

**Climate warming and the effectiveness of restoring longitudinal river
connectivity for endangered non-anadromous Taiwan salmon
(*Oncorhynchus formosanus*)**

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Abstract

Climate warming and the effectiveness of restoring longitudinal river connectivity for endangered non-anadromous Taiwan salmon (*Oncorhynchus formosanus*)

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River restoration is widely practiced to improve river ecosystem functions that have been degraded or impaired through anthropogenic alterations or other causes. Despite the significant amount of resources invested into river restoration efforts, the effectiveness of such actions is hard to evaluate due to the lack of research emphasizing long-term monitoring of the efficacy of restoration practices in areas being impacted by warming temperatures. In central Taiwan, a mid-sized dam was removed to restore longitudinal connectivity of the Cijiawan River with the goal to conserve the endangered Taiwan salmon (*Oncorhynchus formosanus*). However, the ecological benefits of dam removal, especially under the scenario of pre-existing habitat alterations due to land-uses and dams, need to be explored under a climate change scenario. The collective impacts on Taiwan salmon's behavioral responses to certain hazardous conditions cannot be currently evaluated. The goals of this research were to assess the effectiveness of dam removal to restore river connectivity and to provide suitable thermal refugia for the Taiwan salmon under warmer climatic conditions. This research also needed to determine the threshold

temperature that causes Taiwan salmon to express avoidance behavior and to migrate to cooler habitats.

One ecological benefit of dam removal is the ability of Taiwan salmon to swim back to their home range after being washed over the dam (a washdown) and trapped at downstream river sections during extreme flood events. By analyzing historical precipitation data and the spatial population variations of the Taiwan salmon, Taiwan salmon population declines were associated with severe summer flood events, but the degree of decline was not correlated with the severity of the flood events. Also, the spatial distribution of the salmon populations after summer flood events did not fit the general patterns expected during a washdown return situation. Despite washdown return incidents occurring at local scales under specific biotic and abiotic conditions, the dam removal was not significantly correlated to the observed mortality rates of the Taiwan salmon. The dam removal did provide passage for salmon returning behavior to be expressed as they migrated back to their home ranges following the flood-induced displacement events.

Another potential ecological benefit of dam removal for salmon is that downstream Taiwan salmon have access to upstream cold water habitat or thermal refugia when water temperatures exceed their thermal thresholds. A controlled temperature gradient flume experiment was used to identify the temperature threshold at which Taiwan salmon show a significant high temperature avoidance behavior. This experiment identified a water temperature threshold at 16.4°C where salmon express avoidance behavior. By monitoring the summer field temperature regimes on Cijiawan River, the temperatures of river sections below the Cijiawan Two dam regularly exceeded the 16.4°C temperature threshold for extensive periods during the day time in summer. In contrast, the upstream sections near Cijiawan Three dam were consistently thermally suitable for salmon during the same summer

period. These results indicate that the restored longitudinal connectivity resulting from the removal of the dam has potentially significant benefits for downstream Taiwan salmon populations and their access to upstream cold water refugia under today's thermal regimes.

Climate change is predicted to have significant effects on freshwater ecosystems experiencing warmer temperatures and changing hydrologic regimes. By comparing current Taiwan salmon habitat conditions and usage behavior to the projected habitat changes under a climate change trend, the ecological effectiveness of dam removal to restore the longitudinal connectivity of the river appears to have a limited effect on the conservation of the Taiwan salmon populations. This study shows that the increase in the intensity of the extreme precipitation events as well as the warmer water temperatures are having a greater impact on salmon resilience that is not addressed by re-establishing the longitudinal connectivity of the river by the removal of the Cijiawan dam. The increasing flood intensity does not appear to increase the mortality rates of Taiwan salmon but does result in higher rates of salmon being washed down to the lower reaches of the river which are thermally unsuitable for extended hours during the daytime in the summer season.

This research suggests that the greatest impact on salmon survival will be due to the rising river water temperatures resulting from climate change. In this study, approximately half of the river extent between Cijiawan One and Three dam was thermally unsuitable during the daytime period of the summer months. These temperatures will cause salmon to express their avoidance behavior and to migrate to the upper reaches of the river. Taiwan salmon may need to rely more on local small-scale cold water refuge to cool down during the nighttime periods. The restored longitudinal connectivity of the river provided by the removal of the

Cijiawan dam does not mitigate future spatial thermal regime changes or the existence of other migration barriers.

As a thermally sensitive freshwater species restricted to a confined river, Taiwan salmon and Cijiawan River demonstrate that non-anadromous landlocked salmon are extremely sensitive to the possible environmental impacts reported by future climate-change projections. This serves as a warning of the increased vulnerability of Taiwan salmon to climate change when they are restricted to inhabiting river systems isolated from marine environments. Taiwan salmon are highly vulnerable to the continued warming temperatures suggesting that maintaining viable population densities will be challenging. Most of the management tools such as dam removal or vegetation management in the riparian zones are not designed to address the impacts of future projected warming temperatures.

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Introduction

Despite increasing research efforts and large investments in stream restoration projects (BenDor et al. 2015), the benefits and effectiveness of those investments are challenging to measure and the causal relationships have been difficult to identify in research projects (Bernhardt et al. 2005; Bernhardt et al. 2007). For many stream restoration projects, establishing specific ecological objectives and linking them to the monitoring and evaluation protocols are recognized as being important (Kondolf 1995; Palmer et al. 2005), but it has been challenging for many projects to develop criteria to evaluate the effectiveness of their restoration practices (Kondolf et al. 2007). This is a long-term challenge facing researchers and managers because of the need to measure environmental impacts in fluid ecosystems where the natural variability of data being measured is high, the difficulty of measuring the magnitude of an impact, and the need to sample independent sampling points because of time constraints of most research studies (Osenberg et al. 1994).

Longitudinal connectivity of a stream is one of the most important factors controlling the functions of natural stream ecosystems by providing passage for the flow of energy, matter and organisms. However, anthropogenic factors that produce in-stream barriers can seriously impair the connectivity of natural stream ecosystems by altering stream hydrology, morphology and thermal regimes (Bergkamp et al. 2000). It can also obstruct the longitudinal movement of aquatic species (Warren and Pardew 1998; Wheeler et al. 2005), especially during upstream migrations. Dam removal is increasingly been practiced as a stream restoration tool to restore fish population sizes (Kibler et al. 2011; O'Connor et al. 2015), but fewer than 10% of removed dams have been scientifically evaluated for their effectiveness (Bellmore et al. 2017).

To restore the only habitat available for the endangered Taiwan salmon, the Cijiawan One dam was removed in 2011 as part of stream restoration efforts in Taiwan. However, its potential ecological benefits have not yet been evaluated because the necessity of longitudinal river connectivity had not yet been scientifically confirmed for the resident landlocked Taiwan salmon. The newly restored passage could provide access to upstream habitat for downstream Taiwan salmon population under specific scenarios, such as the returning movement back to the home range returning movement after displacement by flood events and the search for cold water refugia when water temperatures exceed the thermal threshold for Taiwan salmon. However, these scenarios and Taiwan salmon's behavioral response to thermal extremes still need to be confirmed by scientific data.

Climate change is predicted to have significant effects on the resilience of freshwater ecosystem due to increasing temperature and changing hydrologic regimes (Kernan et al. 2011; Poff et al. 2002; van Vliet et al. 2013). Non-anadromous fish face unique life history challenges to survive in river systems isolated from marine environments, and they may be more vulnerable to climate change impacts due to their limited available habitat range that reduces their ability to migrate to more suitable areas. As a thermal sensitive freshwater species in a confined system, Taiwan salmon and Cijiawan River demonstrate that non-anadromous landlocked salmon are extremely sensitive to the possible environmental impacts of the climate-change projections, and such combination could serve as an early warning when evaluating climate change and its impact on freshwater habitats and biodiversity.

Dissertation chapters and objectives

In the following three chapters, the necessity for re-establishing the longitudinal connectivity of resident landlocked Taiwan salmon by the removal of the Cijiawan One dam will be explored. Also, the potential ecological benefits of Cijiawan One dam removal on Taiwan salmon under different scenarios such as extreme flood events and increased temperatures are examined to understand Taiwan salmon vulnerability to climate change.

Research presented in Chapter 1 examines the susceptibility of Taiwan salmon to downstream displacement during summer flood events. It was hypothesized that extreme summer flood events will displace Taiwan salmon to downstream sections of the river and restored longitudinal connectivity will increase fish abundance by helping Taiwan salmon return to their original home range. The hypothesis is tested with hydrological patterns of severe precipitation events and the survey of Taiwan salmon abundance in relationship to the hypothetical washdown return and barrier removal scenarios.

The focus of the research described in Chapter 2 is on the design of an experimental system where Taiwan salmon's thermal threshold could be determined with a controlled temperature gradient flume experiment. The experimental system was built to produce a temperature gradient that would identify at what temperature salmon begin to express high temperature avoidance behavior. Using this threshold and field temperature records, the extent and duration of high water temperatures were researched to identify where hazardous habitat areas existed along the Cijiawan River, as well as the identification of potential cold water refugia that would be accessible to salmon with the removal of the Cijiawan One dam.

The third chapter 3 integrated data results from the first two chapters to explore whether re-establishing river connectivity facilitates the increase of suitable thermal habitats for Taiwan salmon. In other words, do the projected temperature and hydrologic changes caused by climate change on the Cijiawan River make the Taiwan salmon population vulnerable to the temperature warming effects of climate change that are currently being experienced in Taiwan? The limitation of various river restoration practices was also evaluated by addressing Taiwan salmon's resilience to a changing environment.

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Chapter 1

Susceptibility of Taiwan salmon (*Oncorhynchus formosanus*) to downstream displacement by seasonal flooding and dam removal

Abstract

In central Taiwan, a dam was removed to restore longitudinal connectivity of the Cijawan River to improve the conservation of the endangered Taiwan salmon (*Oncorhynchus formosanus*). Assessing the benefits of dam removal on the long-distance migration of the resident *O. formosanus* populations requires knowledge of the role of flood events and the impact of washdown return incidents on salmon population dynamics and migration patterns. This base-line information did not exist when this research was conducted. Two alternative hypotheses were tested to understand factors impacting Taiwan salmon abundance and population viability. It was hypothesized that extreme summer flood events will displace Taiwan salmon to downstream sections of the river and the restored longitudinal connectivity will increase fish abundance by helping Taiwan salmon returning their original home range. The hypothesis being tested is whether hydrological patterns of severe precipitation events and the survey of Taiwan salmon abundance can explain the hypothetical washdown return and barrier removal scenarios. The objectives of this research were to characterize the effects of flood events on the distribution of the Taiwan salmon population and the potential for extreme precipitation events to increase the occurrence of washdown return incidents.

This research was designed to identify the washdown return incidents of salmon in relationship to specific hydrological factors. Data were collected between 1997 and 2012 using semi-annual snorkeling survey of fish counts along the entire length of

the river. Each year data on salmon population levels were surveyed before the start of a typical typhoon season and prior to winter spawning season. Fish abundance was recorded by size groups: small (<10 cm length), medium (10-20 cm), and large (>20 cm). The final snorkeling survey was recorded within seven segregated river sections to measure the impact of dam removal on salmon abundance. Hydrological data were available for this research and hourly precipitation was available from the year 1997 to 2012. Four hydrological factors were used to isolate the impact of precipitation duration and intensity on Taiwan salmon abundance: 1) Annual precipitation; 2) Annual total number of severe flood events; 3) Maximum precipitation in any 24-hour period; and 4) Number of consecutive 12-hour periods with precipitation levels that were over a critical intensity threshold. Data were statistically analyzed using several approaches such as principal component analysis, cluster analysis with Jaccard bootstraps, ANOVA and Random Forest.

This research supported that Taiwan salmon population declines are associated with severe summer flood events, but the degree of decline was not correlated with the severity of flood events. Further, the spatial distribution of the populations after summer flood events were not correlated with the general patterns occurring after the washdown return events. However even though there was no evidence for general and systematic washdown return incidents happening after summer flood events, circumstantial data suggested such incidents could occur at local scales under certain biotic and abiotic conditions. Dam removal is assumed to have limited ecological benefits on Taiwan salmon washdown return incidents, since such beneficial scenarios have not generally been observed in Taiwan.

Introduction

Dam removal is increasingly practiced as a river restoration tool to restore fish population sizes (O'Connor et al. 2015), but fewer than 10% of removed dams have been scientifically evaluated for their removal effectiveness on benefiting fish populations (Bellmore et al. 2017). To restore the only habitat where the endangered Taiwan salmon (*Oncorhynchus formosanus*) are found, the Cijiawan One dam was removed in 2011 as part of river restoration efforts. However, the potential ecological benefits of removing this dam could not be evaluated. This was mostly because the longitudinal river connectivity of the resident landlocked Taiwan salmon had not yet been scientifically confirmed as being important enough to evaluate the viability of salmon in these river systems. One goal of dam removal was to enhance the ecological benefits that would come from dam removal which would increase river connectivity for salmon experiencing flood washdown and then help them return upstream. A previous study found that deliberately displaced Taiwan salmon showed an increase and significant long-distance movement of salmon toward their original home range (Chen 2012). Therefore, in the case of failing to withstand high floods and being washed downstream, Taiwan salmon may attempt moving upstream to return their original home range. The research objective described in this chapter explored the susceptibility of Taiwan salmon to downstream displacement by the frequent seasonal flooding events.

Taiwan salmon are known as the southernmost distributed native Pacific salmon in the northern hemisphere (Crawford and Muir 2008; Lin et al. 1990; Oshima 1955; Quinn 2005). Like the fluvial form of masu salmon (*Oncorhynchus masou*) that live in mountain streams in Kyushu, Japan (Sakata et al. 2005), Taiwan salmon attain maturity, spawn and live their entire life in freshwater riverine systems and maintain

parr marks on their flanks into adulthood. They are now endangered due to habitat degradation, regional agricultural development and channel-altering in-stream hydraulic facilities. The Taiwan salmon population decreased sharply in the 1980s and only ~200 fish were counted during the snorkeling survey in 1989 (Lin and Chang 1989). In fact, in 1996, Taiwan salmon were listed as critically endangered in the Red List of the International Union for Conservation of Nature (Baillie and Groombridge 1996; Kottelat 1996).

Longitudinal connectivity is one of the most important factors controlling the functions of natural stream ecosystems by providing passage for the flow of energy, matter and organisms. However, anthropogenic in-stream barriers can seriously impact the connectivity of natural stream ecosystems by altering stream hydrology, morphology and thermal regimes (Bergkamp et al. 2000). Further, they can obstruct longitudinal movement of aquatic species (Warren and Pardew 1998; Wheeler et al. 2005), especially during upstream migrations. Smaller scale in-stream barrier improvements, such as culvert replacement and fish passage construction, are becoming common stream restoration practices and effective ways to increase or improve the availability of additional habitat (Hart et al. 2002; Roni et al. 2002). Meanwhile the removal of larger-sized dams are increasingly being proposed for the restoration of river functions (Bednarek 2001; Stanley and Doyle 2003).

In spite of increasing efforts and large investments in stream restoration practices, the benefit and effectiveness of those investments are not yet substantially identified (Bernhardt et al. 2005; Bernhardt et al. 2007). Due to the lack of clearly quantified objectives, many projects are challenged by setting criteria for what will be used to determine the effectiveness of stream restoration efforts (Kondolf et al. 2007). For stream restoration projects, the importance of specific ecological objectives and corresponding monitoring has been emphasized (Kondolf 1995;

Palmer et al. 2005), but rarely put into practice. Stream restoration effectiveness evaluations usually need long-term monitoring data to identify ecological responses that occur over time (Pess et al. 2008; Woodward et al. 2008). Ecological responses to dam removal likely occur over a range of time scales even though some responses, such as fish movements upstream in river systems previously blocked by the dam, can begin within days after dam removal (Chen 2012; Pizzuto 2002).

Due to the lack of understanding Taiwan salmon's need for longitudinal river connectivity, the benefits of Cijiawan One dam removal to Taiwan salmon habitat have not yet been scientifically evaluated. Unlike most of the anadromous or fluvial life-forms of salmonid, Taiwan salmon have evolved into a resident life-form and spend their whole life only in mountain streams without major migrations. Previous radio telemetry tracking research documented their sedentary nature and that fish occupy a small habitat range without long-distance movement (Liao 2012). Adult Taiwan salmon are basically sedentary in summer but undertake small-scale movements to secure food using an effective foraging strategy for the supply of drifting food. Thus, long-distance migration between marine saltwater and freshwater streams has not been a necessary foraging strategy for the Taiwan salmon. Although the usage of the new dam removal passage was confirmed by radio telemetry tracking conducted pre-, during and post-dam removal phase (Chen 2012), the benefits from the dam removal on the effects of increased direct longitudinal river connectivity on Taiwan salmon's life history still remain uncertain.

This research was designed to examine the susceptibility and correlation of Taiwan salmon to downstream displacement during summer flood events and relate the Taiwan salmon distribution to precipitation patterns. Two hypotheses were tested to determine what factors impact Taiwan salmon abundance and population viability in relationship to extreme precipitation events and from the re-

establishment of river connectivity due to a dam removal.

H₁: *High intensity flooding events following extreme precipitation events will increase salmon washdown incidents and decrease their population levels upstream of the dam since salmon are unable to swim back to their previous and more suitable home ranges;*

H₂: *Dam removal will increase the abundance of Taiwan salmon in the total river extent because of the increased river connectivity and subsequent access to more suitable habitat for the salmon.*

The objectives of this research were:

1. Describe and build a data-base characterizing the frequency and intensity of four hydrological parameters that result from severe precipitation events.
The four hydrological factors are: total annual precipitation in mm, number of annual significant precipitation events, annual maximum precipitation in mm within a consecutive 24-hour period, annual number of consecutive 12-hour periods exceeding the 2-year recurrence frequency [2-year recurrence frequency = accumulates more than 130 mm in a continuous 12-hour period in the Cijiawan watershed].
2. Relate the four hydrological factors to the seasonal and annual Taiwan salmon abundance; and
3. Compare post-flood Taiwan salmon distribution and abundance following the re-establishment of river connectivity from the removal of a dam on the washdown return and barrier removal scenarios.

Data and Methodology

Site description

Taiwan salmon are currently only found in the Cijiawan River in the upper Ta-Chia River basin located in central Taiwan (Figure 1.1). The stream is approximately 13 km long with an average width of 9.7m. The Cijiawan basin encompasses an area of 76 km² (Lin et al. 1990) and has a 120 m elevation range from its lower to its upper extent (1,700 to 1,820 m). The dominant vegetation along the hill slopes west of the Cijiawan River are secondary forests that are a result of the reforestation projects that were initiated in the 1950s to 1960s. Grasslands dominate the eastern slopes along the river developed on lands formerly used for agriculture. The stream geography is steep with an average channel slope of 1.2 %. River dissolved oxygen levels are consistently greater than 7 mg/l, and pH values range from 7.0-8.3 (Lin and Chang 1989; Techu Reservoir Management Committee 1983). The local air temperature ranges from -8 to ~29 °C and the streambed is characterized as being predominantly a cobble-boulder substrate (Wang 1989).



Figure 1.1. A map showing the location of the Cijiawan River study site which is found in the Ta-Chia river watershed in Taiwan.

Precipitation data

The hydrological data for this research was retrieved from regional daily precipitation data collected at the Tao-Shan station (24.38739N, 121.30457E), which is located inside the Cijiawan River basin (Figure 1.2). Hourly precipitation data were available from 1996 to 2013. However, of the 2,147 study days (study days defined as all days between the summer and fall surveys during the 19-year study period), 145 (6.8%) of them had one or more hours of missing data. Substitute values for those missing hourly values were obtained by using values derived from the nearby Si-Yuan Pass station located 5.4 km away in the Tao-Shan River basin (24.39710N, 121.35679E) (Figure 1.2). A linear regression model was created for all overlapping non-missing hourly data from both sites. As there was a large number of overlapping missing hourly values for both sites during 2013, that year was omitted from the study.



Figure 1.2. Map showing the Cijiawan River sections divided by existing and removed dams 2004 (shown as rectangular black boxes) and two precipitation stations at Tao-Shan and Si-Yuan pass. Cijiawan Two dam was breached in 2004 and Cijiawan One dam was removed in 2011.

Defining a realistic rainfall level threshold impacting salmon is challenging because of the difficulty of separating critical precipitation events from continuous precipitation data. The definition of a rainfall threshold has varied according to different research topics and needs to be customized to characterize regional hydrological conditions. Bankfull discharge is considered as the water level that "corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or reforming bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels" (Dunne and Leopold, 1978). Bankfull discharge is also known as one of most important conditions influencing river morphology, sediment transport, flood dynamics and river ecology (Andrews 1984; Castro and Jackson 2001; Harrelson et al. 1994; McCandless and Everett 2002; Nolan

et al. 1987; Williams 1978), and its probability of occurrence could be used as the critical precipitation event threshold. Bankfull discharge is defined as the flow when water level just fills the channel, reaches the top of the bank, and starts to overflow into a floodplain (Kilpatrick and Barnes 1964; Leopold et al. 2012; Pickup and Rieger 1979). Several different methods can be used to calculate the exact value of bank-full discharge for different river types. Previous researchers suggest a bank-full discharge recurrence interval can be 1.4 to 1.8 years while base flow dominated gravel-bed streams may experience less frequent flood events (Lawlor 2004; McCandless 2003; Navratil et al. 2006). Considering the availability of intensity-duration-frequency (IDF), the rainfall threshold in this research was designated as a 2-year recurrence frequency for this region. According to the IDF curve developed by Taiwan Water Resource Agency for a hydraulic engineering design, any precipitation event that accumulates more than 130 mm in a continuous 12-hour period in the Cijiawan watershed is estimated to return at a 2-year recurrence frequency. From the year 1997 to 2012, all rainfall events exceeding this threshold were considered significant events and included in further analysis.

Precipitation events in this research were designed to isolate and analyze whether precipitation duration and intensity have any significant effects on Taiwan salmon abundance. Calculated from each year's precipitation data, four hydrological factors were used in this research to compare with Taiwan salmon population variations: (1) Annual total precipitation (mm), the most common hydrological factor collected as part of precipitation analyses; (2) Number of severe flood events annually, which specifically evaluates single event and precipitation distribution patterns; (3) Maximum precipitation accumulations in any 24-hour period each year (mm), designed to account for precipitation intensity events. A 24-hour duration is chosen because it corresponds to the average duration of precipitation during

typhoon events in Taiwan; and (4) Critical rainfall intensity threshold – The number of consecutive 12-hour periods with precipitation over 130 mm in a continuous 12-hour period, which addresses the duration effect by counting how long the habitat experiences critical precipitation events.

Snorkeling data

The effects of flood events on Taiwan salmon and the possible existence of washdown return incidents were analyzed using the potential relationship between the variations in the Taiwan salmon abundance and specific habitat hydrological factors. For this research, seasonal and annual variations in Taiwan salmon population data were collected from field records obtained between 1997 and 2012 (Shei-Pa National Park 1997; Shei-Pa National Park 1998; Shei-Pa National Park 1999; Shei-Pa National Park 2000; Shei-Pa National Park 2001; Shei-Pa National Park 2002; Shei-Pa National Park 2003; Shei-Pa National Park 2004; Shei-Pa National Park 2005; Shei-Pa National Park 2006; Shei-Pa National Park 2007; Shei-Pa National Park 2008; Shei-Pa National Park 2009; Shei-Pa National Park 2010; Shei-Pa National Park 2011; Shei-Pa National Park 2012); these data were obtained as part of semi-annual whole river snorkeling surveys conducted in the Cijiawan River (Figure 1.3) (See Appendix A).

In each year, two snorkeling survey assessments were conducted - one in early summer before the start of a typical typhoon season and one in late fall. The summer snorkeling survey timing was chosen to record salmon parr spawned during the previous winter and were sufficiently large for snorkelers to be able to identify during under water surveys. The fall snorkeling assessment timing was chosen to represent the post summer typhoon season but before the spawning winter season, which

usually starts in mid-November. The exact dates of each snorkeling survey depended on the daily weather conditions and under water visibility conditions.

The snorkeling surveys were conducted by a total of four to six groups of snorkelers who started their survey at the same time at different sections of the river. Each group had two snorkelers covering the same cross-sections in the river and one other person taking notes on the river bank. On snorkeling assessment dates, water visibility needed to be at least 10 m. The river has an average width of 20 m and average depth of 1 m. Hand signals were used between snorkelers and notetakers when any group of fish were spotted and counted (See Figure 1.3).

Taiwan salmon annual snorkeling survey

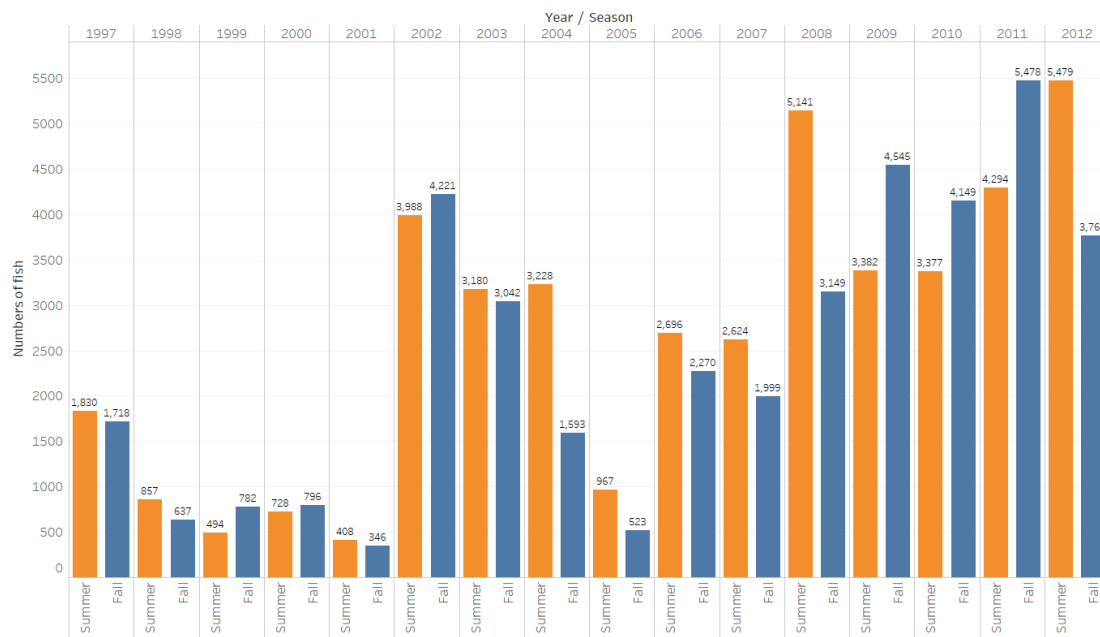


Figure 1.3. Semi-Annual (early summer - before the typhoon season; early fall - after typhoon season) snorkeling survey of Taiwan salmon abundance.

Fish abundance is reported in three different size groups based on snorkelers' visual estimation of fish length in cm: small (<10 cm), medium (10-20 cm), and large (>20 cm). According to year-class average growth rate, each size group also represents a distinct age group of salmon: small fish are 0+ age and spawned the

previous winter, medium sized fish are 1+ age and spawned the year before last, and large fish are >2 years of age and spawned two years before the last year or earlier. The fish were identified using the same size groupings during the summer and autumn snorkeling surveys. Their size groupings do not reflect the growth of the salmon in between the sampling time gap. The final whole river snorkeling survey data were recorded as seven segregated sections separated by their proximity to the existing or removed dams: S_{01} (below Cijiawan One dam), S_{12} (Cijiawan One dam and Cijiawan Two dam), S_{23} (Cijiawan Two dam and Cijiawan Three dam), S_{34} (Cijiawan Three dam and Cijiawan Four dam plus the north fork tributary), S_{45} (Cijiawan Four dam and Cijiawan Five dam), S_{56} (Cijiawan Five dam and Cijiawan Six dam), and S_k (Kaoshan tributary) (Figure 1.2).

Data Analyses

This research was designed to identify potential hydrological drivers of changes in the dynamics of the Taiwan salmon populations. Each of the four hydrological factors individually were investigated for any significant linear relationships with annual salmon population changes between the summer and fall snorkeling surveys. Correlations were developed among the four hydrological factors chosen as potential drivers of changes in salmon populations. Next, principal component analysis (PCA) was used to generate a set of linearly uncorrelated principal components to use in later analyses. The salmon population abundance data were separated by age and size categories to explore whether hydrological factors were correlated to salmon abundance in the different segments of the river. The effects of spatial differences in habitat structure were explored by separately analyzing the population data by location within the river.

Because differences existed between each year's precipitation levels, a cluster analysis approach was used to identify years experiencing a similar annual precipitation pattern. A partitioning around medoids (PAM) analysis and standardized hydrological factor ranking were used to test for any significant year clusters. The stability of each cluster in the original clustering was calculated using the mean value of its Jaccard coefficient over all bootstrap iterations. Clusters with Jaccard bootstrap means higher than 0.85 were considered significant and highly stable. If there were any significant cluster of years with similar patterns, the differences between clusters were analyzed by comparing hydrological factor averages among each cluster.

Washdown return patterns were identified by analyzing population spatial proportional changes in river sections connected to the removed barriers. Assuming a migration barrier exists between two river sections and the fish tend to return to their home range when displaced, flood washdown individuals were trapped at the downstream section. When the migration barrier was removed, individuals would be able to return to their upstream home range that had been inaccessible before the dam removal. Box-and-whisker charts and t-tests were used to identify any significant change in fish abundance and spatial proportion of sections adjacent to the barrier before and after its removal. The Cijiawan Two dam was breached during the typhoon season in 2004 and then became a barrier-free passage in 2005. Thus, differences in abundances and spatial proportion in sections S_{12} and S_{23} across two time-periods 1997 to 2004 and 2005 to 2012 were tested. Possible effects from different fish sizes and annual hydrological conditions were also tested against fish age group data and within hydrological year clusters.

Results

Flood events and hydrological factors

Between 1997 and 2012, 18 precipitation events exceeded the 2-year recurrence frequency threshold of 12-hours of consecutive rainfall of 130 mm (Table 1.1). These events had an average duration of 59.5 ± 23.1 (s.d.) hours with an average 476.5 ± 229.5 (s.d.) mm of total accumulated precipitation. Except for one event in December 2004, the 17 other events were all caused by summer typhoons.

Table 1.1. The duration and accumulated amount of precipitation for the critical rainfall events (exceeded the 2-year recurrence frequency) from 1997 to 2012. [Prec = Precipitation; Consec = Consecutive] [Any precipitation events that accumulates more than 130 mm in a continuous 12-hour period in the Cijiawan watershed exceeds the 2-year recurrence frequency]

Critical Rainfall Event Date (Year/Month/Day)	Duration of Prec Event (hours)	Total Amount of Prec/Event (mm)	Max Prec Within a Consec 12-Hour Period/Event (mm)	Max Prec Within a Consec 24- Hour Period/Event (mm)	Numbers Consec 12-hour periods with >2-year recurrence frequency/event
1997/08/17	40	362	243	348	17
1997/08/28	34	224	145	205	6
2000/08/23	57	239	133	200	5
2002/07/04	35	296	185	243	13
2004/07/03	59	304	130	248	8
2004/08/25	56	822	397	619	36
2004/12/04*	34	196	140	175	2
2005/07/18	76	582	229	424	26
2005/08/04	49	213	136	154	2
2005/10/02	30	422	334	410	18
2007/08/18	55	524	301	434	20

2007/10/06	85	630	270	424	22
2008/07/28**	76	559	259	439	23
2008/09/14	96	876	218	371	48
2008/09/28	75	650	317	524	24
2009/08/07	91	645	184	298	16
2010/09/19	26	185	160	172	7
2012/08/01	97	844	196	370	40

* Event happened in winter and not caused by typhoon.

**Event happened before the summer snorkeling monitoring.

For most years, summer snorkeling surveys were completed before the occurrence of significant flood events, and autumn snorkeling surveys started after these flood events. The only exception occurred in 2008 when the summer snorkeling began after the precipitation event in July. As a result, 16 significant precipitation events occurred during this research (Table 1.1).

The four hydrological factors were significantly related to the annual population variation between summer and fall (Figure 1.4): annual total precipitation ($p=0.001$), annual total significant precipitation events numbers ($p=0.086$), annual maximum precipitation in mm within a consecutive 24-hour period ($p=0.001$), and annual numbers of consecutive 12-hour periods that exceeded the 2-year recurrence frequency of 130 mm ($p=0.001$). However, the four hydrological factors were also significantly correlated to each other ($p<0.01$) with Pearson correlation coefficient (ρ) ranging from 0.644 to 0.919.

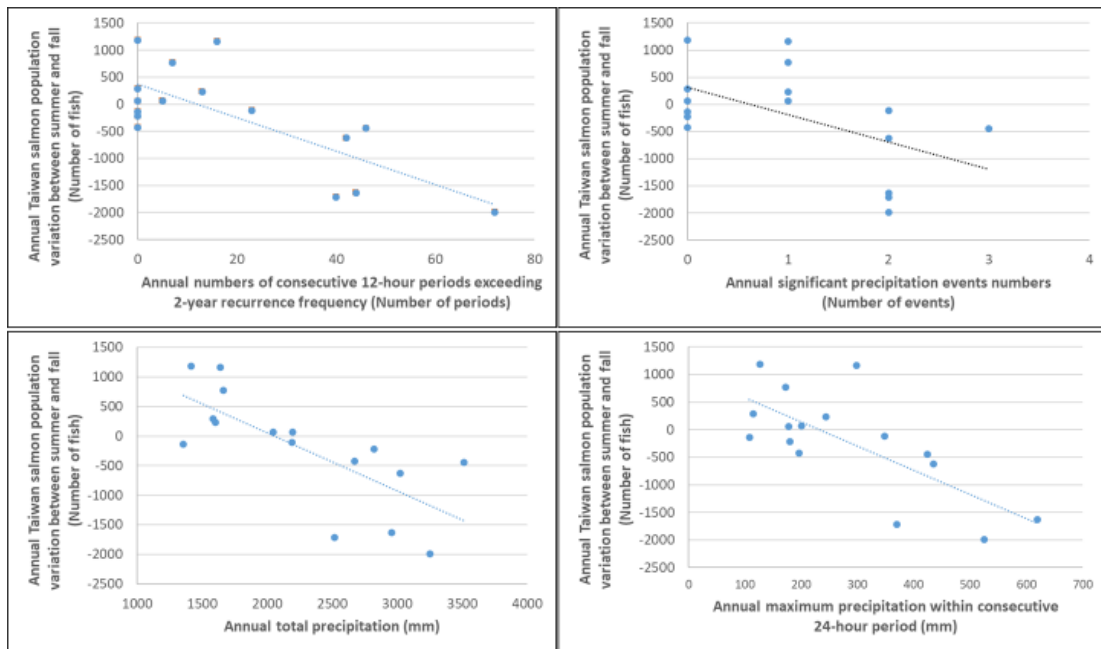


Figure 1.4. The relationship between four hydrological factors and fluctuations in the annual Taiwan salmon population densities between the summer and fall for 1997 to 2012. [The four hydrological factors are: total annual precipitation in mm, annual significant precipitation events numbers, annual maximum precipitation in mm within a consecutive 24-hour period, annual numbers of consecutive 12-hour periods exceeding the 2-year recurrence frequency]

Using the four hydrological factors' ranking as standardized variables, the PAM cluster analysis of four standardized hydrological factors showed two distinct clusters (Figure 1.5). The Jaccard bootstrap means of the two clusters of hydrological factors produced an 0.99 and 0.98, indicating significant and stable differences between clusters (when Jaccard bootstrap means were > 0.85).

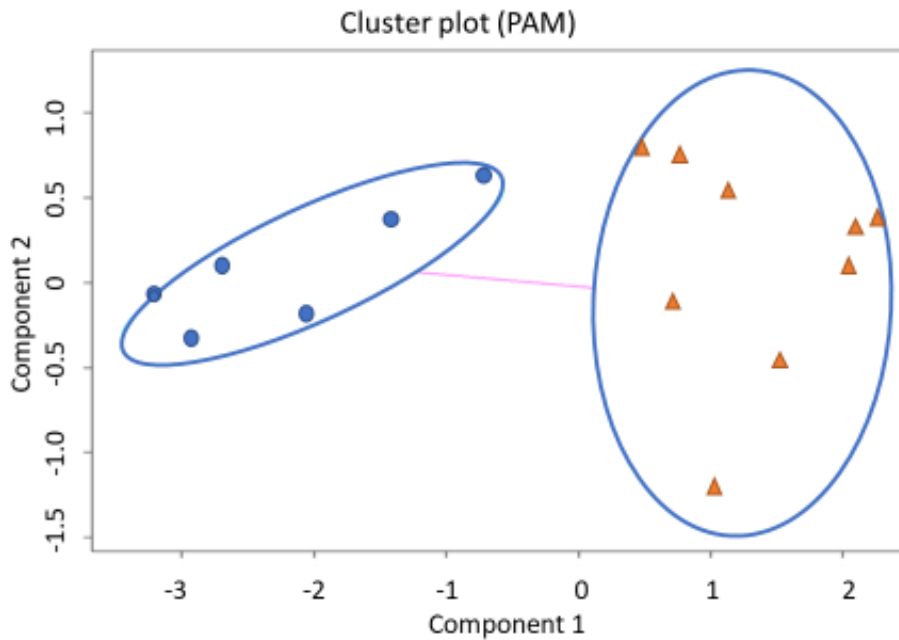


Figure 1.5. Result of year clusters (1997-2011) from partitioning around medoids (PAM) cluster analysis with standardized ranking of four hydrological factors. [The four hydrological factors are: total annual precipitation in mm, annual significant precipitation events numbers, annual maximum precipitation in mm within a consecutive 24-hour period, annual numbers of consecutive 12-hour periods exceeding the 2-year recurrence frequency]

One of the clusters had all four hydrological factors highly correlated with one another compared to the other cluster where the p-values were smaller than 0.001 in a 1-tailed T-Test. The first cluster of years (1997, 2004, 2005, 2007, 2008, and 2012) was identified as wet years with more annual total precipitation and more critical precipitation events of longer duration and higher intensity. In contrast, other cluster years (1998, 1999, 2000, 2001, 2002, 2003, 2006, 2009, 2010, and 2011) were identified as being dry years (Figure 1.6).

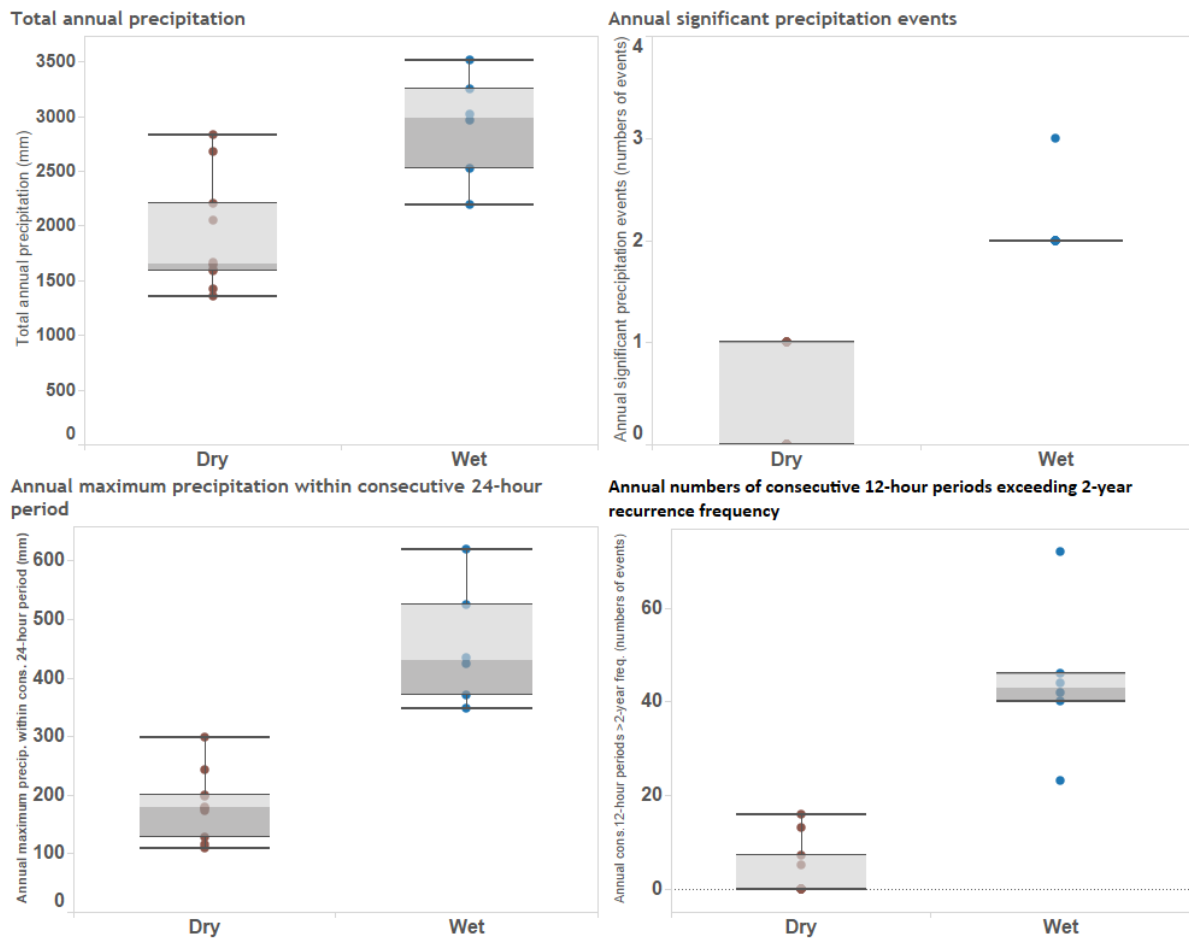


Figure 1.6. Relationships among four hydrological factors for wet (1997, 2004, 2005, 2007, 2008, and 2012) and dry year (1998, 1999, 2000, 2001, 2002, 2003, 2006, 2009, 2010, and 2011) clusters from 1997 to 2012. [The four hydrological factors are: total annual precipitation in mm, annual significant precipitation events numbers, annual maximum precipitation in mm within a consecutive 24-hour period, annual numbers of consecutive 12-hour periods exceeding the 2-year recurrence frequency] [The box charts represents medium and the 25th to the 75th percentile; the whisker range is 1.5 times the inter-quartile range (IQR)]

Population loss during summer floods

A two-tailed t-test showed that population losses during the summer flood season was significantly different between the wet years and dry years ($p < 0.001$). A

1-tailed Z-test showed that only wet years had significant losses in salmon populations ($p < 0.001$) and that there was no significant loss ($p = 0.944$) of salmon through the summer flood season during the dry years. The population losses in the wet years were significant among all size groups of salmon (Figure 1.7): Small ($p = 0.005$), Medium ($p = 0.016$), and Large ($p = 0.052$).

Principal component analysis (PCA) found an integrated independent variable PC1 that explained 84% of the variation of all four correlated hydrological factors. The PC1 then was used as a new independent variable of the hydrological condition for later population-loss analysis. The linear regression showed that the overall population loss in salmon populations during the summer flood season was related to PC1 ($p < 0.001$), and among all size groups (small $p = 0.013$; medium $p = 0.034$; large $p = 0.001$). Because PC1 was also significantly different among wet and dry years (2-tailed t-test; $p < 0.001$), and only wet years had significant population loss due to summer floods, the relationship between hydrological condition and population loss was further analyzed among wet years only.

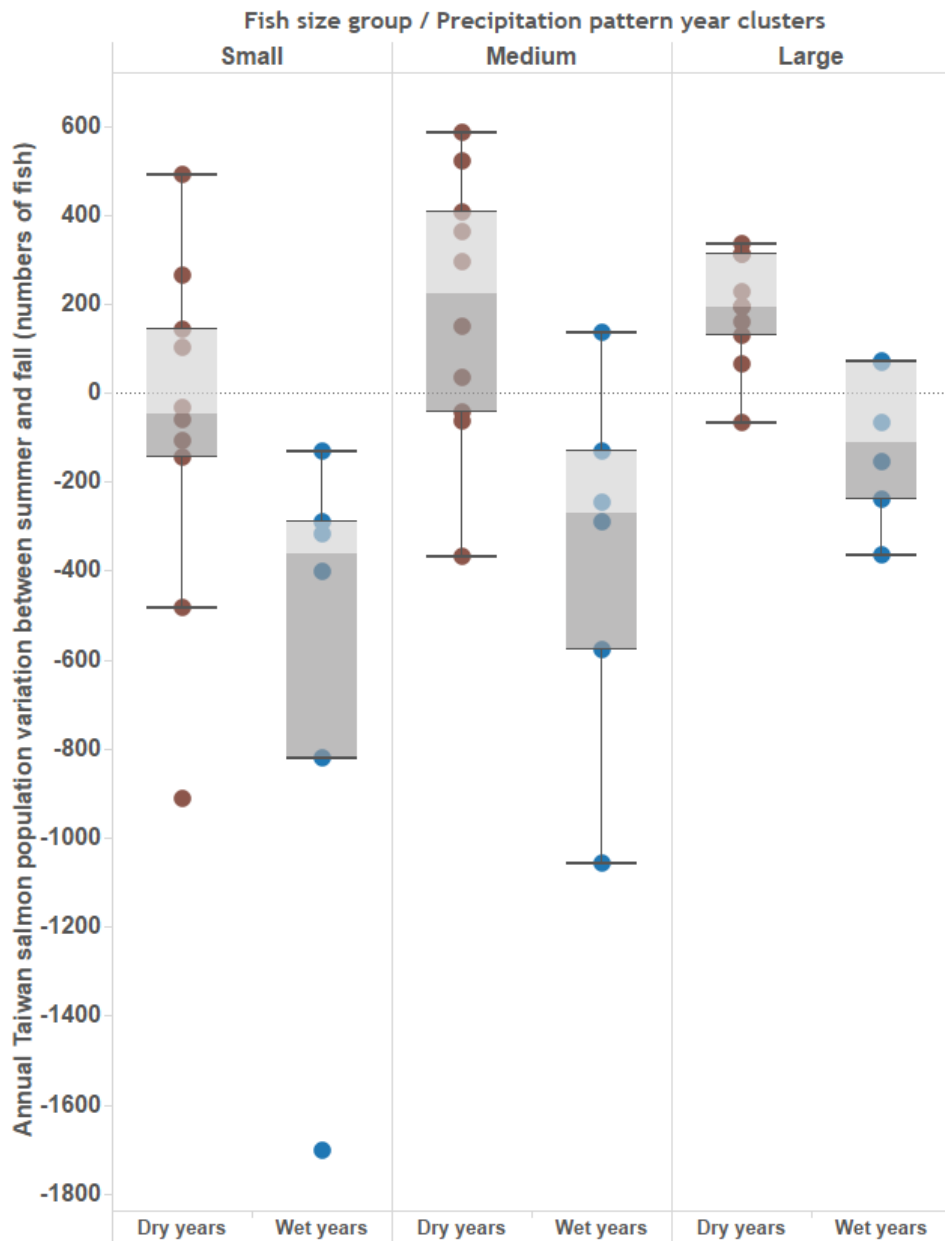


Figure 1.7. Annual variations in Taiwan salmon population between the summer and fall in wet and dry year clusters and fish size groups (small, medium and large) from 1997 to 2012. [Wet years - 1997, 2004, 2005, 2007, 2008, and 2012) and dry years - 1998, 1999, 2000, 2001, 2002, 2003, 2006, 2009, 2010, and 2011] [The box represents the median and the 25th to the 75th percentile; the whisker range is 1.5 times of inter-quartile range (IQR)].

Within wet years, linear regression showed that overall population loss during the summer flood season was not related to hydrological condition variables PC1 ($p=0.360$), nor among each size group (small $p=0.248$; medium $p=0.993$; large $p=0.690$) (Figure 1.8). For smaller scale spatial analysis, there was no individual section with a significant relationship between the salmon population loss during the summer flood and hydrological conditions in the wet years.

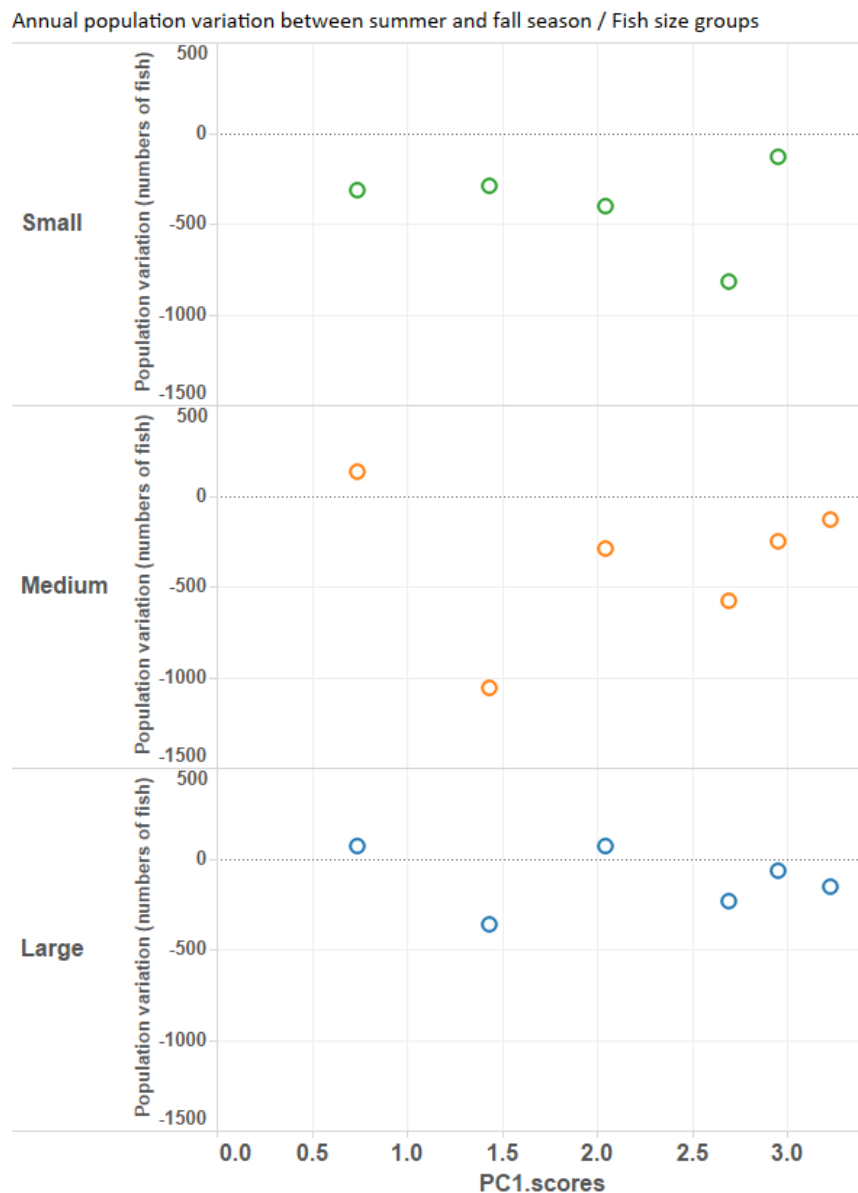


Figure 1.8. Annual Taiwan salmon population variations in the summer and fall by fish size groups (small, medium and large) and the integrated hydrological condition variable (PC1) during the wet years. [Wet years: 1997, 2004, 2005, 2007, 2008, and 2012]

Population spatial proportion variation

The two hydrological clusters of years had different population loss rates and redistribution patterns after the summer flood events at two river sections adjacent to the Cijiawan Two dam (sections S_{12} and S_{23}). Those differences were reflected in spatial variations in the proportion of salmon population by river section (Table 1.2). Among wet years, the proportion of salmon found in the upstream section S_{23} had an overall significant increase ($p=0.040$), but further salmon size group analyses also showed a significant contradictory decrease in the medium size group of salmon ($p=0.020$). Among dry years, there was a significant decrease in salmon populations at the downstream section S_{12} ($p=0.021$). For different size groups of salmon, all size groups had a decreased population proportion during the dry season, but only the relationship with large fish was statistically significant ($p=0.046$).

For time periods 'before' and 'after' the 2004 Cijiawan Two dam breach, there were no significant overall flood-related spatially proportional changes in the salmon populations in the sections above and below the dam breach (Table 1.2). Further size group analysis showed only one significant proportion change by fish size group where large fish decreased in abundance at the downstream section S_{12} before the dam breach ($p=0.025$). However, the other two size groups at the same section in the same year cluster showed no significant changes in abundance. This is also the same river section and salmon size group that showed a significant decrease in the population abundance in the dry year cluster analysis.

Table 1.2. Spatial change of Taiwan salmon population (in percentage) by size groupings (small, medium and large) after the summer flood season near the Cijiawan Two dam. [Fish size data analyses were conducted separately by pre- and post-Cijiawan Two dam breach in 2004 and then by wet and dry year clusters].

Fish Size Group (# Years Surveyed (n))	Cijiawan River section S ₁₂ (between One dam and Two dam)		Cijiawan River section S ₂₃ (between Two dam and Three dam)	
	Average change (%)	P-value	Average change (%)	P-value
Pre-dam breach				
Small (n = 8)	-6.03	0.275	+3.90	0.160
Medium (n = 8)	+2.92	0.538	-3.44	0.264
Large (n = 8)	-5.02	0.025	+4.14	0.256
All sizes (n = 8)	-0.62	0.686	+1.11	0.630
Post-dam breach				
Small (n = 8)	-0.75	0.758	+4.20	0.134
Medium (n = 8)	-4.12	0.288	+2.42	0.425
Large (n = 8)	-6.37	0.172	+0.91	0.828
All sizes (n = 8)	-2.97	0.275	+2.58	0.328
Wet Year Clusters - 1997, 2004, 2005, 2007, 2008, and 2012				
Small (n = 6)	+0.63	0.892	+7.65	0.007
Medium (n = 6)	+3.02	0.658	-2.89	0.020
Large (n = 6)	-5.31	0.277	+6.08	0.002
All sizes (n = 6)	+0.33	0.925	+2.50	0.040
Dry Year Clusters - 1998, 1999, 2000, 2001, 2002, 2003, 2006, 2009, 2010, and 2011				
Small (n = 10)	-5.80	0.135	+1.89	0.433
Medium (n = 10)	-2.77	0.346	+0.92	0.787
Large (n = 10)	-5.93	0.046	+2.93	0.447
All sizes (n = 10)	-3.07	0.021	+1.45	0.586

By consolidating two temporal factors (e.g., hydrological year clusters and Cijiawan Two dam breach incident), the spatial population proportion variations were further analyzed in four subsets (Table 1.3). The significant decrease at downstream section S₁₂ under dry hydrological condition were only detected a few years after ($p=0.018$), and not before ($p=0.304$), the dam breach. On the other hand,

the significant increase at upstream section S₂₃ under wet hydrological condition were only detected during the years before the dam breach (p=0.001), and not after this time (p=0.295). However, the contradictory decrease at medium size group showed a trend before and after dam breach, even though these relationships were not significant.

Table 1.3. Spatial change of Taiwan salmon population (in percentage) by size groupings (small, medium and large) after the summer flood season near Cijiawan Two dam where fish size data were statistically assessed by combining data by pre- and post-dam removal and wet and dry year clusters.

Fish Size Group (# Years Survey Results (n))	Cijiawan River section S ₁₂ (between One dam & Two dam)		Cijiawan River section S ₂₃ (between Two dam & Three dam)	
	Average change (%)	P-value	Average change (%)	P-value
Wet Years - 1997, 2004, 2005, 2007, 2008, and 2012				
PRE-DAM BREACH				
Small (n = 2)	-6.90	0.653	+3.90	0.160
Medium (n = 2)	+16.4	0.072	-3.44	0.264
Large (n = 2)	-3.85	0.620	+4.14	0.256
All sizes (n = 2)	+2.78	0.430	+1.11	0.630
POST-DAM BREACH				
Small (n = 4)	+4.40	0.168	+5.70	0.101
Medium (n = 4)	-3.66	0.656	-3.03	0.081
Large (n = 4)	-6.04	0.405	+4.65	0.048
All sizes (n = 4)	-0.89	0.868	+1.19	0.295
Dry Years - 1998, 1999, 2000, 2001, 2002, 2003, 2006, 2009, 2010, and 2011				
PRE-DAM BREACH				
Small (n = 6)	-5.74	0.390	+1.35	0.634
Medium (n = 6)	-1.57	0.747	-3.71	0.376
Large (n = 6)	-5.41	0.027	+2.54	0.589
All sizes (n = 6)	-1.75	0.304	-0.24	0.935
POST-DAM BREACH				
Small (n = 4)	-5.89	0.001	+2.69	0.589
Medium (n = 4)	-4.57	0.051	+7.87	0.118
Large (n = 4)	-6.70	0.361	+3.51	0.651
All sizes (n = 4)	-5.04	0.018	+3.98	0.480

Besides the spatial proportion change, there are also some unusual disproportionate population variations in raw fish count data in some river sections in certain years. In 2004, the total population of salmon decreased by 50.7% after the summer flood season. However, at the section below Cijiawan One dam, the population increased from 213 to 254 individuals between the seasonal snorkeling surveys. In 2007, the section between Cijiawan Four dam and Cijiawan Five dam had a 860% population increase in population density (from 10 to 96) while the total abundance across whole river decreased by 23.82% after the summer flood events.

Discussion

This research was designed to explore the potential ecological benefits on the resident landlocked Taiwan salmon by the removal of a dam to restore the longitudinal connectivity of a river system in Taiwan. A goal for dam removal was to provide ecological benefits from re-establishing stream connectivity for salmon experiencing flood washdown return incidents. This chapter was designed to explore the susceptibility of Taiwan salmon to downstream displacement by seasonal flooding events. Two alternative hypotheses were tested to research the factors impacting Taiwan salmon abundance and population viability: (H₁) High intensity flooding events following extreme precipitation events will increase salmon washdown incidents and decrease their population levels upstream of the dam since salmon are unable to swim back to their previous and more suitable home ranges; and (H₂) Dam removal will increase the abundance of Taiwan salmon in the total river extent because of the increased river connectivity and subsequent access to more suitable habitat for the salmon. These were important hypotheses to test since the existence of such downstream displacement had not yet been scientifically

confirmed.

Flow regime is one of the characteristics that has long been recognized as having a major influence on both in-stream biotic and abiotic structures (Bunn and Arthington 2002; Jackson et al. 2001; Poff et al. 1997), and stream flooding is also known as one of the most common causes of variation in freshwater fish biomass and population density (Bain et al. 1985; Hall and Knight 1981; Schlosser 1985). Although stream flooding under certain conditions can have some beneficial effects on fish populations, such as fine sediment deposit flushing (Allen 1965) and lateral floodplain habitat connection (Thoms 2003), it also may directly cause major decreases in fish due to fish mortality (Erman et al. 1988), or indirectly by disturbing habitat (McMahon and Harned 1998) or food web structures (Power et al. 2008; Wootton et al. 1996). Fish size is one factor that affected the outcomes of flooding scenarios. For example, larger fish with better swimming ability might be less likely to be washed away (Good et al. 2001), but also they might be too large to fit into the limited number of available, but small sized, safe shelter against high flow velocity (Angermeier and Karr 1984; Pearsons et al. 1992).

Taiwan salmon need stream longitudinal connectivity since they are non-anadromous and need to be able to utilize the entire river extent to respond to climate impacts on river temperature regimes. If fish are washed below an existing dam during flood events, the migration barrier keeps them from moving back upstream where river conditions are more suitable for their survival and which they instinctively return to since it is their home range. However, during flood events, Taiwan salmon were observed using large boulders and deep pools in the main river channels as temporary refuge (Makiguchi et al. 2009).

Previous research reported that deliberately displaced Taiwan Salmon did show a rapid and significant long distance movement toward their original home range

(Chen 2012). Thus in the case of failing to withstand high floods and being washed downstream, Taiwan Salmon may attempt to swim back upstream. The presence of in-stream migration barriers would permanently keep salmon in downstream sections of the river which provide a lower quality habitat due to warmer river temperatures during the hottest period of a year (see Chapter 2). Because of downstream channel widening and solar energy accumulation, upstream temperatures are colder than downstream in the Cijiawan basin and low stream temperatures are needed for Taiwan salmon survival and egg hatching (Liao 2012; Yang 1997). Former agricultural activities and recent tourist activities near downstream region also make upstream habitat for Taiwan salmon more suitable in terms of a higher water quality and less inflow of pollutants.

Precipitation data and critical events threshold

Variability in precipitation levels is the single most important factor determining the characteristics of flood events in non-snowmelt areas (Pitlick 1994). Although there are several geological and hydrological factors that could affect the correlation between discharge and precipitation (e.g., watershed drainage density, antecedent moisture conditions and soil infiltration rates), precipitation data were strongly related to the magnitude and variability of discharge at basins larger than 10 km² in area (Burt 1989). This situation was especially relevant for the larger discharge events that occurred more infrequently (Benson 1964; Costa 1987).

This research showed that a significant negative linear relationship existed between each of the four hydrological factors and the variability in the surveyed Taiwan salmon population abundance between the summer and autumn periods. However, since all the hydrological factors were highly correlated, it was not possible

to separate the influences of individual hydrological factors on the survival of the salmon population or to identify a single hydrological factor that had a more significant impact on the salmon. The strong correlation between hydrological factors might have been caused by the general pattern of seasonal precipitation within any given year. Big typhoon events during the summer months usually produce heavy rainfall that are both of high intensity and of long duration, whereas precipitation events in other seasons usually are of a lower intensity and have a shorter duration and rarely exceed the critical 2-year threshold of recurrence. This research suggested that summer typhoon flood events significantly influence Taiwan salmon mortality rates, but the correlated data did not allow individual testing of the importance of precipitation patterns, or their intensity and duration, on fish population dynamics. However, depending on the time of occurrence, non-typhoon precipitation events might cause significant mortality if they occur in the late autumn by disrupting spawning ground condition or scouring out the buried egg pockets.

There are many factors that need to be considered to analyze how precipitation patterns impact river discharge and habitat conditions for fish. In addition to the total quantity of rainfall, its duration and intensity may influence other river conditions that are detrimental to the survival of fish. Low-intensity long-duration events usually have a longer time to reach peak flow, giving fish more time to find refugia to hide when currents are strong, such as in side channels on the floodplain or pools behind big boulders. However, the long duration events also expose fish to turbid water with heavy sediment loads for a longer time period and increases the risk of fish suffocating or being wounded by sharp rocks. On the other hand, high-intensity shorter-duration events, with a shorter time lag reaching peak flow, usually give fish a shorter response time to reach nearby refuge in time. However, a shorter recession period to peak flow often helps flow and turbidity return faster to normal.

Population loss in wet and dry year clusters

Despite the strong correlation between precipitation intensity and duration factors, significant differences between wet and dry year clusters indicate that there are two distinct annual precipitation patterns in the study region. All four hydrological factors and the integrated independent variable (PC1) are significantly different between the wet and dry clusters of years. Wet years have larger PC1 values with more total precipitation, more critical events, higher intensity, and longer duration than dry years. The annual variation in fish populations after summer flood season was also significantly different between the wet and dry years. Fish abundance showed a significant decrease only in the wet years, and not during the dry years. This implies that there are no major population losses during the dry years when the flood events are smaller. This result also indicates that the 2-year recurrence 130 mm rainfall threshold is reasonable for this research because it distinguishes the distinct annual precipitation patterns recorded in this region of Taiwan.

For this study, the overall variation in fish population abundance was significantly related to precipitation for all years, but this relationship was not significant within wet years. This result shows that the relationship between population loss and severe flood events might not be a linear relationship, but alternatively maybe driven only by flood occurrence events. Therefore, when flood events exceed the critical threshold, they can cause significant loss of fish. However, despite some flood events causing larger discharges and stronger currents, loss of fish does not appear to be related to the severity of the precipitation events. Other research also found similar results. Battle et al. (2016) and Battle et al. (2020) used a

Taiwan salmon population variation model with various typhoon events under a climate change prediction model in the KaoShan tributary and river sections above Cijiawan Three dam. They simulated flood mortality rates for the salmon and were unable produce results showing increasing salmon mortality rates when increasing the intensity of the typhoon events to extreme levels.

The lack of relationship between flood severity and the abundance of fish populations during the wet years may be explained by several contradictory effects of flood events on the physical habitat conditions in the river. Although the higher water levels may connect more flood plains or side channel habitats resulting in more offsite low-velocity refuges, the resulting stronger currents during these events makes it more difficult for fish to move toward nearby refuge habitats. Another possible explanation may be that during floods fish might try to find local refuge in deep pools but the turbulence behind large boulders or in the slow-velocity zone near river sediments may not be sufficiently calm to protect them from strong currents. Previous radio telemetry tracking research suggest that some Taiwan salmon swim behind large boulders during severe flood events (Makiguchi et al. 2009). Because of the drag force generated by the friction between water body and the riverbed substrate, river flow velocity has a distinct vertical profile and is slower when closer to the riverbed. As discharge and surface velocity increase, the velocity of the near-bottom-slow-flow zone does not linearly increase accordingly. The velocity at the very bottom of the riverbed next to the substrate surface is theoretically static. If fish are able to use this hydraulic phenomenon to avoid the harsh underwater environment during flood events, it is reasonable that the influence of flood events on population loss is not linearly related to their severity.

Fish size and flood mortality

During wet years, when critical flood events occur, there was no relationship between the hydrological condition (PC1) and overall decreases in fish population abundance during the summer flood season. This pattern holds true within the specific size classes of fish being monitored. Fish size is known to linearly relate to swimming ability. Moving under different levels of strong current to reach distant low-velocity refuge requires different levels of swimming ability. The lack of differences across size classes indicate that swimming ability was irrelevant to the survival of Taiwan salmon during the various flood events. The result might also support the assumption that instead of trying to move around when currents are strong, Taiwan salmon might use local refuge to survive and reduce their susceptibility to downstream displacement.

Despite the apparent lack of importance of swimming ability in this case, fish size might still play a role on fish survival during flood events. This study did find that small fish appear to experience greater decreases in population levels after flood events. In contrast, large fish show a borderline significant population loss in abundance after these weather events and appear to be less impacted by these events. This pattern indicates that, besides swimming ability, larger fish might still have some physiological endurance advantage for surviving under certain conditions. How fish size and flood characteristics impact fish population redistribution and mortality along a river section will be discussed later.

Spatial population distribution of Taiwan salmon and flood mortality

In this study no significant relationship existed between summer flood-related fish abundance data and hydrological conditions across all river sections. This result

indicates Taiwan salmon mortality rates was spatially independent of the summer flood events, and the severity of flood events had no effect on this variable despite in-stream habitats potentially changing in response to different flow conditions. River channel morphology responds to geomorphic and hydrological changes as the river flows. It usually results in longitudinal differences in-stream habitats, from step pools at the headwater with its steep gradients to pool-riffle sequences or its meandering at downstream section, e.g., from narrow confined bedrock channel to wide open floodplain channel. During different flow conditions, low-velocity refuges in different in-stream habitats also vary in locations and accessibility, providing habitats and refuge for assorted sizes of fish with various swimming abilities.

In this study, the spatial independence of flood-related decreases in population abundance were consistent with the lack of significant relationships between Taiwan salmon's swimming ability and survival from previous fish size analyses.

Circumstantial evidence suggests that Taiwan salmon rely more on local low-velocity refuge rather than off-channel ones. Specific local scale micro habitats, such as deep pools or scouring tail of big boulders, can serve as local refuges during flood events that are easily accessible to all fish size groups. With limited movement under high discharge conditions, it might also reduce their susceptibility to downstream displacement. However, the presence and capacity of such local refugia under strong current and its utilization by Taiwan salmon will need finer scale habitat surveys and additional behavioral data collected to confirm.

Wet and dry year clusters

Because precipitation patterns are significantly different between wet and dry years, the spatial population proportion data was analyzed within two separate

precipitation year clusters. In wet years, there were flood-related fish population losses but river sections with different channel morphologies may offer a diversity of refuge habitats. The spatial distribution of fish populations by size might change because of the different population loss rates observed at different river sections and fish redistribution caused by displacement incidents. In dry years, there was no significant flood-related population loss, so the spatial population proportion among sections should remain constant. Even with temporary displacement by strong currents that reduces low-velocity refugia, the home range returning behavior should keep the spatial distribution of the fish population constant, except under a barrier-trapping scenario.

During wet years, the significant increase in fish at the upstream section S_{23} does not support the flood-related displacement trend. This can be explained locally by a low change in population abundance during these extreme weather events. However, there was an inconsistent pattern by fish size groups with large and small sized fish both showing a significant increase in their population size during these extreme weather events. In contrast, medium sized fish experienced a significant contradictory decrease in its population size during these events. Any systematic cause explaining of the variations in the spatial distribution of a fish population should have affected all fish in a similar manner. There is no rational field scenario that may explain why only medium sized fish experienced large population changes in contrast to the large and small fish sizes at the same time period. There is also no rationale that explains why only medium sized fish were washed down river and trapped beneath physical barriers during these events. This contradictory correlation may also be caused by the lack of statistical power due to the small sample size.

During dry years, there was a significant proportional decrease in fish populations in the downstream section S_{12} . This pattern does not fit into the flood

induced displacement redistribution trend. In further size group analyses, despite all three size groups having a decreased spatial population proportion after a flood season, only the changes in the large-sized fish group statistical analyses were statistically significant. This result might indicate that some river sections suffers from specific local population losses during the dry years, but the small sample size and its lack of statistic power may also explain this trend. It might also imply the unusual decreases in population abundance under smaller flood events is fish size related. Larger fish may have difficulties in finding the limited number of local refuges. On the other hand, this local high change in fish abundance might result from unusual habitat conditions at this particular location, such as being under Cijiawan Two dam and influenced from the dam breach incident. This needs further research to understand the trends suggested by the data.

Before and after Cijiawan Two dam breach

Pre-dam removal, the changes in the spatial distribution of fish populations by size may be explained by a differential mortality of fish across different sections of the river. In sections near the migration barriers, displacement and barrier trapping may have caused a change in spatial distribution of fish populations following flood washdown events, e.g., a decrease in fish numbers at upstream sections and an increase at downstream section. This spatial distribution pattern of fish, however, was not eliminated once the dam barrier was removed. Once the dam was removed, previous studies suggest that Taiwan salmon will start to return to their original home range within ten days after being displaced since their swimming speed allow them to migrate as far as two kilometers in a two to three day period (Chen 2012). Since the dates of each year's fall snorkeling surveys are usually chosen at least a

week after any rainfall event to assure better underwater visibility, these surveys would have detected any changes in fish population spatial distribution along the river following summer flood events. Further, the dates of all severe precipitation events occur at least three weeks before each year's fall snorkeling survey. So they did not coincide with the flood events.

In this study, no significant changes in the spatial distribution of fish populations were recorded by the surveys before and after the 2004 Cijiawan Two dam breach. This study does not support the general occurrence of salmon washdown return incidents after extreme flood events. However, several patterns of change in fish population distributions were recorded which provided evidence of unusual population increases after flood events. There are many physiological and behavioral factors that can affect fish mortality or population redistribution after flood events, such as swimming ability, fine sediment and low oxygen endurance, and ability to find refuge habitats. Therefore, the possibility of washdown incidents cannot be eliminated as causal factors to explain the changes in fish distribution along the river.

A significant decrease in fish population size was recorded in the downstream section S_{12} after the dam breach. It implies that the local decreases in fish abundance may be due to habitat disturbance induced by the dam breach, including increased turbidity and significant morphological changes in the river caused by sudden sediment release. The fish size group analysis showed that only the large sized fish did not experience this significant decrease in their population levels after the dam breach. This provides circumstantial evidence that large fish have a greater advantage in withstanding possible suffocation or physiological injuries in turbid waters. However, this deduction assumed that lethal underwater environment was filled with fine sediments and sharp particles during flood events following the dam breach. This requires further field sediment transport research to confirm the impact

of these changes on fish populations.

The spatial proportion analysis also indicated that although fish size can be related to some swimming ability and physiological differences, such differences might affect fish survival and distribution in other ways under different hydrological and local morphological conditions. Large fish experienced site-specific reductions in population abundance during the dry years at section S₁₂ before Cijiawan Two dam was breached but had a lower loss of fish under similar condition after the dam breach. These trends might imply that large fish can withstand turbid waters better compared to small sized fish, but they might have trouble fitting into limited local refuge under a specific level of discharge. Also, medium sized fish also showed a contradictory trend from the other fish groups at section S₂₃ during the wet years. This result suggested that size groups might each have individual effects on flood related decreases in abundance and distribution, so flood wash-down return incidents might only occur to specific size groups under different conditions.

Conditions for possible washdown and return incidents

The restored longitudinal connectivity that resulted from the removal of the dam did provide passage for displaced Taiwan salmon return to their original home range. This research suggests that specific hydrological and regional morphologic conditions are needed for the washdown and return incidents to occur. During critical flood events, although fish size might provide some physiological advantage for survival, the flood-level-independent population decreases in abundance show Taiwan salmon might utilize local low-velocity refugia behind boulders or near the river bed during these events. This would lower their chances of being displaced. Thus, washdown incidents might be an uncommon occurrence during flood events

because larger fish find safe havens and smaller fish, despite being easier to wash-down, might not be strong enough to survive the process.

One of the critical control factors determining fish abundance should be the river's relative current velocity. It needs to be strong enough to wash away the fish, but at the same time mild enough for the fish to survive the process and be able to migrate back to their original home range. The local current velocity in flood events is controlled by regional river channel morphology and hydrological factors, such as precipitation pattern and concentration process of the watershed. Besides, different size groups of fish with different swimming ability and physiological condition will also have different flood survival strategies under the various current velocities that occur at different locations in the in-stream habitats. In order to understand the exact process and conditions of Taiwan salmon flood-induced washdown and return incidents, further surveys and research are needed that focus on assessing the size specific flood survival strategies in laboratory and at the finer scale of local habitat conditions during the flood events.

Site fidelity and homing behavior are known to benefit fish survival by providing them with better access to nearby habitats to avoid predators, search for food resources, and to find refuges from hazard river conditions (Brown 2001; Letty et al. 2003; Piper 2011). However, those benefits for Taiwan salmon washdown return incidents might not be strong enough to be systematically reflected in the spatial population proportion analyses. Since there are no major predators feeding on Taiwan salmon and food resources are relatively abundant throughout its habitat range, no particular section of the river should experience a significant population loss following a severe flood event. This suggests the spatial location of Taiwan salmon along the river stretch is not a major factor determining whether they survive extreme flood event. The other explanation is that, due to strict abiotic and biotic

conditions for washdown-return incidents to happen, detecting these changes in fish population levels is not feasible with the small sample size in this research. Other possible ecological benefits of washdown-return incidents on other longitudinal habitat differences, such as temperature increase and spawning habitat availability, will be discussed in later chapters.

Conclusions

The Taiwan salmon population declines tend to be associated with severe summer flood events. Individual influences of different hydrologic event duration or intensity could not, however be analyzed because all the hydrological factors were highly correlated due to seasonal precipitation patterns. The annual precipitation data can be further divided into two distinct clusters of years, wet years and dry years. During wet years, there were more severe precipitation events, more total rainfall, stronger intensity, longer duration, and significant salmon population loss after the flood season. Using integrated hydrological principal component, fish abundance showed a significant decrease in abundance that was related to the occurrence of severe flood events. But the degree of salmon abundance decline was not correlated with the severity of the flood events. Additionally, there were some differences in flood related mortality among different fish size groups. These results indicate that, although swimming ability may not significantly relate to flood survival, larger sized fish might still have some physiological advantage under certain high discharge conditions. Furthermore, there were no significant spatial population loss patterns under different level of flood events. This suggests that Taiwan salmon might be able to utilize local habitat-unit scale low-velocity refuge, rather than

moving to access off channel habitats at reach scale or even larger scale. Their reduced movement under strong current might also reduce their susceptibility to downstream displacement.

The spatial distribution of Taiwan salmon after summer flood events was not consistent with patterns expected from the washdown return scenario. Despite having no evidence for the occurrence of general and systematic flood washdown return incidents, some circumstantial data implies that such incidents could occur at local scales under some specific biotic and abiotic conditions. There were some size-specific disproportional increases in fish populations at particular sections after severe flood events, which otherwise caused significant population decreases in all the other river sections. The data suggest that such incidents might exist when flooding events are large enough to displace Taiwan salmon but not too severe to explain fish survival rates and their return to their home ranges. Fish might also need to be sufficiently large to survive the flood processes, or at least survive under certain discharge and local morphological river conditions. The newly opened passage after the removal of the dam restored the river's longitudinal connectivity, but the exact conditions explaining the washdown-return incidents will need to be further researched under laboratory physiology experimental conditions and at a finer scale field data to confirm the patterns observed during this research. The ecological benefits of dam removal on salmon abundance is currently limited and requires additional analysis on longitudinal habitat differences.

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Chapter 2

High temperature avoidance behavior of Taiwan salmon (*Oncorhynchus formosanus*) and cold water refugia accessibility after dam removal

Abstract

Restoration of riverine habitat characteristics is essential when land-use changes or disturbances have altered a habitat, so it no longer supports a diverse population of organisms dependent upon them. To restore the habitat for an endangered landlocked Taiwan salmon (*Oncorhynchus formosanus*) in Taiwan, a mid-size dam was removed to restore river longitudinal connectivity with the goal of improving habitat accessibility for downstream fish populations to the cooler temperatures found at up-river conditions. Water temperature is known to be one of the most important environmental factors determining whether freshwater fish species can complete all their life stages in river systems. This is especially important for the Taiwan salmon that are restricted to living in confined river sections due to dams that produced migration barriers limiting their ability to avoid river sections no longer providing suitable habitat for their survival. However, the potential ecological benefits of connecting down- and up-stream habitats has not yet been evaluated because information is lacking on Taiwan salmon's response to different temperature regimes found along the river extent.

This research aims to identify the thermal threshold of Taiwan salmon's high temperature avoidance behavior and whether cold water refuges exist for them during the summer months. The research design used a controlled temperature

gradient flume experiment and recording of river temperatures during the highest temperature period in the summer months.

The flume experiment showed Taiwan salmon moving away from warmer water sections when temperature exceeded 16.4°C. River temperature records indicated that water temperature in some river sections would exceed this temperature threshold during the summer season and cold water refugia are found mostly at higher elevation upstream locations. Cijiawan One dam removal with its newly opened longitudinal passage did facilitate parts of Taiwan salmon population to access higher elevation cooler stream section during summer seasons. However, the long-term benefit might be limited by the declining thermally suitable habitats resulting from existing dams and warming temperature due to global climate change.

Introduction

In freshwater ecosystems, water temperature is one of the most important environmental factors that can directly affect fish population distribution and viability (Caissie 2006; Webb et al. 2008). Previous research reported that freshwater fish exploit and move between different temperature regimes for their specific needs at different life stages. For example, bull trout (Muhlfeld and Marotz 2005) and juvenile Coho salmon (Armstrong and Schindler 2013) show diel horizontal or longitudinal migration from cold water feeding grounds to warm sections of the river for better digesting their food. Other fish species make spawning related movements between the main stem of a river and its backwater habitats in response to changes in water temperatures and other environmental factors (Hohausová et al. 2003).

Some thermally sensitive species, such as anadromous salmonids, are more resilient when facing thermal extremes resulting from anthropogenic habitat alterations and/or global climate change because of their ability to move towards more suitable water temperature conditions (Jonsson and Jonsson 2009; Waples et al. 2009). For non-anadromous salmon living only in freshwater ecosystems, such a resilience strategy is not possible due to their restricted distribution range that limits their ability to migrate to suitable temperature habitats (Beechie et al. 2006; Halupka et al. 2003; Himes-Cornell and Kasperski 2015). Further, the existence of obstructions, such as dams, reduces the ability of non-anadromous salmon to utilize an entire connected river system to find refugia (Bergkamp et al. 2000; McCully 1996). This is further aggravated by climatic disturbances that alter the temperature regimes of river sections, so they become hotter and exceed the temperature thresholds needed by non-migratory salmon.

In Taiwan, a mid-size dam (Cijiawan One Dam) was removed in 2011 to restore longitudinal connectivity and provide access to upstream habitat for the endangered target species, Taiwan salmon (*Oncorhynchus formosanus*). One of the goals of the dam removal was to make upstream colder river sections available for downstream Taiwan salmon population whose habitat was restricted below the dam and were possibly being exposed to water temperatures exceeding their thermal threshold during summer season. Although previous radio telemetry research confirmed increased salmon accessibility and their usage of the new passage (Chen 2012), the ecological benefits of Cijiawan One dam removal was still unknown due to the lack of information on Taiwan salmon's high temperature threshold that would cause them to migrate to cooler temperature refugia and their behavioral responses when exposed to these temperature extremes. Also, there was no data available on overall spatial and temporal patterns of summer season river water temperatures for the rivers in Taiwan.

Taiwan salmon are known as a temperature sensitive landlocked non-anadromous resident species distributed only in central Taiwan high mountain streams. Based on field observations only, a high temperature thermal threshold for salmon was assumed to be 17°C (Tzeng 1999). Previous field temperature records had shown that the water temperature of some downstream reaches exceeded 17°C during sometime part of the day during the summer months (Tung et al. 2009). Whether Taiwan salmon can migrate to cold water refugia under such high temperature conditions has not yet been confirmed. Also, the assumed high temperature threshold reported in the literature may not realistically represent the temperature threshold for Taiwan salmon when exposed to such temperature gradients.

Conventional methods of identifying salmon species' thermal threshold include lethal tolerance experiments in uniform and gradually heating environments (Brett 1952; Eliason et al. 2011), water temperature related physiological experiments (Brett 1971; Anttila et al. 2013), or thermal experiments focusing on specific life stage or habitat needs (Elliott 1991; Olson and Foster 1957). By exposing hatchery Taiwan salmon to various temperature gradients in flume experiments, this research uses Taiwan salmon's behavioral responses and avoidance movements as an integrated indicator (combining environmental and physiological factors) in determining Taiwan salmon's suitable thermal threshold.

The objectives of this research were to: 1) Identify the high thermal threshold for Taiwan salmon, using a controlled temperature gradient flume experiment to record Taiwan salmon high temperature avoidance movement responses to a temperature gradient; 2) Determine the extent and duration of river temperatures reaching the high temperature threshold for Taiwan salmon during the summer months; and 3) Determine the benefits of dam removal and the re-establishment of river connectivity on increasing the cooler temperature refugia for Taiwan salmon. This research is designed to determine the temperature threshold at which the non-anadromous Taiwan salmon become vulnerable to high temperature conditions and whether there exists suitable river habitat below the temperature threshold capable of providing temperature refugia for the Taiwan salmon to migrate to in response to climate warming. It will also clarify whether there are potential ecological benefits of dam removal for Taiwan salmon under current and future temperature regimes.

Materials and Methods

Site Description

Found only in the Cijiawan River basin (within the Ta-Chia River basin) located in Shei-Pa National Park in central Taiwan (Figure 2.1), Taiwan salmon are known as the most southerly distributed salmonid in the world (Lin et al. 1990; Oshima 1955). They are now endangered due to habitat degradation, regional agricultural development and channel-altering by in-stream hydraulic facilities. Like the fluvial form of landlocked Masu salmon (*Oncorhynchus masou*) that live in a mountain stream in Kyushu in Japan (Sakata et al. 2005), Taiwan salmon attain maturity, spawn and live their whole life in freshwater and maintain parr marks on their flanks into adulthood. However, Taiwan salmon have evolved into non-anadromous resident form and do not make regular long-distance migrations throughout their life stages. Due to habitat degradation and overfishing, the population levels of Taiwan salmon have decreased sharply in the 1980s. Only about 200 fish were counted during the snorkeling survey in 1989 (Lin et al. 1990). In 1992, Shei-Pa National Park was established as a conservation and habitat protection area for Taiwan salmon. In 1996, Taiwan Salmon were listed as an endangered in the red book of the International Union for Conservation of Nature and Natural Resources (IUCN).

This research was conducted on the Cijiawan River which is located in the upper Ta-Chia River basin in central Taiwan. The river is approximately 13 km long and has an average width of 9.7 m. The Cijiawan basin area is 76 km² in size and has a 120 m elevation range (from 1,700 to 1,820 m). The east slopes of the riparian areas are dominated by secondary forests that were planted as part of reforestation efforts in

the 1950s to 1960s. The western slopes along the Cijiawan basin were planted into grasslands that were formerly used for agriculture cover.



Figure 2.1. A map showing the locations of the Ta-Chia River watershed in Taiwan and the locations of the temperature gage stations.

The stream is steep with an average channel slope of 1.2%. The dissolved oxygen levels are consistently greater than 7 mg/l, and the pH values range from 7.0-8.3 (Lin and Chang 1989; Techi Reservoir Management Committee 1983). The upper

Ta-Chia River basin mean air temperatures range from -8°C to $\sim 29^{\circ}\text{C}$. The streambed is characterized as being predominantly cobble-boulder substrates (Wang 1989). Regular snorkeling survey data occurs along a 6.5 km stretch of the river habitat on the main stem of the Cijiawan River from the downstream confluence with the Ta-Chia River to the upstream Cijiawan Six dam.

Dam removal

A series of mid-size sediment trapping dams were built around upper Ta-Chia watershed during late 1970s to prevent sediment accumulation in the impoundment of the downstream Te-Chi reservoir. The Te-Chi reservoir was built in 1974 for hydroelectricity production, and to supply water for irrigation and for drinking water usage. A total of six such dams were built in Cijiawan river system. However, due to the dynamic hydrologic regimes and heavy sediment loads, all six dams were filled in just five years after the dams were built. Despite the channel morphology and river ecology mostly being restored to pristine status by natural processes after 30 years, the existence of those dams remains as longitudinal migration barriers and causes the isolation of salmon populations in certain stretches of the river. After Cijiawan Two dam was breached in a storm event in 2004, Cijiawan One dam was removed in 2011 to restore river longitudinal connectivity and provide access of more suitable habitat for downstream Taiwan salmon populations.

Experimental thermal threshold system

An 800 cm x 35 cm x 23 cm deep rectangular tank was used to establish an experimental and stable temperature gradient system (Figure 2.2). A 1000W heater was submerged at one end of the tank. The tank had no inflow and out flow ports and external air was pumped into the tank to maintain suitable environment for fish. A stable water temperature gradient was established approximately 2 hours after turning on the heater when a heat exchange equilibrium was reached. By setting up the experimental system during the day time during the winter months (2013/10/29 to 2013/11/07), it was possible to obtain a water temperature range varying from 14°C to 21°C, which included the potential thermal threshold of 17°C. Fish were added into the tank two days before commencing the experiment to avoid non-temperature related movements, e.g. fish acclimation to a new habitat acclimation effect and the thermal shock influence from transferring between environments.

The experimental thermal threshold system could not be replicated in a statistically robust manner because the Taiwan salmon is listed as an endangered species. Therefore, no experiments could be established that have the potential to kill the salmon. The salmon used in this experiment were obtained from the



Figure 2.2. Photo of the experimental temperature gradient flume used to determine the temperature threshold at which salmon would express temperature avoidance behavior. This experiment was set up in the Taiwan salmon hatchery adjacent to the research site.

hatchery with a special permit. Two different age groups of Taiwan salmon, age <1yr (small) and >1yr (large), were used for the experiment to determine whether there would be size differences in the salmon response behavior when exposed to high temperature environments. For each age group, twenty fish were placed into the tank to record their movement pattern under different temperature conditions. The tank was divided and marked into four sections (A, B, C, and D) that were of equal length without any moving barriers. The temperature of each section was monitored, and fish movement recorded. The heating device was located in section D of the experimental system. Fish distribution among the four sections was used to record salmon's preferred habitat selection.

Each fish-size group was experimentally tested twice with a functioning heating device. The number of fish in each section was counted about every 5 to 10 minutes from a distant observation deck to avoid the salmon expressing intimidating concealing behavior. Water temperatures of each section were measured with a handheld electronic thermometer about every 30 minutes. Control temperature experiments were set up before temperature gradient trials with heating device turned off to understand other possible environmental factors impacting fish distribution, such as preference for shading at specific tank corners or the proximity to the submerged heating device.

Field-based river temperature monitoring

To obtain a record of the spatial and temporal temperature variations of the Cijiawan River, field river water temperature was recorded from 2007 to 2012 at three different permanent gauges (Figure 2.1). The underwater temperature data

were recorded using a logging device (STARMON-MINI, Star-Oddi, Iceland). The location of the gauges was based on monitoring river sections with different Taiwan salmon habitat usage related to the Cijiawan One dam removal: (1) C1 at the confluence to Ta-Chia River is 1.67 km downstream of the dam removal site and also the most downstream boundary of the distribution of the Taiwan salmon populations; (2) C4 is 0.85 km upstream of the Cijiawan One dam removal site and accessible to downstream Taiwan salmon population with the newly opened passage due to the dam removal; and (3) C7 below the Wuling suspension bridge that is located 2.06 km upstream of the Cijiawan One dam removal site and also on top of the existing Cijiawan Three dam which represents the most accessible upstream habitat for downstream Taiwan salmon populations. The three gauges automatically measured water temperatures every 20 minutes.

The average daily maximum and minimum water temperature from April to October was compared with the potential high temperature avoidance threshold to identify possible Taiwan salmon's exposure to thermally undesirable conditions. The water temperature daily diel variation range and spatial thermal profile were analyzed for possible local or longitudinal cold water refugia.

Statistical analyses

Because of the inability to conduct multiple experiments using an endangered species, threshold regression models were developed using four experimental trials – two trials used small-sized Taiwan salmon and the other two used large-sized fish. The measured time series water temperature and fish count data in each temperature gradient were plotted to identify possible high temperature avoidance

behavior. The comprehensive thermal threshold was estimated using threshold regression models with both time series fish distribution variation among tank sections under different temperature gradient and normalized unit-time temperature exposure data.

Threshold regression models are a class of regression models where the predictors are associated with the outcome in a threshold-dependent way. The R package “*chngpt*” (Fong et al. 2015) was used in this research to identify significant changepoint for the relationship between water temperature and the fish count per unit time of exposure. The hinge mode estimation was used in this research, assuming water temperature had no effect on Taiwan salmon prior to the change point temperature and had a constant effect after the change point. Fong et al. (2017) also notes that, for the same sample size, the hinge model was preferable over the segmented model as it can be estimated with greater accuracy. The hinge mode of threshold regression model was formulated as:

$$y_i = \alpha_1 + \beta_1(x_i - e)_+ + \varepsilon_i$$

$$(x_i - e)_+ = \begin{cases} x_i - e & \dots x_i \geq e \\ 0 & \dots x_i < e \end{cases}$$

where y is the count per minute exposed, x is the temperature, and e is the threshold parameter. The subscript i was an index for temperature bins with 0.2°C range. For the small fish, i ranged from 1 to 24, and for the large fish, i ranges from 1 to 20. In the hinge model, the parameter α_1 represented the constant association between counts per minute exposed and temperatures colder than the changepoint e . The parameter β_1 represented the average change in count per minute exposed for every 1°C increase in temperature above the threshold e . The threshold e was assumed to be independent and identically distributed following a normal

distribution. For each candidate changepoint e , the likelihood ratio statistic for comparing the model with the threshold term (e.g., with non-zero β_1) to the null model was calculated, conditional on the candidate changepoint e . The candidate changepoint that resulted in the maximum likelihood ratio statistic was chosen as the estimated changepoint.

Results

Taiwan salmon thermal threshold

The distribution of fish was affected by the acclimation effect after being exposed to the new environment for the first 24-hour period. After being transferred from the hatchery tank to the experimental flume system, all experimentally introduced fish showed an obvious preference for staying in the corners of the experimental tank system. Depending on the shading conditions occurring during the day, the fish remained and moved to the corners that were most shaded. After 24 hours, the introduced fish were evenly distributed across all four sections of the experimental flume system. There were no effects of the submerged heating device on fish distribution patterns, and no territorial competition behavior was observed during the initial 24-hour period. Therefore, the experimental temperature gradient treatments were conducted after the introduced fish had experienced at least 24 hours in the confined experiment flume without any temperature interference.

With the size of the experiment flume and heating power of the device, stable temperature gradients were successfully established for the treatments. The temperature gradient ranges included the presumed high temperature avoidance threshold of 17°C (Table 2.1). Salmon in the temperature gradient flume were evenly distributed at the beginning of the heating treatment, when all sections were at similar temperature. No temperature avoidance thresholds were being expressed. All treatment groups, and both salmon-size groups, showed high temperature avoidance movement patterns as significantly fewer fish were counted in section D with the higher temperatures and the location of the heating device (Figure 2.3). However, the time of presence of high temperature avoidance was not consistent,

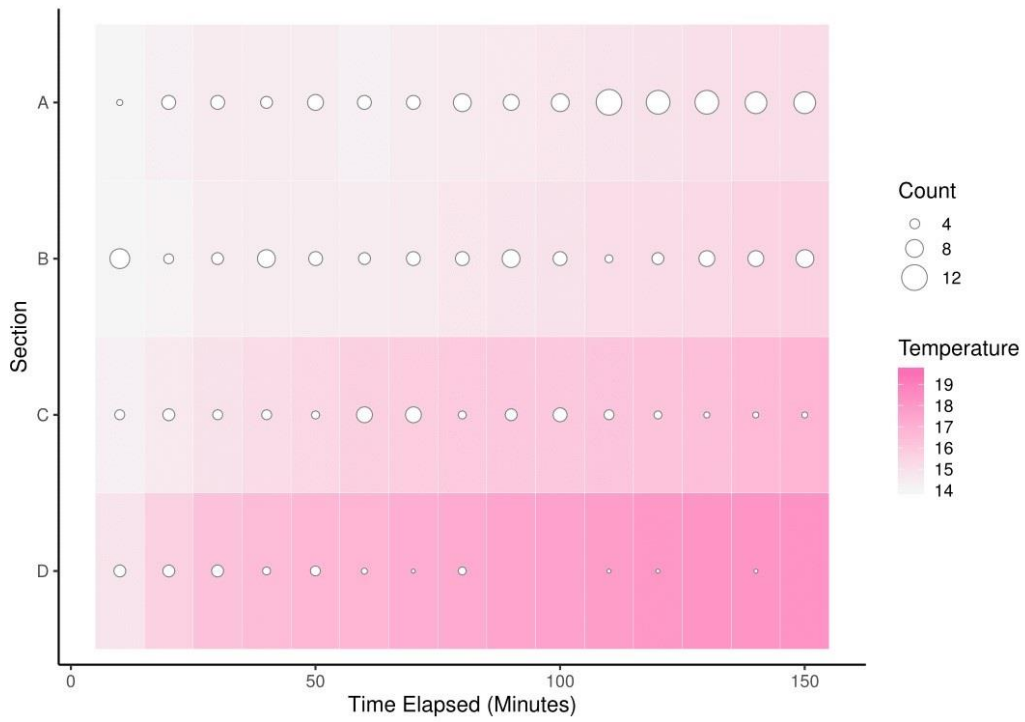
even within the same fish-size group, due to the different starting conditions and the temperature gradient range (Figure 2.4).

Table 2.1. The starting and ending temperature-gradient range reached in each experimental trial in the temperature gradient flume experiment used to assess the thermal threshold of Taiwan salmon.

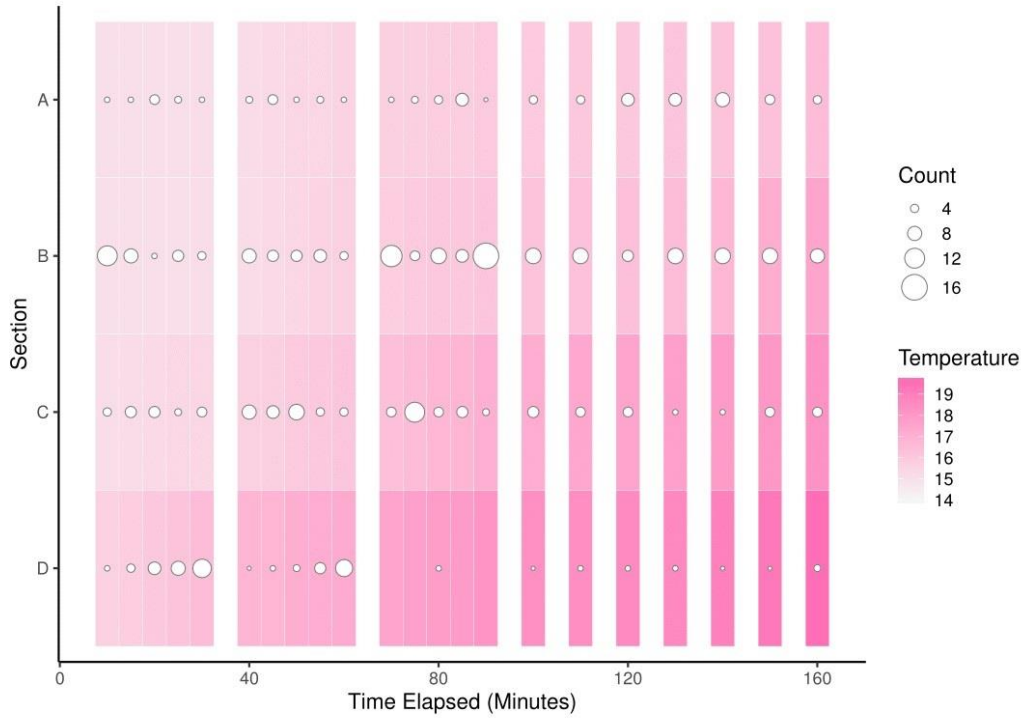
Fish Size	Trial #	Number of Observations	Start Temperature (°C)	End Temperature (°C)
Small	1	15	13.8-14.0	15.1-18.1
Small	2	22	14.8-15.0	16.4-19.4
Large	1	21	15.4-15.8	16.5-19.6
Large	2	20	16.4-16.6	17.0-19.4

The total amount of time the salmon remained in each temperature section was not evenly distributed and fish-count data needed to be normalized to conduct further high temperature avoidance behavior analyses. Because of the heating device setting and daily background environmental condition differences (e.g., air temperature, sun light exposure, building shading angle, and starting water temperature), certain temperature levels occurred more frequently than other temperatures. To account for fish-count frequencies resulting from various availabilities of each temperature range, fish-count numbers at each designated temperature level were further divided by the total amount of time fish were recorded in each section in minutes to normalize the data per unit time for further temperature series distribution analyses.

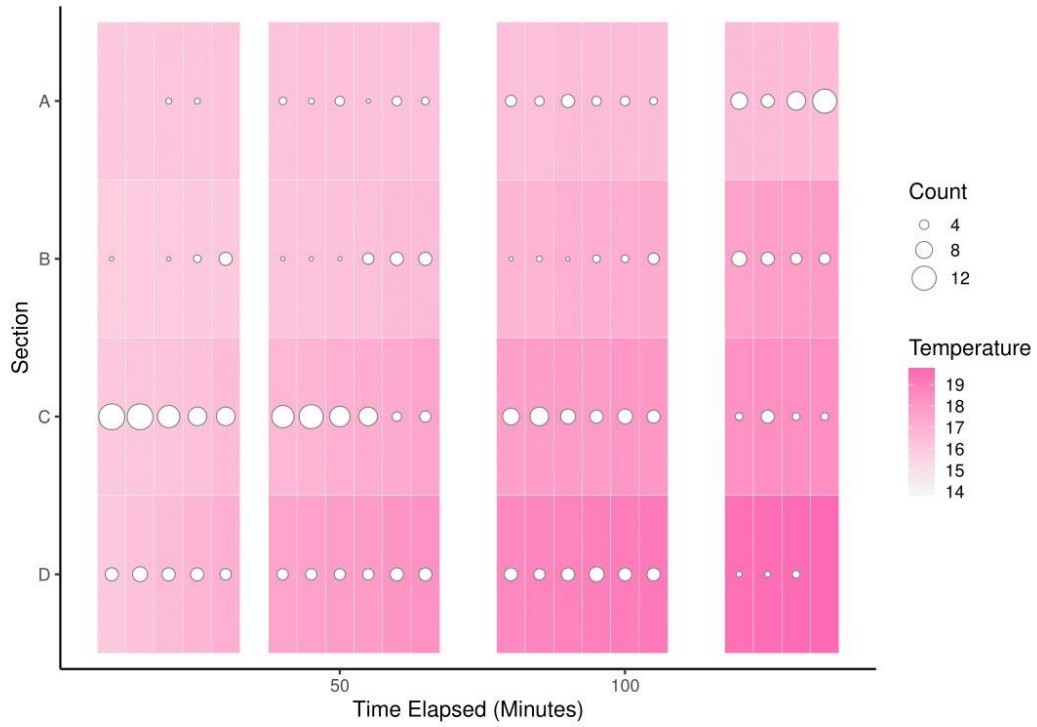
(a) Small Fish; Trial 1



(b) Small Fish; Trial 2



(c) Large Fish; Trial 1



(d) Large Fish; Trial 2

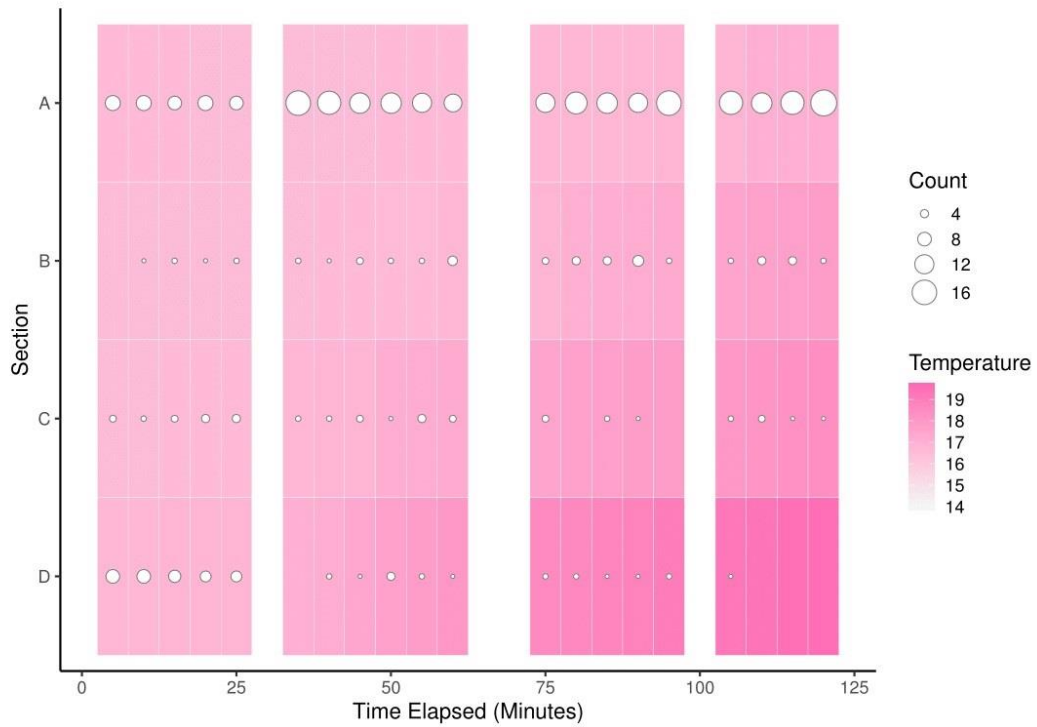


Figure 2.3. The temperature gradient heat map and fish counts at each temperature gradient section of the experimental temperature gradient flume. [Figure legends:

(a) Small Fish, Trial 1; (b) Small Fish, Trial 2; (c) Large Fish, Trial 1; and (d) Large Fish, Trial 2].

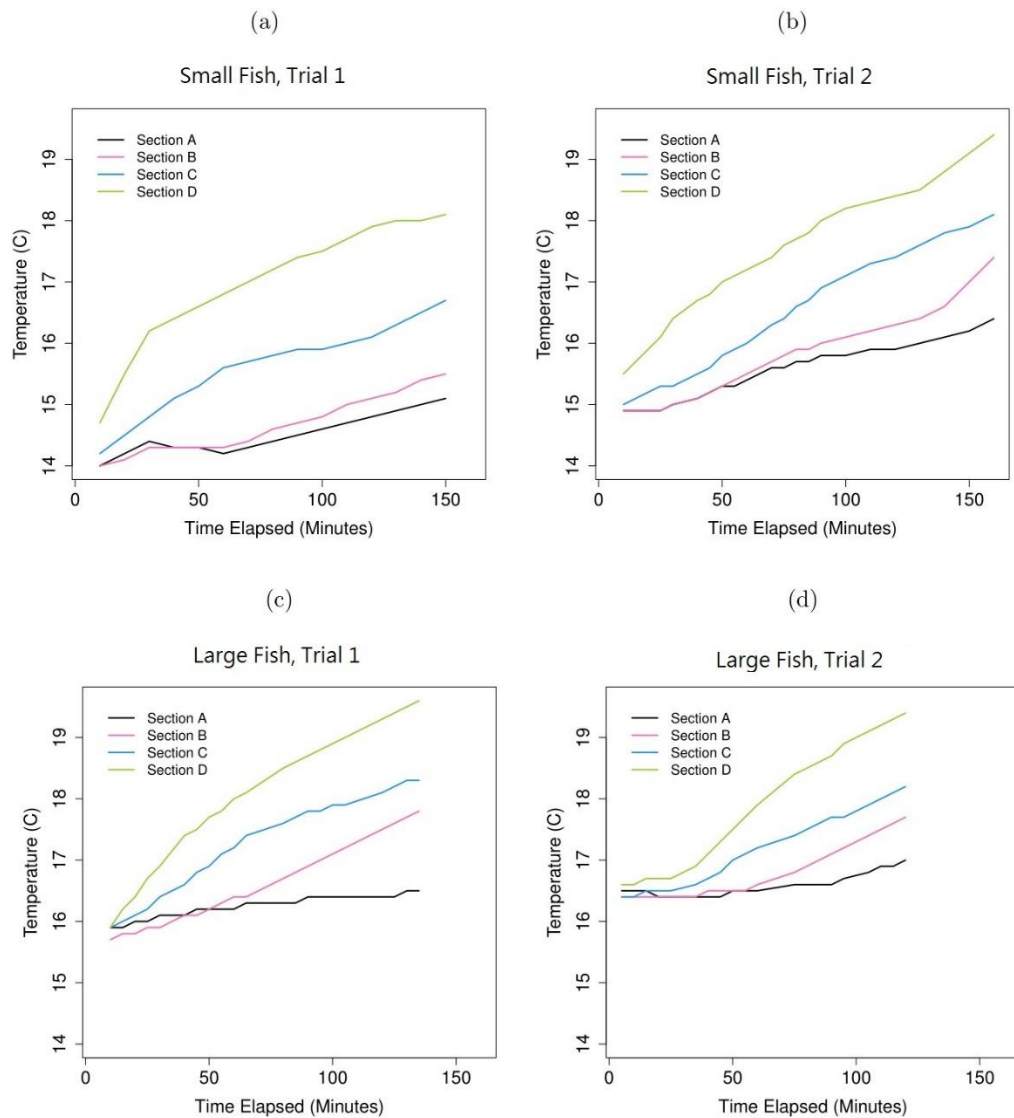


Figure 2.4. Plots of the time series temperature changes for each section of each experimental trial in the experimental temperature gradient flume. [Figure legends: (a) Small Fish, Trial 1; (b) Small Fish, Trial 2; (c) Large Fish, Trial 1; and (d) Large Fish, Trial 2]

To create a comparable measure of salmon activity, bins of temperatures were created. The bin width was set at 0.2°C, since it was wide enough to reduce some of the error arising from interpolating temperatures while keeping the overall trend of

the temperature profile. Temperature bins were inclusive of the starting temperature and exclusive of the ending temperature. For the small fish, the first bin was 14.0-14.2°C, and the final bin of fixed width was 18.4-18.6°C. To ensure there was more than one observation falling in the final temperature bin, the hottest temperature bin for the small fish was a cumulative bin of temperatures that were 18.6°C or higher. For the large fish, the first bin temperature range was 15.7-15.9°C, and the last bin had a temperature range of 19.5-19.7°C. There were 24 temperature bins for the small fish and 20 temperature bins for the large fish.

The number of minutes the water temperature fell within each temperature bin is plotted in Figure 2.5. This measurement aggregates the time the four sections of the tank spent at temperatures within each temperature bin and can be thought of as a measure of accumulated exposure time of each size group of fish at each range of temperatures. The normalized fish distribution among different temperature ranges was then calculated by dividing total number of salmon observed at each temperature bin by the total amount of time when water was at that temperature. This ratio is referred to as fish count per minute exposed and used for further temperature series avoidance behavior analysis.

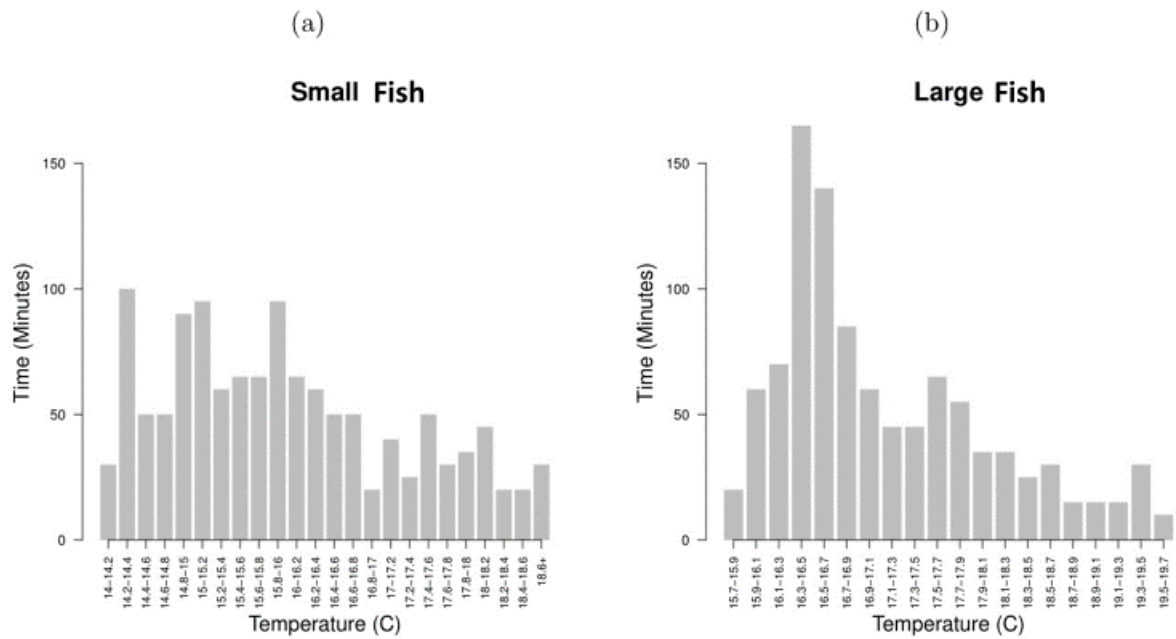


Figure 2.5. Total amount of time spent in minutes by each fish size group (Small and Large Fish) in each temperature bin when experimental trials were pooled in the experimental temperature flume experiment.

Fish counts per minute exposed from all trials of each fish size group is pooled and plotted within temperature bins as shown in Figure 2.6. For small-sized fish, the mean count per minute exposed appeared to be higher for cooler temperatures than warmer temperatures, and there was a potential thermal threshold triggering high temperature avoidance behavior. However, for pooled large-sized fish group, no obvious temperature threshold was detected or identified that separate the normal distribution from that produced by the high temperature avoidance, although there was a weak negative association between temperature and fish counts per minute exposed. There is also a potential outlier for the lowest temperature bin (15.7-15.9°C) for large-size fish group. This may be due to a limitation in the experiment design and background condition, as only one of the temperature gradient trials for the large-sized fish reached temperatures below 15.9°C. For that trial, only part of

tank sections experienced temperatures in the 15.7-15.9°C range for a shorter period. Later analyses were performed both with and without this potential outlier for the large-sized fish group, but no notable differences occurred in the threshold estimation.

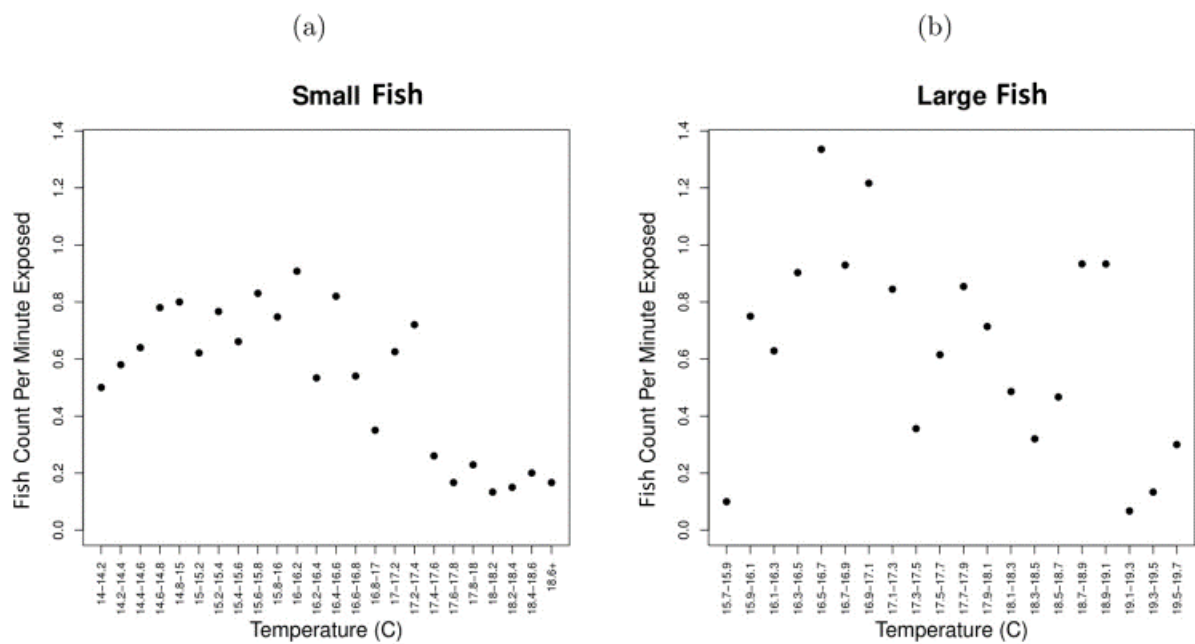


Figure 2.6. Total amount of time spent in minutes by each fish size group (Small and Large Fish) in each temperature bin when experimental trials were pooled in the experimental temperature flume experiment.

The pooling of all size groups for the analysis assumes that at any given time and range of temperatures in the tank, salmon can choose any temperature section to swim in. However, this assumption might be violated if moving distance is one of the potential factors and nearby sections are more preferred than others despite the salmon having temperature preferences. To explore this possibility, another analysis was performed by including only section D data with the warmest temperatures

instead of pooling data from all sections. Section D was chosen because it was designed to produce the highest temperature section and had the largest range of temperature variations. Fish appearances at section D are viewed as the result from the fish's choice to be or not be in the section in terms of its thermal preferences. Each experimental trial was analyzed separately because of the temporal variation of the temperature gradient for each experiment. In this analysis, the actual or interpolated temperature measurements from each observation were used instead of the temperature bins.

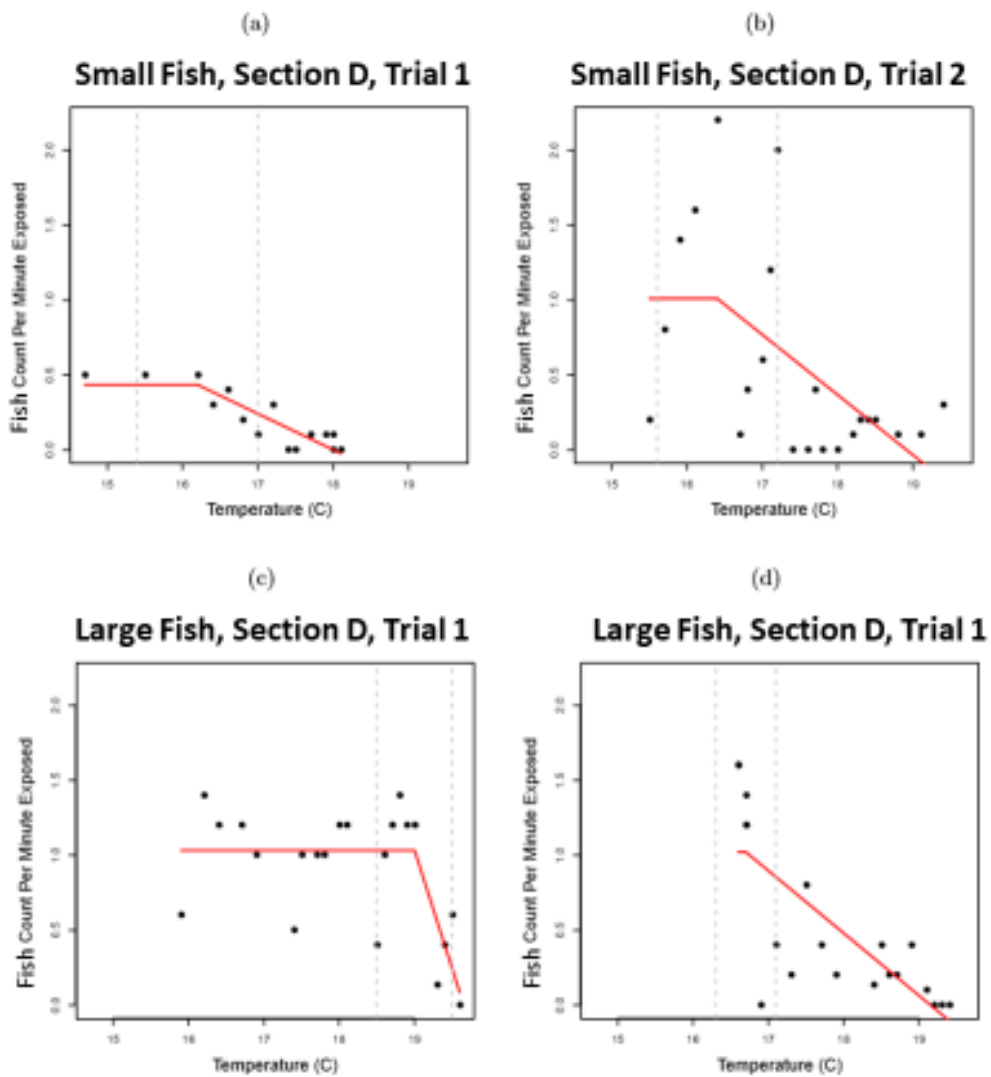


Figure 2.7. Threshold regression analysis of fish count per minute exposed to temperature bins and change point estimation using R package “*chngpt*” hinge

models with 95% bootstrap confidence intervals for section D (the warmest section in flume experiment). [Figure legends: (a) Small Fish, Section D, Trial 1; (b) Small Fish, Section D, Trial 2; (c) Large Fish, Section D, Trial 1; (d) Large Fish, Section D, Trial 2]

The section D count per minute exposed and temperature range data (Figure 2.7) showed a trend of a negative relationship between fish distribution and high temperature environments. Consistent with the pooled data analyses, no obvious threshold of high temperature avoidance pattern for large fish was detected. However, the different data scattering patterns between each experimental trial also revealed how background environment condition could affect the experiment outcome due to various temperature ranges covered from each setting.

Using the *chngptm* R package with a robust method to estimate better confidence intervals due to the small sample size, the hinge model identified a significant temperature threshold for Taiwan salmon that resulted in a high temperature avoidance behavior. For the pooled all-size group data, the estimated changepoints for small fish occurred at 16.0°C and for large fish at 16.9°C (Table 2.2a). However, the wide 95% bootstrap confidence intervals, especially for pooled large-sized group, also indicate its limited statistic power resulted from the small sample size, inconsistent background conditions, and restricted temperature ranges. For the large-sized group, the result also showed that there was no effect of including or excluding the potential outlier, i.e., coldest bin (15.7°C-15.9°C).

For section D which had the warmest temperatures in the experimental flume experiment, Table 2.2b provides data analyses of each individual treatment which showed both small-size fish trials had similar estimated changepoint at 16.2° C and 16.4°C and had a relatively narrow confidence interval compared to the pooled

analysis. The estimated changepoints of two large-sized fish trials varied more widely (16.7°C and 19.0°C). This result is consistent with the extremely wide confidence intervals that resulted from the pooled large-fish group data analysis and indicates both analyses on large fish were less informative in identifying temperature thresholds.

Table 2.2. The results of threshold regression analysis of fish count per minute exposed to temperature bins and change point estimation using R package “*chnngpt*” hinge models with 95% bootstrap confidence intervals for section D (the warmest section in flume experiment) among small- and large-sized Taiwan salmon. The threshold regressions were analyzed with (a) pooled small and large fish size groups, and (b) individual trials.

a	Fish Size	Parameter	Point Estimate	95% Bootstrap CI ¹
	Pooled Small	α_1	0.71	(0.63, 0.79)
		β_1	-0.24	(-0.46, -0.02)
		Changepoint (<i>e</i>)	16.0	(14.8, 17.2)
	Pooled Large (with coldest bin)	α_1	0.82	(0.59, 1.05)
		β_1	-0.19	(-2.02, 1.64)
		Changepoint (<i>e</i>)	16.9	(14.9, 18.9)
	Pooled Large (without coldest bin)	α_1	0.92	(0.67, 1.16)
		β_1	-0.22	(-2.03, 1.58)
		Changepoint (<i>e</i>)	16.9	(14.9, 18.9)

¹ Confidence Interval

b	Size and Trial	Parameter	Point Estimate	95% Bootstrap CI ¹
	Small, Trial 1	α_1	0.43	(0.26, 0.61)
		β_1	-0.24	(-0.31, -0.17)
		Changepoint (<i>e</i>)	16.2	(15.4, 17.0)
	Small, Trial 2	α_1	1.01	(0.52, 1.50)
		β_1	-0.40	(-0.72, -0.08)
		Changepoint (<i>e</i>)	16.4	(15.6, 17.2)
	Large, Trial 1	α_1	1.03	(0.89, 1.17)
		β_1	-1.58	(-2.87, -0.29)
		Changepoint (<i>e</i>)	19.0	(18.5, 19.5)
	Large, Trial 2	α_1	1.021	(0.60, 1.44)
		β_1	-0.42	(-0.58, -0.25)
		Changepoint (<i>e</i>)	16.7	(16.3, 17.1)

¹ Confidence Interval

River temperature monitoring

During the research study period, high rainfall events resulted in the occurrence of flash summer flood events. The impact of the flash floods was further aggravated by the steep river morphological conditions that existed at the research site. This caused in-river temperature monitors to be washed away during these storm events. This meant that only few complete monthly data collection points exist for the research analysis (Table 2.3). Also, data are lacking between the months of July through October at location C1 (Figure 2.1).

Table 2.3. Months by year that have a complete monthly field water temperature record obtained by river section (C1, C4, and C7) in the Cijiawan River (See Figure 1.2 for the location of the sampling station).

Station	Year	Months with complete data
C1	2007	April, May, June
	2008	April, May
	2009	April, May
	2010	April, May
C4	2007	April, May, June
	2008	April, May
	2010	April, May
	2011	April, May, June, July, August, September, October
2012	April, May, June, July, August	
C7	2007	April, May, June, July, August, September, October
	2008	April, May, August, September, October
	2009	April, May, June, July, August, September, October
	2010	April, May, June, July, August
	2011	April, May, June, July, August, September, October
	2012	April, May, June, July, August

Using the potential high temperature avoidance threshold (16.4°C) developed using changepoint analysis of the small-sized fish, the average daily maximum water temperature (Table 2.4) at location C4 exceeded this temperature threshold between the months of July through September. At the upstream C7 location, the high temperature avoidance threshold was never reached during the entire sampling period. The total time period in which the downstream location C1 exceeded the temperature threshold varied from 340 minutes in April to 4800 minutes in June. In contrast, C4 the mid-stream location ranged widely from the lowest time period of 27 minutes in May to the highest time period of high temperatures of 9240 minutes in July. At no time did the minimum water temperatures at nighttime ever exceed the high temperature avoidance threshold at all locations. The longitudinal temperature differences between the C1 location and C4 among all month monitored ranged from 1.1°C to 1.5°C, with fixed variance of 0.2°C.

Table 2.4. Average daily maximum and minimum temperatures (°C) and total times (in minutes) that the temperatures exceeded the high-temperature avoidance threshold for Taiwan salmon (16.4°C) in the Cijiawan river sections. [Data are shown by month and by the water temperature gauge stations (C1, C4, and C7)]

Month/Site	Average daily maximum temperature			Average daily minimum temperature			Total time in minutes exceed threshold		
	C1	C4	C7	C1	C4	C7	C1	C4	C7
April	14.3	13.3	11.3	11.6	10.9	10.2	340	87	0
May	16.1	14.5	12.6	12.8	12.1	11.5	2550	27	0
June	16.2	15.7	13.9	13.8	13.2	12.6	4800	2560	0
July	N/A	17.7	15.2	N/A	14.1	13.5	N/A	9240	0
August	N/A	17.7	14.5	N/A	14.4	13.2	N/A	8760	0
September	N/A	17.2	13.9	N/A	14.0	12.8	N/A	7020	0
October	N/A	15.1	12.4	N/A	12.8	11.6	N/A	360	0

Discussion

Climate change is expected to impact the survival of non-anadromous fish which have fewer options to avoid the high temperatures that may negatively impact their survival. When these temperature extremes occur, it causes high temperature avoidance behavior by non-anadromous salmon but the limited habitat area available restricts their ability to adapt to these changes in river temperatures (Katz et al. 2013; Parra et al. 2014). Dam removal is one of the restoration practices used to address this issue. The assumption is that the restored river longitudinal connectivity could help fish migrating from warmer parts of a riverine system to the cooler upper parts of the river, especially for non-anadromous fish with limited habitat accessibility (Palmer et al. 2009; Perry et al. 2011; Stanley and Doyle 2003).

In this research, a dam was removed in Taiwan to improve the connectivity of a river where the endangered Taiwan salmon continue to survive. The goal of the dam removal was to increase the access of the Taiwan salmon to cold water refugia during temperature extreme conditions that may cause their high temperature avoidance behavior. The overall air and water temperature in Taiwan are predicted to increase under a global climate change scenario (Hsu and Chen 2002; Li et al. 2009; Yu et al. 2002). This research was designed to experimentally determine the high temperature avoidance threshold for Taiwan salmon and to determine whether river temperatures exceeded these high temperature thresholds during the summer months. Since the Taiwan salmon is found in one river system currently in Taiwan and is endangered, it is critical to determine whether the habitat of these salmon can be restored or managed to increase its viability under a climate change scenario (IPCC 2001). A high temperature threshold of 17°C has been used to assess the impact of temperature increases on Taiwan salmon (Tzeng 1999). Prior to this

research no data existed to calculate the high temperature threshold for Taiwan salmon. If this high temperature threshold is lower than what had been predicted, it will be essential to monitor river temperatures to develop appropriate management and restoration options.

Taiwan salmon high temperature threshold

The effect of water temperature on salmonid, usually anadromous, has been thoroughly studied globally (Crossin et al. 2008; Farrell et al. 2008; Jonsson and Jonsson 2009; Jonsson 1991; Mueter et al. 2002). Most of the research studies focused on habitat usage at a specific life stage in thermal-controlled experiments, incubation and hatching rate, digesting metabolism rate, rearing physiological growth, and mortality from high temperature (Dowd et al. 2015). However, using only an extreme or critical temperature condition threshold is not appropriate (Rodnick et al. 2004) because there are more thermal regime components other than temperature itself that might have significant ecological influences that need to be understood (Steel et al. 2017). The high temperature avoidance behavior could be a natural response of fish after considering all thermal-related factors. It could also serve as one integrated index in understanding species optimal thermal condition and evaluating potential impact from thermal regime changes caused by anthropogenic habitat alteration or climate change.

Freshwater fish of different sizes respond to water temperature in various ways due to their physiological differences (Breau et al. 2011; Clark et al. 2012). Smaller fish tend to have higher thermal tolerance level and are less sensitive to temperature changes (Fowler et al. 2009; Lund et al. 2000; Pörtner and Farrell 2008).

Larger fish are found occupying cooler habitats in the wild (Breau et al. 2007a; Morita et al. 2010). When exposed to warmer temperatures, larger fish are also more readily abandoning their normal territorial and foraging behavior to move to cold water refugia (Breau et al. 2007a; Cunjak et al. 2005). In contrast, smaller fish tend to remain in their territory and continue their normal foraging activities (Breau et al. 2007b). However, this research was unable to provide statistically supported results for comparison between different size groups because of the inconsistent temperature range between treatment trials, either in pooled temperature series or individual analysis. Also, due to the endangered status of the Taiwan salmon, the replication and sample sizes could not be increased to improve the statistical power of the analyses.

In this research, the small-sized group of Taiwan salmon showed significant avoidance behavior when water temperatures exceeded a temperature threshold of $\sim 16.4^{\circ}\text{C}$. This experimentally produced result was used as the high temperature avoidance behavior threshold and the critical indicator for Taiwan salmon and their thermal suitability condition. The 16.4°C temperature threshold is lower than previous predictions based on field observations and suggests that the 17°C threshold does not adequately represent the avoidance behavior for the Taiwan salmon (Tzeng 1999). As for the large-sized fish group treatments, the threshold temperature could not be determined from the changepoint analysis, possibly resulting from the lack of data at the lower temperature range. Although large-sized fish did show significant decreased preference to move to higher temperature sections and may have a lower threshold triggering avoidance behavior, the experimental system and data could not identify some of those assumptions in details. However, the threshold for smaller fish of 16.4°C could still serve as a

relatively more conservative critical thermal indicator for further analysis for Taiwan salmon.

The 16.4°C thermal threshold of Taiwan salmon is similar to thermal threshold and preferred water temperature studies of masu salmon. As the closest salmon species to Taiwan salmon, juvenile masu salmon are found with upper thermal tolerance for active feeding and growth of at 18°C with the preferred range being 8°C to 15°C (Mayama 1992). Wild masu salmon also occupy their primary holding position at river sections with water temperature close to 15°C (Morita et al, 2016). There is also significant population abundance change from forested reaches (summer max. ~16°C) to grassland (summer max. ~20°C) (Inoue et al. 1997).

River temperatures and Taiwan salmon high temperature avoidance thresholds

Using the small-sized fish high temperature avoidance threshold of 16.4°C as the critical thermal indicator, river temperature data records show that water temperature at river sections below the Cijiawan Two dam breach site consistently exceeded this high temperature avoidance threshold during the day time for the summer season. Water temperatures at the mid-stream section already exceeded 16.4°C beginning in late April. This suggested that half of the river length did not provide suitable habitat for the salmon during these summer periods. With the average daily maximum water temperatures exceeding the 16.4°C threshold from July to September, the total time period in July which river temperatures exceeded this threshold was 9240 minutes. This averaged to almost 5-hours per day of temperatures capable of causing the expression of the avoidance behavior by the fish during an entire month.

Further downstream from the Cijiawan One dam removal site to the furthest salmon population distribution boundary on the main stem confluence (site C1), the daily maximum water temperatures always exceeded the high temperature threshold suggesting this section of the river is unsuitable during the summer months for the Taiwan salmon survival. This section of the river also provides no cold water refugia for the salmon during these months. This section of the river experiences a steady longitudinal warming pattern of the region and mostly results from solar energy accumulation (Lee et al. 2012; Tung et al. 2006). This reduced the suitable cooler temperature refugia for the Taiwan salmon to the upper half of the riverine system.

Cold water refugia accessibility and dam removal

With the newly opened passage from Cijiawan One dam removal and Cijiawan Two dam breach, the longitudinal and diel water temperature variations indicated cold water refugia exist for half of the river system during the summer high water temperature season. This upstream section was accessible without any migration barriers for fish now. There was a scouring pool below Cijiawan Three dam that was located 2 km from Cijiawan One dam site. The pool is located close to (within 60 m) of the C7 water temperature station that is located on top of the Cijiawan Three dam and below the Wuling suspension bridge. This proximity suggested that the Cijiawan Three dam should have a similar water temperature regime as the C7 station. Therefore, water temperature at that scouring pool probably will not exceed 16.4°C at any time during summer season, and the upstream sections can serve as cold water refugia for downstream population if they choose to move upward.

In addition to potential existence of upstream cold refugia during the daytime, the diel temperature patterns also indicated that a more thermally suitable habitat did exist during the nighttime at all river sections. The minimum daily water temperature at mid-stream C4 dropped at least 3°C from the daily maximum during the entire summer season, and never exceeded 16.4°C. From limited field record, the nighttime longitudinal water temperature difference between C1 and C4 was smaller than the daytime temperature difference ($<0.8^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$), so the nighttime water temperature at downstream sections was well below 16.4°C. This diel pattern indicates water temperatures decreased into a suitable range for Taiwan salmon every day during the non-daytime period. Taiwan salmon's high temperature avoiding strategy of moving longitudinally for cold water refugia or staying for local diel variance might need more in-field telemetry tracking with habitat temperature to detect these finer scale changes to understand these temperature fluctuations. The impact of the variations in the daytime and nighttime temperatures needs further research to determine if the daytime high temperature thresholds will negatively impact the survival of the Taiwan salmon.

Research design limitation and future opportunities

Despite the obvious high temperature avoidance behavior recorded when temperature gradients reached the high temperature conditions in the flume experiment, the statistical analysis was unable to identify the specific thermal threshold at these finer confidence intervals, especially for the large-sized group of fish. The limited statistic power mostly due to the small sample size, inconsistent temperature range, and possible statistics assumptions violations. Being listed as IUCN endangered species, the total available amount of hatchery Taiwan salmon for

use in these experiments is usually strictly managed. Further, the tank size of the flume and of the power of heating device also limited the capacity of the experimental system, as did the number of fish that could be utilized in the experiments. The statistical rigor could have been increased if the individual fish movements could have been identified and monitored in independent trials. However, the 20 fish utilized in each experiment could not have been externally color coded and would have been challenging to be tracked individually only using visual observations.

Limited by experiment design and background environment, the temperature range varied between each experimental treatment and the total time of each temperature bins was not evenly distributed. Since the temperature gradients in the treatment trials were created by continuously heating one end of flume, it should be expected that fish would have more opportunities to access sections within the middle temperature range than either the coldest or warmest ends of the experimental system. The temperature range of each treatment was also impacted by other experimental conditions that the experimental system was less able to control, e.g., the daily background conditions, such as the starting water temperature (13.8°C to 16.6°C), air temperature (14.4°C to 23.9°C), the sun light angle and the building shading.

The power of the threshold regression statistical analysis was limited by not only the small sample size and inconsistent range, but also by the possible independence violation and correlated parameters caused by the experiment design. Fish count observations at each section were used as an independent result of the fish thermal suitability choice of habitat under different temperature gradient conditions. However, not all sections had equal opportunities to be chosen by the

fish. Environmental and behavioral factors, such as corner crowding or shading preference, territorial competence in limited space, movement distance between sections, are likely make some sections preferable than others with no water temperature related reasons. Even the count numbers themselves were correlated at some level, because total number of fish sample in the tank was fixed and fish count of fourth section, which can be derived from other sections, was not independent.

Despite the factors that limited the ability to statistically analyze the experimental results, the temperature gradients triggering Taiwan salmon high temperature avoidance behavior developed in the experimental system are useful to compare with the temperature regimes measured in the study research system during the summer season. These conditions existed for an extended time period, especially in river sections downstream below the old Cijiawan One dam. This research provides circumstantial support that the newly restored longitudinal connectivity from Cijiawan One dam removal might provide critical passage for Taiwan salmon to access cold water refugia located upstream during the summer seasons when river temperatures exceed the temperature threshold for this species. However, the definite proof of the efficacy of Cijiawan One dam removal and its ecological benefits on helping Taiwan salmon to reach upstream cold water refugia under such conditions needs further research. Research needs to explore the impact of the thermal thresholds based on the size of Taiwan salmon, as well as to record the finer scale field temperature records and telemetry tracking of Taiwan salmon to monitor their actual avoidance movements in response to temperature fluctuations in the river.

Conclusions

This research was designed to evaluate one aspect of the potential ecological benefit of Cijiawan One dam removal by understanding Taiwan salmon's behavioral responses when exposed to high temperature environment and river temperature regime during the summer season. The flume experiment showed that Taiwan salmon have significant high temperature avoidance behavior, but their thermal threshold is lower than previously assumed. The field temperature records showed that water temperature at some downstream sections exceeded the thermal threshold for substantial hours during the daytime in summer seasons, but there were cold water refugia located upstream which became accessible after the removal of the Cijiawan One dam. However, the temperature warming trends under global climate change scenario and remaining existing dams might reduce the amount of cold water refugia and limit Taiwan salmon's ability to reach for more thermal suitable habitat.

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Chapter 3

Potential response of non-anadromous fish to climate change impacts

Abstract

The vulnerability and resilience of fish living in freshwater and marine environments to warming water temperatures due to climate change is an important research area that needs to address whether the local extirpation of fish species is more likely in freshwater ecosystems that are disconnected from marine environments. The climate change impacts on the resilience of fish populations must also be put in the context of a highly altered landscape. For example, habitat fragmentation due to dams and other land use changes may alter riverscape structural characteristics by reducing the available habitats capable of providing sufficient thermal refugia for non-migratory fish.

It is important to understand if river restoration is an effective technique to decrease the vulnerability of non-anadromous fish to rising water temperatures. Here we show that a non-anadromous fish population will be at risk of extirpation due to warming and extreme storm events that management and restoration tools do not address effectively. Dam removal is commonly used to restore river longitudinal connectivity helping fish to access thermal refugia even under short periods of extreme hot temperatures that negatively impact their survival. A dam removal project on the Cijiawan River in Taiwan, only half of the river extent was available for an endangered species (e.g., *Oncorhynchus formosanus*, Taiwan salmon) during the hottest temperature periods. The temperature refugia were only found in river sections located at higher elevations. The survival of non-anadromous

fish therefore is confined to available river habitats at the higher elevations that are less impacted by warmer temperatures. Management of endangered fish species and hydro-ecological restoration plans need to assess the extent of rivers that are impacted by warming temperatures since they do not provide temperature refugia during the short periods of extremely hot temperatures.

Introduction

The vulnerability of anadromous fish populations to warmer temperature and the development of management approaches to restore the hydro-ecology of riverscapes altered by dams and other land uses has received considerable research attention (Diefenderfer et al. 2012; Mattocks et al. 2017; Schtickzelle and Quinn 2007). Pinsky et al. (2019) suggested that local extirpation of species would be higher in oceans compared to terrestrial areas and that habitat fragmentation and land use changes would have the greatest impact on terrestrial areas because of the loss of thermal refugia. Such studies provide insights to design assessment protocols for fish vulnerable to warming temperatures and the feasibility of using restoration measures to address these issues. However, it might not reflect the vulnerability of non-anadromous fish living in rivers disconnected from marine environments.

Monitoring and assessing the resilience of non-anadromous fish populations to changes in freshwater river habitats can provide early warning of the potential extirpation of endangered fish species due to climate change impacts on river conditions threatening their survival in the near future. Non-anadromous fish could potentially serve as sensitive indicators to assess whether the proposed management practices and restoration tools can address the alterations to river conditions from anthropogenic activities that are now further impacted by climate change. Re-establishing viable and resilient fish populations are important indicators of whether engineering tools can be used to restore river systems impacted by land-uses and engineering structures like dams.

Non-anadromous fish face unique life history challenges to survive in river systems isolated from marine environments since their foraging and reproduction needs are limited to a single river system, or sections of a river. In these situations,

they are unable to migrate to habitat conditions more suitable for their continued survival (e.g., temperature refugia, foraging habitat, spawning habitat). Warming temperatures and other environmental factors impacted by climate change might greatly change habitat suitability for fish. When a fish is listed as endangered, such as the Taiwan salmon that already has a low population density (see Chapter 1), increases in extreme weather events (e.g., higher temperatures, extreme flood events) will further lower their resilience to climate change when a river's structural characteristics and connectivity reduce their ability to migrate to more suitable habitat conditions.

Beechie et al. (2013) developed key factors to evaluate the potential impacts of climate change on salmon recovery and stream restoration project planning and design: 1) the necessary habitat restoration actions to recover local salmon populations; 2) The possibility of future stream flow and temperature scenarios altering habitat restoration actions for salmon recovery; 3) The effect of restoration actions under predicted climate change effect on stream flow or temperature; and 4) The effect of restoration actions on increasing habitat diversity and salmon population resilience. These factors were not considered when a dam was removed to restore longitudinal connectivity of the Cijiawan River to improve the conservation of the endangered Taiwan salmon. Since the Taiwan salmon are non-anadromous and are disconnected from the marine environments, all possible habitat restoration activities are limited to a smaller spatial scale in the mountainous region of Taiwan. Also, the ecological benefits of restoration may be weakened with changing habitat conditions under future current climate change trends.

Stream restoration is widely practiced to improve river ecosystem attributes altered by anthropogenic or other land-uses with the goal of managing and using engineering interventions to restore habitat characteristics needed to conserve

certain target species. One common restoration tool has been the removal of anthropogenic structures such as dams that reduce the migration range of fish to improve river longitudinal connectivity and the amount of accessible fish habitat (van Puijenbroek et al. 2019). One of the main purposes of longitudinal connectivity restoration, often by removal of dams or other migration barriers, is to reestablish accessibility of previously restricted upstream habitat for aquatic species' needing certain environmental conditions during specific life stages. Dam removal and the restored longitudinal connectivity are known to allow fish accessing upstream cool water habitats when downstream areas become too warm (McClure et al., 2008; Pess et al. 2008). However, the effectiveness of dam removal as a restoration project may only address some of the factors mentioned by Beechie et al. (2013) and be less suitable to address the climate change impacts that cause river temperatures to become warmer.

Another common river restoration practice is instream habitat restoration aiming to improve habitat conditions and diversity by creating specific types of instream habitats or restore channel diversity with introduced structures (e.g. wood debris, boulders, log jams, spawning gravel, etc) or other channel altering engineering measures (e.g. channel re-meandering, pool and riffle sequence) (Roni et al. 2008). Although instream habitat restoration actions are effective in improving both physical habitat and fish production from various cases (Cederholm et al. 1997; Roni and Quinn 2001; Solazzi et al. 2000), it is also considered not sustainable and require regular additional intervention or maintenance because of the lack of re-establishment of natural processes (Roni et al. 2002). Research has also shown that it is difficult to have significant water cooling effect due to the relatively small scale of restoration actions, compared with the natural temperature regime (Crispell and Endreny 2009; Hester et al. 2009; Poole et al. 2008).

For non-anadromous salmon living only in freshwater ecosystems, their restricted range limits their ability to migrate to suitable temperature habitats (Beechie et al. 2006; Halupka et al. 2003; Himes-Cornell and Kasperski 2015). In these rivers, habitat accessibility for downstream fish populations to cooler temperatures found in up-river stretches of the river will determine whether these freshwater fish can complete all their life stages in river systems (Caissie 2006; Webb et al. 2008).

Climate change impacts on Taiwan salmon habitat

Taiwan salmon have evolved into landlocked form and spend their entire life stage in freshwater system. They also have become residents of these riverine systems and do not regularly migrate. They are limited to using a small home range for routine forging and resting behavior. Habitat impacts from climate change, such as warming temperature and changing hydrology still could affect Taiwan salmon population in various ways on different life stages (Table 3.1).

Table 3.1. Habitat impacts from climate change on Taiwan salmon population on life stages.

Climate change impacts	Life stages	Possible effects
Warming temperature	All	Thermally suitable habitat
Increasing high flow	Egg	Fine sediment suffocation Redd scouring
	Fry	Flood displacement
	Juvenile and Adult	Flood related mortality
	Spawning	Substrate composition and stability

Warming Temperature

Climate change has resulted in warming air temperature conditions that has caused the average warming rate for the global land and ocean temperatures to be above normal in 2005, 2010, and during 2014 to 2019 (NOAA National Centers for Environmental Information 2020). The observed changes in mean air temperature in Taiwan already show statistically significant increases in temperatures that ranged between 1.0-1.4°C/100 years increases using field recorded data range between 1897 to 1999 (Hsu and Chen 2002).

The daily maximum air temperature during summer season (May to October) have also increased steadily for the past century, especially since 1990 (Figure 3.1) (Taiwan Climate Change Projection Information and Adaptation Knowledge Platform 2017). Furthermore, based on the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC), Taiwan air temperatures are predicted to rise from 1.6 -2.0°C to 3.0-3.7°C, depending on different greenhouse gas scenarios, by the end of 21st century (Figure 3.2) (Taiwan Climate Change Projection Information and Adaptation Knowledge Platform 2017).

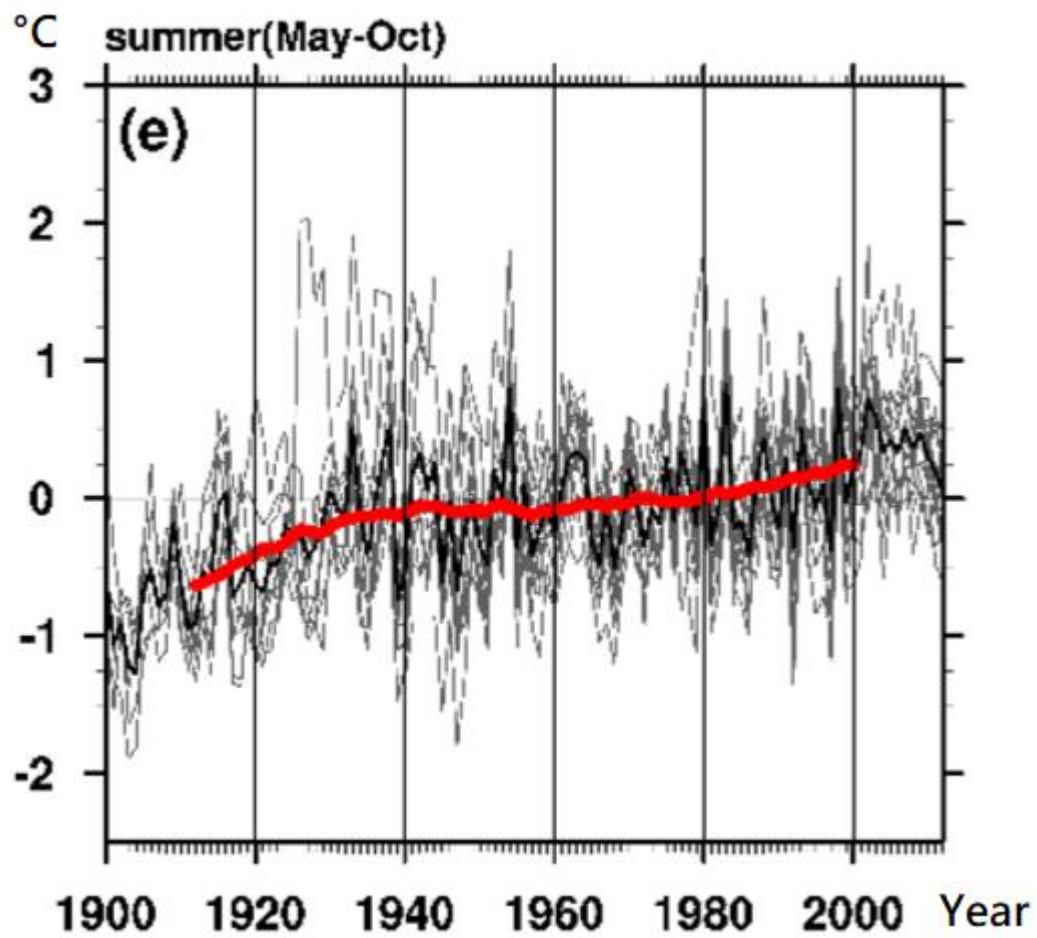


Figure 3.1. Taiwan daily maximum air temperature of summer season (May to October); differences to the average daily maximum air temperature from 1961 to 1990. (Adapted from 2017 Taiwan Climate Adaptation Scientific Report by Ministry of Science and Technology, Taiwan). [Red line indicates 25-year moving average].

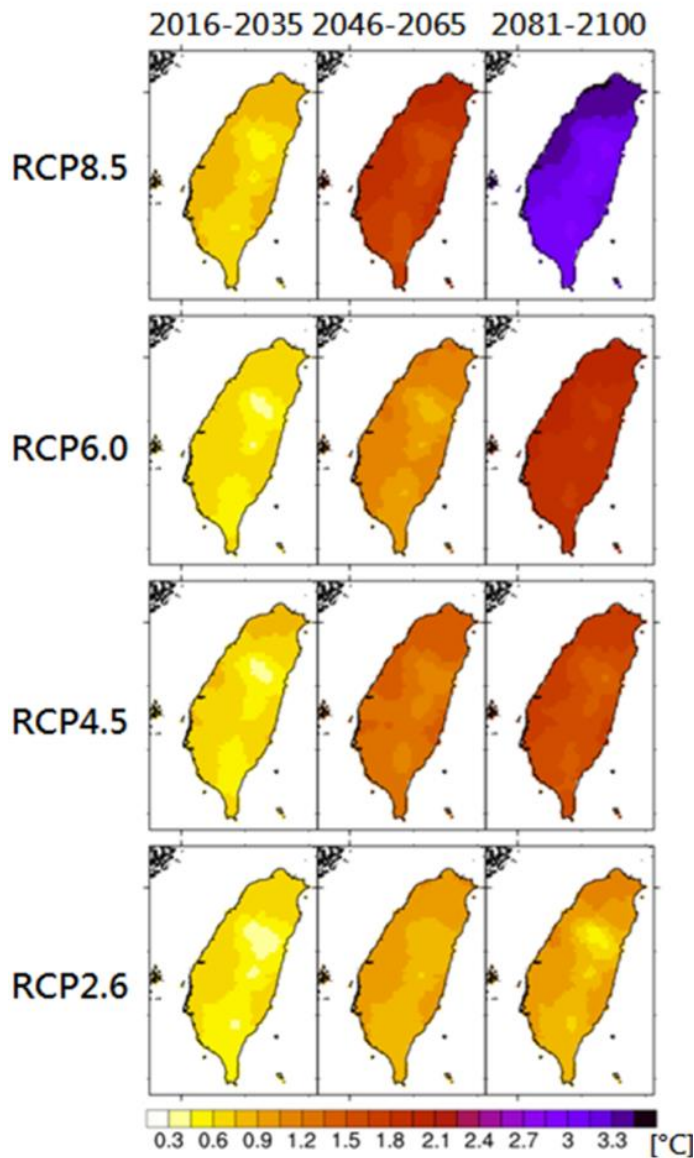


Figure 3.2. Projected increases in temperature under different climate change scenarios (Representative Concentration Pathways, RCPs; Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC)) (Adapted from 2017 Taiwan Climate Adaptation Scientific Report by Ministry of Science and Technology, Taiwan).

In most freshwater systems, solar energy accumulation is the most important factor of longitudinal thermal regimes and air temperature is usually highly related to river water temperatures, and water temperature will increase about 0.75°C when air temperature increase 1°C (Stefen and Preud'homme 1993). Therefore, water temperature in Cijiawan basin is projected to have a 1.2°C to 2.8°C increase at

the end of 21st century under current climate change trend. Air temperature and water temperature projections show warmer temperatures have persisted for several decades and will continue to impact conservation efforts for the non-anadromous Taiwan salmon. These recorded temperature changes are higher than what was recorded during the study period which ended in 2012 (see Chapter 2) suggesting that Taiwan salmon will experience a longer period of river temperatures that are higher than their thermal threshold of tolerance.

The possible climate change induced temperature change will reflect not only in mean temperature, but also in the duration and other thermal patterns. The total days of heat wave condition (daily maximum air temperature exceed 93% percentile in three consecutive days) will increase from currently 20 days per year to 80 - 180 days per year by the end of 21st century (Figure 3.3) (Taiwan Climate Change Projection Information and Adaptation Knowledge Platform 2017). Shiu et al. (2009) using field data reported a 1.4°C increase in air temperature from 1911 to 2005 as well as that daily maximum temperatures were higher than 36°C. The rate of increase in the mean air temperature was significantly higher during the warm season than during the winter (Hsu and Chen 2002). These higher temperatures during the warm season are at a level where Taiwan salmon show high temperature avoidance behavior (see Chapter 2).

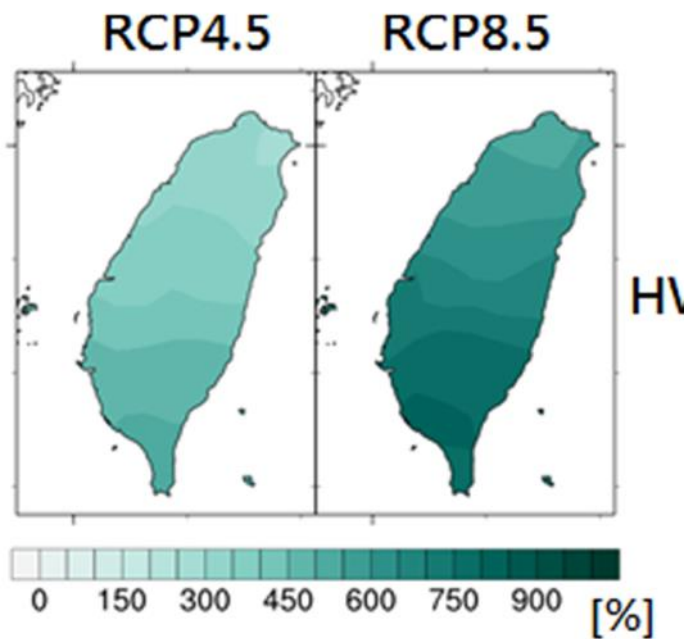


Figure 3.3. Projected percentage of increase of Heat Wave Duration Index (HWDI*) in 2081 - 2100 under different climate change scenarios (RCPs; IPCC AR5) (Adapted from 2017 Taiwan Climate Adaptation Scientific Report by Ministry of Science and Technology, Taiwan). [HWDI: period (days) in each year of at least three consecutive days where the maximum temperature exceeded 93% percentile of the annual records].

Previous analyses indicate that Taiwan salmon show significant high temperature avoidance at 16.4°C (see Chapter 2). Using this result as a threshold for thermally suitable habitat, more than half of the river sections below the existing Cijiawan Three dam currently exceed the temperature threshold during the daytime for most of the summer season. This study also found suitable cold temperature refugia during periods of extreme hot temperatures were limited and mostly found on river reaches located at higher elevations. Although the exact number will need a finer scale temperature model to decide, the daily maximum water temperature at all downstream sections of Cijiawan river (below Cijiawan Three dam) might exceed such threshold under a climate change scenario. Taiwan salmon might rely more on instream habitat and diel variation to provide cold water refuge in the future. Other Cijiawan River temperature studies also found similar results. Using global climate

trend and water temperature model for river section between Cijiawan One dam and Cijiawan Three dam, water temperature at this section is assumed to rise 0.5°C to 2.8°C in the future and become thermally unsuitable for extended periods (nearly three months) under certain climate change scenarios (Tung et al. 2006; Tung et al. 2007).

The restored longitudinal connectivity, benefited from the removed Cijiawan One dam and the breached Cijiawan Two dam, enables Taiwan salmon to migrate to cooler upstream section for now. However, under the climate change scenario, the projected rising air temperature and extended heat wave might make all downstream section thermally unsuitable for a significant number of days during future summer seasons. Instead of moving upstream to find scarce cold water refuge, Taiwan salmon will rely more on the river thermal diel variations for water temperature to drop back to suitable range during nighttime (Figure 3.4). Under such a scenario, although Taiwan salmon may not stay continuously in thermally unsuitable conditions, the accumulative effect of salmon regularly exposing to temperatures near the high thermal thresholds may still have negative impacts on the resilience of Taiwan salmon.

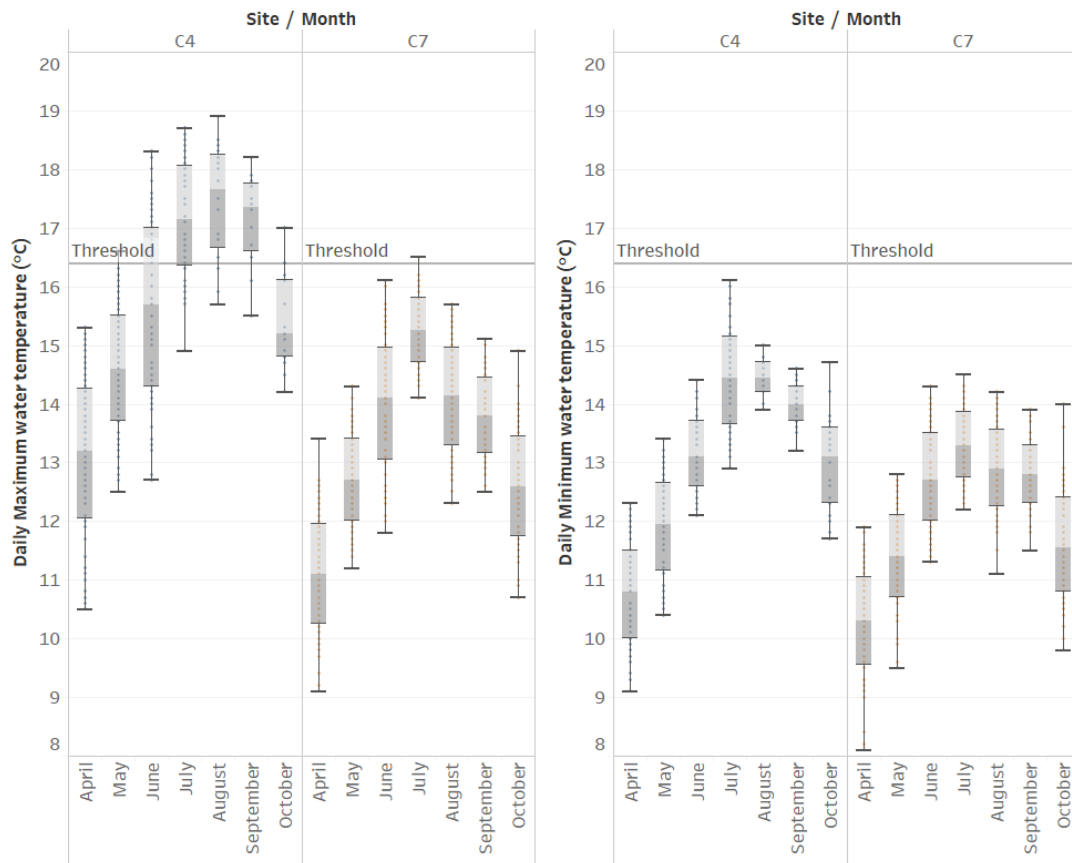


Figure 3.4. The daily maximum and minimum water temperature at C4 and C7 station in Cijiawan River from 2007 to 2012. The Threshold line indicates the high temperature avoidance threshold of 16.4°C for Taiwan salmon (see Chapter 2). [Only included months with complete data]

For Taiwan salmon and the Cijiawan River, the potential ecological benefit from additional dam removal to restore more longitudinal connectivity might be limited due to other existing migration barriers and the level of projected rising temperature due to climate change trend. With new passages from the removal of Cijiawan One dam and the breached Cijiawan Two dam, Taiwan salmon are able to move freely from downstream confluence to the existing Cijiawan Three dam. Previous analysis indicates that the restored longitudinal connectivity can help the downstream Taiwan population access upstream cold water habitats when facing unsuitable thermal environment during the hot summer temperature periods under the current

thermal regimes. However, the projected climate change rising temperature might make the whole river section (from confluence to Cijiawan Three dam) unsuitable for significant periods during summer season in near future. Almost 55% of total Taiwan salmon population ($54.8\% \pm 10.3\%$ s.d. based on the Taiwan snorkeling survey between 1997 and 2012) currently living in that river section will be exposed to a hazardous environment by the end of the century.

Compared to the mid-size removed Cijiawan One dam and breached Cijiawan Two dam, Cijiawan Three dam is more challenging for migrating salmon to move to the upper reaches of the river because of its 20-meter height. There is also concern that its removal might cause irreversible damage on downstream habitats due to its larger sediment release and severe morphological impacts. Also, even if the Cijiawan Three dam could be removed successfully without permanent environmental impacts, its ecological benefit will be minimal since it is providing less than 500 meter of river section as suitable habitat due to its close proximity to Cijiawan Four dam. Therefore, dam removal and longitudinal connectivity restoration might not be the most effective action choice to conserve Taiwan salmon facing possible rising temperatures under a future climate change scenario.

Hydrologic changes

Based on the west Pacific typhoon trend projection, the average number of typhoons per year in the west Pacific is projected to decrease by the end of 21st century, but the intensity of each typhoon event will have a 20% -40% increase island-wide and 60% increase in the central mountain region (Taiwan Climate Change Projection Information and Adaptation Knowledge Platform 2017). This research suggests that a potential increase in the summer typhoon intensity might

have minimal effect on Taiwan salmon populations. Previous analysis suggested that although annual Taiwan salmon mortality is significantly related to critical flood events during summer season that are mostly accompanied with extreme typhoon events, it only significantly related to the existence of such events but not to their severity (see Chapter 1). Since the total number of extreme typhoon events is not projected to increase under the current climate change scenarios, Taiwan salmon population mortality are not expected to be influenced by critical flood events more than what they are currently experiencing already.

Flood events with extreme intensity might relate to instream aquatics mortality, and floodplain habitats can sometimes provide temporary refugia. Riparian and floodplain restoration measures usually aim to restore river lateral connectivity to improve habitat diversity and help aquatic species accessing such habitats during specific life stages (spawning or rearing) or under certain conditions (Pess et al. 2005; Waples et al. 2009). The restored side channels and floodplain habitats could provide some cold water habitat and low-velocity refuge under the potential rising temperature and changing flow regime in future climate change projections. However, the ecological benefit of riparian and floodplain restoration in Cijiawan River under climate change scenarios might be limited because of the possible Taiwan salmon behavioral responses under high flow situations and local geological and hydrologic conditions.

Previous analyses showed that Taiwan salmon mortality rates during significant flood events is independent of the severity of the flood event and fish size, indicating that the amount of connected floodplain areas and fish swimming ability are relatively irrelevant to fish survival (see Chapter 1). As a result, even the intensity of extreme summer flood events is projected to increase significantly in the future under climate change, the riparian and floodplain restoration measures and the

restore lateral connectivity might not help Taiwan salmon survive under such condition. However, Cijiawan River is located in a mountainous region in Central Taiwan, so most of river sections are located in relatively deep valley confined by steep slopes. Therefore, there are few potential riparian areas to be connected by restoration measures. The flashy hydrology and constrained morphology make river channels relatively dynamic in a limited valley space, so it is hard to develop stable riparian forests to provide substantial shading effect on cooling river water temperatures. Besides, because of confined channel width and relatively high flow velocity, the active water exchange and mixture may also reduce any lateral water temperature variation.

Based on the west Pacific precipitation trend projection of AR5 and local model results, the annual total precipitation in Taiwan is projected to not significantly change, but there will be some changes in average duration, intensity and seasonal distribution of extreme precipitation events (Taiwan Climate Change Projection Information and Adaptation Knowledge Platform 2017). These precipitation events are predicted to be of shorter duration but with a higher intensity. It also suggests that there will be fewer extreme events and longer dry periods in between these events. As for changes in seasonal distribution of rainfall, total precipitation levels during the wet seasons (May to October) is expected to increase by 4% -20%, while the dry season (November to next April) will experience a 2% -20% decrease in precipitation levels depending on different RCPs scenarios (Figure 3.5).

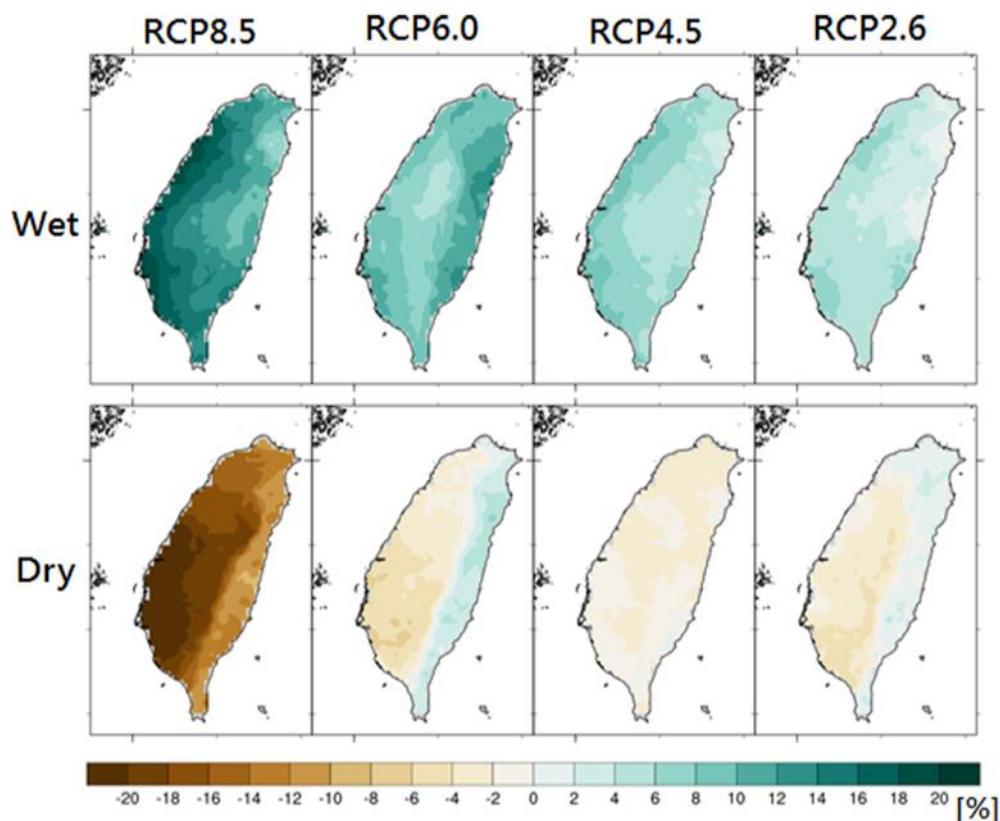


Figure 3.5. Projected change (in percentage) of total seasonal precipitation in 2081 - 2100 under different climate change scenario (RCPs; IPCC AR5) (Adapted from 2017 Taiwan Climate Adaptation Scientific Report by Ministry of Science and Technology, Taiwan). (Wet seasons (May to October) and dry seasons (November to next April))

Since the total annual precipitation is expected to stay the same under current climate change predictions, it suggests a low future risk of discharge drop or even a devastating dry out in Cijiawan River during low flow seasons. However, the increased intensity of the wet season precipitation events, especially during late summer and early fall, may impact river morphology and river bed substrate composition that could directly impair spawning ground quality. Taiwan salmon spawning season usually starts in mid-November, and the quality of spawning grounds of all salmonids usually highly depends on stream bed conditions (Liao 2012). Salmonids of different size and physiological abilities are known to have their own preferred physical habitat conditions for spawning grounds, such as specific

water depth, flow velocity and substrate composition (Morbey and Hendry 2008). Only appropriate spawning habitats can provide adequate cover and hyporheic exchange for well-functioning redds with protection and oxygen supply (Quinn 2018). If there are any significant flood events during the spawning season, it might take a while for river morphology and in-stream habitats to reach stable conditions needed for spawning salmon. This could delay or affect adult Taiwan salmon's timing and access to suitable spawning grounds.

Another possible impact on Taiwan salmon spawning and egg survival from even later flood events is the increased fine sediment in turbid flow. The rapid accumulation of fine sediments is known having harmful effects on salmon's life cycle. The survival of salmon eggs buried in redds is dependent on sufficient hyporheic flow through graveled stream bed supplying oxygenated water and taking away metabolic wastes (Malcolm et al. 2004). The increased fine sediment accompanied with late flood events during spawning season might block the pores between substrates and lead to suffocation of eggs (Sear et al. 2008). Other possible impacts from later flood events induced unstable hydraulics and morphology might also include the risk of redd scouring and downstream fry displacement at emergence (Gibbins et al. 2008). The critical intensity threshold for influential late flood events after spawning activities might be smaller than typical summer flood events, because the impacts are from fine sediments, not discharge. Although the projected increasing summer flood intensity might not have significant influence on Taiwan salmon population, the extended summer season and possible late flood event right before or during spawning season might have impacts on Taiwan salmon specific life stage by reducing egg and fry survival rate with fine sediment accumulation and changing stream bed condition.

Conclusions

Non-anadromous fish populations face a higher risk of extirpation due to warming temperatures and extreme storm events that are challenging for any river restoration project to address. The most direct possible impact from current climate change projections and field measured air and river temperatures suggest the greatest threats to endangered Taiwan salmon is the increasing river temperatures and changing hydrologic conditions. For Taiwan salmon and its habitat, the intensity of summer extreme precipitation events is predicted to increase significantly, and rising water temperature might make most downstream habitats thermally unsuitable for extended hours during summer season daytime in the future. The increasing flood intensity might not have major impact on Taiwan salmon's mortality, but the rising water temperature and new thermal regime might have significant impact on downstream Taiwan salmon populations. Taiwan salmon are vulnerable because their river habitat is disconnected from marine environments so that migration is not an option for salmon swimming to areas providing thermal refuge during the hottest periods during a year.

The ecological effectiveness of the recent dam removal to restore longitudinal connectivity might have limited effects on mitigating the warming temperatures resulting from climate change. Restoration options to directly improve the future resilience of Taiwan salmon are limited due to the limited extent of the river systems inhabited by salmon. Although the removal of Cijiawan One dam did currently provide a new passage for downstream Taiwan salmon to access upstream cold water habitat, but approximately half of the river extent was no longer suitable habitat for them during the hottest periods of the year. Taiwan salmon expressed thermal avoidance behavior at summer temperatures that are already occurring in

Taiwan. This suggests that non-anadromous salmon that are unable to migrate to more suitable thermal regimes because they are confined to their river will have fewer options to swim to temperature refugia when river temperatures increase. Thus, they provide an early warning that they are disproportionately impacted by warming temperatures and unable to adapt to their habitat.

Dam removal projects might not be as effective as previous projects because of the ecological risks of removing a larger dam in a small river system and the limited opened habitat even when implemented. In future summer seasons, Taiwan salmon may rely more on local small-scale cold water refuge and temperature diel variation to cool down during the nighttime. There are some restoration options to improve such habitats, such as riparian reforestation and in-stream habitat recreation, but the ecological effectiveness of those practices in Cijiawan river system might be limited by geological and hydrological conditions and requirement of constant maintenance of restored sites. The most effective strategy and prioritized option for Taiwan salmon conservation under a climate change scenario will be to preserve upstream habitat and population. As a thermal sensitive freshwater species in a confined system, Taiwan salmon and Cijiawan River demonstrate that non-anadromous landlocked salmon is extremely sensitive to the possible environmental impacts corresponding to climate change projections, and it serves as an alarm when evaluating climate change conditions and predictions.

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Conclusions

River restoration is widely practiced to improve river ecosystem functions that have been degraded or impaired through anthropogenic alterations or other causes. Despite the significant amount of resources invested into river restoration efforts, the effectiveness of such actions is hard to evaluate due to the lack of quantified ecological objectives and long-term monitoring. In central Taiwan, a mid-sized dam was removed to restore longitudinal connectivity of the Cijawan River with the goal to conserve the endangered Taiwan salmon (*Oncorhynchus formosanus*). However, the ecological benefits of dam removal have not yet been evaluated without clarification of non-anadromous Taiwan salmon's need for longitudinal connectivity. This study examined Taiwan salmon's potential need for longitudinal connectivity under two specific scenarios and evaluate dam removal's ecological benefits under climate change impacts.

This study supported the idea that Taiwan salmon population declines are associated with severe summer flood events, but the degree of decline was not correlated with the severity of flood events. Further, the spatial distribution of the populations after summer flood events were not correlated with the general patterns occurring after the wash down return events. The dam removal has limited ecological benefits on Taiwan salmon washdown return incidents since such scenario is not a general pattern happening in the field.

The temperature gradient flume experiment showed that Taiwan salmon have significant high temperature avoidance behavior and the thermal threshold is lower than previously assumed. The field temperature records showed that water temperature at some downstream sections exceed the thermal threshold for substantial hours during the daytime in summer seasons, and there are cold water

refugia located upstream which become accessible after the removal of the Cijiawan One dam. However, the ecological effectiveness of current dam removal to restore longitudinal connectivity might have limited effects on mitigating the warming temperatures resulting from climate change.

Under current climate change trend, despite the projected hydrologic change might have no major effect on Taiwan salmon's flood-related mortality, the projected rising water temperature and extended summer season might make all downstream section thermally unsuitable for a significant number of days at the end of century. As a thermal sensitive freshwater species in a confined system, Taiwan salmon and Cijiawan River demonstrate that non-anadromous landlocked salmon is extremely sensitive to the possible environmental impacts corresponding to climate change projections, and it serves as an alarm when evaluating climate change conditions and predictions.

Appendix A: Taiwan salmon snorkeling survey results

Year	Season	Date	Fish Size	River sections and number of individuals						
				S ₀₁	S ₁₂	S ₂₃	S ₃₄	S ₄₅	S ₅₆	S _k
1997	Summer	7/15/1997	Small	4	24	634	32	8	30	411
1997	Summer	7/15/1997	Medium	16	15	174	18	7	12	89
1997	Summer	7/15/1997	Large	102	115	45	28	9	9	33
1997	Autumn	10/10/1997	Small	61	70	568	28	24	12	72
1997	Autumn	10/10/1997	Medium	60	76	223	26	14	9	59
1997	Autumn	10/10/1997	Large	82	95	95	40	32	19	47
1998	Summer	6/15/1998	Small	8	30	96	44	30	14	7
1998	Summer	6/15/1998	Medium	18	39	141	18	43	3	29
1998	Summer	6/15/1998	Large	46	86	140	14	7	8	31
1998	Autumn	10/10/1998	Small	6	23	61	14	8	4	5
1998	Autumn	10/10/1998	Medium	46	29	75	18	15	3	61
1998	Autumn	10/10/1998	Large	45	55	66	33	9	9	52
1999	Summer	6/15/1999	Small	2	11	61	45	5	7	60
1999	Summer	6/15/1999	Medium	18	33	69	35	12	2	24
1999	Summer	6/15/1999	Large	30	26	31	6	2	4	11
1999	Autumn	10/22/1999	Small	0	17	29	14	6	10	56
1999	Autumn	10/22/1999	Medium	10	37	77	22	13	6	63
1999	Autumn	10/22/1999	Large	29	99	152	10	37	25	70
2000	Summer	6/2/2000	Small	17	54	56	5	86	51	70
2000	Summer	6/2/2000	Medium	5	20	69	22	13	13	34
2000	Summer	6/2/2000	Large	37	59	47	7	6	13	44
2000	Autumn	9/29/2000	Small	4	17	41	15	52	21	43
2000	Autumn	9/29/2000	Medium	19	42	107	27	52	24	55
2000	Autumn	9/29/2000	Large	33	52	82	11	28	20	51
2001	Summer	6/9/2001	Small	1	37	2	1	1	3	11
2001	Summer	6/9/2001	Medium	1	16	1	3	0	12	17
2001	Summer	6/9/2001	Large	34	103	62	27	41	6	29
2001	Autumn	10/23/2001	Small	5	27	4	3	17	12	21
2001	Autumn	10/23/2001	Medium	3	57	11	6	14	15	8
2001	Autumn	10/23/2001	Large	6	39	26	22	23	17	10
2002	Summer	6/8/2002	Small	89	660	335	482	566	774	509
2002	Summer	6/8/2002	Medium	21	211	120	41	21	0	28

2002	Summer	6/8/2002	Large	4	69	15	3	0	0	40
2002	Autumn	10/1/2002	Small	120	489	471	569	341	518	425
2002	Autumn	10/1/2002	Medium	64	314	166	125	101	85	108
2002	Autumn	10/1/2002	Large	48	131	86	4	11	3	42
2003	Summer	5/31/2003	Small	11	82	106	150	82	31	215
2003	Summer	5/31/2003	Medium	46	480	290	372	248	355	195
2003	Summer	5/31/2003	Large	118	195	96	43	3	7	55
2003	Autumn	10/23/2003	Small	32	79	104	142	72	152	198
2003	Autumn	10/23/2003	Medium	17	208	338	338	189	374	153
2003	Autumn	10/23/2003	Large	32	250	148	90	9	56	61
2004	Summer	5/28/2004	Small	95	780	167	57	68	29	252
2004	Summer	5/28/2004	Medium	45	250	170	105	149	296	219
2004	Summer	5/28/2004	Large	73	216	63	42	9	35	108
2004	Autumn	10/15/2004	Small	160	212	136	71	7	17	25
2004	Autumn	10/15/2004	Medium	74	272	86	99	8	70	49
2004	Autumn	10/15/2004	Large	20	130	60	56	1	14	26
2005	Summer	7/1/2005	Small	22	53	17	109	1	2	76
2005	Summer	7/1/2005	Medium	40	200	37	62	14	26	44
2005	Summer	7/1/2005	Large	21	103	18	48	5	21	48
2005	Autumn	10/21/2005	Small	14	23	20	59	0	3	31
2005	Autumn	10/21/2005	Medium	25	37	12	48	1	8	44
2005	Autumn	10/21/2005	Large	34	59	27	42	1	7	28
2006	Summer	7/8/2006	Small	205	402	731	169	7	173	211
2006	Summer	7/8/2006	Medium	46	135	141	90	2	50	153
2006	Summer	7/8/2006	Large	14	62	42	42	2	1	18
2006	Autumn	10/11/2006	Small	134	132	313	142	1	129	135
2006	Autumn	10/11/2006	Medium	161	141	274	103	8	56	168
2006	Autumn	10/11/2006	Large	58	89	86	62	5	35	38
2007	Summer	6/29/2007	Small	40	196	309	367	0	59	57
2007	Summer	6/29/2007	Medium	59	268	404	174	6	139	37
2007	Summer	6/29/2007	Large	143	150	92	72	4	27	21
2007	Autumn	10/19/2007	Small	29	179	212	131	27	47	N/A
2007	Autumn	10/19/2007	Medium	39	263	273	153	34	36	N/A
2007	Autumn	10/19/2007	Large	38	196	151	139	35	17	N/A
2008	Summer	8/23/2008	Small	108	730	1252	498	186	509	295
2008	Summer	8/23/2008	Medium	55	236	302	184	23	47	134
2008	Summer	8/23/2008	Large	47	158	188	69	9	32	79

2008	Autumn	10/8/2008	Small	N/A	491	634	453	63	234	N/A
2008	Autumn	10/8/2008	Medium	N/A	251	259	269	19	50	N/A
2008	Autumn	10/8/2008	Large	N/A	134	136	83	6	67	N/A
2009	Summer	6/3/2009	Small	27	153	98	372	93	121	129
2009	Summer	6/3/2009	Medium	86	325	483	345	103	175	62
2009	Summer	6/3/2009	Large	89	240	174	170	79	16	42
2009	Autumn	10/14/2009	Small	48	124	326	463	236	252	33
2009	Autumn	10/14/2009	Medium	121	281	873	232	99	270	66
2009	Autumn	10/14/2009	Large	154	160	491	108	51	95	62
2010	Summer	6/20/2010	Small	65	197	99	307	228	228	178
2010	Summer	6/20/2010	Medium	31	322	280	343	103	364	74
2010	Summer	6/20/2010	Large	32	173	117	148	20	47	21
2010	Autumn	10/10/2010	Small	15	149	245	312	181	339	202
2010	Autumn	10/10/2010	Medium	63	277	624	397	99	304	158
2010	Autumn	10/10/2010	Large	51	348	205	88	5	50	37
2011	Summer	6/4/2011	Small	40	323	529	459	80	32	360
2011	Summer	6/4/2011	Medium	25	246	377	455	224	277	202
2011	Summer	6/4/2011	Large	24	229	191	43	37	42	99
2011	Autumn	10/11/2011	Small	168	288	523	328	120	172	488
2011	Autumn	10/11/2011	Medium	108	351	401	540	182	413	396
2011	Autumn	10/11/2011	Large	47	200	154	258	72	119	150
2012	Summer	7/30/2012	Small	119	175	270	374	108	145	354
2012	Summer	7/30/2012	Medium	71	507	894	528	106	304	500
2012	Summer	7/30/2012	Large	30	421	212	133	34	63	131
2012	Autumn	10/10/2012	Small	45	215	380	197	18	149	249
2012	Autumn	10/10/2012	Medium	52	279	439	387	29	266	400
2012	Autumn	10/10/2012	Large	21	114	163	89	4	110	158