), but was normalized so that the maximum value of P was 1. P is used as an expression of preference for many environments, and is used in habitat evaluation procedures (Tanaka and Shoten, 2006).

When W_j for a single factor is considered, it does not matter when W_j/W_{max} = 1, and the result can be ignored. However, when multiple factors are involved, it is necessary to set a value for P_j. After setting P_j using a single factor experiment, an experiment was carried out using two factors (j, j`) to obtain $W_j$ and $W_j$`. Likewise, the values for P_j, W_j, and W_j` are relative. Normalization was performed when the maximum value = 1. Furthermore, W_j is not independent from P_j. Therefore, I cannot discuss the importance of a factor by comparing only the values of W_j.

3.3.2 Formulation of the concept of rheotaxis

I developed rheotaxis preference values from paired comparisons of the upstream and downstream fish distribution ratios. I did not compare between the left and right sides of the watercourse (Fig. 3-2b). I added multiple fish at a flow rate of 0 cm/s (when the other conditions are uniform, then $D_{up} = D_{down} = 0.5$) (Fig.3-3a). I then increased the current speed. Fish position was noted as follows: if fish swam against the current (positive rheotaxis), then D > 0.5. If fish swam following the current or oriented downstream (negative rheotaxis), then D < 0.5.



(a) (b) (c)

Fig. 3-3 Determination of rheotaxis preference. (a) no flow; (b) positive rheotaxis; (c) negative rheotaxis

To convert the distribution ratio into rheotaxis preference (P_r), I did the following: when positive rheotactic behavior was displayed and the present position of the fish was in the downstream area (D_{down}) and the front of the fish was facing the upstream area (D_{up}), I used (D_{up}) for the preference value (Fig. 3b). For negative rheotaxis, I assumed that even though the position of the fish was in the upstream area (D_{up}), the fish would be facing downstream (D_{down}), so (D_{down}) was used for the rheotaxis preference value (Fig. 3c).

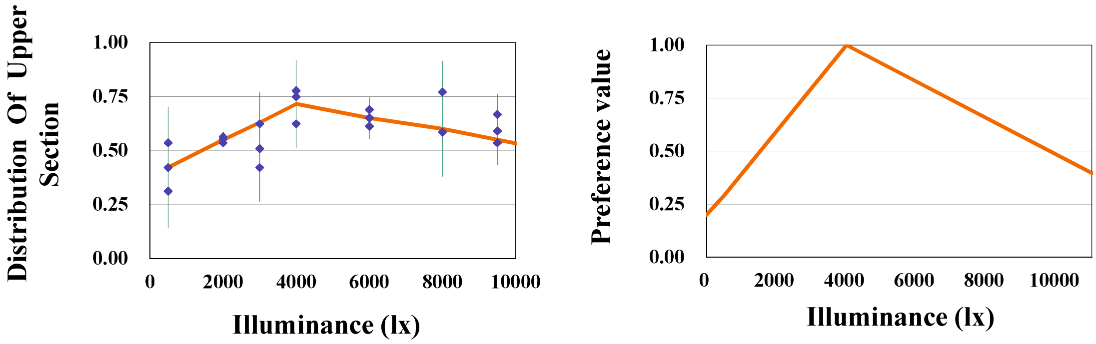
3.4 Results

3.4.1 Illumination experiment

The results of the experiment shown in Table 3-2 were estimated from the data presented in Figs. 3-4 and 3-5. On the upstream side, the maximum distribution ratio for juvenile (0.72) and adult (0.72) ayu occurred at 4000 lux . The distribution ratios at 11000 lux = 0.5 and at 4000 lux = 0.72. Our results indicate that juvenile and adult ayu tend to remain in 4000 lux illumination conditions. I used this result for the composite experiment to obtain the weight values, illumination upstream area:illumination downstream area = 11000 lux:4000 lux.

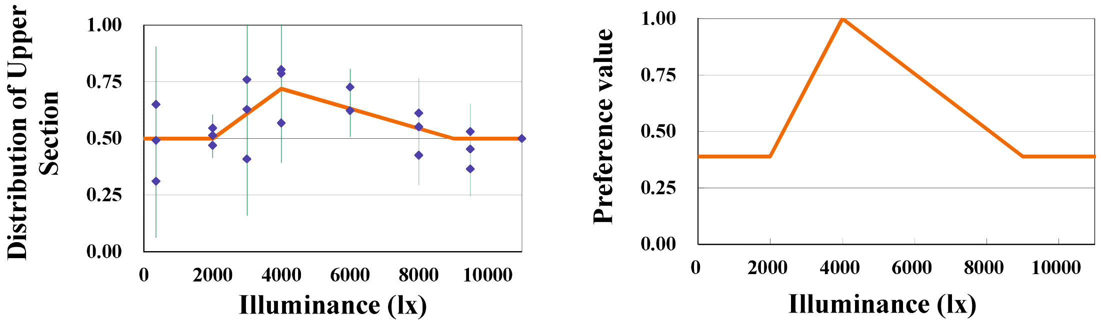
Table 3-2
Experiment results for illumination preferences.

Illumination (lx)	Distribution ratio of juvenile Ayu at upstream area	Distribution ratio of adult Ayu at upstream area
11000	0.5	0.5
9500	0.45	0.6
8000	0.53	0.65
6000	0.66	0.65
4000	0.72	0.72
3000	0.6	0.52
2000	0.51	0.55
500	0.48	0.42



(a) (b)

Fig. 3-4 Results for the various illumination conditions for the adult ayu. (a) distribution curve; (b) preference curve

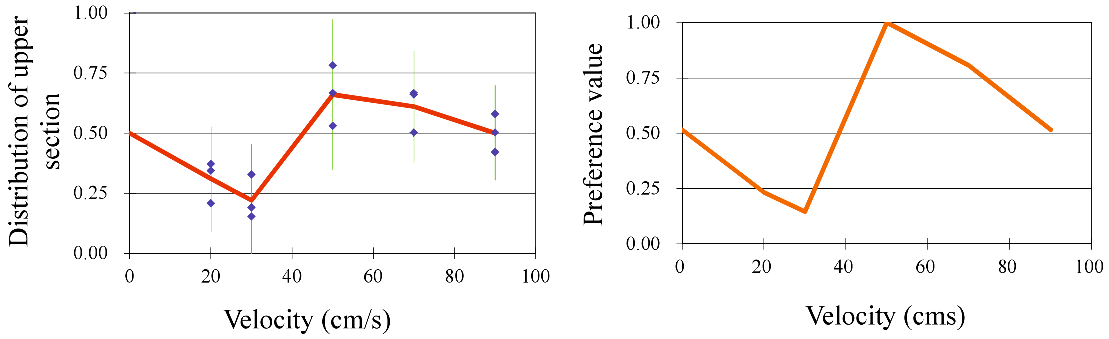


(a) (b)

Fig. 3-5 Results for the various illumination conditions for the juvenile ayu. (a) distribution curve; (b) preference curve

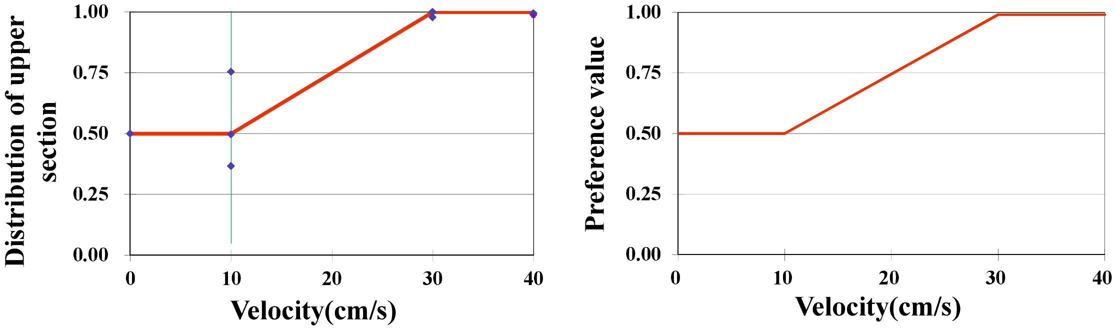
3.4.2 Rheotaxis experiment

The distribution data for the upstream side of the experimental watercourse are presented in Figs. 3-6 and 3-7. Table 3-3 presents a summary of the results and includes the calculated preference weights based on Eqs. (1) – (3). Juveniles in all flow rate conditions exhibited positive rheotaxis behavior that was particularly strong at 30–40 cm/s. Adult fish exhibited slightly negative rheotaxis behavior at flow rates <30 cm/s and positive rheotaxis at 50 and 70 cm/s.



(a) (b)

Fig. 3-6 Rheotaxis experiment result for adult ayu. (a) distribution curve; (b) preference curve.



(a) (b)

Fig. 3-7 Rheotaxis experiment result for juvenile ayu. (a) distribution curve; (b) preference curve

The results of these experiments indicate that rheotaxis depends on current velocity. As the velocity increased, a greater number of fish turned against the current. However, this progression was not always linear. Although pushed back by strong currents, most fish continued to be oriented against the flow, and active downstream swimming was rarely observed. Some fish on the bottom did face downstream or lay crosswise. Sometimes fish facing upstream turned around and faced downstream. Only adult ayu (i.e., no juveniles) displayed a slightly negative rheotaxis at flow rates of 20 cm/s and 30 cm/s.

Table 3-3
Distribution ratios for the upstream rheotaxis experiment and the composite experiment. Estimated ratio values for the composite experiment using the intensity distribution preference values.

	Juvenile Ayu				Adult Ayu					
Flow rate	0	10	30	40	0	20	30	50	70	90
Observed upstream distribution for rheotaxis experiment	0.5	0.54	0.99	0.99	0.5	0.37	0.33	0.8	0.61	0.5
Rhotaxis (+: positive, -: negative)	±	+	+	+	±	-	-	+	+	±
Observed upstream distribution for composite experiment	0.28	0.18	0.91	0.98	0.28	0.04	0.11	0.58	0.34	0.11
Weight of rheotaxis	-	-	0.71	1	-	-	-	1	0.63	-
Weight of illumination	-	-	1	0.74	-	-	-	0.36	1	-
Calculated upstream distribution for composite experiment with Weight	0.28	0.31	0.91	0.98	0.28	0.15	0.1	0.58	0.34	0.28
Calculated upstream distribution for composite experiment without Weight	0.28	0.31	0.97	0.97	0.28	0.15	0.1	0.43	0.38	0.28

3.4.3 Composite experiment

In the composite experiment, the distribution ratio for the upstream area decreased in all conditions because of the high preference for 4000 lux illumination. However, the rate of decline was smaller at 30 – 40 cm/s for the juveniles and at 50 cm/s for the adult ayu. This result indicates that ayu have a higher weight for rheotaxis at these flow rates. The upstream distribution of 10 cm/s for juveniles and 90 cm/s for adults was lower than expected based on the preference for illumination. This kind of disagreement is often observed for conditions that are not as important for, or severely affect, the fish. For adult fish, weights for the 20 and 30 cm/s velocities could not be calculated because in these cases the rheotactic and illumination preferences were higher for the lower watercourse.

Figure 3-8 presents the calculated and the observed distribution ratios. A weight value=1 was used for the conditions for which weights were not obtained. High reproducibility results when weights are used, but the direction of movement can be correctly determined without weights. Non-weighted calculations are useful for behavioral simulations (e.g., for studying the direction of movement of fish).

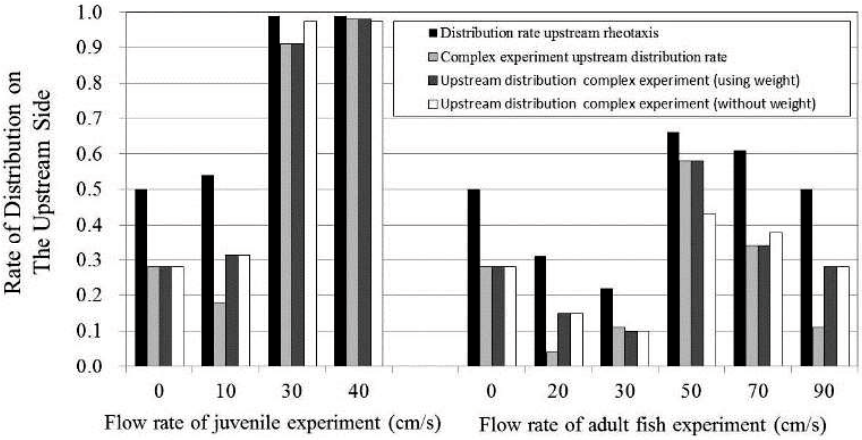
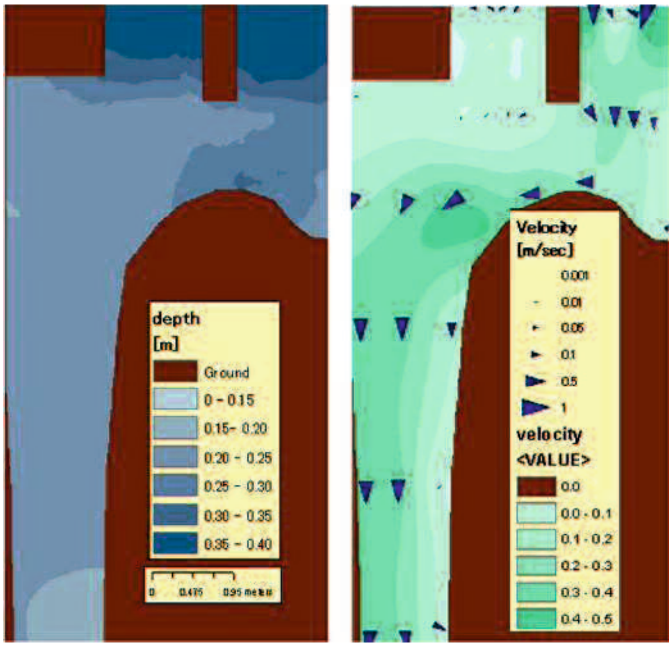


Fig. 3-8 Estimated distribution ratios for the rheotaxis experiment and the composite experiment

3.5 Application for behavioral simulation

I presented a modeling framework for the simulation of fish behavior. The model was validated using fish movement data. I also performed a field experiment in the Sawanami River near our university campus. The experiment was conducted on 20 April 2007. The water temperature was approximately 15°C. The experimental section was set downstream of the entrance of a fishway, and I tracked the behavior of fish released at the lowest point in the section. I released 20 juvenile ayu (10 cm body length) into the river and videotaped their behavior. Figure 3-9 presents the experimental river section, surrounded by a net. Figure 3-10 presents the velocity and depth conditions.

Fig. 3-9 The observation area



(a) (b)

Fig. 3-10 Environmental conditions. (a) depth; (b) velocity magnitude and flow direction.

In this outdoor research, I used only velocity preference in addition to rheotaxis preference because the depth of the raceway section was deep enough for juvenile ayu to maintain a constant preference. Except for a rock and concrete substrate at the upstream entrance, the substrate was a uniform mixture of gravel and sand. The velocity preference curve is presented in Fig. 3-11. In this simulation, nine surrounding locations, including the current location of a virtual fish, were compared. The virtual fish moved to the most preferred location, based on Eq. (1). When there was more than one high preference location, fish chose randomly. As discussed in the previous section, preference weight was not used in this calculation. Figure 3-12 presents the surrounding locations and the rheotaxis calculation method. The simulation was performed using Visual Basic for Applications (Microsoft Corporation, Redmond, WA USA) and ArcGIS 8.3 (ESRI, Redlands, CA USA). In this simulation, I supply the velocity preference raster layer (CSI), the horizontal velocity raster layer (Vx), and the vertical velocity raster layer (Vy). The initial location of a virtual fish is supplied as a point layer (Track). When the program runs, the virtual fish movement at each time step is tracked as a point on the "Track" layer.

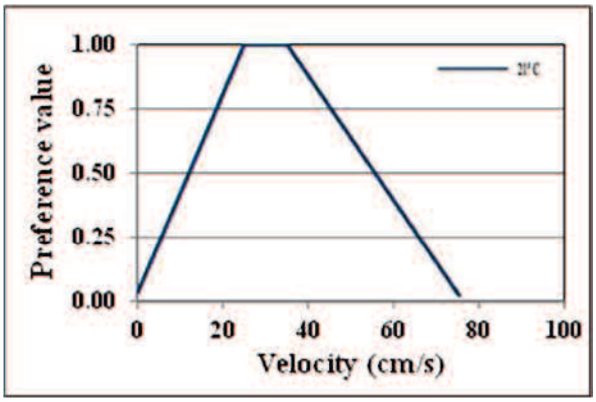
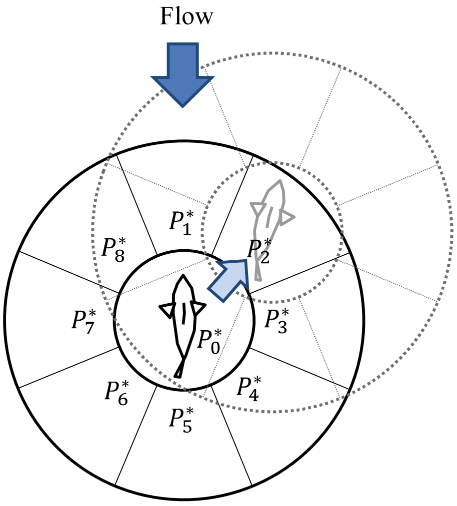


Fig. 3-11 Velocity preference curve



Preference for positive rheotaxis:

$P_r0 = 1 - D_{up}$
$P_r1 = D_{up}$
$P_r2 = P_r1 \times \sin 45°$
$P_r3 \sim P_r7 = 0.01$
$P_r8 = P_r1 \times sin\,45°$

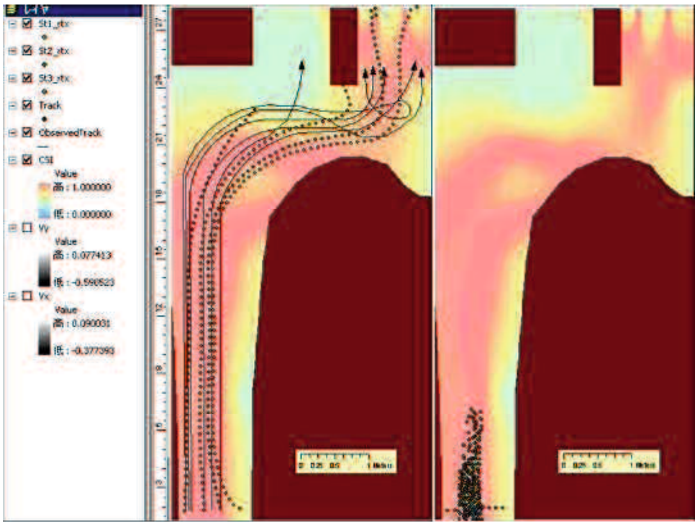
Preference for negative rheotaxis:

$P_r0 = D_{up}$
$P_r1 \sim P_r3 = 0.01$
$P_r4 = P_r5 \times \sin 45°$
$P_r5 = 1 - D_{up}$
$P_r6 = P_r5 \times \sin 45°$
$P_r7 \sim P_r8 = 0.01$

D_{up} : distribution of upper section in rheotaxis experiment

Overall preference P^*n for each direction n is calculated using equation (1) :
$P^*n = P_rn \times P_vn$ where P_vn is a preference for velocity at for direction n.

Fig. 3-12 Estimation of overall preference in the simulation study



(a) (b)

Fig. 3-13. Simulation results for juvenile ayu. (a) with rheotaxis; (b) without rheotaxis

Figure 3-13 presents results using four initial locations. Using rheotaxis preference values, the calculated results show good agreement with observed fish behavior. Without rheotaxis values, virtual fish tend to stay at a local peak of velocity preference. Our modeling is in the initial stages of the quantitative evaluation of rheotaxis. However, our simulation model successfully reproduced an observed juvenile ayu migration behavior in a river.

3.6 Conclusion

I modeled rheotaxis preferences in juvenile and adult ayu. Juvenile ayu displayed a strong positive rheotactic response at flow rates of 30–40 cm/s. Adult ayu displayed a positive response at flow rates of 50–70cm/s, but it was a weaker response than for the juvenile fish. I also estimated weight values for rheotaxis and illumination. For the rheotaxis response, estimated weight values =1 (for 40 cm/s) and 0.71 (for 30 cm/s). For the response to illumination, weight values = 0.74 (for 40 cm/s) and 1 (for 30 cm/s). At a flow rate of 50 cm/s, weight values for rheotaxis and illumination responses in adult ayu were 1 and 0.36, respectively. At a flow rate of 70 cm/s, rheotaxis and illumination weight values were 0.63 and 1, respectively. I also proposed a framework for the incorporation of rheotaxis into fish behavior simulations. Our simulation model successfully reproduced natural juvenile ayu migration behavior. I have demonstrated that the rheotaxis response can be accurately modeled and quantified.

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CHAPTER 4

PREFERENCE MODEL OF UNDERWATER SOUNDS TO FIND AN ENTRANCE OF FISH PASSAGE

4.1 Introduction

The auditory system is one of the most important sensory systems for an aquatic animal because it provides information about food, competitors, predators, and potential mates through the perception of intended and unintended acoustic signals in the environment (Myrberg, 1978). Studies of fish hearing and sound production (bioacoustics), and the importance of sounds to the lives of fishes, were not initiated, however, until the early part of the 20th century (Moulton, 1963; Tovolga, 1971). The level of investigation of fish hearing and sound production increased considerably in the second half of the 20th century (Popper and Fay, 1999; Zelick et al., 1999; Popper et al., 2003; Ladich and Popper, 2004). Fishes are able to respond to a wide range of sounds, discriminate between sounds of different magnitudes or frequencies, detect a sound in the presence of other signals, and determine the direction of a sound source (sound source localization). And also fish can listen to sounds produced by either conspecifics or heterospecifics, and they can take corresponding actions such as retreating or escalating agonistic behavior or being attracted to source if the sounds are courtship signal (Yan et al., 2010).

Sounds are believed to elicit changes in the behavior of fish (Yan et al., 2010). Few studies have shown that sound can attract or repel fish over great distances or for long lengths of time. Water sounds are believed to have a considerable roll for fish to trigger their ascending behavior. Modeling effect of underwater sound on fish preference must play an important role in determining the migration path for comprehensive river habitat evaluation. Thus the purpose of this research is to model fish preference on underwater sounds. This research consists of two experiments. Firstly, I observe fish distribution with various sound sources in different sound pressure levels using an experimental tank in laboratory. Based on the observed fish distribution, I quantitatively describe the preference of fish on sounds as suitability index, and determine weight of sound preference to compare with other environmental factors. Secondly, I build the sound preference into our fish behavior simulation model on GIS software, and try to reproduce an observed fish migration behavior through a field experiment in a river.

4.2 Materials and methods

4.2.1 Experimental sound source

Sound sources are pure sound (100 Hz, 200 Hz, 400 Hz and 800 Hz), white noise, a recorded sound at a fish ladder in Misumi River (Fig. 4-1a), and a recorded sound at a weir in Fushino River (Fig. 4-1b). The fish ladder is selected as that of fish can pass through and the weir is selected as a water gap which fish cannot pass through. Fig. 4-2 shows sound frequency observed in the sound of the fish ladder and weir. Frequencies of pure sounds are selected from under 1000 Hz, because literatures suggest that common fish is sensitive to that range of frequency (Fay, 1988; Ishioka et al., 1988; Schellart and Popper, 1992; Kojima et al., 1992; Fujieda et al., 1996; Motomatsu et al., 1996; Park and Iida, 1998; Popper and Fay, 1993, 1999; Akamatsu et al., 2003).

(a) (b)

Fig. 4-1 Location of sounds recording. (a) Fish ladder in Misumi River; (b) weir of Fushino River.

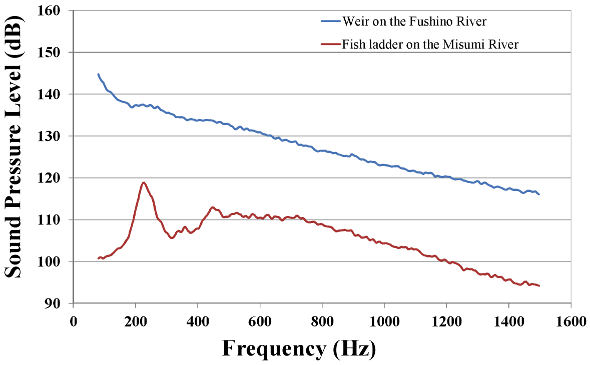


Fig. 4-2 Frequency analysis result

4.2.2 Experimental animal

As an experimental fish, I choose ayu (*Plecoglossus Altivelis Altivelis*) because it is an amphidromous species and is the most important commercial fish in Japan (Ishida, 1976). Juvenile Ayu (8±1 cm) and adult ayu (16±1 cm) are purchased from Fushinogawa fishing cooperative. I maintain the fish in a tank (90 cm long x 30 cm width x 50 cm heights) under recirculated, temperature-controlled conditions (21±1°C) with supplemental aerator. I fed them compound feed (0.5 g/fish, *Kawazakana no esa*, KYORIN Co. Japan) once per day after experiments, or at 15:00 on the days they were not included in an experiment.

4.2.3 Experimental set up

To determine sound responses, juvenile and adult ayu are placed in experimental apparatus (Fig. 4-3). It is made of transparent acrylic and an underwater speaker is installed in the one end. Inside the apparatus, a frame made of vinyl chloride pipe is installed about 5 cm apart from the apparatus walls, and 5 cm thick sound absorption materials made of white polyester are placed all interior side of the frame except the speaker face and upper side. Another wall of sound adsorption material is placed 60 cm apart from the speaker face to limit the experimental section to 60 cm long. The sound absorption material is also intended to minimize visual stimulation for fish. Water is poured until depth of 25 cm from the bottom absorption material. One fluorescent lamp is installed 2 m above the apparatus to maintain light condition at approximately 250 lux at the water surface. A PC is connected to the speaker through amplifier (Aiwa Digital Audio System XG-320). Underwater sound pressure meter (Oki Electric SW1020) is used to measure the sound pressure in the apparatus.

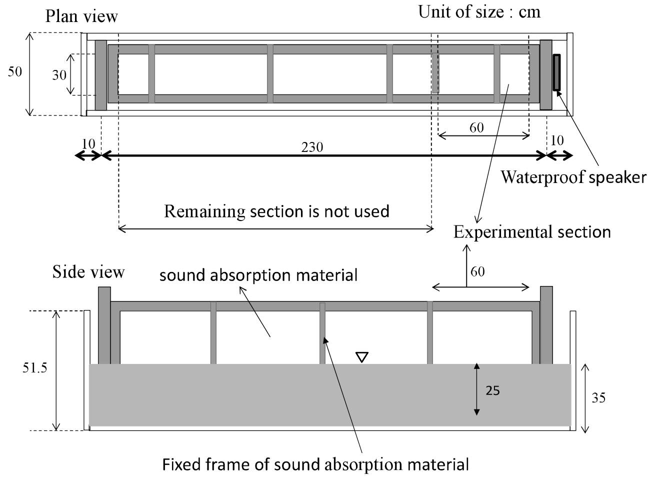


Fig. 4-3 Experimental Apparatus

4.2.4 Experimental method

The experiments are performed between 10:00 to 18:00 to control the effects of diurnal variability in behavior (Jidong et al., 2001). For each test, three fishes at a time were randomly selected from the stock tank and placed in the watercourse to acclimate for 10 min at water temperature = 21±1°C. After one testing is completed, fishes are moved to a different tank to avoid using them in multiple experiments in the same day.

At the beginning of a sound experiment, no sound was emitted during the 10 min acclimation period. Then I emit sound from speaker, and fish distribution in the apparatus is recorded during 3 minutes with a video camera (SONY SR-60) placed above the apparatus. 3 minutes of experimental duration is determined through a pre-observation of 10 minutes. Through the pre-observation, fish show higher response on sound during the first 3 minutes, and they start losing concentration on sound afterward. Ronald et al (2008) also stated that fish lose their concentration on sound within 5 minutes in their research.

Using the recorded fish distribution, I count the number of fish which stay in each 10 cm long sub-section in the 60 cm long experimental section every 3 second. I repeat three experiments for one sound condition, and determine fish distribution for one sound condition by averaging total 180 observations.

Different importance on preference exists between different environmental factors. By conducting experiments which combine two environmental factors, such difference of importance can be examined. Since my purpose is to model fish migration behavior in a river, it is necessary to determine “weight” of preference for sound compared with velocity or other important environmental factors. Authors have already determined preferences for velocity, shade, rheotaxis and their weights for Ayu (Febrina et al., 2012). In this research, I conduct weight experiments combining shade and sound. To create different shade, we divide the experimental section into two 30 cm sections, and cover one of them with black cheesecloth. Since lower shade shows higher preference for ayu in our previous research, we set lower shade to a section closer to the speaker when combined with avoided sound, and set lower shade to a section apart from the speaker when combined with preferred sound.

4.3 Theory of analysis

4.3.1 Sound pressure level and its effect on fish

The underwater sound as it relates to fish is the presence of a substantial particle motion component in the aquatic sound field, along with pressure. Sound pressure level (SPL) or sound level is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. It is measured in decibel (dB) above a standard reference level. SPL in water can be calculated with the following equation:

$$\text{SPL (dB)} = 20 \log (p/p_0) \tag{1}$$

Where p is the pressure level of sound in μPa and p_0 is reference pressure level (1 μPa for underwater sounds); therefore, underwater sound pressure is usually expressed as dB re 1 μPa. Hatakeyama (1996) characterized effect of underwater SPL on fish such as “attractive level” (110-130 dB), “aversive level” (130-160 dB), and “injurious level” (220 dB ≤).

4.3.2 Formulation of preference

Authors have formulated preference of fish on environmental factors through laboratory experiments based on pair comparison using a U-shaped experimental watercourse (Sekine et al., 1997), and the formula have been validated through several researches (Sekine et al., 2001, Karim et al., 2003, Sekine et al., 2004, Fukuda and Hiramatsu, 2008, Sekine et al., 2009, Febrina et al., 2012). The formula is described as below:

$$P^{*} = \prod_{j=1}^{J} \left(P_j\right)^{\frac{W_j}{W_{\max}}} \tag{2}$$

$$W_{\max} = \begin{cases} \max_{J \in V} \left(W_j\right) & V \neq \phi \\ \infty & V = \phi \end{cases} \tag{3}$$

$$V = \left\{ j \middle| \left(\exists i, i`\right)\left(P_{j,i} \neq P_{j,i}\right) \right\} \tag{4}$$

Where P^{*} is overall preference, P_j is preference for environmental condition j, W_j is weight of environmental condition j, W_{max} is maximum weight among weight sets, V, that had different preference levels in surrounding water body, ϕ represents the null set, $\exists$ is an existential quantifier, and i represents a segmented location of water body. This formula has an important advantage that environmental preference and its weight can be determined separately. Consequently, a new environmental factor can be added or removed without affecting other environmental factors. Thus I employ this formula to newly add the sound preference on already existing preference information.

4.3.3 Concept of sound

In this research, I observe fish distribution at every sub-section in the experimental section to get sound preference formula (Fig. 4-4). I emit sound from the speaker with seven different sound pressure levels. As sound propagates, sound pressure level decreases inversely with increasing distance from source, and create different SPL at each sub-sections. I assume that the distribution of fish is proportional to the preference of SPL at each sub-section.

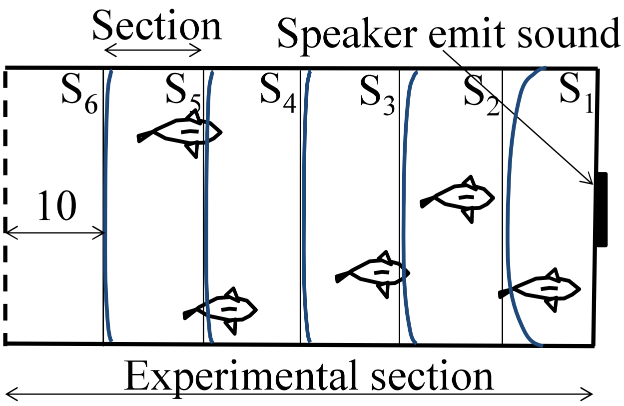


Fig. 4-4 The concept of watercourse for sound experiment

Since I cannot get enough range of SPL difference from one experimental condition of sound, I combine seven different SPL experimental results into one preference curve. Fig.5 shows an example of combining seven results and building one preference curve (data taken from the experimental result).

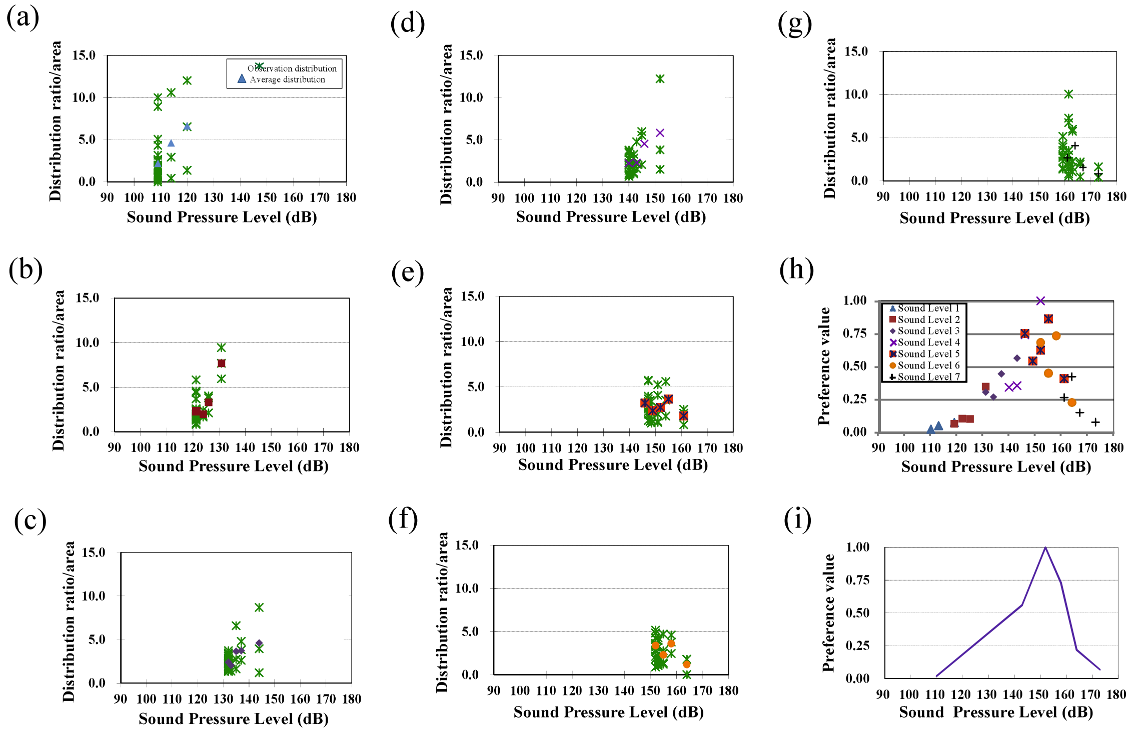


Fig. 4-5 An example how to determine preference for sound, data taken from the experiment using fish ladder sound with adult Ayu. (a) Sound level1; (b) sound level 2; (c) sound level 3; (d) sound level 4; (e) sound level 5; (f) sound level 6; (g) sound level 7; (h) preference (sound level 1~ 7); (i) Preference curve for sound recorded of fish ladder.

4.4 Results and discussion on determining sound preference

4.4.1 Sound Experiment

Data of fish's distribution at every sub section are presented at Table 4-1 to 4-4 Figure 4-6 and Figure 4-7 show all experimental results of preference for sound at every sound level. In both figures, I gave small markers for juvenile distribution at the subsections near edge because the edges of apparatus seems affecting the distribution of juvenile.

Table 4-1
Fish distribution at every sub section for juvenile Ayu with pure sound source

Sound source		100Hz				200Hz				400Hz				800Hz			
	a	b	c	d	e	b	c	d	e	b	c	d	e	b	c	d	e
Sound Level 1	5	118	0.00	2.04	1.02	124.6	1.67	0.00	0.83	115.4	0.74	3.15	1.94	115.8	0.37	0.00	0.19
	15	106	0.00	13.33	6.67	108.3	12.1	1.85	6.94	104.2	6.67	10.2	8.43	101.8	3.33	8.15	5.74
	25	103	0.19	14.81	7.50	102.3	16.3	19.3	17.8	98.3	11.1	7.04	9.07	100.3	10.6	17.2	13.9
	35	102	8.70	2.96	5.83	98.3	2.96	12.4	7.69	97.9	8.52	6.67	7.59	98.3	9.63	5.56	7.59
	45	100	18.7	0.19	9.44	96.3	0.37	0.00	0.19	98.3	6.11	5.56	5.83	97.2	8.33	2.22	5.28
	55	98	5.74	0.00	2.87	96.3	0.00	0.00	0.00	98.7	0.19	0.74	0.46	96.9	1.11	0.19	0.65
Sound Level 2	5	128	0.00	1.67	0.83	134.1	4.26	0.00	2.13	125.2	0.56	0.02	0.29	122.7	0.37	1.11	0.74
	15	117	0.00	13.52	6.76	121.9	15.2	2.04	8.61	107.9	4.07	0.06	2.07	109.8	2.78	10.4	6.57
	25	112	0.00	15.74	7.87	105.8	13.3	20.2	16.8	99.8	9.44	0.04	4.74	101.8	10.2	11.9	11.1
	35	108	0.19	2.41	1.30	100.9	0.56	11.1	5.83	98.6	10.7	0.04	5.39	99.1	12.1	7.04	9.54
	45	104	14.8	0.00	7.41	99.8	0.00	0.00	0.00	99.2	7.78	0.03	3.90	97.6	7.41	2.41	4.91
	55	102	18.3	0.00	9.17	101.4	0.00	0.00	0.00	100.4	0.19	0.00	0.09	98.5	0.56	0.56	0.56
Sound Level 3	5	138	0.19	0.00	0.09	144.9	1.67	0.00	0.83	130.4	0.00	3.52	1.76	128.7	0.19	0.37	0.28
	15	125	0.56	0.00	0.28	125.4	16.5	0.93	8.70	115.8	0.19	12.1	6.11	114.9	4.07	5.74	4.91
	25	120	1.67	0.93	1.30	113.5	13.3	14.4	13.9	104.3	3.33	10.2	6.76	112.8	9.44	12.4	10.9
	35	115	8.70	9.44	9.07	104.3	1.67	17.2	9.44	103.1	13.5	4.63	9.07	102.3	11.3	10.9	11.1
	45	111	14.3	18.89	16.57	104.3	0.19	0.74	0.46	100.4	15.9	1.67	8.80	99.2	6.85	2.78	4.81
	55	109	7.78	3.89	5.83	108.6	0.00	0.00	0.00	99.2	0.37	1.30	0.83	100	1.48	0.37	0.93
Sound Level 4	5	144	0.00	0.00	0.00	150.4	0.00	0.00	0.00	138.3	0.37	7.59	3.98	135.4	0.74	0.00	0.37
	15	133	0.00	0.00	0.00	131.8	13.2	2.59	7.87	123.1	1.67	8.15	4.91	122.3	3.52	4.26	3.89
	25	127	1.11	0.19	0.65	119.8	19.8	16.9	18.3	108.3	5.56	6.30	5.93	115.4	10.7	15.9	13.3
	35	123	10.7	7.41	9.07	111.8	0.37	13.7	7.04	105.8	14.1	5.74	9.91	105.8	12.6	11.5	12.1
	45	118	15.4	18.52	16.94	106.3	0.00	0.19	0.09	102.3	11.5	3.70	7.59	102.3	5.00	1.48	3.24
	55	117	6.11	7.22	6.67	115.5	0.00	0.00	0.00	100.9	0.19	1.48	0.83	101.3	0.74	0.19	0.46
Sound Level 5	5	154	0.00	0.00	0.00	158.7	0.00	0.00	0.00	145.5	0.00	6.30	3.15	148.5	0.37	0.19	0.28
	15	142	0.00	0.00	0.00	138.3	17.4	2.04	9.72	128.3	1.67	7.22	4.44	130.3	2.22	5.19	3.70
	25	136	2.41	0.19	1.30	127.1	15.0	15.0	15.0	116.3	5.74	8.15	6.94	120.9	9.07	13.2	11.1
	35	130	10.4	4.26	7.31	121.9	0.74	15.7	8.24	110.4	15.9	6.48	11.2	111.8	13.0	10.2	11.6
	45	127	14.3	20.74	17.50	113.5	0.19	0.56	0.37	107.1	10.0	3.89	6.94	105.8	7.04	4.26	5.65
	55	124	6.30	8.15	7.22	122.8	0.00	0.00	0.00	103.2	0.00	1.30	0.65	102.3	1.67	0.37	1.02
Sound Level 6	5	157	0.00	0.00	0.00	164.9	0.19	0.00	0.09	153.5	0.00	6.11	3.06	151.4	1.30	0.74	1.02
	15	146	0.00	0.00	0.00	145.8	22.4	0.19	11.3	132.3	0.56	10.7	5.65	135.8	2.59	7.04	4.81
	25	141	0.00	0.00	0.00	131.8	9.81	13.9	11.9	119.2	4.81	6.30	5.56	124.3	12.8	12.2	12.5
	35	136	6.48	2.59	4.54	125.5	0.56	19.1	9.81	114.3	15.9	4.63	10.3	116.3	12.1	9.81	10.9
	45	132	16.5	20.00	18.24	122.3	0.37	0.19	0.28	110.4	12.1	3.89	7.96	110.6	4.63	3.33	3.98
	55	129	10.4	10.74	10.56	126.4	0.00	0.00	0.00	106.3	0.00	1.67	0.83	103.1	0.19	0.19	0.19
Sound Level 7	5	164	0.00	0.00	0.00	176.4	0.19	0.00	0.09	166.2	2.22	5.93	4.07	163.8	1.67	0.37	1.02
	15	158	0.00	0.00	0.00	160.9	15.6	0.00	7.78	149.9	7.22	7.59	7.41	149.9	3.70	9.63	6.67
	25	146	0.00	0.00	0.00	149.6	15.7	13.2	14.4	138.1	5.37	6.30	5.83	138.1	9.63	14.3	11.9
	35	135	4.07	1.67	2.87	142.6	0.93	19.8	10.4	130.8	7.96	6.48	7.22	127.6	11.9	7.96	9.91
	45	127	14.3	18.33	16.30	137.4	0.93	0.37	0.65	123	10.0	4.44	7.22	118.1	5.93	1.11	3.52
	55	122	15.0	13.33	14.17	134.9	0.00	0.00	0.00	119.2	0.56	2.59	1.57	110	0.56	0.00	0.28

Note: a: Distance from speaker (cm). b: Sound Pressure Level (dB). c: Fish distribution ratio/ area of run 1; area = sub section = 0.1 for length (m) x 0.3 for width (m). d: Fish distribution ratio/ area of run 2. e: Fish distribution ratio/ area of run 3.

Table 4-2
Fish distribution at every sub section for juvenile Ayu with sound source recorded and white noise

Sound source		White noise				Weir				Fish ladder			
	a	b	c	d	e	b	c	d	e	b	c	d	e
Sound Level 1	5	125.5	0.00	0.00	0.00	117	0.19	0.37	0.28	112	0.00	0.00	0.00
	15	110.6	0.37	1.11	0.74	109	5.37	5.37	5.37	103.9	7.78	8.52	8.15
	25	105	3.89	9.26	6.57	103	6.11	9.81	7.96	103.9	10.74	13.52	12.1
	35	102	10.93	17.78	14.35	100	10.56	8.89	9.72	100.9	12.41	8.89	10.7
	45	103	17.22	5.19	11.20	100	10.19	8.33	9.26	100.9	2.41	2.22	2.31
	55	102.9	0.93	0.00	0.46	100	0.37	0.56	0.46	100.4	0.00	0.19	0.09
Sound Level 2	5	134.9	0.00	0.56	0.28	130	0.00	0.00	0.00	122.6	0.74	0.00	0.37
	15	120.1	0.56	2.41	1.48	123	10.74	5.74	8.24	111.4	6.30	8.70	7.50
	25	111.5	2.59	5.37	3.98	115	12.22	10.56	11.39	104.9	10.74	11.67	11.2
	35	109.5	13.89	17.04	15.46	113	7.96	12.22	10.09	101.8	11.11	9.07	10.1
	45	108	15.74	7.96	11.85	113	2.22	4.81	3.52	102.2	4.07	3.52	3.80
	55	108	0.56	0.00	0.28	110	0.19	0.00	0.09	100.9	0.37	0.37	0.37
Sound Level 3	5	144.4	0.00	0.19	0.09	140	0.37	0.00	0.19	133.4	0.37	0.00	0.19
	15	129.5	0.19	2.41	1.30	133	7.41	4.26	5.83	119.9	8.15	10.19	9.17
	25	120	2.96	7.04	5.00	125	11.67	13.15	12.41	108.1	12.04	16.11	14.1
	35	118.5	14.81	13.15	13.98	125	9.26	9.26	9.26	104.1	9.44	5.93	7.69
	45	117	15.37	10.37	12.87	123	4.63	6.67	5.65	103	3.33	1.11	2.22
	55	118	0.00	0.19	0.09	120	0.00	0.00	0.00	103	0.00	0.00	0.00
Sound Level 4	5	153.2	0.00	0.19	0.09	151	2.96	0.00	1.48	141.5	0.93	0.00	0.46
	15	139.9	0.19	5.74	2.96	142	10.56	6.30	8.43	126.9	10.74	5.93	8.33
	25	128.9	1.30	7.96	4.63	137	8.89	11.85	10.37	115	10.74	12.04	11.4
	35	126.8	10.93	9.44	10.19	133	7.96	9.63	8.80	109.4	7.41	10.37	8.89
	45	125.8	19.44	9.81	14.63	133	2.78	5.56	4.17	108.3	3.52	5.00	4.26
	55	126.4	1.48	0.19	0.83	129	0.19	0.00	0.09	110.6	0.00	0.00	0.00
Sound Level 5	5	161.1	0.00	0.00	0.00	157	4.81	0.19	2.50	149.4	0.19	0.19	0.19
	15	148	1.11	2.41	1.76	150	6.85	5.93	6.39	135.4	7.04	7.96	7.50
	25	136.8	5.37	7.22	6.30	143	8.89	11.67	10.28	126.6	10.74	14.07	12.4
	35	134.5	15.00	15.93	15.46	140	8.15	10.19	9.17	117.2	11.11	8.33	9.72
	45	134.4	11.48	7.78	9.63	138	3.89	5.19	4.54	116.1	4.26	2.78	3.52
	55	133.3	0.37	0.00	0.19	138	0.74	0.19	0.46	115.7	0.00	0.00	0.00
Sound Level 6	5	165.5	0.00	0.00	0.00	162	0.56	0.00	0.28	154.8	0.00	0.19	0.09
	15	151.5	0.74	1.11	0.93	153	14.44	5.00	9.72	138.1	7.22	4.81	6.02
	25	142	4.26	6.30	5.28	149	12.96	12.78	12.87	129.4	13.33	10.74	12.1
	35	138.4	13.33	13.89	13.61	145	3.89	10.19	7.04	122.2	9.07	12.04	10.6
	45	137.4	14.81	12.04	13.43	145	1.11	5.37	3.24	119	3.52	5.37	4.44
	55	138	0.19	0.00	0.09	140	0.00	0.00	0.00	122.8	0.19	0.19	0.19
Sound Level 7	5	175.4	0.00	0.19	0.09	173	0.00	0.00	0.00	165.2	0.56	0.00	0.28
	15	161	0.00	3.33	1.67	163	6.85	1.67	4.26	146.9	8.33	7.96	8.15
	25	150.8	2.04	11.48	6.76	157	15.37	9.07	12.22	137.9	11.85	13.70	12.8
	35	147.6	12.41	12.59	12.50	155	9.63	14.07	11.85	131.1	8.52	7.59	8.06
	45	146.5	18.70	5.74	12.22	153	1.48	8.52	5.00	130	3.89	3.89	3.89
	55	147.1	0.19	0.00	0.09	153	0.00	0.00	0.00	131.1	0.19	0.19	0.19

Note: a: Distance from speaker (cm). b: Sound Pressure Level (dB). c: Fish distribution ratio/ area of run 1; area = sub section = 0.1 for length (m) x 0.3 for width (m). d: Fish distribution ratio/ area of run 2. e: Fish distribution ratio/ area of run 3.

Table 4-3
Fish distribution at every sub section for adult Ayu with pure sound source

Sound source		100Hz				200Hz				400Hz				800Hz			
	a	b	c	d	e	b	c	d	e	b	c	d	e	b	c	d	e
Sound Level 1	5	99.8	0.76	1.40	1.08	99.8	5.56	8.52	7.04	99.8	3.89	9.07	6.48	115.8	2.04	12.22	7.13
	15	99	1.84	2.02	1.93	99	5.37	6.11	5.74	99	4.81	8.52	6.76	101.8	4.07	7.78	5.74
	25	97.6	5.85	4.33	5.09	97.7	4.63	4.44	4.54	97.7	5.74	7.22	6.76	100.3	2.96	5.74	4.35
	35	96.9	2.59	2.90	2.75	96.9	5.37	5.37	5.37	96.9	6.30	10.00	7.04	98.3	4.26	3.52	3.89
	45	98.9	10.61	9.10	9.86	98.9	6.67	4.63	5.65	98.9	6.30	6.48	5.37	97.2	8.15	2.59	5.37
	55	96.9	1.77	1.68	1.73	96.9	5.19	4.26	4.72	96.9	6.30	6.11	3.98	96.9	11.85	1.48	6.67
Sound Level 2	5	117.5	0.33	0.55	0.44	124.5	7.59	3.52	5.56	115.4	5.00	6.48	5.65	122.7	3.33	15.00	9.17
	15	106.1	0.78	2.44	1.61	108.3	7.59	5.19	6.39	104.2	5.19	6.85	6.02	109.8	4.26	10.00	7.13
	25	103	4.53	5.56	5.04	102.3	4.44	4.63	4.54	98.3	4.26	7.41	6.30	101.8	3.89	4.81	4.35
	35	101.7	1.78	1.23	1.50	98.3	5.56	6.11	5.83	97.9	6.30	10.19	8.43	99.1	5.74	2.04	3.89
	45	100.1	11.32	9.88	10.60	96.3	5.19	5.93	5.56	98.3	7.04	8.89	6.94	97.6	6.85	0.93	3.89
	55	98.1	9.47	8.23	8.85	96.3	2.78	7.78	5.28	98.7	5.56	7.22	6.30	98.5	9.26	0.74	5.00
Sound Level 3	5	128.4	0.71	0.22	0.46	134.1	7.41	6.85	7.13	125.2	6.30	6.67	6.20	128.7	3.33	11.85	7.59
	15	116.9	1.29	1.03	1.16	121.9	6.67	5.74	6.20	107.9	5.19	6.48	5.37	114.9	4.63	9.26	6.94
	25	111.7	4.86	3.24	4.05	105.8	5.56	5.19	5.37	99.8	5.37	6.48	5.93	112.8	4.63	6.30	5.46
	35	108.4	10.74	8.71	9.73	100.9	5.93	3.33	4.63	98.6	6.11	6.11	6.02	102.3	4.81	3.89	4.35
	45	104.2	8.71	12.36	10.54	99.8	4.81	4.63	4.72	99.2	5.19	9.07	7.69	99.2	7.78	1.67	4.72
	55	101.7	6.48	8.31	7.40	101.4	2.59	7.78	5.19	100.4	5.19	6.85	6.57	100	8.15	0.37	4.26
Sound Level 4	5	138.1	0.00	0.37	0.19	144.9	5.93	5.37	5.65	130.4	4.07	4.63	5.46	135.4	2.41	12.04	7.22
	15	125.2	1.27	1.69	1.48	125.4	7.96	5.74	6.85	115.8	6.67	3.15	4.72	122.3	3.89	7.78	5.83
	25	119.5	2.38	2.09	2.24	113.5	6.30	5.56	5.93	104.3	5.93	4.63	5.37	115.4	4.26	5.19	4.72
	35	115	10.95	8.56	9.76	104.3	4.44	5.00	4.72	103.1	5.74	3.15	4.44	105.8	5.37	4.26	4.81
	45	110.7	10.76	11.15	10.95	104.3	5.93	5.93	5.93	100.4	5.56	4.81	5.28	102.3	8.33	2.59	5.46
	55	109.3	4.58	4.98	4.78	108.6	2.78	5.74	4.26	99.2	5.37	6.85	6.67	101.3	9.07	1.48	5.28
Sound Level 5	5	144.4	0.05	0.60	0.33	150.4	6.48	6.48	6.48	138.3	4.26	3.52	4.91	148.5	2.96	9.81	6.39
	15	133	1.38	2.25	1.81	131.8	8.52	6.67	7.59	123.1	5.00	4.44	5.74	130.3	5.93	7.96	6.94
	25	127.2	4.08	6.93	5.50	119.8	2.96	4.63	3.80	108.3	6.30	5.74	5.46	120.9	5.74	6.30	6.02
	35	123	12.23	7.54	9.89	111.8	5.37	4.63	5.00	105.8	5.74	3.15	4.35	111.8	6.11	2.78	4.44
	45	118.1	4.06	3.84	3.95	106.3	6.67	5.74	6.20	102.3	4.81	2.78	3.80	105.8	7.41	3.15	5.28
	55	116.5	5.71	4.08	4.89	115.5	3.33	5.19	4.26	100.9	7.04	4.26	5.74	102.3	5.19	3.33	4.26
Sound Level 6	5	153.7	0.54	0.00	0.27	158.7	5.74	7.22	6.48	145.5	1.85	2.96	4.63	151.4	2.04	7.96	5.00
	15	141.7	2.13	0.51	1.32	138.3	6.11	6.30	6.20	128.3	5.37	4.07	4.81	135.8	4.26	8.15	6.20
	25	136.1	6.03	5.02	5.53	127.1	5.74	6.11	5.93	116.3	6.30	1.85	3.52	124.3	4.63	6.85	5.74
	35	130.1	9.44	11.25	10.35	121.9	4.44	4.26	4.35	110.4	6.48	0.74	3.06	116.3	5.37	5.00	5.19
	45	126.5	3.42	4.73	4.08	113.5	5.37	5.74	5.56	107.1	7.22	1.30	4.17	110.6	7.59	4.81	6.20
	55	124.4	3.62	5.63	4.62	122.8	5.93	3.52	4.72	103.2	6.11	2.04	4.07	103.1	9.44	0.56	5.00
Sound Level 7	5	156.7	0.00	0.00	0.00	164.9	0.00	0.00	0.00	153.5	0.00	0.00	0.00	163.8	0.00	0.00	0.00
	15	146.1	0.00	0.00	0.00	145.8	0.00	0.00	0.00	132.3	0.00	0.00	0.00	149.9	0.00	0.00	0.00
	25	140.7	0.00	0.00	0.00	131.8	0.00	0.00	0.00	119.2	0.00	0.00	0.00	138.1	0.00	0.00	0.00
	35	136.2	0.00	0.00	0.00	125.5	0.00	0.00	0.00	114.3	0.00	0.00	0.00	127.6	0.00	0.00	0.00
	45	132.1	0.00	0.00	0.00	122.3	0.00	0.00	0.00	110.4	0.00	0.00	0.00	118.1	0.00	0.00	0.00
	55	129.4	0.00	0.00	0.00	126.4	0.00	0.00	0.00	106.3	0.00	0.00	0.00	110	0.00	0.00	0.00

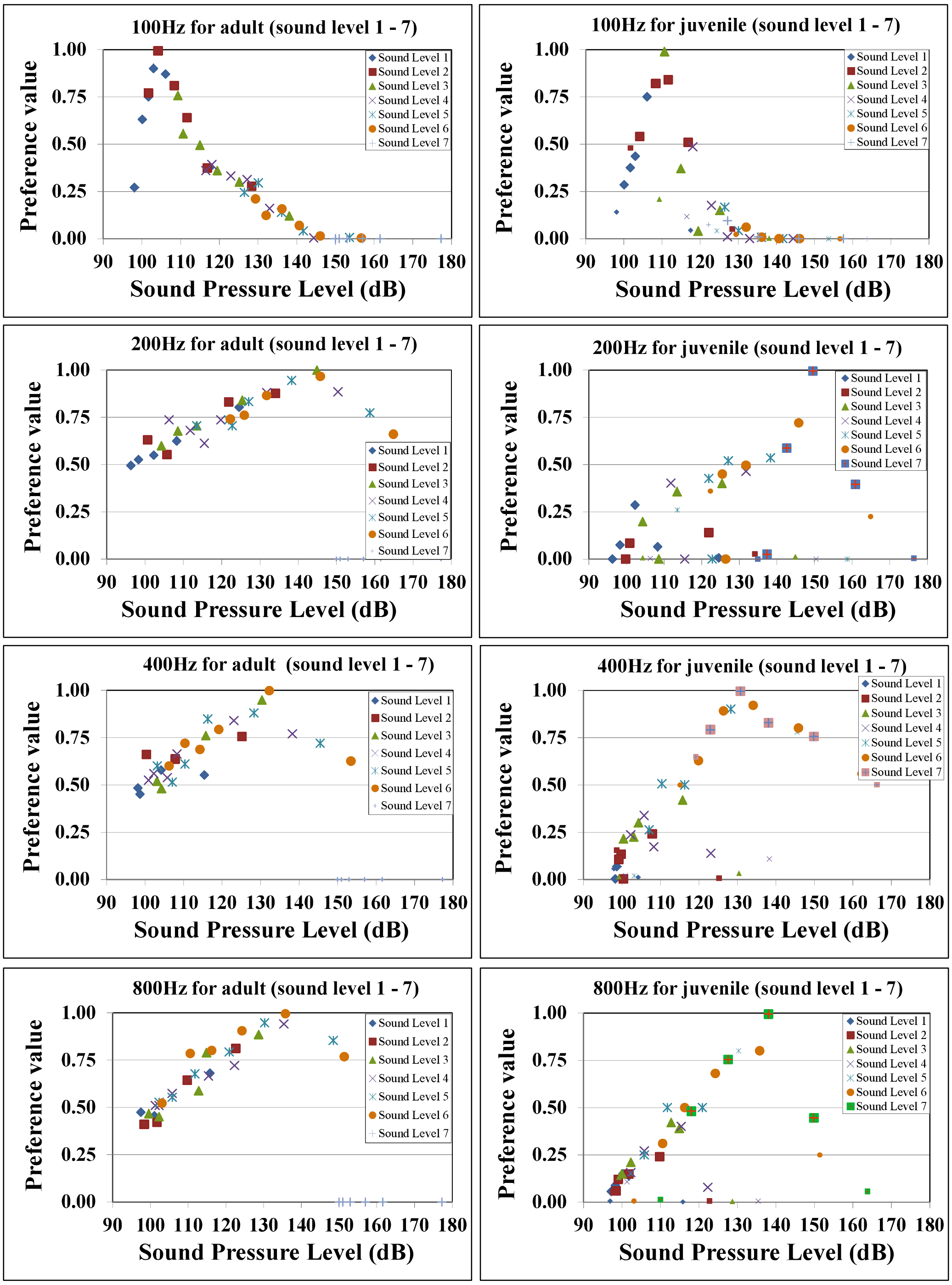
Note: a: Distance from speaker (cm). b: Sound Pressure Level (dB). c: Fish distribution ratio/ area of run 1; area = sub section = 0.1 for length (m) x 0.3 for width (m). d: Fish distribution ratio/ area of run 2. e: Fish distribution ratio/ area of run 3.

Table 4-4

Fish distribution at every sub section for adult Ayu with sound source recorded and white noise

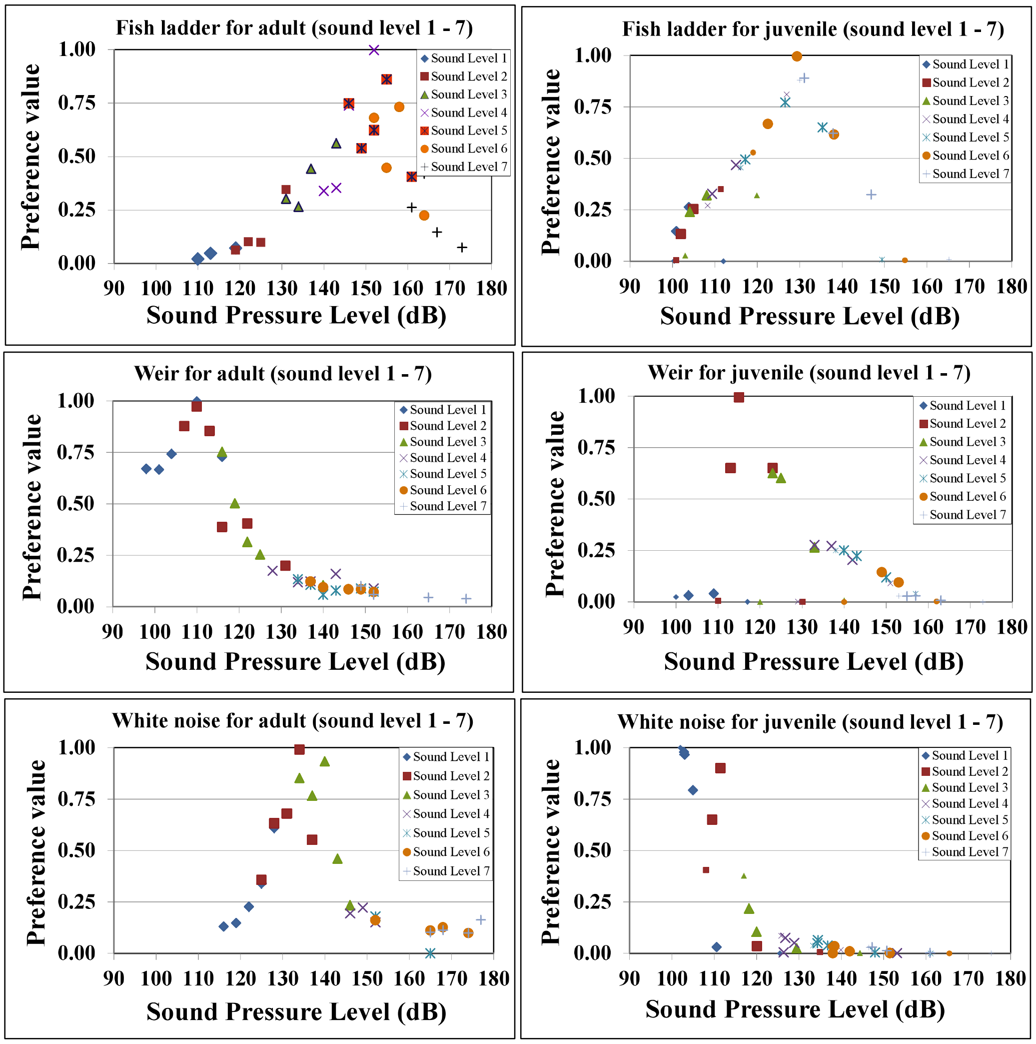
Sound source		White noise				Weir				Fish ladder			
	a	b	c	d	e	b	c	d	e	b	c	d	e
Sound Level 1	5	129	5.62	9.64	-	117	0.93	3.52	1.30	120	1.37	6.52	12.1
	15	124	4.86	4.61	-	109	2.78	6.11	3.15	114	0.42	2.91	10.6
	25	121.5	4.18	2.44	-	103	2.41	2.04	1.85	110	1.64	1.49	4.31
	35	119	3.12	2.17	-	100	1.48	1.48	1.11	110	0.46	1.97	2.67
	45	119	2.79	0.00	-	100	4.26	1.11	1.85	110	5.06	0.96	0.68
	55	118	2.17	2.85	-	100	5.37	2.96	3.89	110	8.93	2.55	0.21
	65	118	2.71	1.76	-	100	3.70	1.48	3.15	109	1.51	1.39	1.97
	75	118	2.49	2.24	-	100	3.70	2.04	2.41	109	0.81	3.13	0.46
	85	116.5	2.44	0.95	-	100	3.89	1.48	3.52	108	1.39	1.85	0.58
	95	116.5	0.95	2.58	-	100	1.85	3.52	4.44	108	1.74	2.55	0.00
	105	116.5	1.12	3.52	-	99	2.22	4.81	3.70	108	1.39	2.43	0.70
	115	116	2.17	2.17	-	99	0.74	2.41	2.96	108	10.01	1.43	1.91
Sound Level 2	5	138	4.12	0.75	-	130	0.93	3.15	1.11	131	9.44	5.94	7.69
	15	133	2.72	6.57	-	123	0.37	3.33	1.11	126	3.80	2.11	4.02
	25	131	3.08	3.57	-	115	0.56	2.04	2.04	124	1.67	1.82	2.42
	35	129	2.91	2.15	-	113	1.48	1.30	2.59	123	1.94	5.82	4.37
	45	128	1.90	1.01	-	113	2.22	1.11	2.59	122	1.30	1.77	2.48
	55	127	3.03	1.39	-	110	2.78	3.33	3.70	122	2.60	1.65	1.89
	65	127	4.17	3.71	-	110	5.00	2.96	5.00	122	2.36	1.39	0.97
	75	127	5.20	5.72	-	110	7.41	2.96	3.15	122	3.68	4.54	3.68
	85	126	0.76	2.02	-	110	4.44	3.70	3.33	120	2.01	2.48	2.01
	95	126	1.34	2.09	-	110	1.48	2.41	2.59	120	1.89	1.42	0.83
	105	125.5	1.52	1.64	-	107	4.44	3.89	2.59	120	0.94	1.89	1.53
	115	125	2.66	2.66	-	107	2.22	3.15	3.52	120	1.42	2.36	1.89
Sound Level 3	5	145	0.94	0.94	0.94	140	0.19	0.74	1.11	144	3.95	8.69	1.19
	15	141.5	0.86	3.71	0.86	133	1.48	1.85	3.15	137	3.82	4.78	2.63
	25	139	3.07	5.73	1.64	125	2.04	0.56	2.22	135	6.58	1.65	2.74
	35	137	3.99	5.42	2.55	125	1.67	0.74	2.41	133	1.37	2.40	2.40
	45	136.5	4.15	6.06	2.55	123	2.59	0.74	2.59	133	1.60	2.27	1.87
	55	136	3.99	2.71	1.28	120	3.89	1.30	2.41	133	1.87	2.40	1.47
	65	136	1.75	0.00	3.22	120	3.70	1.30	3.15	133	3.42	1.71	1.47
	75	136	0.00	0.00	4.59	120	2.41	9.26	1.67	132	2.80	2.27	2.54
	85	135.5	2.63	0.94	6.58	117.5	2.78	1.67	2.96	132	2.67	1.89	3.15
	95	134	3.03	3.03	3.67	117	5.37	4.07	3.52	131.5	3.34	1.33	3.47
	105	134	3.83	2.39	2.87	117	2.59	8.52	4.63	131	2.13	3.07	3.74
	115	134	3.35	1.44	5.26	115	4.63	2.41	3.52	131	2.00	2.27	3.07
Sound Level 4	5	155	0.00	4.68	1.70	151	6.85	0.74	0.56	152	3.82	12.22	1.53
	15	152	1.29	4.11	1.54	142	5.56	2.22	2.22	145	5.54	6.00	2.08
	25	149	1.84	1.66	1.84	137	3.89	2.04	0.56	143	2.12	1.59	4.77
	35	147.5	3.72	2.88	7.11	133	2.59	1.11	1.30	142	3.31	3.31	0.99
	45	147	2.44	2.58	2.58	133	3.70	2.41	1.48	142	1.16	2.06	1.68
	55	147	3.69	4.74	5.00	129	3.33	3.15	2.59	142	1.93	2.84	1.93
	65	146.5	2.44	2.30	2.30	129	0.93	5.00	5.56	142	2.84	0.71	3.78
	75	146	3.59	3.88	1.58	127	1.67	2.04	1.30	140	1.68	2.71	3.61
	85	145.5	3.02	3.02	4.60	127	1.85	3.52	1.85	140	2.06	2.06	3.48
	95	145	4.45	1.15	1.72	127	1.30	3.89	3.52	140	3.50	1.06	3.80
	105	145	2.95	2.36	2.36	127	0.93	4.63	5.93	139.5	2.06	0.90	2.19
	115	144.5	1.87	2.15	0.86	127	0.74	2.59	6.30	139	2.32	0.90	1.42
Sound Level 5	5	164	0.00	0.00	0.00	157	3.70	1.30	0.74	161	2.10	2.53	0.84
	15	160	0.00	2.43	4.86	150	3.70	0.93	2.22	154	3.56	5.60	1.78
	25	157.5	2.52	1.94	3.68	143	1.85	1.67	2.59	151	2.74	2.01	1.09
	35	156	3.02	1.96	2.85	140	1.67	1.48	1.48	151	5.26	4.09	1.17
	45	155.5	4.07	2.11	3.77	138	2.22	2.41	3.33	149	1.42	1.28	2.13
	55	155.5	1.66	1.38	4.43	138	2.96	2.22	3.15	148	2.42	0.99	3.41
	65	155	2.41	2.57	2.72	135	3.15	4.44	3.52	148	2.34	3.52	1.17
	75	154	4.38	5.58	2.41	135	2.96	7.41	2.78	148	5.73	2.87	1.30
	85	153	3.17	3.47	2.26	133	2.59	2.96	2.41	147	1.99	2.84	5.68
	95	153	3.47	3.77	2.26	133	2.41	1.85	4.07	147	2.27	2.70	3.98
	105	153	3.62	3.77	2.26	133	2.04	2.41	3.89	147	3.41	2.70	3.69
	115	153	2.48	2.48	6.20	133	4.07	4.26	3.15	147	2.84	3.98	2.56
Sound Level 6	5	173	4.39	0.00	-	162	2.78	1.67	1.11	164	0.00	1.80	1.80
	15	168	3.10	2.43	-	153	2.78	2.41	2.59	158	3.80	4.62	2.45
	25	166	2.06	1.27	-	149	2.59	1.85	2.04	155	4.73	1.39	2.78
	35	164	2.33	3.93	-	149	2.59	2.04	4.44	155	1.25	1.25	2.50
	45	163	2.22	2.10	-	145	2.59	2.96	1.85	153	2.14	4.29	1.56
	55	163	1.36	1.48	-	145	3.15	2.59	1.85	153	1.67	3.19	1.06
	65	163	2.60	1.98	-	141	2.78	2.78	4.81	153	1.67	3.95	1.21
	75	163	4.53	3.40	-	140	2.04	2.22	3.33	152	4.25	3.49	3.49
	85	162	1.61	2.97	-	140	2.96	3.33	1.48	152	4.25	3.64	2.12
	95	162	5.59	9.65	-	138.5	2.41	3.70	2.22	152	3.19	2.88	5.16
	105	161.5	2.10	2.35	-	137	2.41	4.26	4.26	152	3.34	1.82	4.86
	115	161	1.73	1.48	-	137	4.26	3.33	3.33	152	2.68	0.89	4.83
Sound Level 7	5	177	5.76	1.65	-	173	0.19	3.33	1.11	173	0.40	1.61	0.40
	15	172.5	2.24	2.49	-	163	1.11	2.04	2.22	166	2.19	1.95	0.49
	25	168	2.68	5.53	-	157	2.22	1.85	1.67	163	1.05	1.57	2.27
	35	168	3.75	3.61	-	155	1.48	0.74	0.93	163	5.74	5.99	2.25
	45	167.5	2.64	3.06	-	153	2.04	2.04	0.56	163	7.27	10.07	0.56
	55	167	2.13	2.46	-	153	1.48	2.04	3.70	161	0.82	1.36	1.63
	65	167	2.22	3.20	-	151	3.52	5.19	4.44	161	1.63	2.18	3.00
	75	167	2.22	0.83	-	150	2.96	2.96	4.44	161	6.74	3.53	1.93
	85	167	2.55	1.78	-	150	4.07	4.44	5.00	160	1.50	2.31	5.17
	95	167	2.29	1.71	-	149.5	4.63	2.22	2.22	159	1.36	1.36	4.22
	105	166	2.92	1.25	-	149	3.15	1.85	3.33	159	2.86	2.72	3.95
	115	165.5	2.22	3.34	-	148	6.48	4.63	3.70	159	3.54	3.00	1.36

Note: a: Distance from speaker (cm). b: Sound Pressure Level (dB). c: Fish distribution ratio/ area of run 1; area = sub section = 0.1 for length (m) x 0.3 for width (m). d: Fish distribution ratio/ area of run 2. e: Fish distribution ratio/ area of run 3.



Note: Small marker markers for juvenile distribution at the subsections near edge

Fig. 4-6 Preference for pure sound at every sound level



Note: Small marker markers for juvenile distribution at the subsections near edge

Fig. 4-7 Preference for recorded sound and white noise at every sound level

Preferences for sound are presented at Figure 4-8 and Figure 4-9. Dashed lines are used at the range where data plots only consist of small markers. Both adult and juvenile ayu seem dislike 100 Hz and the weir sounds, since fish preference on these sounds become high at SPL of lower end or even lower than "attractive level". On the other hand, both adult and juvenile ayu prefer 200 Hz and the fish ladder sounds, since fish preference on these sounds become high at SPL of “aversive level”. They also prefer 400 Hz and 800 Hz sounds, but they preferred SPL are 10 to 20 dB smaller than that of 200 Hz.

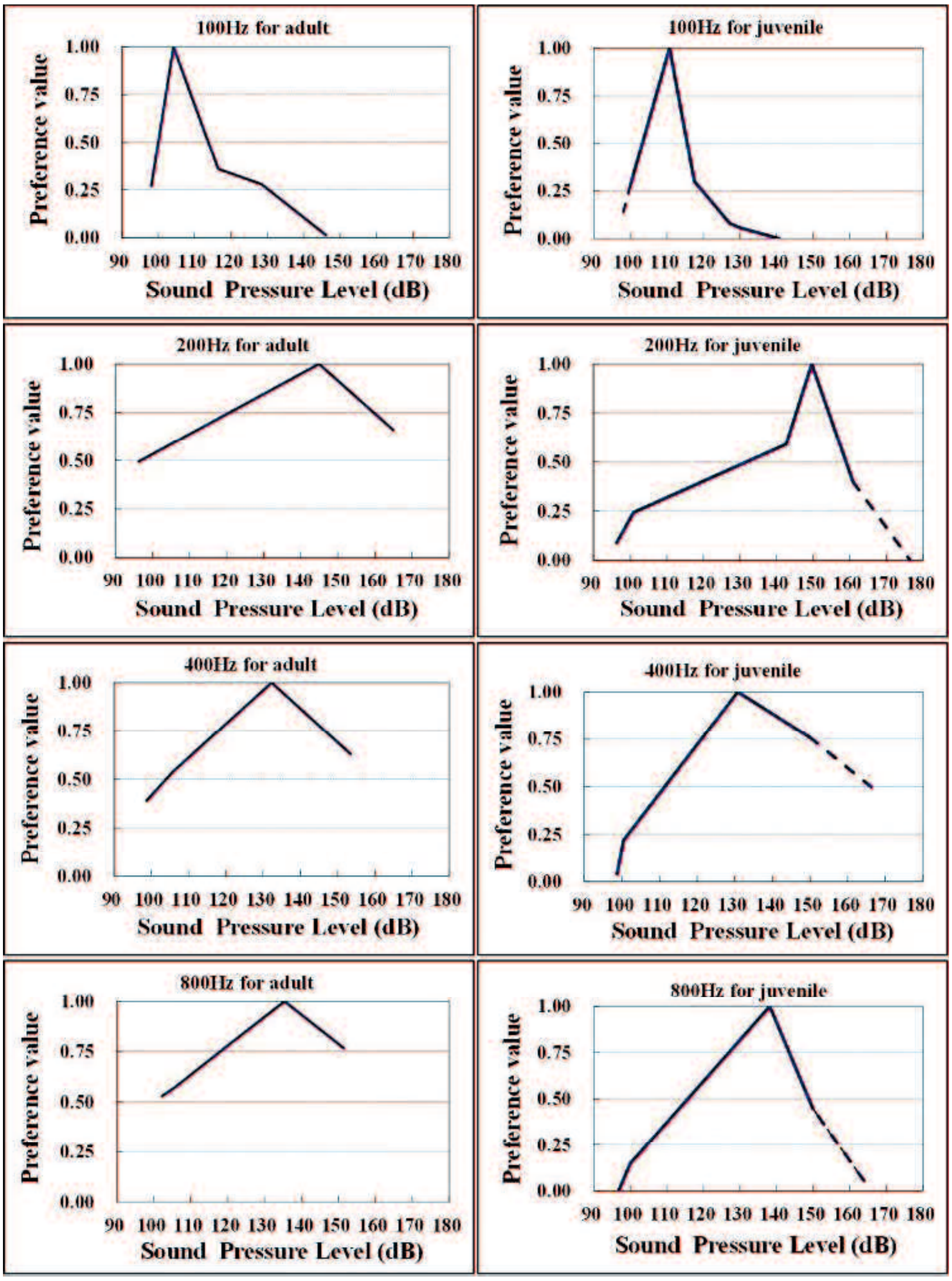


Fig. 4-8 Preference curve for pure sound

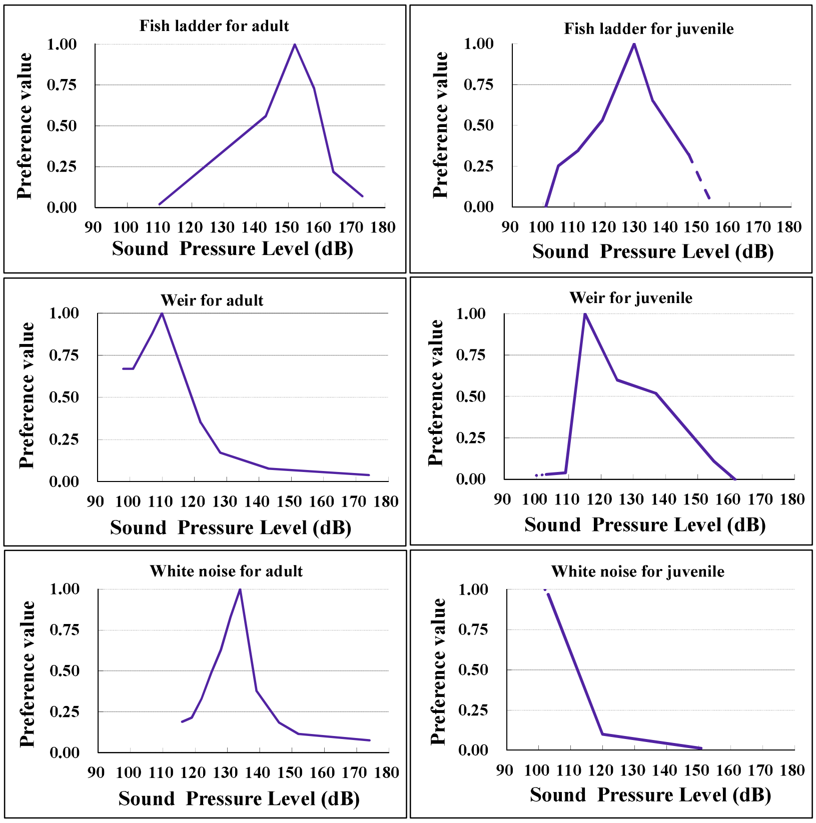


Fig. 4-9 Preference curve for recorded sounds and white noise

Literature on auditory sense of fish clearly demonstrated that fish detect and respond to sound in their environment (Hawkins, 1986; Fay, 1988; Kalmijn, 1988; Roger and Cox 1988). This is indicated by fish behavior. In observation, ayu avoid 100Hz (dominant in weir sound) and preferred 200Hz (dominant in fish ladder). In the preference equation, adult ayu shows higher avoidance to sound.

4.4.2 Weight Experiment

To determine weight of sound, I used a part of apparatus as shown in Figure 4-10. Figure 4-11 shows preference curves for shade (Noguchi et al., 2007). Table 4-5 reveals the data of weight experiment.

Table 4-5

Fish distribution at every sub section for weight experiment

			Adult						Juvenile					
a	b	c	d	e	f	g	h	i	d	e	f	g	h	i
100Hz	No cover	5	0	0.02	0.01	117.5	0.35	0.2	0.16	0.02	0.1	104.5	0.99	0.20
		15	0.01	0.5	0.08	106.1	0.75	0.23	0.19	0.08	0.14	102.6	0.94	0.23
		25	0.03	0.17	0.08	103	0.65	0.42	0.10	0.10	0.16	100.9	0.85	0.42
	With cover	35	0.23	0.07	0.24	101.7	0.40	0.84	0.27	0.27	0.36	99.1	0.37	0.84
		45	0.56	0.06	0.36	100.1	0.30	0.99	0.19	0.31	0.21	98.8	0.30	0.99
		55	0.17	0.18	0.23	98.1	0.10	0.99	0.13	0.28	0.08	98.1	0.13	0.99
200Hz	No cover	5	0.08	0.01	0.01	150.4	0.98	0.20	0.11	0.27	0.27	144.9	1.00	0.20
		15	0.21	0.06	0.14	131.8	0.49	0.23	0.11	0.26	0.25	125.4	0.67	0.23
		25	0.32	0.18	0.28	119.8	0.39	0.42	0.19	0.13	0.12	113.5	0.55	0.42
	With cover	35	0.26	0.29	0.31	111.8	0.37	0.84	0.21	0.13	0.14	104.3	0.44	0.84
		45	0.11	0.38	0.21	106.3	0.27	0.99	0.16	0.14	0.12	104.3	0.44	0.99
		55	0.03	0.08	0.04	115.5	0.38	0.99	0.22	0.07	0.11	100	0.39	0.99
400Hz	No cover	5	0.01	0.04	0.01	153.5	0.90	0.20	0.08	0.16	0.07	132.3	1.00	0.20
		15	0.07	0.16	0.14	132.3	0.95	0.23	0.16	0.17	0.07	121.1	0.83	0.23
		25	0.21	0.21	0.26	119.2	0.55	0.42	0.15	0.13	0.11	113.0	0.60	0.42
	With cover	35	0.33	0.32	0.33	114.3	0.36	0.84	0.22	0.22	0.24	104.1	0.50	0.84
		45	0.33	0.24	0.24	110.4	0.29	0.99	0.24	0.15	0.24	101.4	0.50	0.99
		55	0.06	0.04	0.03	106.3	0.27	0.99	0.15	0.18	0.27	100.0	0.51	0.99
800Hz	No cover	5	0.00	0.00	0.02	148.5	0.58	0.20	0.23	0.01	0.14	135.8	1.00	0.20
		15	0.16	0.09	0.21	130.3	0.85	0.23	0.22	0.02	0.12	123.4	0.83	0.23
		25	0.28	0.19	0.22	120.9	0.68	0.42	0.08	0.07	0.13	114.4	0.63	0.42
	With cover	35	0.27	0.35	0.31	111.8	0.32	0.84	0.17	0.17	0.17	103.0	0.45	0.84
		45	0.20	0.32	0.21	105.8	0.29	0.99	0.16	0.36	0.17	100.7	0.38	0.99
		55	0.09	0.05	0.04	102.3	0.25	0.99	0.15	0.37	0.27	99.6	0.33	0.99
White Noise	No cover	5	0.15	0.34	0.22	108	0.22	0.99	0.13	0.12	0.15	133	0.91	0.18
		15	0.2	0.36	0.33	108	0.22	0.99	0.07	0.12	0.1	127	0.63	0.18
		25	0.26	0.17	0.21	109.5	0.24	0.84	0.08	0.09	0.04	125	0.53	0.18
	With cover	35	0.12	0.05	0.11	111.5	0.5	0.42	0.1	0.2	0.14	124	0.49	0.22
		45	0.17	0.04	0.07	120.1	0.95	0.23	0.22	0.18	0.22	123	0.44	0.99
		55	0.11	0.04	0.06	134.9	0.25	0.2	0.4	0.29	0.34	122	0.39	0.99
Weir	No cover	5	0.26	0.2	0.21	100	0.11	0.99	0.19	0.11	0.06	140	0.24	0.99
		15	0.39	0.28	0.27	100	0.11	0.99	0.2	0.11	0.04	128	0.39	0.99
		25	0.16	0.23	0.22	100	0.11	0.84	0.21	0.06	0.03	120.1	0.49	0.84
	With cover	35	0.07	0.11	0.17	103	0.2	0.42	0.18	0.21	0.22	113	0.87	0.42
		45	0.06	0.13	0.09	109	0.7	0.23	0.13	0.26	0.33	112	0.92	0.23
		55	0.07	0.05	0.09	117	0.95	0.2	0.08	0.27	0.33	110.7	0.99	0.2
Fish Ladder	No cover	5	0.13	0.26	0.21	103	0.2	0.99	0.05	0.21	0.03	155	1.00	0.18
		15	0.14	0.37	0.21	103	0.2	0.99	0.26	0.17	0.08	143	0.54	0.18
		25	0.08	0.22	0.14	104.1	0.25	0.84	0.37	0.1	0.17	133	0.44	0.18
	With cover	35	0.11	0.04	0.1	108.1	0.45	0.42	0.22	0.03	0.32	130	0.40	0.22
		45	0.28	0.06	0.17	119.9	0.65	0.23	0.04	0.28	0.26	129	0.39	0.99
		55	0.26	0.04	0.17	133.4	0.9	0.2	0.06	0.21	0.15	127	0.37	0.99
100Hz Avoidance	With cover	5	0.05	0.21	0.15	157	0.1	0.99	0.07	0.15	0.05	147.1	0.01	0.99
		15	0.23	0.17	0.31	150	0.25	0.99	0.10	0.16	0.09	136	0.18	0.99
		25	0.19	0.1	0.24	143	0.4	0.84	0.12	0.06	0.11	131.2	0.33	0.84
	No cover	35	0.11	0.03	0.1	140	0.49	0.42	0.21	0.13	0.23	123.1	0.52	0.42
		45	0.19	0.28	0.09	138	0.63	0.23	0.24	0.25	0.24	123.1	0.52	0.23
		55	0.22	0.21	0.11	138	0.63	0.2	0.26	0.24	0.27	124	0.53	0.20

Note: a: Sound source. b: Division of the area at experimental section. c: Distance from speaker (cm). d: Fish distribution ratio of run 1. e: Fish distribution ratio of run 2. f: Fish distribution ratio of run 3. g: Sound Pressure Level (dB). h: Preference value for sound. i: Preference value for illumination.

I calculate weight of sound by using Eq. (5). Table 4-6 shows the weights of each frequency obtained from preferred sound experiments and avoided sound experiments. Comparing the obtained weight, adult has higher value than juvenile ayu in sound.

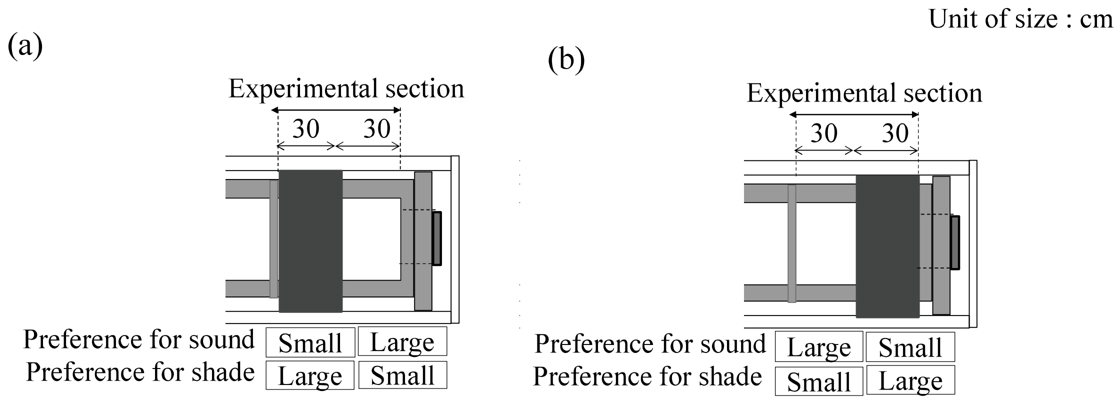


Fig. 4-10 Weight experiment apparatus for (a) preferred sound; (b) avoided sound

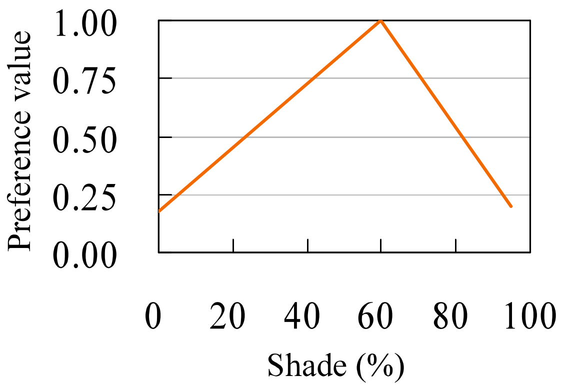


Fig. 4-11 Preference curve for shade

$$R = \frac{D_{right}}{D_{left}} = \frac{P_{(sound,right)}^{\frac{w_{sound}}{w_{max}}}}{P_{(sound,left)}^{\frac{w_{sound}}{w_{max}}}} \frac{P_{(shade,right)}^{\frac{w_{shade}}{w_{max}}}}{P_{(shade,left)}^{\frac{w_{shade}}{w_{max}}}} \qquad (5)$$

Where R is distribution ratio of fish, D_{right} and D_{left} is distribution of fish at the weight experimental apparatus, *right* means the section apart from the speaker and *left* means the section closer to the speaker, P is preference value I determined in the former section, weight, W , and maximum weight, W_{max} , are the same as in equation (3) and (4).

Table 4-6
Weight of sound obtained through weight experiments

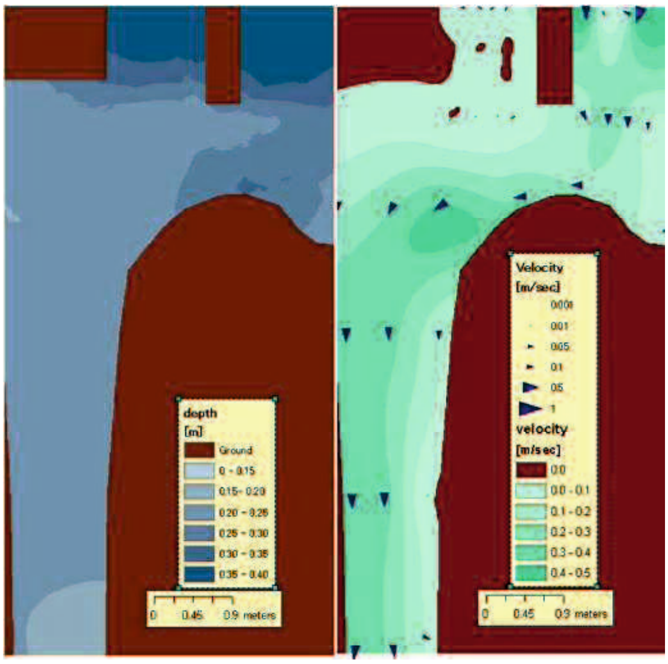
Experiment	Sound source	W_{sound}	
		Adult	Juvenile
Preferred sound	200Hz	0.42	0.24
	400Hz	0.18	0.11
	800Hz	0.11	0.13
	Fish ladder	0.13	0.12
	White noise	0.04	0.02
Avoided sound	100Hz	0.68	0.26
	Weir of Fushino River	1	0.18

4.5 Field experiment and example of numerical simulation

4.5.1 Field experiment

I conduct a field experiment in the Sawanami River near our university campus on 20 April 2007. The experimental section of about 7.5 m is set downstream of the entrance of a fish ladder. Figure 4-12 shows the experimental river section delimited by a net. The fish ladder consists of two watercourses; flow rate of the left bank one is higher than that of right bank. At the entrance of each fish ladder, underwater speakers are set to create different sound condition. I release 20 juvenile ayu of 10 cm body length at the lowest point of the section, and video the behavior of fish from the river bank. The water temperature is approximately 15°C. I also measure velocity, depth, and sound pressure at measurement points distributed in the experimental section. Figure 4-13 shows the observed velocity and depth.

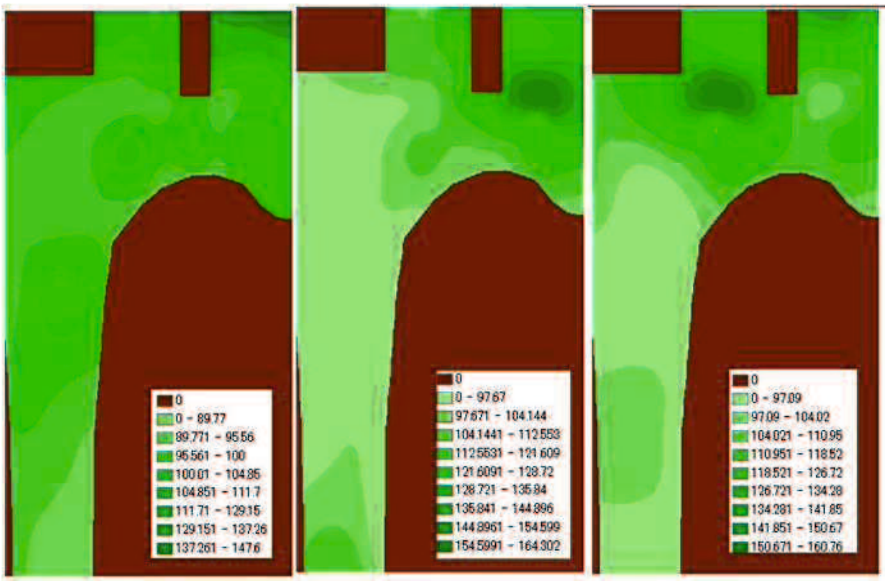
Fig. 4-12 The observation area



(a) (b)

Fig. 4-13 Environmental conditions. (a) Depth; (b) velocity magnitude and flow direction

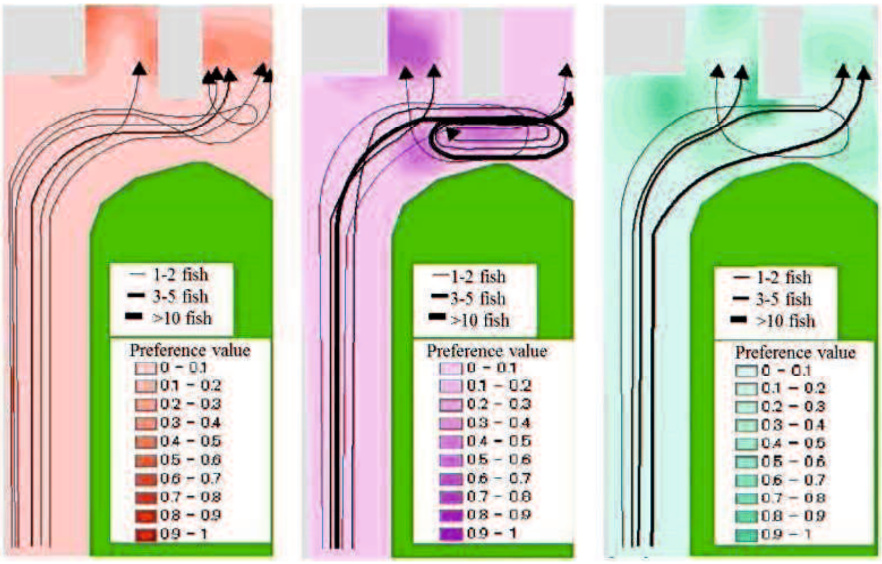
The experiments are conducted in three conditions. Second condition is conducted with sound emission of 100 Hz pure sound from the left bank side speaker. Third condition is conducted with sound emission of 200 Hz pure sound from the right bank side speaker. Figure 4-14 shows the sound pressure distribution of three conditions in the experimental area, and Figure 4-15 shows the observation result of fish behavior during experiment.



(a) (b) (c)

Fig. 4-14 Sound pressure distribution at the experimental area. (a) No sound emission from both of speaker; (b) sound emission of 100 Hz pure sound from the left bank side speaker; (c) sound emission of 200 Hz pure sound from the right bank side speaker.

Figure 4-15 reveals overall preference value of sound for each conditions and migration path of fish. In first condition where there is no sound emission from both speakers, I found many fish go to upstream at left bank side because left bank side had higher preference value for velocity than right bank side. In the second condition, I observed fish are turning in front of the fish ladder entrance. It seemed fish avoid 100Hz sound which emitted from left bank side speaker. In third condition, I found more fish go to upstream at right bank side than other condition. These results show fish migrate through the location which has higher preference value for sound in the actual river.



(a) (b) (c)

Fig. 4-15. The observation of fish behavior during experiment in three conditions. (a) First condition, No sound emission from both of speaker; (b) second condition, sound emission of 100 Hz pure sound from the left bank side speaker; (c) third condition, sound emission of 200 Hz pure sound from the right bank side speaker.

4.5.2 An example of fish behavior numerical simulation

In this section, I demonstrate an example of incorporating the sound preference information in fish behavior simulation. Here I focus on sound of 100 Hz and 200Hz since these frequencies have higher weight than 400 Hz and higher frequencies. I also include preference of rheotaxis and velocity as additional preference other than sound. Other important environmental conditions, depth and substrate, are omitted since the depth of this section is deep enough to show rather constant preference for juvenile Ayu, and the substrate is also uniform mixture of gravel and sand except rock and concrete substrate at the entrance of the fish ladder at the upstream end of the section. Preference curve of velocity (Sekine et. al., 2004) is shown in Fig. 4-16, and that of rheotaxis (Febrina et. al., 2012) is shown in Fig. 4-17.

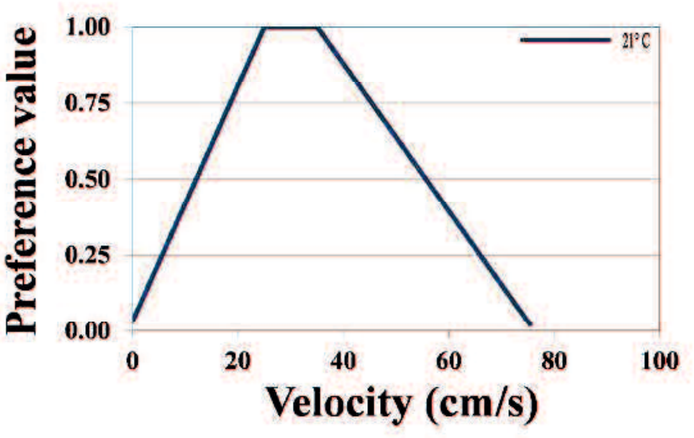
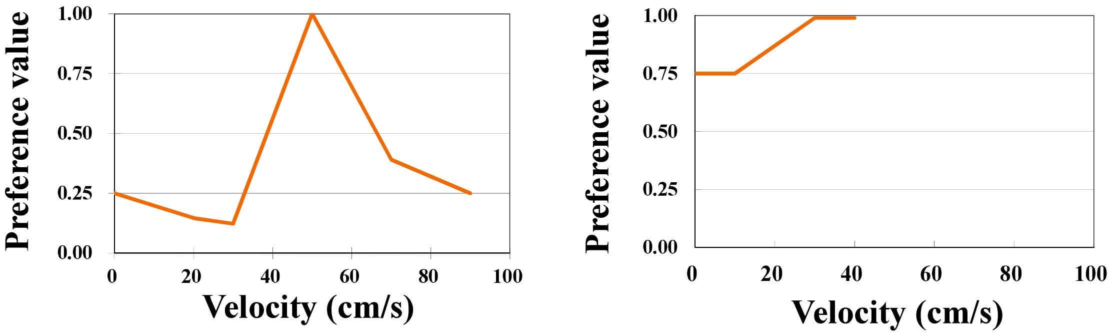


Fig. 4-16 Preference curve for velocity



(a)
(b)

Fig. 4-17 Preference curve for rheotaxis. (a) Adult ayu; (b) juvenile ayu.

In this simulation, nine surrounding location including current location of a virtual fish are compared, and the virtual fish move to the location which has the highest preference (P^*) based on equation (2). When there are more than one highest preference locations, the fish choose a location among them randomly. Figure 4-18 shows the surrounding location of sound. The simulation is performed using Visual Basic for Applications (Microsoft Corporation, Redmond, WA USA) and ArcGIS 8.3 (ESRI, Redlands, CA USA). I supply the velocity preference raster layer, sound pressure level 100 Hz preference raster layer named “SPL100”, the sound pressure the level 200 Hz preference raster layer named “SPL200”, the horizontal velocity raster layer named “Vx”, and the vertical velocity raster layer named “Vy”. The initial location of a virtual fish is supplied as a point layer named “Track”. When the program runs, the virtual fish movement at each time step is tracked as a point on the “Track” layer.

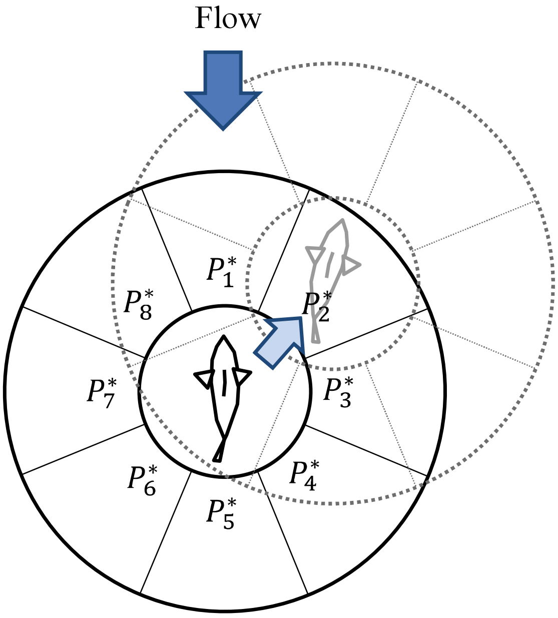


Fig. 4-18. Overall preference (P^*n) for each direction n is calculated using equation (2): $P^*n = P_v n^{\frac{w_v}{w_{max}}} . P_{spl100} n^{\frac{w_{spl100}}{w_{max}}} . P_{spl200} n^{\frac{w_{spl200}}{w_{max}}} . R$ where $P_v n, P_{spl100} n, P_{spl200} n, R$ are velocity, SPL100, SPL200 and rheotaxis respectively at for direction n.

Figure 4-19 shows the result without sound emission and with sound emission of 200 Hz from the right bank side speaker. By using preference for sound, the calculated results show the trend of observed fish migration in the actual river.

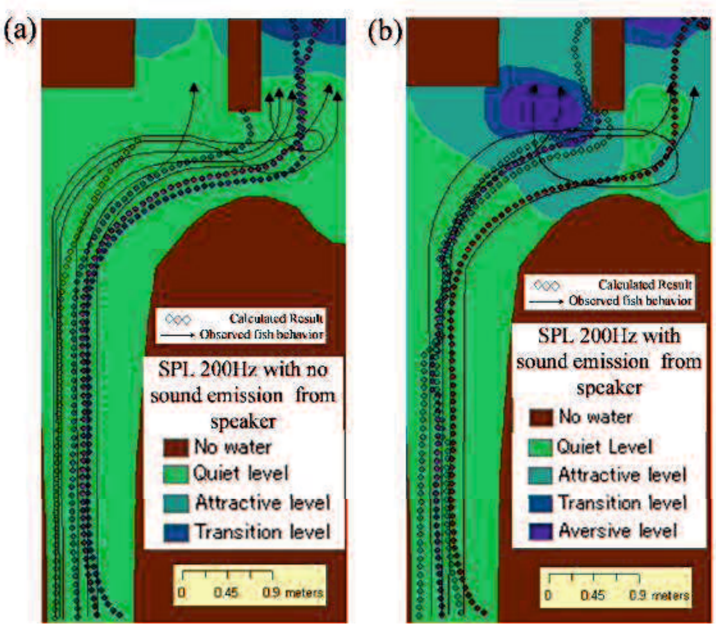


Fig. 4-19 Simulation cases juvenile Ayu. (a) Sound pressure level 200Hz with no sound emit from speaker; (b) Sound pressure level 200Hz.

4.6 Conclusions

My work has led I to conclude: firstly, through laboratory experiment, preference and weight for 100Hz, 200Hz, 400Hz, 800Hz, weir, fish ladder and white noise were determined. 100 Hz sound, which is dominant in weir sound, was revealed to be important as avoided frequency, and 200Hz ,which is dominant in fish ladder, was revealed to be important as preferred frequency. Adult ayu showed higher avoidance to 100 Hz and weir sound. Secondly, I proved that the fish behavior observed in the field experiment agreed with the preference determined through the laboratory experiments qualitatively. Ayu avoided 100Hz sound and prefer 200Hz sound in the field experiment. Thirdly, I demonstrated a fish behavior simulation incorporating the sound preference. The simulation model properly reproduced the trend of observed juvenile Ayu migration behavior in a river.

Through this research, I successfully modeled fish preference on underwater sounds.

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CHAPTER 5
EVALUATION ON PASSABILITY OF STONES EMBEDDED FISH PASSAGE BASED ON PREFERENCE

5.1 Introduction

Fish populations are highly dependent upon the characteristics of their aquatic habitat which supports all their biological functions. Migratory fish require different environments for the main phases of their life cycle which are reproduction, production of juveniles, growth and sexual maturation.

Recent studies have shown that river regulation with dams and weir which creates large barriers to fish migration can greatly reduce the abundance of native species (Mallen-Cooper and Brand, 1992; Harris and Mallen-Cooper, 1994; Mallen-Cooper et al., 1995). Whilst large dams can often extinguish migratory species upstream, the impact on fish population of low barriers such as weirs, floodgates, road crossing and culvert is usually not so extreme. But their cumulative impact may be large because of the prevalence of these structures (Harris, 1984). To minimize the severe impact on the river ecosystem, when constructing hydraulic structures crossing the rivers, fishways are installed. Fishways usually consist of a sloping channel partitioned by weirs, baffles, or vanes with openings for fish to swim through. The in-channel devices act hydraulically together to produce flow conditions that fish can navigate. Several types of fishways have been developed and are usually distinguished by the arrangement of in-channel devices such as vertical slot, Denil, weir, culvert and rock ramp fishways. Nowadays, the use of natural-like fishways as a viable fish passage alternative is becoming more accepted around the world. The design philosophy for these fishways is simple, ecologically minded, and aims to achieve a good fit with the specific riverine environment they are constructed in. Because of that the rock ramp is more often used than other type because these structures which are designed to mimic natural stream riffles may also provide fish passage (Harder, 1991; Newburry and Gaboury, 1998), low cost, operate over a wide range of flows and allow fish to pass without requiring jumping.

Many examples of these nature-mimicking structures now exist in countries throughout Europe, as well as Australia, Canada and Japan. In Japan, there are almost 1400 fishways, most of which are pool and weir type in various forms. A small number (about 0.1%) are Denil fishways, and about the same small percentage are fish locks and special eel fishways (Sasanabe, 1990). The pool and weir fishways are intended mainly to provide passage upstream for the Ayu. The pool and weir fishways are of varying effectiveness, and there seems to be little rationality in the design of most of them.

Recently, stone embedded fish passage (SEF) is getting popularity in some areas of Japan as an inexpensive small-scale river restoration works. Fushino River SEF (Fig. 5-1) is one of such works intended to improve or substitute existing pool and weir fish passage. Although Fushino River SEF was widely introduced through a book (Project Team "Mizube no Kowaza", 2007) and was highly appreciated, efficiency of the SEF has not been evaluated well and the design parameters of it is not clear enough yet. I conducted a preliminary survey on Fushino River SEF in 2011. Unlike the expectation that stones are used as roughness in the SEF, the Fushino River SEF was revealed to be a network of small pools and channels under its operating discharge (Fig. 5-2). Also, through observation during the survey, air bubble, high velocity, and small depth in pools and channels seemed major obstacle for fish ascendance.

Fig. 5-1 Stone embedded on fish passage at Fushino River

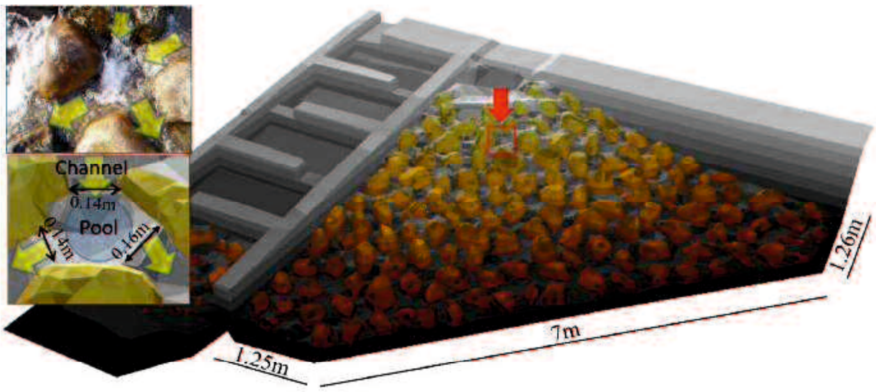


Fig. 5-2 Network of small pool and channel at Fushino River SEF

Existing researches on SEF (Miyazono et al., 2003, 2005; Fujihara et al. 2006) modeled it as stones on a flat bed, and none of them take air bubble into account. A small amount of air bubbles would increase the dissolved oxygen and create favorable conditions for fish. However, a large amount of air bubbles would reduce the water density and inhibit fish movement. The aims of this research was to build simple model, applicable to the SEF design stage, to estimate the passability of the SEF for ayu using preference information on velocity, depth, and air bubble. We then verified the model through field experiment in the Fushino River SEF.

5.2 Materials and methods

5.2.1 Laboratory experiment

The experimental apparatus consists of a pool and a channel (Fig. 2a). The structure of experimental apparatus is shown in Fig. 2b. It is made of transparent acrylic. In this experiment, we change depth of pool (DoP) by replacing bottom plate spacers, length of channel (LoC) by replacing the channel parts, and slope of channel (SoC) by lifting the upper tank in accordance with the experimental condition. Width of channel (WoC) is fixed to 10 cm. Slope of flood gate (SoG) is adjusted to make smooth transition of water surface level in the channel and pool. Flow rate (Q) of the experiment is measured at the flood gate. Depth of channel (DoC) are measured at the center of the channel. Velocity of channel (VoC) is calculated using VoC = Q / (DoC x WoC).

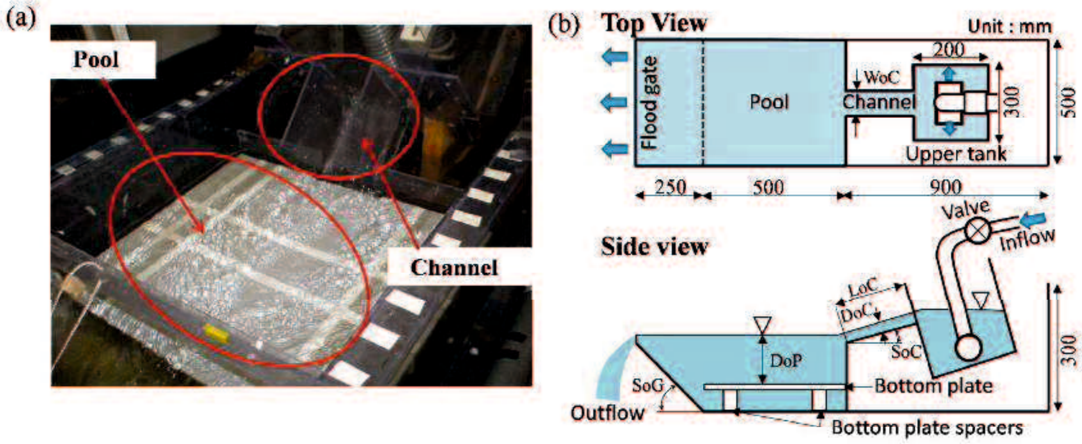


Fig. 5-3. Experimental setup. (a) Pool and channel; (b) a schematic top and side view of the setup.

I attempt to represent the condition of Fushino River SEF in laboratory experiments. Table 5-1 shows the observed characteristics in the SEF and experimental conditions. I also measure velocity and air bubble in the pool at the points shown in Fig. 5-3. Velocity of pool (VoP) is measured using two propeller type velocity meters (KENEK VR-201 or SV-3) depending on the depth. I also observed the bubble condition index (BCI), where BCI = 0: no air bubble; 0.1: air bubbles appear on the surface; 0.5: air bubbles reach in the middle of pool; 1: air bubbles reach to the bottom of pool.

Table 5-1

Pool and channel parameters in the Fushino River SEF and laboratory experiments

		Pool parameters		Channel parameters			
		Area (AoP)	Depth (DoP)	Length (LoC)	Width (WoC)	Slope (SoC)	Depth (DoC)
		cm^2	cm	cm	cm	-	cm
Fushino River SEF (446 channels & 109 pools)	Minimum	210	1.5	3.0	0.2	0.0	0.5
	Average	1040	9.0	14.9	11.4	0.44	4.8
	Maximum	16240	22.5	50.7	98.2	3.39	15.0
	Std. deviation	2020	3.9	6.7	9.9	0.54	3.7
Experimental conditions (All combinations have tested except AoP 2500×DoC10.0)		625 (25×25)	2.0	5.0	10.0	0.1	1.0
		2500 (50×50)	9.0	15.0		0.5	4.0
			18.0	30.0		1.0	10.0

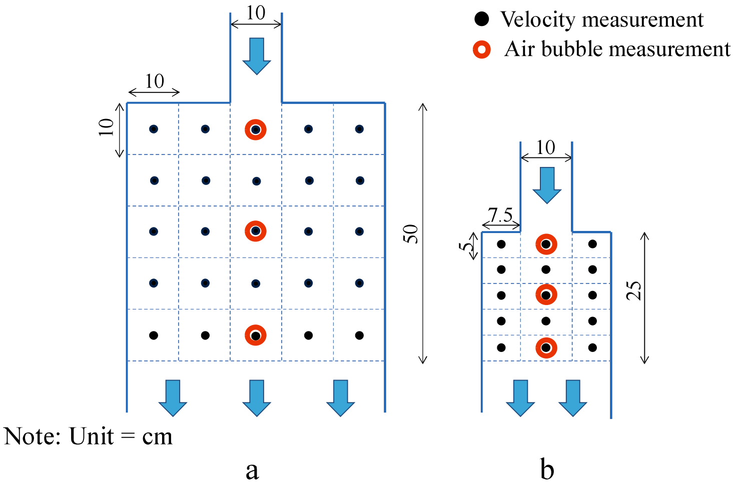


Fig. 5-4 Measuring points. (a) 50cm x 50cm Pool; (b) 25cm x 25cm Pool.

5.2.2 Field Experiments for Decision Tree Verification

To verify the model, I apply the decision tree to Fushino River SEF. I set up three experimental conditions. Experiment 1 uses whole area of the SEF. Experiment 2 uses central zone of the SEF which represents the area of few air bubbles and low flow rate. Experiment 3 uses right bank of the SEF which represents the area of dense air bubbles and high flow rate. I released 100 (experiment 1), 50 (experiment 2) and 100 (experiment 3) Ayu with body length 7±1 cm at the downstream of the entrance of fish passage and videoed the number of Ayu which successfully pass through the SEF.

5.3 Theory of analysis

5.3.1 Formulation of preference

Authors have formulated preference of fish on environmental factors through laboratory experiments based on pair comparison using a U-shaped experimental watercourse (Sekine et al., 1997), and the formula have been validated through several researches (Sekine et al., 2001, Karim et al., 2003, Sekine et al., 2004, Fukuda and Hiramatsu, 2008, Sekine et al., 2009, Febrina et al., 2012). The formula is described as below:

$$P^{*} = \prod_{j=1}^{J} \left(P_j\right)^{\frac{W_j}{W_{\max}}} \tag{1}$$

$$W_{\max} = \begin{cases} \max_{J \in V} \left(W_j\right) & V \neq \phi \\ \infty & V = \phi \end{cases} \tag{2}$$

$$V = \left\{ j \middle| \left(\exists i, i`\right)\left(P_{j,i} \neq P_{j,i}\right) \right\} \tag{3}$$

Where $P^{*}$is overall preference, P_j is preference for environmental condition j, $W_j$is weight of environmental condition j, W_{max} is maximum weight among weight sets, V, that had different preference levels in surrounding water body, ϕ represents the null set, ∃ is an existential quantifier, and i represents a segmented location of water body. This formula has an important advantage that environmental preference and its weight can be determined separately. Consequently, a new environmental factor can be added or removed without affecting other environmental factors.

5.3.2 Preference calculation method

In this research, I create the condition of SEF in laboratory, which consist of a pool and channel, and determine preference model of the SEF using physical condition such as velocity, air bubble, depth in channel and pool. I convert velocity to preference of velocity (PV) by using preference curve of velocity (Sekine et. al., 2004). Preference curve of velocity is shown in Figure 5-5. Preference of bubble (PB) is obtained by using equation as below:

$$PB = BCI \times PBM_{rate} + (1 - BCI) \tag{4}$$

Where PB is preference of bubble, BCI is bubble condition index (0 = no air bubble; 0.1 = air bubble appear on surface; 0.5 = air bubble reaches in the middle of pool; 1 = air bubbles reaches until the bottom of pool) and PBM_{rate} is preference of bubble mixing rate. Preference curve of bubble mixing rate (Sekine et. al., 2004) is shown in Figure 5-6. We calculate overall preference (P^*) by using Eq. (1) as shown below:

$$P^* = PV \times PB \tag{5}$$

If the result of $P^* = 0$ or close to 0 means fish dislike the condition of pool and if the result of $P^* = 1$ or close to 1 means fish prefer the condition of pool.

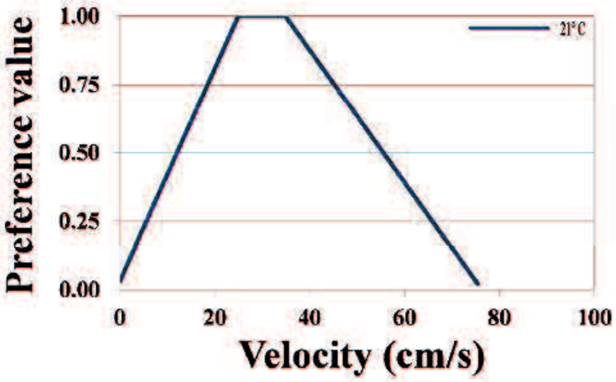


Fig. 5-5 Preference curve for velocity

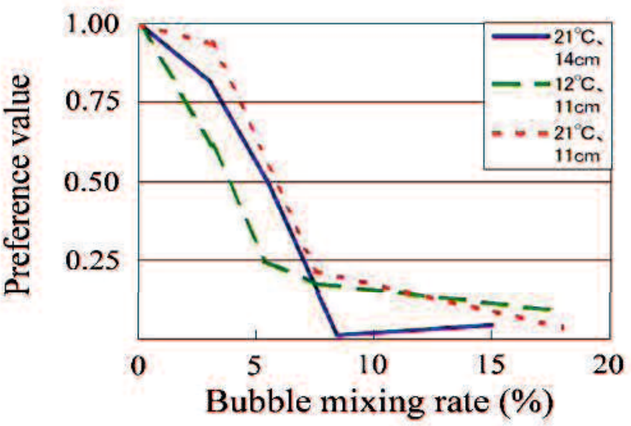


Fig. 5-6 Preference curve of air bubble

5.3.3 Estimation of Passability on Laboratory Experiments

I define a set of rules to estimate the passability on laboratory experiment based on preference information on velocity, air bubble, depth, and space. In this analysis, we assume that the body length (BL) of Ayu is 6cm, and body height (BH) of it is 1.3cm, since they are common size when they start migration toward upstream, and some of our previous researches we refer below used BL6 Ayu in their experiments.

Velocity

Nakamura (1995) stated that fish can swim at burst speed just for a few seconds, while they can swim for hours at cruising speed. Ayu's burst speed is 12~18 BL/s and their cruising speed is 4~7 BL/s. Sekine et al. (2009) used a preference model in which Ayu could not swim more than 4 s at burst speed (Fig. 5-7).

With this information I defined two rules: time of ascending (ToA) < 4 s and VoP < cruising speed.

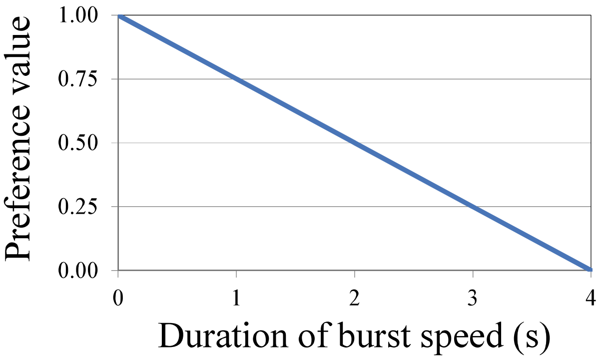


Fig. 5-7 Preference curve for time to burst speed for Ayu

Air bubble

Noguchi et al. (2007) demonstrated experimentally that no-air water showed the highest preference of 1.0 and it showed a slight decrease to 0.75 at 5v/v% air. After that, preference quickly decreased down to 0.13 at 10v/v% air and became almost zero for 20v/v% air. Water with 5v/v% air bubbles was acceptable for fish to stay and move. We also learned through our field observations that bubbles tended to stay in the upper layer of the water and that fish could stay in the bottom layer when it had no bubble area. With this information I defined a rule: BCI ≤ 0.1 under DoP = 2 cm and BCI ≤ 0.5 under DoP = 9, 18 cm.

Depth

Nakamura (1995) stated that the minimum water depth for swimming was two times BH. However we frequently observed Ayu swimming through shallow water with their back emerged in the air. With this information I define a rule: DoP $\geq$ BH.

Space

Nakamura (1995) stated that minimum rest place size was 2~4 BL long and ½ BL wide. I determined the passability of a channel and each cell (a rectangular area with one velocity measuring point in a pool) based on the rules described above. However, the cell length of the 25 x 25 cm pool was 5 cm along the flow, which was smaller than Ayu's BL of 6 cm. To determine the passability of a pool, I defined a rule: at least two connected passable cells were necessary for the 25 x 25 cm pool and one passable cell was necessary for the 50 x 50 cm pool.

With the rules above, I estimated the passability (IP: impassable, P: passable) for each experimental condition.

5.3.4 Decision Tree on Passability of a Pair of Channel and Pool

I employed the decision tree (Hullet, 2006) as a simplified method to estimate the passability of a channel and pool pair in the SEF designing stage. The explanatory variables were Q, SoC, LoC, DoP and WoP, all of which could be determined in the designing stage. By using a set of these explanatory variables and the passability as a dependent variable obtained through laboratory experiments, we built a decision tree using the statistical package R.

5.3.5 Model to Estimate the whole SEF`s Performance

To estimate the whole SEF`s performance, I determined the following equation:

$$E_w = \frac{1}{N_r}\sum_{1}^{N_r}\left(\frac{1}{N_c}\sum_{1}^{N_c}E_p\right) \tag{6}$$

where E_w: estimation of the whole SEF, N_r: total number of routes to ascend the SEF, N_c: number of channels on a route, and E_p: estimation for a channel-pool pair using the decision tree. We counted up all possible routes, N_r, for Ayu to ascend the SEF.

5.4 Results and discussion

Figure 5-8 and Figure 5-9 show the laboratory experimental results of preference for velocity, and bubble at pool 25x25 and pool 50x50 respectively. Based on the calculation for all preference, the result shows Fushino River SEF is not suitable for habitation of Ayu more than 50 % (Fig. 5-10). Figure 5-11 and Figure 5-12 show the resting area evaluation for Ayu at pool 25x25 and 50x50 respectively.

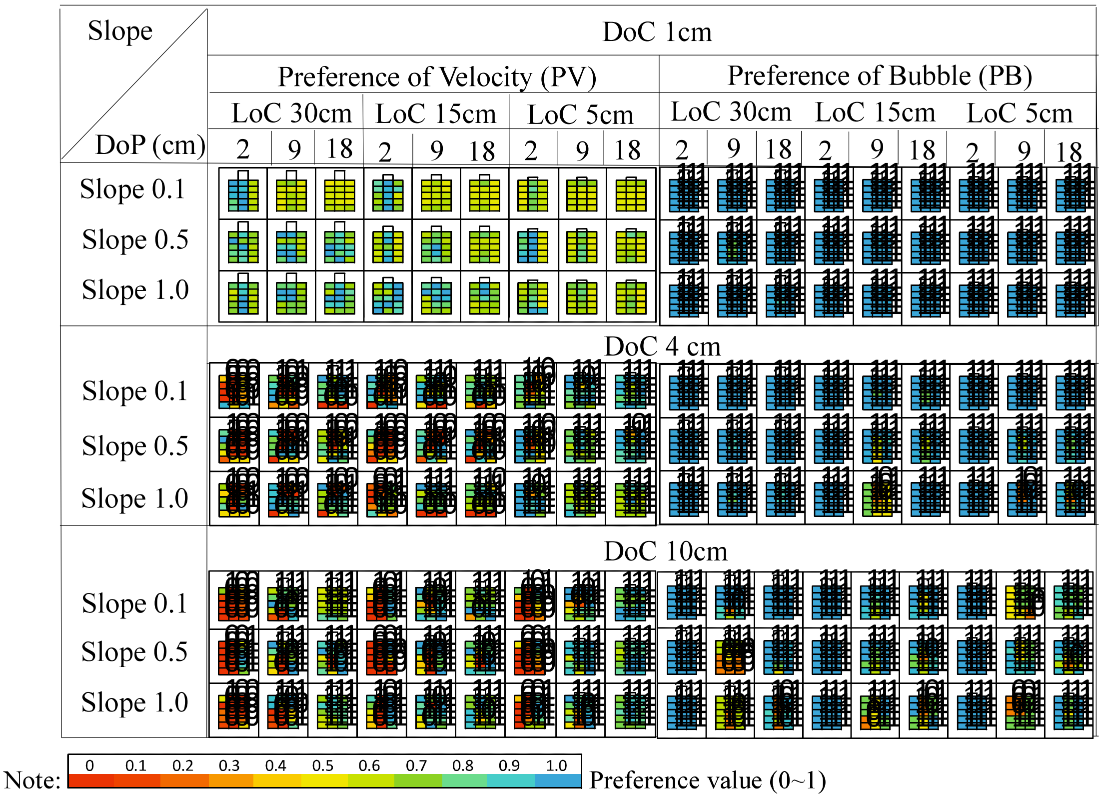


Fig. 5-8 Preference values of velocity and bubble for pool 25x25

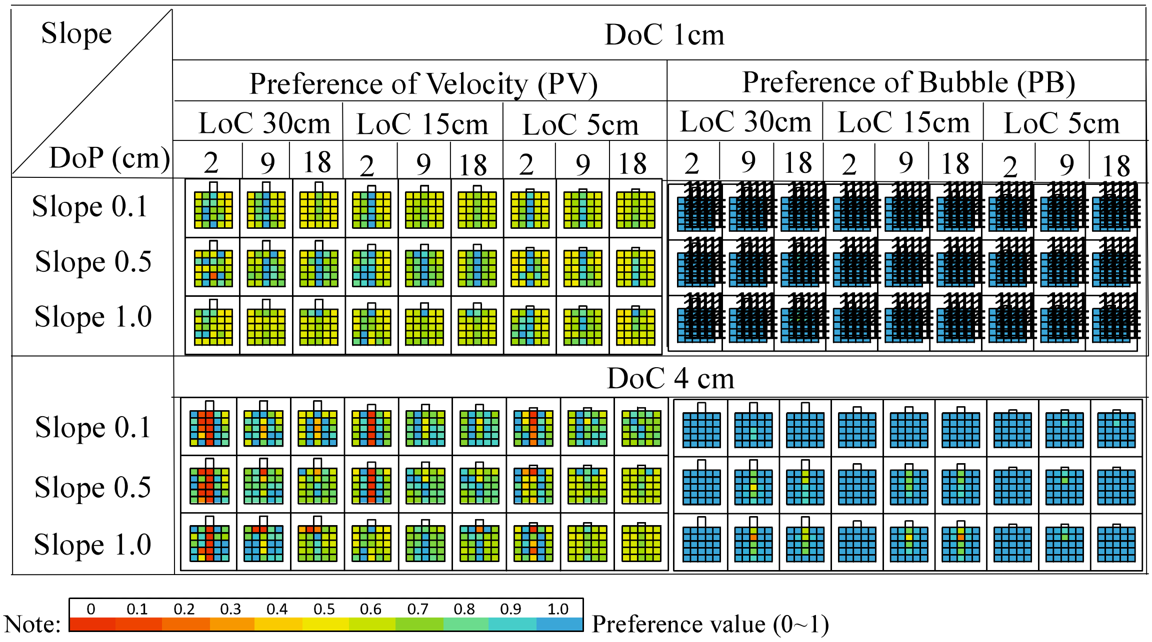
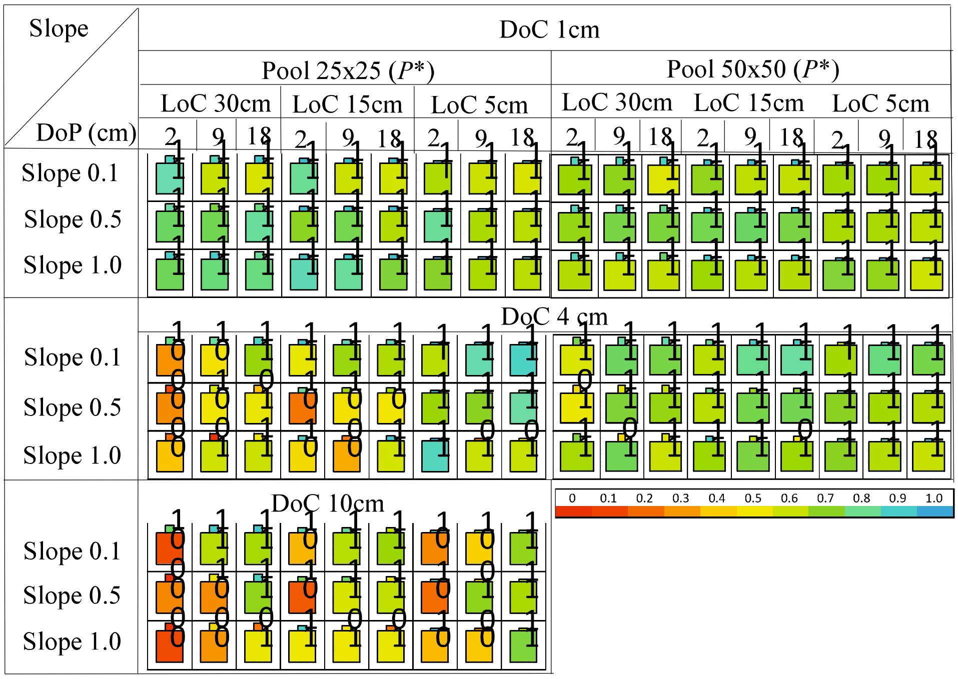
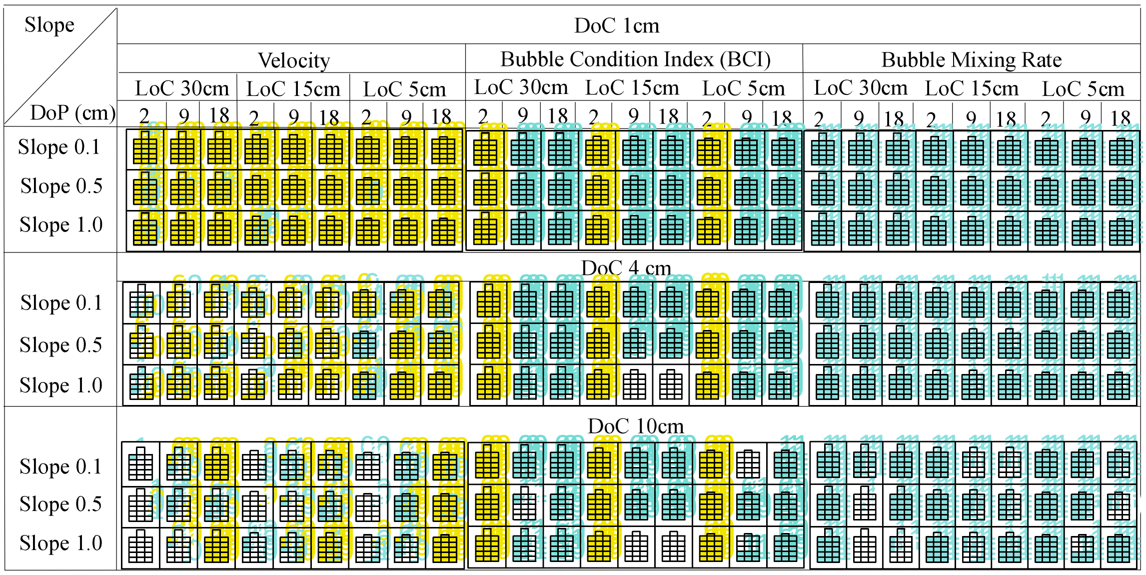


Fig. 5-9 Preference values of velocity and bubble for pool 50x50



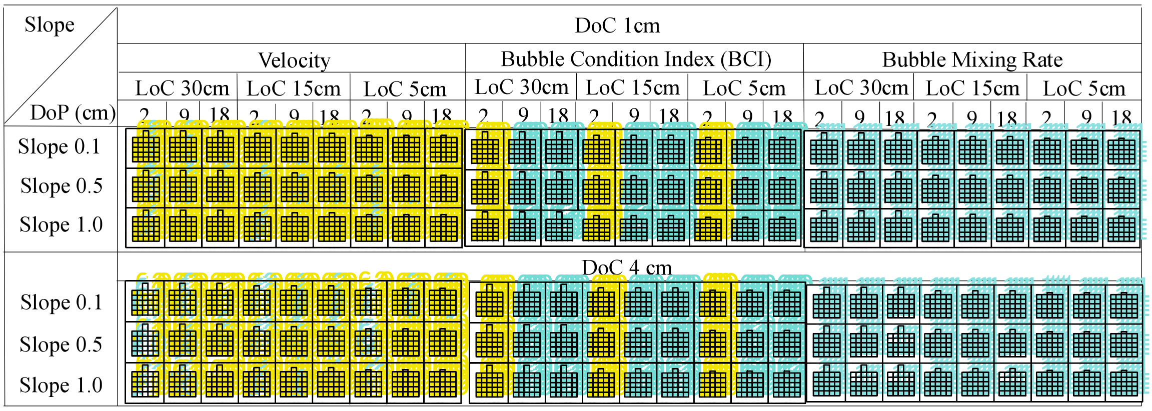
Note: Preference value (0~1)

Fig. 5-10 Combine for all preference (P^*)



Note: Velocity (blue cell ≤ 0.605m/s ,yellow ≤ 0.33m/s and white cell > 0.605m/s); bubble condition index (blue cell = 0.5, yellow ≤ 0.1 and white cell = 1); bubble mixing rate (blue cell ≤ 20% and white cell >20%).

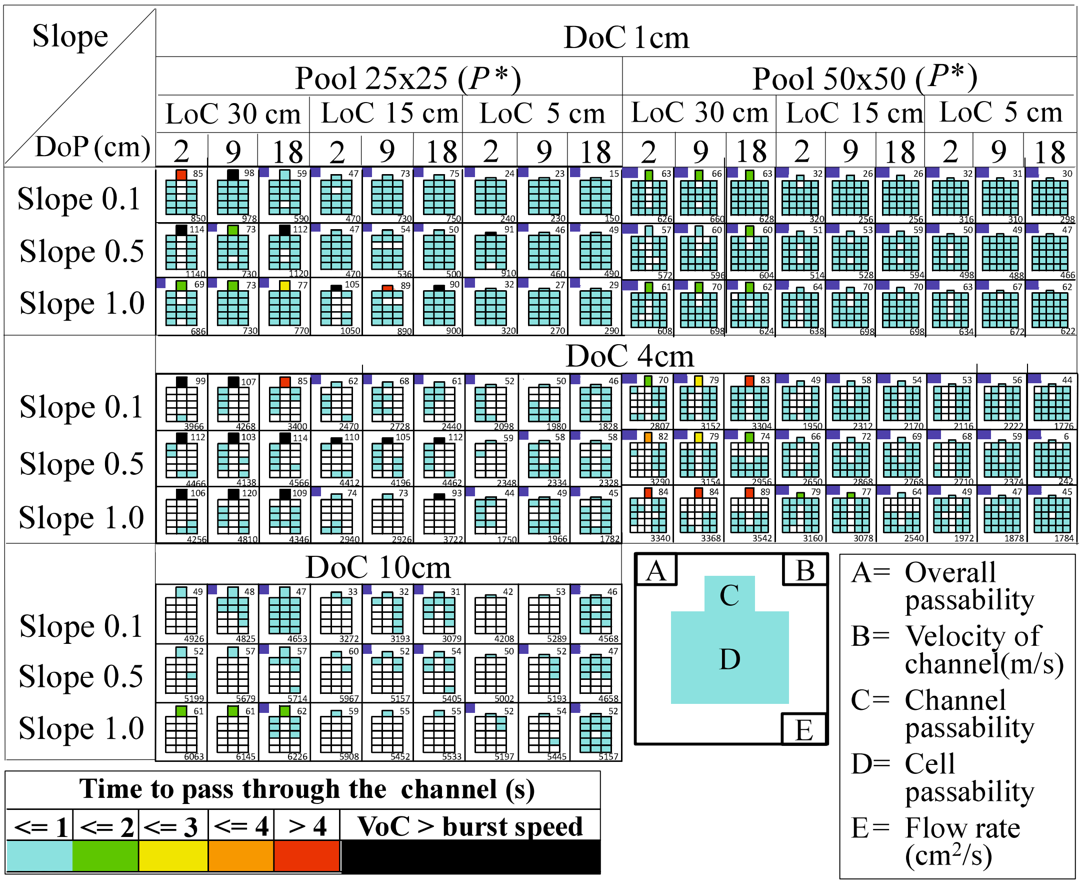
Fig. 5-11 The resting area evaluation for Ayu with size of pool 25x25



Note: Velocity (blue cell ≤ 0.605m/s ,yellow ≤ 0.33m/s and white cell > 0.605m/s); bubble condition index (blue cell = 0.5, yellow ≤ 0.1 and white cell = 1); bubble mixing rate (blue cell ≤ 20% and white cell >20%).

Fig. 5-12 The resting area evaluation for Ayu with size of pool 50x50

Figure 5-13 shows the results of passability estimation on laboratory experiments. The most significant parameter is DoC, which is strongly related with Q. When DoC becomes deeper, passability becomes low. Larger pool size positively affect passability since it increase the number of passable cells. Longer LoC and steeper slope negatively affect passability.



Note: The estimated passability in pool (light blue cell = Ayu can rest in the cell, white cell in pool = Ayu cannot rest in the cell); the estimated passability of channel (red and black channel = Ayu cannot pass through the channel, other colors=Ayu can pass through it); total passability pool and channel (dark blue = good, white = not good).

Fig. 5-13 Passability estimation on laboratory experiments.

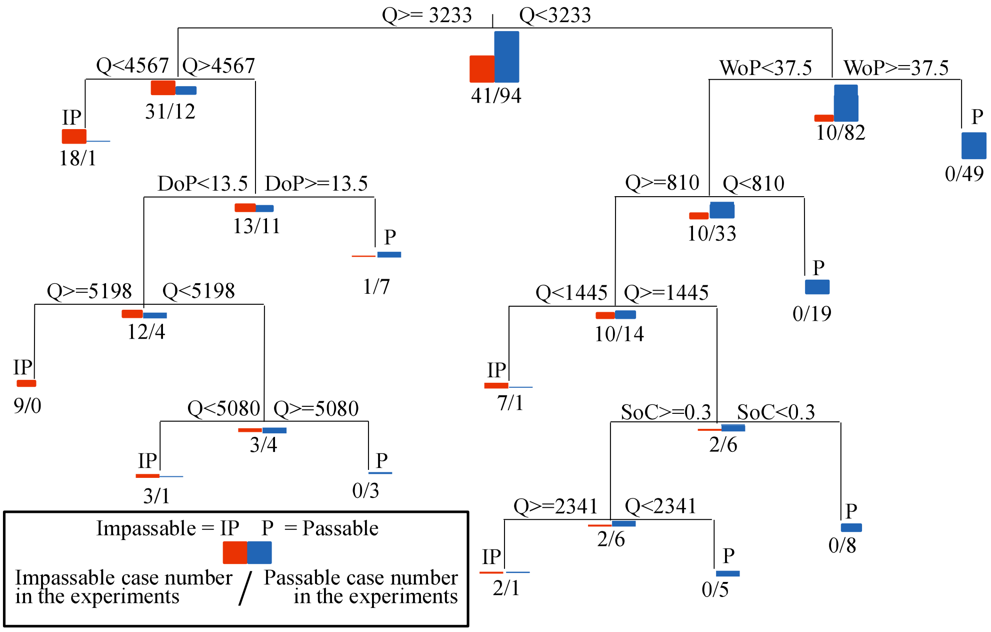


Fig. 5-14 Decision tree on overall passability of a pair of channel and pool.

Figure 5-14 shows the decision tree on passability of a pair of channel and pool. Decision tree also shows that Q is the most significant variable, and WoP, DoP, and SoC follow. Please note that the values appear in Figure 5-14 strongly depend on the experimental conditions of this research. For example, the value 37.5 of WoP for the second branch just distinguishes 25cm and 50cm WoP. No difference happens even when this value is 25.1 or 49.9 while I am estimating the results of laboratory experiments. In this meaning, I only show the framework of SEF estimation model here. To increase the applicability of the decision tree to other SEFs, extra numbers of laboratory experiments with different condition would be essential.

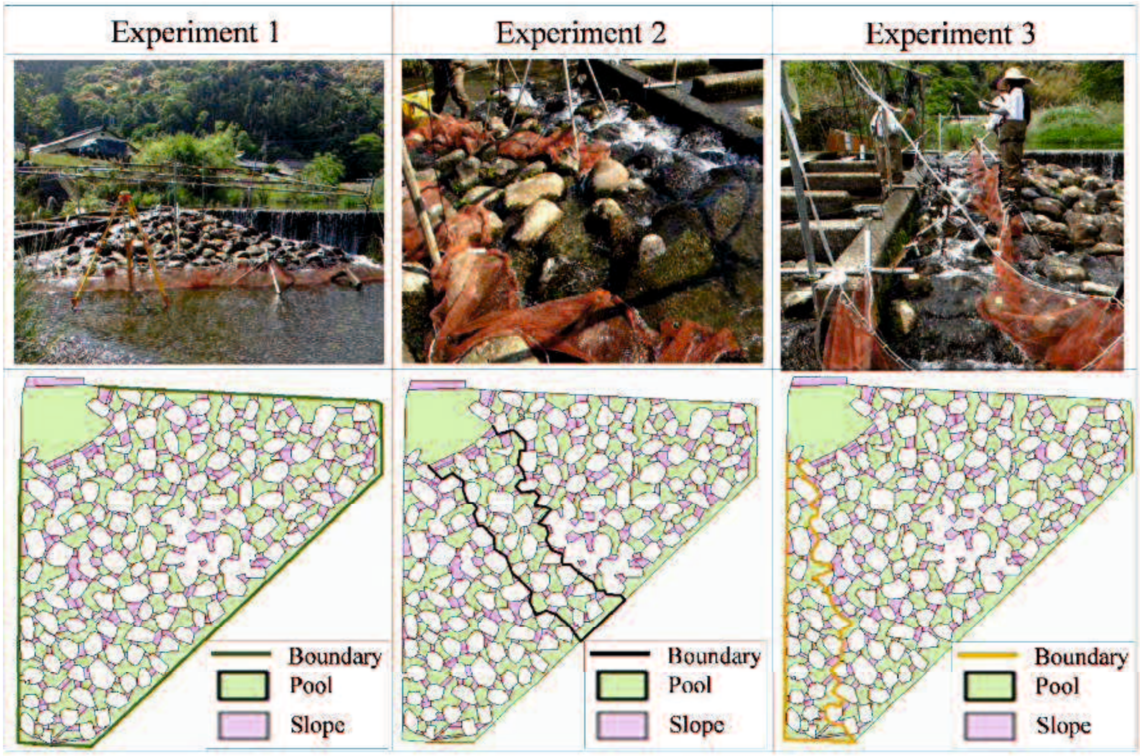


Fig. 5-15 The Experimental area.

Figure 5-15 shows the set-up of field experiments. Figure 5-16 shows the environmental conditions at the SEF together with the location of the net. The experiments were conducted on 12th (experiment 1), 14th (experiment 2), 15th (experiment 3) May, 8th June (environmental condition) 2013. The flow rate entering the SEF during these date are 0.050m^3/s, 0.064m^3/s, 0.058m^3/s, and 0.058m^3/s respectively. Water temperature was approximately 17 degree centigrade for all experiments. Table 5-2 shows the Number of successfully ascended Ayu. It is interesting that even if fish ascending routes in experiment 1 include all ascending routes in experiment 2, ascent success rate of experiment 1 within 30 minutes is much smaller than that of experiment 2. It might because fish cannot estimate the whole route passability, and it has chance to enter impassable route even when passable route exists.

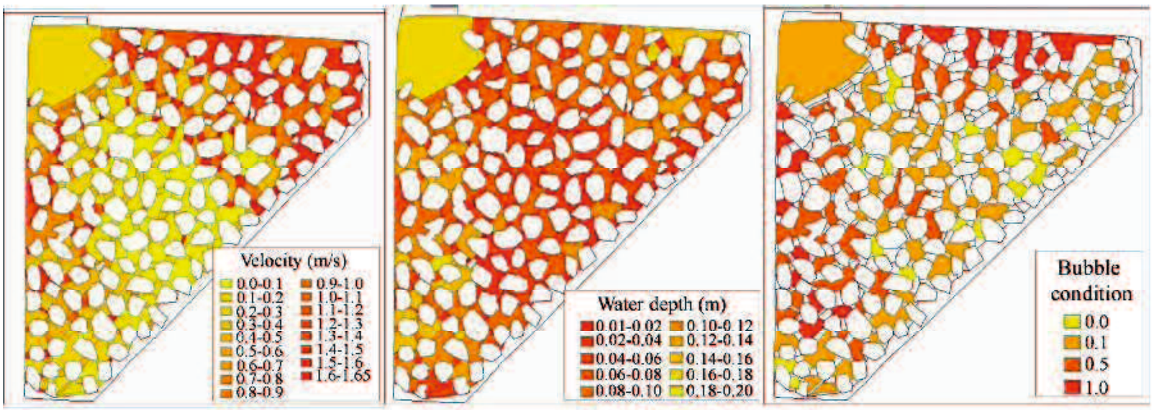


Fig. 5-16 The Environmental conditions at Fushino River SEF. (a). Velocity; (b). water depth; (c). bubble condition.

Table 5-2
Number of successfully ascended Ayu.

	Investigation Time (h)	Number of Released Ayu	Number of ascended Ayu	Number of ascended Ayu within 30 minutes	Ascent success rate within 30 minutes (%)
Experiment 1	20	100	71	4	4
Experiment 2	0.5	50	27	27	54
Experiment 3	0.5	100	17	17	17

Based on the environmental condition, I calculated preference of SEF and the result shows in Fig. 5-17. In Fig. 5-17, central zone and part of right bank of SEF show prefer condition for fish to stay and pass through channel. Based on the preference result of SEF, possible routes to ascending SEF for Ayu is central zone. I evaluated the Fushino River SEF by using the decision tree and based on the environmental conditions (Fig. 5-18). To estimate Q for each channel, the flow rate entering the upper pool was distributed to each downstream channel based on their discharge section area. Then, the estimated results of the decision tree (IP=0, P=1) were given to each channel, not to each channel and pool pair.

This was because some pools were paired with multiple channels and such pairs, sharing the same pool, sometimes showed different results. In Fig. 5-18 all ascending routes had more than one impassable channel and pool pair. This was even true for experiment 2, in which more than 50% fish had ascended. This might be because of the BL difference between the field observation (7cm) and the decision tree (6cm).

Furthermore, I estimated the whole SEF`s performance by using equation (6). Total route for ayu to ascend the SEF, N_r was 171,071, 192, and 1,584 for experiments 1, 2, and 3, respectively.

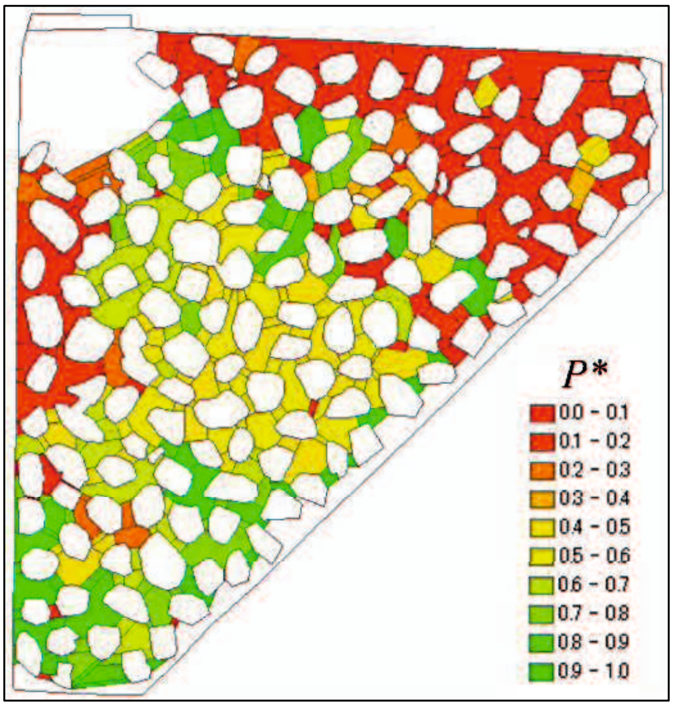


Fig. 5-17 The calculation SEF result based on preference (P^*)

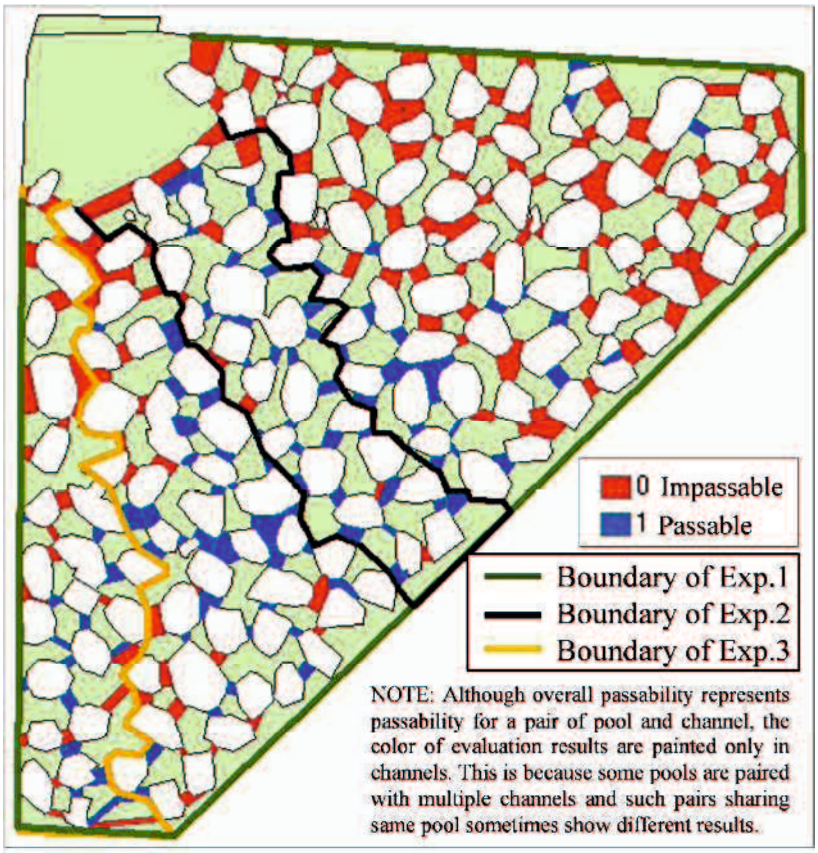


Fig. 5-18 Overall passability, based on the decision tree for BL6 Ayu.

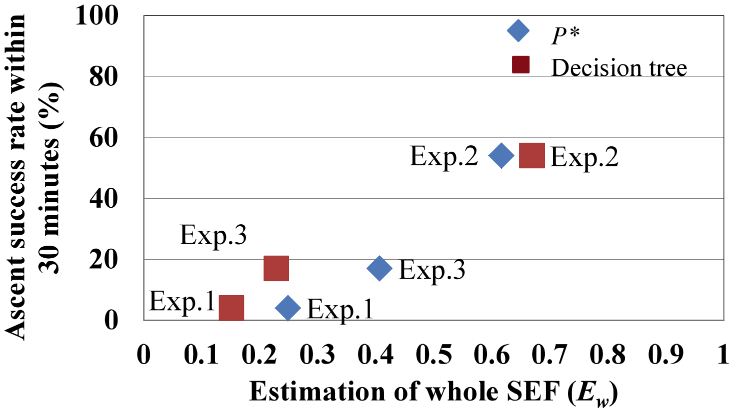


Fig. 5-19 Relationship between estimation of whole SEF and ascent success rate within 30 minutes.

Figure 5-19 shows the relationship between estimation of the whole SEF performance, E_w, and the ascent success rate within 30 minutes, which was positive. This was also true for different time spans of 15 to 30 min. This indicates that our estimation model successfully explained the efficiency of the Fushino River SEF.

5.5 Conclusions

First, I define threshold to estimate for Ayu whether it can rest and pass through SEF or no. Second, I developed a decision tree to estimate the passability of a pair of channel and pool in SEF based on laboratory experiment. Then I proposed an equation to estimate whole SEF combining the estimation result of the decision tree. The estimation equation showed a good relationship with the fish ascent success rate in field experiments. Through this research, I could show a framework of SEF estimation. To increase the applicability of this method to other SEFs, experiments with different conditions would be required.

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CHAPTER 6
CONCLUSION AND FUTURE WORK

6.1 Conclusions

The techniques for designing river works to facilitate fish migration based on preference are developed. The general conclusions are summarized below:

1. First stage: determining the approach to gap section.

   For rheotaxis experiment:

   - Preference and weight of rheotaxis for juvenile and adult ayu are determined.
   - Juvenile ayu shows strong positive rheotaxis are 1 (30 cm/s to 40 cm/s) and adult ayu shows positive rheotaxis are 1(for 50 cm/s) and 0.81 (for 70 cm/s).
   - For juvenile, weight values of rheotaxis are 1 (for 40 cm/s) and 0.71 (for 30 cm/s).
   - For adult, weight values of rheotaxis are 1 (for 50 cm/s) and 0.63 (for 70 cm/s).
   - Simulation model successfully reproduced an observed juvenile ayu migration behavior in river.

   For underwater sound experiment:

   - Preference of sound and its weight for 100Hz, 200Hz, 400Hz, 800Hz, weir, fish ladder and white noise are determined.
   - 100 Hz sound, which is dominant in weir sound, is revealed to be important as avoided frequency, and 200Hz ,which is dominant in fish ladder, is revealed to be important as preferred frequency.

- For adult, weight value for sound is 1 (for 100 Hz) and 0.68 (for weir sound).
- For juvenile, weight value for sound is 0.26 ((for 100 Hz) and 0.18 (for weir sound).
- Fish behavior observed in the field experiment agreed with the preference determined through the laboratory experiments qualitatively.
- The simulation model properly reproduced the trend of observed juvenile Ayu migration behavior in a river.

2. Second stage: evaluating gap section.
   - A decision tree was developed to estimate the passability of a pair of channel and pool in SEF based on laboratory experiment.
   - An equation was proposed to estimate whole SEF combining the estimation result of the decision tree.
   - The estimation equation showed a good relationship with the fish ascent success rate in field experiments.

6.2 Future Work

Create simulation model based on air bubble and build it into our fish behavior simulation model on ArcGIS. Complete for whole simulation model based on rheotaxis, sound and air bubble preference.

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