AN ABSTRACT OF THE THESIS OF

Arthur Bass for the degree of Master of Science in Fisheries Science presented on July 26, 2010.

Title: Juvenile Coho Salmon Movement and Migration Through Tide Gates

Abstract approved: ____

Guillermo Giannico

Tidal marshlands in the upper estuary ecotone provide essential habitat for juvenile salmonids. In this environment, salmonids grow rapidly and acclimate to saltwater. Worldwide, tidal marshes have been diked and drained to provide agricultural and residential land. Tide gates are one-way doors integrated into dike systems that prevent saltwater flooding and allow upland drainage to the estuary during low tide. By preventing tidal exchange, tide gates have significant upstream effects on water temperature and chemistry, plant and animal community structure, and geomorphology. Since they are closed most of the day and may be difficult to pass when open, tide gates may act as fish passage barriers for juvenile salmonids. They may also affect juvenile salmon migration timing by altering environmental variables that influence emigration rate in upstream habitats. We conducted our research in Coos Bay, one of the many Oregon estuaries with extensive use of tide gates. We studied three streams, one with a top-hinged tide gate, one with a side-hinged gate, and one without any tide gates that acted as our reference site. Our study species was coho salmon, *Oncorhynchus kisutch*, which may encounter tide gates both in the subyearling and smolt life stages in our study streams. Our objectives were to: 1) quantify upstream and downstream fish passage occurrence at all three sites, 2) determine whether juvenile coho salmon passage is associated with a specific range of gate conditions, and 3) identify any associations between coho smolt emigration rate and environmental variables that are influenced by tide gates. We installed stationary passive integrated transponder (PIT) antennae around both tide gates and a tidal channel in the non-gated stream to record the movement of PIT tagged juvenile coho salmon. Coho salmon smolts passed upstream most frequently at the non-gated channel (48% of all smolts detected at the array), next the side-hinged gate (28%), and lastly, the top-hinged gate (3%). Juvenile coho salmon passed more frequently at a specific range of gate angles and tailwater depths at both top hinged and side-hinged tide gates. Smolts passed downstream more frequently at greater gate angles and tailwater depths than available on average at both tide gates. Subyearlings passed upstream more frequently during small gate angles and a narrow range of tailwater depths at the top-hinged gate but did not pass more frequently under a particular range of conditions at the side-hinged gate. At the top-hinged gate, conditions favorable for subyearling upstream passage occurred towards the end of the gate open period and therefore subyearlings were severely limited in their opportunities for passage. At multiple sites, emigration rate was associated with environmental variables that may be altered by tide gates. Increases in water temperature were associated with an increasing likelihood of smolt emigration at multiple sites. At a tide gate that allowed upstream estuarine influence, increasing salinity was associated with a decreasing likelihood of emigration. Our results suggest that tide gates may interfere with salmonid movement and migration by creating physical barriers to fish passage and potentially influencing migratory timing by altering environmental variables. When installing or retrofitting tide gates, these factors should be taken into consideration since a tide gate's design may determine the severity of its effects on salmonids. Our work should be considered a case study and the findings should not be assumed to be transferable due to the great diversity of tide gate installations in use. We recommend further research, including a more in depth analysis of the affects of tide gates on subyearling coho salmon and an investigation of piscivorous predator exploitation of tide gates.

Juvenile Coho Salmon Movement and Migration Through Tide Gates

by

Arthur Bass

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented July 26, 2010
Commencement June 2011

Master of Science thesis of Arthur Bass presented on July 26, 2010.

APPROVED:

Major Professor, representing Fisheries Science

Head of the Department of Fisheries and Wildlife

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Arthur Bass, Author

ACKNOWLEDGEMENTS

This thesis would not have been possible without the support of many individuals and organizations. Thanks to Guillermo Giannico, my advisor, who will make a better writer out of me one of these days! Adam Weybright, with whom I worked closely on this project, was a pleasure to work with. He and his wife, Elizabeth, and their son, Miles, were my surrogate family in Coos Bay. Thanks to my hardworking field technicians: Justin Arriola, Andrew McClary, John Winkowski, Dave Nelson, and Donald Danesi. The Coos Watershed Association set the stage for the project with many years of field and restoration work at all of our field sites. Thanks to the CoosWA staff: Jon Souder, Freelin Reasor, Nick Sheidt, Dan Draper, and Amy Peters for helping in a variety of ways. Thanks to South Slough Estuarine Research Reserve for providing a great location to conduct research and especially: Ali Helms, Steve Rumrill, and Craig Cornu. Bruce Miller, of ODFW, was a great source of ideas and support. Gabriel Brooks provided priceless training in the construction of PIT antennae and lots of follow up support. Thanks to Chris Jordan for bailing us out with equipment loans on multiple occassions! Thanks to Bruce Hansen for providing us a location to construct PIT antennae, sorry I broke all your tools! Thanks to Joe Ebersole for loaning us equipment and giving great feedback. Thanks to Marv Pyles for helping me navigate the murky waters of tide gate hydrodynamics. Thanks to the following for help in the field and with PIT antenna construction: Katherine Nordholm, McKenzie Miller, Matt Anderson, Ethan Wilensky-Lanford, Dennis Feeney, Matt Sloat, Brooke Penaluna, Shivonne Nesbit, Brett Hanshew, Nate Hostetter, Abby Bass, John Colby, Veronique Theriault, Erin Kunisch, and Jason Schilling. Thanks to Justin Finn for teaching me LaTeX. Thanks to the fisheries and wildlife grad students for being a great crew to commiserate with and learn from. Speaking of commiseration, thanks to my office mate Jeremy Romer who made me laugh often and is the man. Thanks to the Corvallis ski posse for keeping me sane! Thanks to my Mom and Dad who made me. Funding for this project was provided by an Oregon Watershed Enhancement Board Research Grant.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF APPENDIX FIGURES

LIST OF APPENDIX FIGURES (Continued)

LIST OF APPENDIX FIGURES (Continued)

LIST OF APPENDIX TABLES

Juvenile Coho Salmon Movement and Migration Through Tide Gates

Chapter 1 – General Introduction

Estuaries provide essential habitats during various stages of salmonid life cycles (Healey, 1982; Miller and Sadro, 2003; Quinn, 2005). By utilizing the diverse range of estuarine environments and water chemistry, subyearling salmonids can select food resources and salinity concentrations to maximize growth (Otto, 1971; Tschaplinski, 1982; Webster and Dill, 2006). Salmonid smolts may also experience high growth rates in the estuary (Sandercock, 1991; Simenstad et al., 1982) and large body size has been associated with increased odds of survival in the ocean (Reimers, 1971; Ward and Slaney, 1988; Holtby et al., 1990; Virtanen et al., 1991). It is suspected that the estuarine salinity gradient (from freshwater in the upper estuary to seawater at the estuary mouth) reduces osmotic stress that smolts can experience due to an abrupt transition from fresh to salt water (Thorpe, 1994; Jobling, 1995; Linley, 2001). Despite these benefits, salmonids may experience high estuarine mortality rates due to a large diversity and concentration of predators coupled with the osmoregulatory challenge presented by leaving freshwater (Handeland et al., 1996; Mather, 1998; Moore et al., 2010). Anadromous salmonids have evolved physiological and behavioral strategies to balance the costs and benefits presented by the estuary. Human alterations of this ecotone, especially the reduction of habitat availability and complexity, hamper this balancing act.

Kennish (2002) demonstrated that habitat loss and alteration resulting from development has affected estuaries worldwide and speculated that this was the great future anthropogenic threat to estuaries. Human tendency to favor coastal settlement has promoted widespread diking and draining of tidal salt marshes to provide agricultural and residential land. Nicholls et al. (1999) estimated that when human activities are combined with sea level rise, an estimated 70% of the world's coastal wetlands could be lost by 2080. In the US, approximately 50% of original tidal saltmarsh habitat has been lost to draining for agriculture (Kennish, 2002). Among Oregon's 17 largest estuaries, close to 70% of tidal wetland was converted to arable and residential land from 1870 to 1970 (Good, 2000). Where tidal marshland is converted, tide gates are employed to drain freshwater from upland areas while preventing the intrusion of saline water by flooding tides (Giannico and Souder, 2005).

Tide gates are usually simple hinged doors regulated by hydraulic head differential, the difference in water levels between the stream and the bay side. Tide gates open when the hydrostatic force on the stream side of the door (pressure from water depth, a function of watershed discharge over the time the gate is closed) exceeds the combination of the hydrostatic force on the bay side of the door (which is determined by tides) and the restorative force of the door (the gravity dependent force that works to return an open gate to a closed position). Since gate opening occurs during low tides, the time the gate is open (hereafter referred to as "open period") rarely exceeds 12 hrs in total per day. For a given tide gate, a wide range of open period durations and hydraulic conditions is possible due to countless unique combinations of precipitation and tides. Although the effects of tide gates on fish have not been well studied, these structures are expected to be fish passage barriers for salmonids and other estuarine dependent organisms due to their frequent closure.

Because of its ease of construction and maintenance, the most common tide gate style is the top-hinged. These are rectangular or round, heavyweight doors with their hinges located at the top of a culvert or tide box (the structure housing a tide gate). Their weight and hinge position create a significant restorative force so that their opening is constricted which creates high water velocities and turbulence. Because these conditions are assumed to impact fish passage, a number of "fish friendly" designs have been introduced by manufacturers. Side-hinged gates, which open like a typical house door, require less hydraulic head differential to open because the position of their hinges reduces restorative force. This results in wider opening, reduced water velocity, and longer open periods across a greater range of conditions. A number of "pet door" designs (a smaller flap mounted upon the gate door remains open into flooding tides) are intended to allow fish passage through a longer period of the tidal cycle. "Self regulating tide gates" extend the open period of conventional tide gates by using floats (or other mechanisms), positioned in the upstream reservoir or on the door itself, to close the door when the reservoir fills to a target water level. For a detailed description of tide gate styles commonly in use, see Giannico and Souder (2005) and Charland (1998).

Tide gates can be positioned across the landscape at the mouths of perennial streams, the confluences of tributaries with these streams, the openings to blind sloughs, or the ends of field drainage networks (Giannico and Souder, 2005). Tide gates may drain into a range of environments from a polyhaline bay to a tidally influenced, oligohaline river. Often large tide gates are placed in dikes at the mouth of streams that flow into estuaries or bays, creating an abrupt transition from fresh to saltwater. Multiple smaller tide gates installed upstream of the main gate feed freshwater from floodplain drainage networks into the main channel, creating a highly fragmented stream network. Since tide gates act like dams while they are closed, they create a temporary impoundment upstream (hereafter referred to as "reservoir"), the size and properties (temperature and water chemistry) of which vary seasonally.

Although a variety of commercially manufactured styles exists, many tide gates in the Pacific Northwest are built by landowners and local community drainage districts. This introduces considerable design variation among tide gate installations. When this diversity of designs is combined with different drainage objectives, maintenance conditions, and local installation environments, the implementation of regulatory standards becomes a challenging proposition. Furthermore, the fact that various tide gate designs are referred to as "fish friendly" by manufacturers, despite the absence of published studies regarding their fish passage efficiencies, complicates gate replacement and operation decisions by management organizations and agencies.

All anadromous species of Pacific salmon and trout may be affected by tide gates, but differences in life history strategies make some more vulnerable than others. Steelhead trout smolts, *Oncorhynchus mykiss*, enter the estuary at a large size and rapidly move to the ocean, minimizing their interactions with tide gates.

Conversely, species that may enter estuaries at a small size and reside in the upper estuary ecotone for a long period, such as chinook salmon, *Oncorhynchus tshawytscha* and coho salmon, *Oncorhynchus kisutch*, may frequently encounter tide gates and associated alterations to stream chemistry and morphology. In Oregon, most coho salmon are thought to spend just over one year in freshwater before emigrating as smolts (Sandercock, 1991). Generally, coho salmon smolts are expected to move quickly through the estuary but there is evidence of prolonged estuarine residence (Myers and Horton, 1982; Sandercock, 1991). Recently, coho salmon "nomads" have received more attention from researchers (Koski, 2009). These subyearling fish rear in the upper estuary shortly after emergence and return to freshwater in the summer or fall before outmigrating as smolts the following year (Tschaplinski, 1982). Both coho salmon smolts and nomads may be affected by tide gates which significantly alter the physcial and chemical properties of upstream aquatic habitats, may act as upstream and downstream passage barriers, and may interfere with migratory timing.

By curtailing estuarine influence and tidal flushing, tide gates have many effects on upstream aquatic habitats (Giannico and Souder, 2005). Tide gates can alter water temperature, salinity, pH; and concentrations of dissolved oxygen, nutrients, and metals in upstream waters. Since tide gate reservoirs are frequently stagnant and left exposed to solar radiation by vegetation removal, temperatures tend to be higher in the reservoir than downstream of the tide gate (Giannico and Souder, 2005). Salinities upstream of well sealed tide gates are greatly reduced. Anoxic conditions may result from high rates of organic decomposition or mixing with a hypoxic salt wedge, resulting in fish and invertebrate mortality (Mashiko et al., 1970; Portnoy, 1991; Winn and Knott, 1992; Anisfeld and Benoit, 1997). Acidification events following summer rainstorms can lower pH to lethal levels and mobilize heavy metals (Anisfeld and Benoit, 1997). Changes to sedimentation processes and sediment quality (Anisfeld et al., 1999) coupled with the above mentioned effects on water quality alters the aquatic flora upstream of tide gates. Water quality and vegetation alterations will in turn control the faunal assemblage composition (Ritter et al., 2008). All of these changes to water quality and ecosystem composition in upstream habitats will have important implications for salmonid habitat use and residence time in tide gated streams.

Estuaries present a salinity gradient that allows anadromous species to adjust their physiology as they transition into seawater (Jobling, 1995; Linley, 2001). A well sealed tide gate creates an artificial boundary between the oligohaline and polyhaline regions of the estuary by replacing the mesohaline region of the upper estuary with a freshwater reservoir. Depending upon the location of a tide gate within a bay or estuary, the severity of the change in water salinity experienced by fish passing through the structure differs. Because this border is only passable for short periods during the day, salmonids of all life stages might be negatively affected by passing to the polyahline side at an inappropriate time. Otto (1971) found that for subyearling coho salmon that were abruptly exposed to a spectrum of salinities mortality started to occur at around 22 ppt, and in seawater ($\geq$33 ppt) half of the individuals died less than 7 hrs after exposure. Osmotic stress experienced by smolts might contribute to decreased survival to adulthood (Virtanen et al., 1991). Handeland et al. (1996) found that 12 to 24 hrs after transfer to seawater (33 ppt), freshwater adapted atlantic salmon smolts exhibited spikes in plasma chloride levels, decreased schooling behavior, and increased vulnerability to predation. Finally, salmonids physiologically unprepared for polyhaline conditions may be confined to the surface waters immediately downstream of a tide gate where they are more vulnerable to predation (Mather, 1998). Mitchell et al. (2008) found that a freshwater lens may be "trapped" downstream of a tide gate by the incoming tide; salmonids unable to osmoregulate in bay conditions might be limited to this shallow depth if they avoid the saline waters beneath (Iwata and Komatsu, 1984).

Tide gates may restrict upstream passage of subyearling salmonids seeking habitat for prolonged residence and smolts seeking lower salinities. The same factors that hinder salmonid upstream passage of culverts: high water velocity; inadequate water depth within the culvert; obstructions at the culvert outlet; and a perched condition at the culvert entrance (Mueller et al., 2008), will impact salmonid upstream passage through tide gates. Unlike culverts, tide gates are only open for a short period daily and juvenile salmonids must be present during proper conditions to pass. Upstream passage is often more difficult for smaller fish and subyearling coho salmon are expected to be especially challenged by tide gate upstream passage (Koski, 2009). Hydraulic conditions associated with tide gates may also impact downstream passage which is primarily associated with the emigration of smolts. Although smolts have been thought to emigrate passively (Flagg and Smith, 1981), recent work suggests they actively avoid accelerating flows, shallow channels, constricted passages, and overhead cover (Haro et al., 1998; Castro-Santos and Haro, 2003; Kemp et al., 2005, 2008; Kemp and Williams, 2009; Enders et al., 2009). These factors are all present at tide gates but their effect on downstream passage during emigration may vary between different gate designs and installations.

Multiple studies have acknowledged the existence of a temporal "smolt window" of optimal riverine, estuarine and early ocean conditions; the duration and quality of which is determined by food resources, predation, environmental conditions, disease, parasites, and smolt physiology (Hansen and Jonsson, 1989; Staurnes et al., 1993; McCormick et al., 1998; Scheuerell et al., 2009). Water quality alterations resulting from tide gate installations may affect emigration timing and result in migration outside the smolt window. As mentioned above, stagnant and exposed tide gate reservoirs are vulnerable to rapid increases in temperature. High water temperatures in the reservoir may alter migratory behavior and timing (Richter and Kolmes, 2005; Zydlewski et al., 2005). Increased water temperature is correlated with increased smolt emigration for atlantic salmon, *Salmo salar*, brown trout, *Salmo trutta*, coho salmon and chinook salmon (McMahon and Hartman, 1989; Whalen et al., 1999; Carlsen et al., 2004; DeVries et al., 2004; Zydlewski et al., 2005; Jonsson and Jonsson, 2009). Emigration outside the smolt window resulting from tide gate habitat alterations could detrimentally affect salmonid populations by causing a timing mismatch with estuary and ocean conditions (Kennedy and Crozier, 2010).

In this study, we provide an empirically derived description of juvenile salmonid behavior around tide gates. We used passive integrated transponder (PIT) technology to monitor the movement and migration of juvenile coho salmon through two types of tide gates and a non-gated stream. Data was collected from March 2008 to December 2009 in Coos Bay, OR. This research has been summarized in two manuscripts included in this thesis. In chapter 2, we report the occurrence of upstream and downstream passage of coho salmon smolts at a top-hinged gate, a side-hinged gate and a non-gated stream channel. We also identify the range of gate angles and tailwater depths at the tide gates utilized by coho salmon subyearlings and smolts for passage. In chapter 3, we examined the emigration rate of and effects of environmental conditions on likelihood of emigration for coho salmon smolts through all three streams and within multiple sections of one stream. We also identified factors that were associated with downstream passage of emigrating coho salmon smolts through the top-hinged tide gate. Chapter 4 summarizes our findings and their implications and outlines management recommendations and directions for future research.

Chapter 2 – Juvenile Coho Salmon Passage Through Two Tide Gates and a Non-Gated Stream

2.1 Introduction

Estuaries provide valuable habitat for multiple stages of the salmonid life cycle (Healey, 1982; Miller and Sadro, 2003; Quinn, 2005). Smolts leaving freshwater nursery habitats traverse the estuarine salinity gradient, which helps prevent the osmotic stress caused by abrupt exposure to salt water (Simenstad et al., 1982; Thorpe, 1994; Jobling, 1995; Linley, 2001). Smolts in the estuary experience high growth rates (Groot and Margolis, 1991; Simenstad et al., 1982) which may improve their odds of survival during early marine residence (Holtby et al., 1990; Virtanen et al., 1991). Estuaries provide habitat for the expression of alternate life histories among age 0 salmonids of multiple species (Bottom et al., 2005b; Koski, 2009). Arriving in this environment shortly after emergence, subyearling salmonids experience a diversity of salinities, habitats and prey that facilitate rapid growth (Otto, 1971; Simenstad et al., 1982; Tschaplinski, 1982). This expression of alternate life history strategies contributes to the resilience of a population in an environment with annually varying conditions (Bottom et al., 2005a; Koski, 2009). Smolt and subyearling salmonids are exposed to rapidly changing salinity, temperature, water level, food resources, and predation pressures in estuaries.

Hence, constraints on movement to more suitable habitat patches in response to these changing conditions will have negative consequences for salmonids.

In estuaries around the world, dikes are often built to convert wetlands to agricultural and residential land. Tide gates are simple hinged doors that prevent tidal flooding behind dikes and allow drainage of upland water. Tide gates close during incoming tides (flood) and open during outgoing tides (ebb) (Giannico and Souder, 2005). Although a wide range of opening durations is possible depending upon precipitation, tidal magnitude, and estuarine infiltration (as a result of a leaky gate), tide gates are generally open less than 12 hours per day. The most common design on the Oregon Coast is the top-hinged tide gate, usually featuring heavy doors with a hinge located at the top. Side-hinged tide gates, which open like the doors of a house, have been introduced as a “fish friendly” alternative since they require a smaller difference between upstream and downstream water levels to open. For a thorough discussion of tide gate designs see Giannico and Souder (2005).

Tide gates are considered to be at least partial passage barriers for salmonids and other estuarine dwelling organisms (Giannico and Souder, 2004; Koski, 2009). In the case of salmonids, tide gates may affect passage of: 1) subyearling fish seeking suitable nursery habitat; 2) emigrating smolts; and 3) adult fish returning to spawn. Many of the same factors that hinder fish passing upstream through culverts (i.e., high flow velocity, inadequate water depth within culvert, obstructions at culvert outlet, and perched condition creating a waterfall at the culvert outlet- see Mueller et al. (2008)), will affect their upstream passage through tide gates.

Upstream passage is more difficult for smaller fish (Bates and Powers, 1998) and in the case of coastal coho salmon, individuals that enter the upper estuary soon after emergence (known as “nomads”) may be particularly affected (Koski, 2009). Nomads perform a reverse migration into freshwater in the summer or fall (at which point they may have to pass a tide gate) before emigrating as smolts the following year (Tschaplinski, 1982; Miller and Sadro, 2003; Koski, 2009).

Downstream passage through tide gates may be difficult primarily for salmonid smolts. Although smolts have been thought to move downstream passively (Flagg and Smith, 1981), recent studies suggest that multiple salmon species actively avoid accelerating flows, shallow channels, constricted passages, and overhead cover (Haro et al., 1998; Castro-Santos and Haro, 2003; Kemp et al., 2005, 2008; Kemp and Williams, 2009; Enders et al., 2009). All these conditions are present at tide gates but their effect on downstream passage will vary across each gate’s diverse range of flow conditions and among different gate designs and installations. Delays to emigration caused by avoidance of downstream passage through tide gates could result in a mismatch with the “smolt window” of favorable migratory conditions as described by McCormick et al. (1998).

Many researchers have studied the effect of tide gates on chemical and physical processes (Portnoy, 1991; Anisfeld and Benoit, 1997; Wetzel and Kitchens, 2007; Mitchell et al., 2008). Some studies have documented fish assemblages and abundances upstream of tide gates by sampling fish with seines, dip nets, and traps (Easton and Marshall, 2000; Raposa, 2002; Ritter et al., 2008). Although tide gates appear likely to act as a passage barrier for many fish species, we found no research describing their effects on fish movement and behavior published in peer-reviewed journals. This is partly due to a lack of adequate, affordable technology to address the issue. Submersible video cameras may not record quality footage due to the high turbidity of the upper estuary. The small body size of subyearlings and smolts prevents the use of acoustic tags (but see McMichael et al. (2010)). Conventional PIT antennae do not function well in saline environments, especially when small tags are required for very young fish.

Our study provides the first account of fine scale movement of any fish species through two types of tide gates, a top-hinged and a side-hinged. Our first objective was to determine how frequently juvenile coho salmon (subyearlings and smolts) pass upstream and downstream through both types of tide gates and a non-gated channel. We hypothesized that there would be no difference in how frequently fish moved upstream and downstream through a top-hinged, side-hinged and non-gated channel. Our second objective was to determine whether juvenile coho salmon pass upstream and downstream more frequently under a particular range of conditions. We hypothesized that juvenile coho would pass upstream and downstream at the same frequency throughout the range of available gate angles and tailwater depths.

2.2 Methods

2.2.1 Study Sites

Three creeks that drain into Coos Bay, a 13 km^2 estuary on the southern Oregon coast, were used for this study. Palouse Creek has a top-hinged tide gate at its mouth, Larson Creek has a side-hinged tide gate, and Winchester Creek has no tide gate and was used as a reference system (Figure 2.1). The two tide gated creeks are located in Haynes Inlet on the north end of Coos Bay, 18.5 km northeast of the estuary mouth. Winchester Creek is located in South Slough, 7 km south of the estuary mouth. Spawning coho salmon populations are present in all of these third order watersheds.

In 2001, the existing wooden top hinged gate at Larson Creek was replaced by two steel, side-hinged doors (3.20 m wide x 2.56 m tall) mounted on a new cement tide gate box. The Palouse Creek tide gate installation was most recently rebuilt in 1985 with two wooden top-hinged doors (4.09 m wide x 2.56 m tall). Due to significant scour around this entire structure, estuarine water moves upstream of the top-hinged tide gate resulting in an average salinity of 12.4 ppt during the period of smolt emigration (0.5 km upstream). This limited tidal flooding also creates a reduced usptream tide cycle. Considerably less estuarine intrusion is observed above the side-hinged gate at Larson Creek (average salinity 0.5 km upstream = 2.1 ppt).

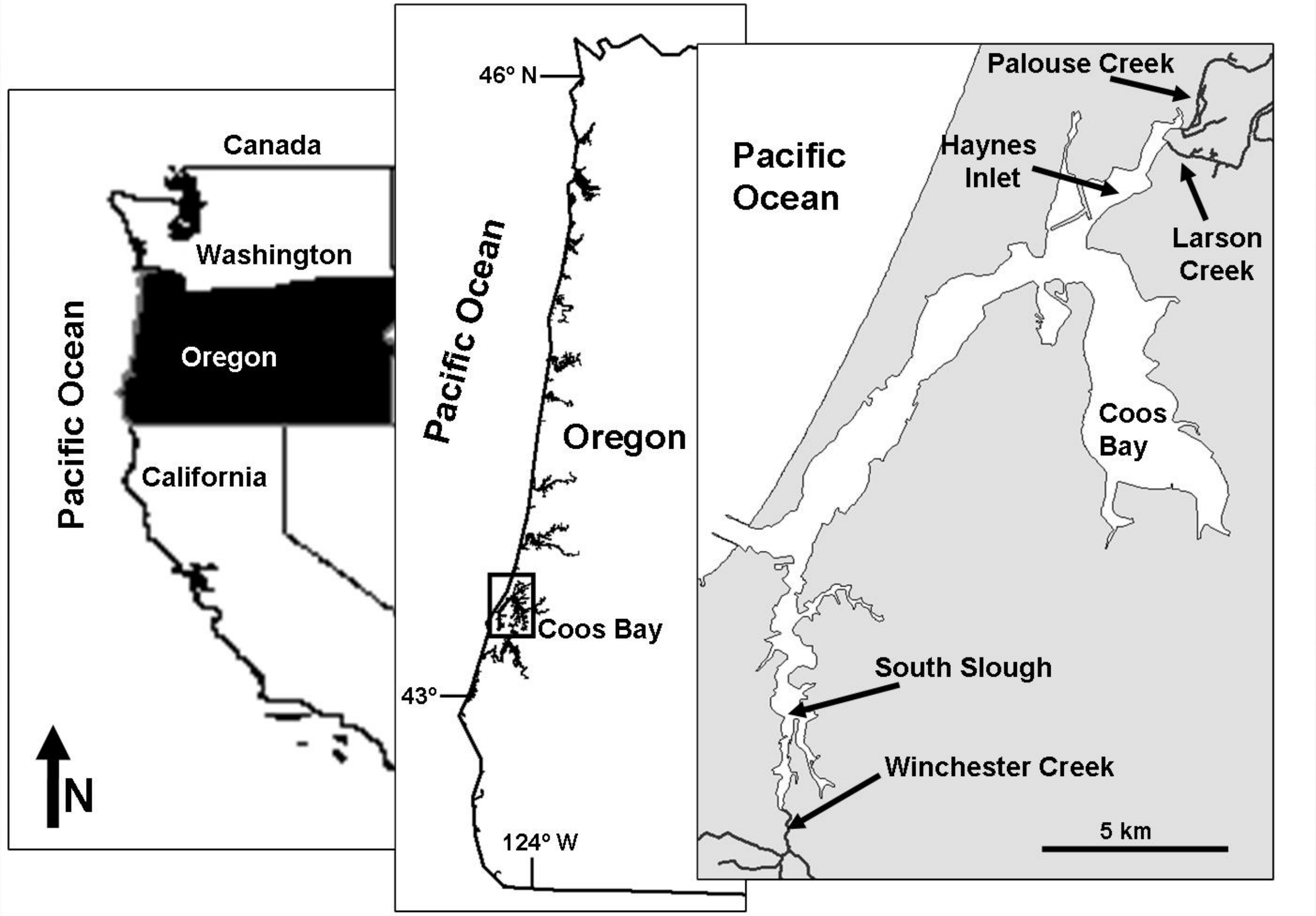

Figure 2.1: Location of study sites. The top-hinged tide gate was in Palouse Creek, the side-hinged tide gate was in Larson Creek, and the non-gated channel was in Winchester Creek.

2.2.2 Fish Trapping and Tagging

In this study, “smolts” were juvenile coho salmon expected to emigrate in the spring of 2009 after at least one year of freshwater residence (average fork length at 2009 tagging = 106 mm, range = 62-158 mm). Subyearling coho salmon were, based on their size, considered recently emerged in early 2009 (average fork length at tagging = 58 mm, range = 46-77 mm). Since all subyearlings included in this study were in the upper estuary at the time of their detection, they are considered nomads. All analyses for smolts were conducted with data collected between March 20th and June 20th, 2009 and for subyearlings, data collected during the month of June, 2009. Both coho salmon life stages were trapped at rotary screw traps located 6 km upstream of the tide gates in Larson and Palouse Creeks and at the head of tide in Winchester Creek. Both life stages were also captured by seining at randomly selected sites (chosen from areas where landowners allowed access) in the tide gated streams and adjacent bay, and at three deep holes in a 2 km reach that included the Winchester Creek antenna array. See Table 2.2 for the number of fish tagged and their tagging location relative to the tide gates. Fish with fork lengths of 61 mm or greater were PIT tagged with Biomark’s TX1411SST (12.5 x 2.07 mm, 0.102 g, hereafter ”12 mm tag”). Fish between 48 and 61 mm were tagged with TXP148511B (8.5 x 2.12 mm, 0.067 g, hereafter ”8 mm tag”). At the low end of each tagging size range, PIT tags accounted for on average 3% (12 mm) and 4% (8 mm) of fish body weight in air; a percentage considered too low to affect behavior (Brown et al., 1999; Acolas et al., 2007). Antenna efficiencies (see below) were not calculated for the 8 mm tags as they had relatively poor performance at the stationary arrays. Hence, the behavior of smaller subyearlings is likely under represented.

2.2.3 Stationary PIT Antenna Arrays

Full duplex PIT antennae were constructed using seven wraps of 1100/40 AWG litz wire housed in a Schedule 80, 11 cm diameter PVC rectangular frame (antenna construction similar to Bond et al. (2007)). In 32 ppt water, all antennae could detect a 12 mm tag within 25 cm of the antenna's center if it was oriented perpendicularly to the plane of the antenna (the most common orientation for passing fish). At all sites, a Destron Fearing FS 1001M multiplexing transceiver (St. Paul, MN) operated all six antennae. At the tide gated sites, four antennae were placed in a 2 x 2 layout upstream of the tide gate doors and two antennae were placed downstream side by side in the bay (Figure 2.2). A 2 x 2 layout allows determination of movement direction since detection timing is recorded to the nearest second. At the non-gated stream one 2 x 2 array, similar in layout to the array upstream of the side-hinged gate, was installed. All antennae were positioned vertically in the water column as "swim through" frames oriented perpendicular to the flow of water (Zydlewski et al., 2006). The effective water column area covered by each antenna's field (including the thickness of the PVC and the additional read range on the outside of the antennae) was 3.32 m x 0.89 m. The four antennae upstream of the side-hinged tide gate were narrower in order to fit the tide gate box, the

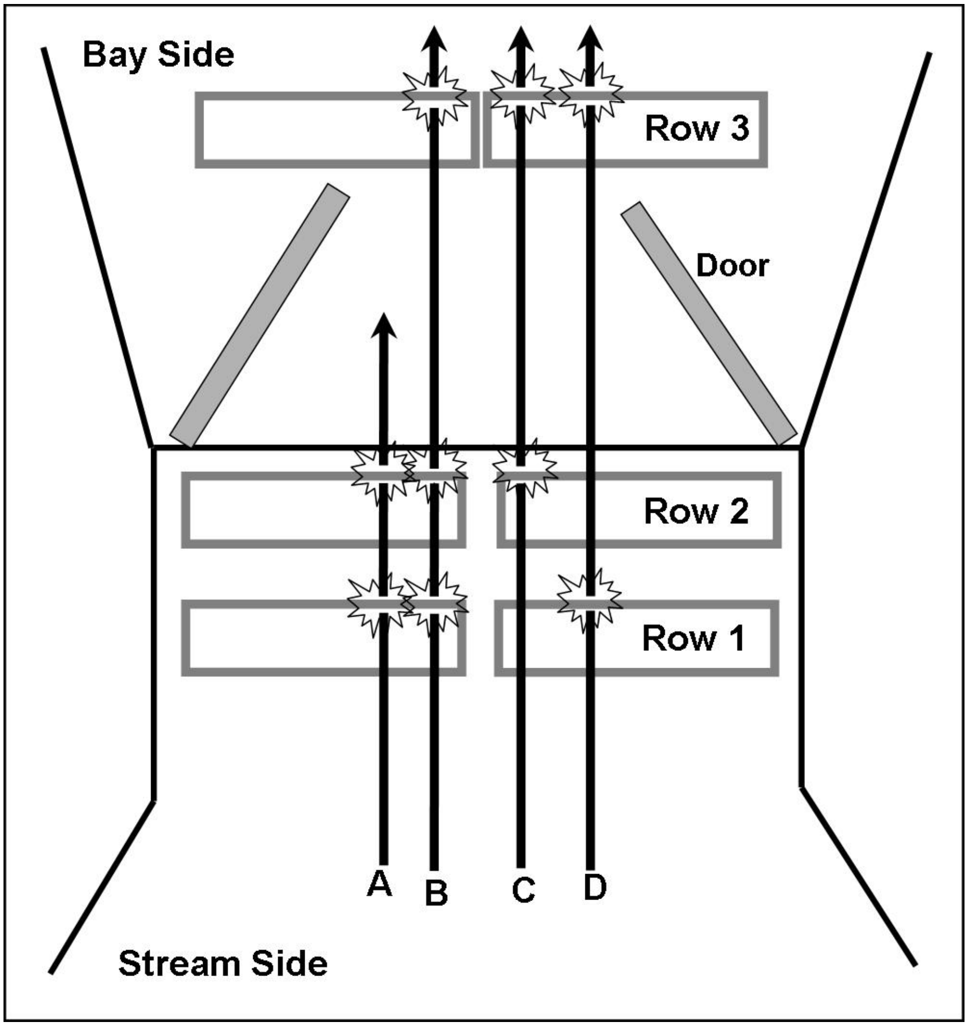

Figure 2.2: Aerial view of PIT antenna array at the side-hinged tide gate (Larson Creek) and different types of "confirmed" downstream passage detections. Arrows represent fish movement paths; bursts on the arrows represent detections at the corresponding antenna. A) Tag detected consecutively at two upstream antennae (2 x 2 array). B) Tag detected at all three antennae. C & D) Tags detected at one upstream antenna row followed by the downstream row.

effective area was 2.72 m x 0.89 m.

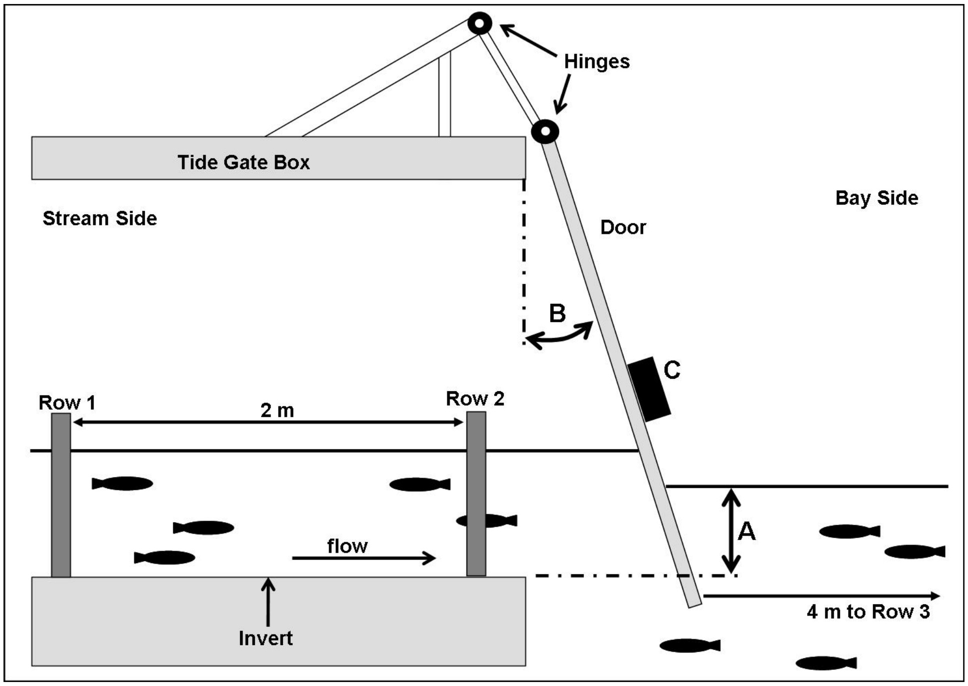

Figure 2.3: Side view of top-hinged tide gate at Palouse Creek. Upstream antenna rows were stationary on the tide box floor (row 3 on the bay side is not visible). A) Tailwater Depth. Positive in figure, negative values would indicate a perched condition. B) Gate angle measured by a tilt logger positioned at C. Angle is ∼ 18° in this picture.

At the top-hinged gate the row closest to the gate was 15 cm from the gate doors and the upstream row was positioned 1.5 m further upstream (Figure 2.3). The antenna array was stationary on the floor of the tide gate (hereafter, invert) at an elevation of -0.33 m (vertical datum = NAVD 1988). On the bay side of the top-hinged tide gate, 2 antennae were mounted side by side vertically within an 8 m frame. The antennae floated 4 m downstream of the tide gate doors in a scour pool created by the flows from the tide gate. This pool was 2 m deep at the lowest tides experienced and 5.5 m deep at the highest tides. The top of the antennae were always at the water's surface.

The lower elevation of the side-hinged gate's invert (-1.51 m NAVD 1988) prevented us from affixing the inside antennae to it. Upstream antennae were mounted on two floating frames (two antennae on each) that were 2.44 m x 0.61 m with a 60 cm space between the antennae. Each frame was attached to two metal poles so that it could rise and fall with the water level inside the tide gate box upstream of the doors. The antenna closest to each tide gate door was 76 cm from the door. This space was necessary since each door was made of steel and we determined that when an antenna was within 55 cm of a door, the antenna's electromagnetic field was reduced. The antennae on the bay side of the the side-hinged gate were installed similarly to those described for the top-hinged gate.

At the non-gated stream, two rows of two antennae were mounted on a floating frame, similar to the one at the side-hinged gate, installed in the channel thalweg (-0.44 m NAVD 1988). The antennae floated at the water's surface in water up to 3 m deep (highest tides). At low tides, the antennae rested on the stream bottom with the top tubes out of the water. Since the width of the side by side antennae only covered ~20% of the high tide channel width, plastic aquaculture netting (3 mm mesh and 3 m height) was strung from the stream banks to the array at approximately a 45° angle to funnel fish through the antennae.

2.2.4 Measuring Gate Angle and Tailwater Depth

To measure tide gate open time and angle, we used gravity reference tilt loggers recording gate angle at 5 min intervals (Pendant G data logger, Onset: Bourne, MA). On the top hinged tide gate a tilt logger was affixed directly to the gate door and angle was measured relative to vertical (for example, gate angle in Figure 2.3$\sim$ 18°). On the side-hinged gate, a "translator" arm was fabricated to convert the opening from a horizontal to vertical axis so that it could be measured by the gravity reference logger (gate angle in Figure 2.2$\sim$ 55°). At each gate, the opening angle was hand measured for accuracy using a protractor. At the top-hinged gate raw logged data were corrected by setting the highest repeated value occurring during gate closure to zero. After this adjustment, values less than 2° and not associated with an opening cycle were considered zero. A simple linear regression (N = 108, $\mathrm{r}^2 = 0.98$) between the manual measurements and the corrected data verified that this method was appropriate.

At the side-hinged gate a similar approach was used to correct the tilt data. However, once the gate opened to 40°, the translator arm pulled in a slightly different direction and the relationship of logged to hand measured angles changed. Therefore, we used two regression equations to convert data from logged to actual: one that covered angles logged at 40° or less ($actual = 1.24 * recorded - 106.12$; r^2=0.89) and another when logged values were greater than 40° ($actual = 2.84 * recorded - 297.35$; r^2=0.92).

A water pressure transducer (HOBO 30 ft Titanium Water Level Logger, Onset:

Bourne, MA) was used to measure the tailwater depth (i.e., vertical distance from the bay side water's surface to the tide gate invert - Figure 2.3). Negative tailwater depth measurements indicate that the tide gate is in a perched condition and describe the distance from the invert down to the tailwater surface. One transducer was located downstream of the side-hinged tide gate. The top-hinged gate was positioned approximately 1 km away (along tidal channels) from the side-hinged gate and is further from the mouth of the bay. Simultaneous measurements at both tide gates indicated that the transducer at the side-hinged gate was capable of recording reliable surface water elevation data for both tide gates.

2.2.5 Velocity Measurements

We measured velocities at both tide gates and the non-gated stream using two methods, a portable velocity meter operated while wading and a deployed acoustic doppler current profiler. During low flow conditions in October, measurements were made with a Marsh McBirney Flo-Mate 2000 (Loveland, CO). Measurements were taken every 5-10 min in the center of the tide box floor in front of the east door at both tide gates, at a 60% water column depth determined by a topsetting rod. The meter averaged velocities for 30 sec for each measurement. During high flow conditions in late November and early December, we installed a SonTek Argonaut XR (San Diego, CA) velocity meter at the same location in each tide gate and in the thalweg, 2 m downstream of the antenna array in Winchester Creek. This instrument was also used in the same location for October low flow measurements in Winchester Creek. The Argonaut recorded one integrated cell velocity measurement every 5 min. Although we initially planned to backcalculate water velocities for fish passage events using gate angle and water depth (as in Burrows et al., 1997), our results had poor resolution and were considered unusable.

2.2.6 Data Analysis

Antenna efficiency was determined at each gate for upstream and downstream passage by counting the detections of fish known to have passed the antenna array as in Zydlewski et al. (2006). Fish were considered to be independently known to pass if they were tagged on one side of the gate and: recaptured on the opposite side; detected on the opposite side when the gate was closed; or detected at another array on the other side of the gate. Due to their larger sample size, smolts were used to calculate all efficiency estimates. For upstream passage at the top hinged gate, data from 5 smolts was combined with data from 16 subyearlings to augment the small sample size. Antenna efficiency was calculated for each row (furthest upstream =row 1, furthest downstream= row 3 - Table 2.1). The combined efficiency of the array was calculated as described in Zydlewski et al. (2006). We also report the number of smolts independently known to pass that were not detected at the array (misses). Although antenna efficiency at the non-gated system could not be calculated based on a small sample size of individuals independently known to pass, efficiency is not expected to vary much based on passage direction due to a lack of swimming challenge (i.e., tide gate).

Table 2.1: Antenna Efficiency calculated for each row of the Top-Hinged and Side-Hinged Gate antenna arrays. N is the sample size. Efficiency is presented for each row (row 1 is the furthest upstream and row 3 is on the bay side of the tide gates). The combined efficiency is an overall efficiency measure for the array. Misses are fish that were known to pass but never detected.

Gate, Direction	N	E_{row1}	E_{row2}	E_{row3}	$E_{combined}$	Misses
Top-Hinged, US	21*	0.68	0.64	0.32	0.95	2
Top-Hinged, DS	47	0.57	0.53	0.15	0.83	8
Side-Hinged, US	11	0.45	0.45	0.09	0.72	4
Side-Hinged, DS	13	0.38	0.38	0.00	0.62	7

*this estimate calculated from detections of 5 smolts and 16 age 0 coho

To test our first hypothesis (i.e., there was no difference between how frequently juvenile coho salmon moved upstream and downstream at the three antenna arrays), we counted upstream and downstream movement of smolts - a combination of “confirmed” and “inferred” passage events. A confirmed passage event was characterized by a sequence of detections indicating directional movement through the array and tide gate. Confirmed detections could involve both rows of stream side antennae (always the case at the non-gated site where there were only 2 antenna rows), a stream side and the bay side antenna row, or all three rows (Figure 2.2). Detections had to occur within five minutes of one another and while the gate was open (the gate open criteria was not relevant at the non-gated array). Confirmed passage events were assigned the gate angle and tailwater depth measurements that were recorded closest in time to the conclusion of each detection.

Inferred passage events were determined by knowledge of a smolt’s position followed by a detection indicating that same smolt’s presence on the other side of an antenna array. At the tide gated streams, individuals detected on the opposite side of the tide gate from where they were last detected or where they were tagged were considered to have passed. At the non-gated stream, inferred passage events occurred when a smolt was detected passing twice in the same direction without a detection indicating passage in the opposite direction. The total count of passage events was a combination of confirmed and inferred passage events. For each antenna array, we counted the number of smolts that passed upstream and downstream. We also counted the number of times each smolt passed upstream.

To test our second hypothesis (i.e., that juvenile coho salmon did not pass tide gates more frequently under a particular range of gate angles and tailwater depths), we compared distributions of "used" and "available" gate angles and tailwater depths. "Used" angles and tailwater depths are those that occurred when a smolt or subyearling was detected passing a gate (for individuals with multiple passes we used the first confirmed passage for each direction). Available angles and tailwater depths are all those that occurred throughout any open period (measured at 5 min intervals) when a smolt or subyearling passed upstream or downstream. Clearly, this would result in many more data points in the "available" group. To compare distributions of used and available angles and tailwaters we used two non-parametric tests, the two sample Kolmogorov Smirnov test (KS test), and Kuiper's test. The KS test quantifies a distance between two empirical distribution functions to determine the probability that they are randomly drawn from the same reference population. If, for example, the distribution of gate angles used by coho smolts for passing upstream is not significantly different from the distribution of available gate angles, we would conclude that coho smolts are randomly using angles for passage from those available and there is no consistent pattern. Kuiper's test, which is closely related to the KS test, was employed because it is more sensitive at the minimum and maximum of the distributions while the KS test is most sensitive at the median. For example, if coho smolts passing upstream used angles at the bottom of the range the KS test may be unable to find the difference signficant while the Kuiper's test could. All statistical analyses were performed using SAS version 9.2.

2.3 Results

In total, 796, 215 and 129 unique coho smolts were detected at the top-hinged, side-hinged, and non-gated arrays, respectively. Many of these smolts were not used in the analysis because there was not sufficient information to assign them a confirmed or inferred passage. For the number of smolts detected at each antenna array and the location where they were originally tagged, see table 2.2. At the top-hinged gate, 50% and 3% of the total detected smolts were known to pass downstream and upstream, respectively (antenna efficiency corrected, DS = 61% and US = 3%, Figure 2.4). At the side-hinged gate 36% and 20% of the total detected smolts were known to pass downstream and upstream(corrected, DS = 58% and US = 28%). At the non-gated array 92% and 47% of the total detected smolts were known to pass downstream and upstream (no efficiency estimates available for correction). The greatest counts of upstream passage per individual smolt occurred at the non-gated array (Figure 2.5) where smolts passing upstream

Table 2.2: Juvenile coho salmon detected from March through June 2009 at all antenna arrays (PTG=Palouse tide gate, LTG = Larson Tide Gate, WIN=Winchester array) and their tagging location. All tagging sites in the creeks were upstream of the antenna arrays. The number of fish tagged for each site is included in the "tagged" row. Coho tagged as subyearlings in 2008 were only detected as smolts in 2009.

		Tagging Location				
Year, Lifestage	Detection Array	Larson Creek	Palouse Creek	D/S Gates*	Winchester Creek	Total
2008, Subyearling	PTG	15	296	3	0	314
	LTG	34	12	1	0	47
	WIN	0	1	0	0	1
	Total	49	309	4	0	362
	Tagged	208	1179	14	0	1401
2009, Smolt	PTG	13	459	10	0	482
	LTG	150	12	6	0	168
	WIN	0	0	0	128	128
	Total	163	471	16	128	778
	Tagged	364	711	42	171	1288
2009, Subyearling	PTG	3	1	33	0	37
	LTG	43	0	9	0	52
	WIN	0	0	0	2	2
	Total	46	1	42	2	91
	Tagged	311	1230	80	3	1624

*Fish tagged in Haynes Inlet within 0.5 km of the Palouse and Larson tide gates.

did so on average 4.4 times (median = 2, average = 4.4, maximum = 27). At both tide gates, smolts rarely passed upstream more than once (top-hinged med. = 1, avg. = 1.2, max. = 4, side-hinged med. = 1, avg. = 1.1, max = 3). Given these results, we rejected our first hypothesis that there would be no difference in how frequently fish moved upstream and downstream through a top-hinged gate, side-hinged gate, and non-gated channel.

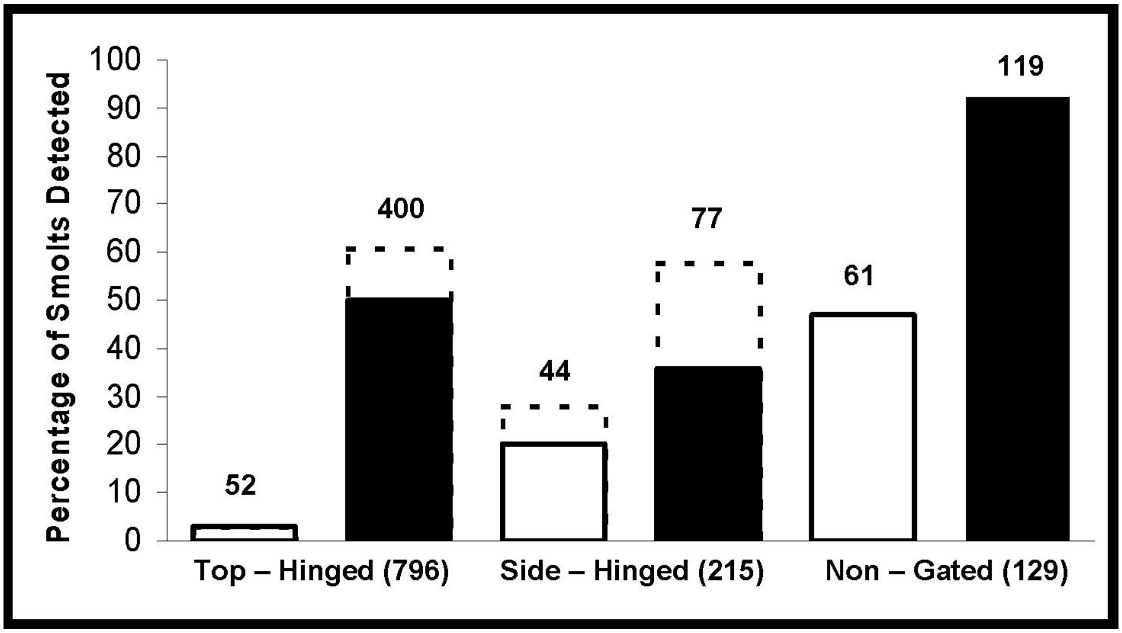

Figure 2.4: Coho smolts passing upstream and downstream expressed as a percentage of the total detected at each site (in parentheses after site). White bars = upstream passage, black bars = downstream passage, dotted bars = percentage adjusted based on antenna efficiency. Numbers listed above bars are respective number detected, not adjusted for efficiency.

Hundreds of subyearling coho salmon were observed and captured by seining around the tide gates from April through June 2009, especially at the side-hinged gate. Of 67 subyearling coho salmon that were PIT tagged below the top-hinged

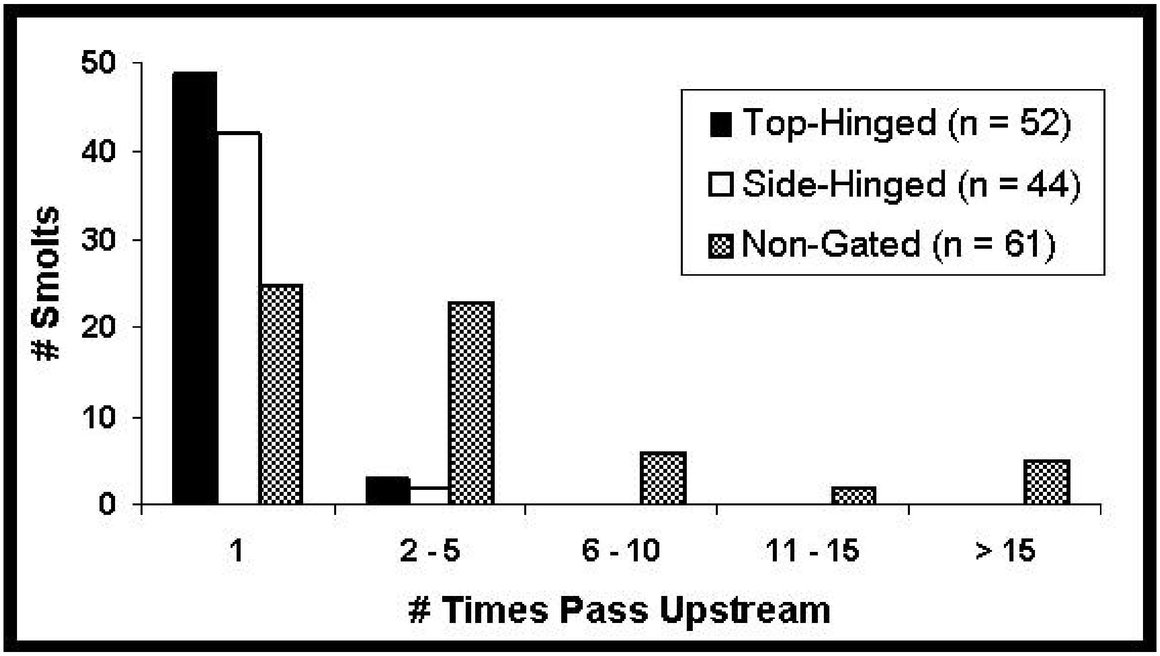

Figure 2.5: Number of coho salmon smolts passing upstream (binned by the number of times they passed) at two tide gates and a non-gated PIT antenna array. The total number of individual smolts passing upstream at each site is listed in parentheses in the legend.

tide gate in early June, 30 were detected on the upstream side and 19 of these were soon after detected 3 km upstream at an additional PIT antenna array (for a description of this array, see Section 3.2.4). Eight of these 67 subyearlings were detected upstream of the side-hinged gate. Of a total of 37 subyearlings detected at the top-hinged gate in May and June, 8% passed downstream and 78% passed upstream (corrected, DS = 10% and US = 82%). Of a total of 52 subyearlings detected at the side-hinged gate 31% passed downstream and 38% passed upstream (corrected, DS = 50% and US = 53%).

At the top-hinged gate, coho smolts passed downstream more frequently with a distribution of gate angles and tailwater depths that was significantly different from the distribution of available angles (KS $p = < 0.0001$) and tailwater depths (KS $p = < 0.0001$) (Table 2.3). Gate angles above 20° were used more frequently than smaller angles. While smolts passed downstream throughout the range of tailwater depths, they passed more frequently at greater depths. There is no statistical evidence that smolts used particular gate angles or tailwater depths for upstream passage. It is noteworthy that nearly 14% of the available tailwater depths at the top-hinged gate were less than 0.2 m (min = -0.36 m) and no smolts were detected passing upstream in this range. At the side-hinged gate, coho smolts also passed downstream under a distribution of gate angles and tailwater depths that was significantly different from the distribution of available angles (KS $p = 0.005$) and tailwater depths (KS $p = 0.02$)(Table 2.3). Smolts passed more frequently with gate angles above 40° and tailwater depths above 1.6 m. For upstream passage at the side-hinged gate, smolts did not use any particular range of conditions. Since

Table 2.3: Results of comparison between used and available gate angles and tailwater depths for juvenile coho salmon downstream passage through a top-hinged and a side-hinged gate. Analyses include Kolmogorov Smirnov (KS) and Kuiper's tests.

Gate Type	Variable	Lifestage	N Used	N Available	Mean Used (SE)	Mean Available (SE)	KS P	Kuiper's P
Top-Hinged	Angle	Smolt	325	3937	27.95 (0.54)	23.02 (0.18)	< 0.0001[1]	< 0.0001[1]
	Tailwater	Smolt	271	3028	0.84 (0.03)	0.50 (0.01)	< 0.0001[1]	< 0.0001[1]
Side-Hinged	Angle	Subyearling	12	312	20.77 (3.64)	33.50 (0.93)	0.01[1]	0.11
		Smolt	44	763	58.79 (2.68)	50.09 (0.62)	0.005[1]	0.02[1]
	Tailwater	Subyearling	12	312	1.01 (0.08)	1.03 (0.02)	0.45	0.29
		Smolt	32	402	1.83 (0.08)	1.66 (0.02)	0.02[1]	0.15

[1]Significant difference between used and available, $p \leq 0.05$

Table 2.4: Results of comparison between used and available gate angles and tailwater depths for juvenile coho salmon upstream passage through a top-hinged and a side-hinged gate. Analyses include Kolmogorov Smirnov (KS) and Kuiper's tests.

Gate Type	Variable	Lifestage	N Used	N Available	Mean Used (SE)	Mean Available (SE)	KS P	Kuiper's P
Top-Hinged	Angle	Subyearling	17	496	14.74 (1.29)	20.84 (0.50)	0.02[1]	0.02[1]
		Smolt	23	901	26.66 (2.13)	24.28 (0.34)	0.89	1.00
	Tailwater	Subyearling	17	496	0.40 (0.07)	0.43 (0.02)	0.10	0.006[1]
		Smolt	12	404	0.70 (0.10)	0.58 (0.02)	0.69	0.80
Side-Hinged	Angle	Subyearling	16	312	38.44 (4.93)	38.26 (0.95)	0.99	1.00
		Smolt	23	877	54.43 (3.27)	48.39 (0.64)	0.44	0.92
	Tailwater	Subyearling	16	312	1.24 (0.11)	1.27 (0.02)	0.64	0.70
		Smolt	14	616	1.68 (0.13)	1.53 (0.02)	0.58	0.93

[1]Significant difference between used and available, $p \leq 0.05$

both coho salmon smolts and subyearlings passed more often than expected under a specific gate conditions, we rejected our second null hypothesis that juvenile coho would not pass more frequently at a particular range of gate angles and tailwater depths.

As reported above, subyearling coho salmon in May and June passed predominantly in the upstream direction at the top-hinged gate. Most (82%) of these 17 fish passed upstream with gate angles between 7° and 16°. No subyearlings passed upstream when the tailwater depth was below the invert sill, which created a waterfall. Most (70%) of these fish passed upstream between 0-40 cm tailwater depth. The sample size of subyearlings passing downstream through the top-hinged gate in May and June was inadequate for statistical analysis (N=3). At the side-hinged gate, subyearling coho salmon did not pass upstream more frequently at a specific range of gate angles or tailwater depths. However, passing downstream they used lower gate angles than expected ($p = 0.01$), with 67% of these fish passing downstream at gate angles of $10 - 17°$.

The use of subyearling coho salmon of a specific range of gate angles and tailwaters at the top-hinged gate limited their available upstream passage during spring tides in June to 1 hr at the end of the gate open period (Figure 2.6). During this 1 hr period, the tailwater depth rose and the gate angle slightly increased. Water velocities measured during this period were consistently low (Appendix B).

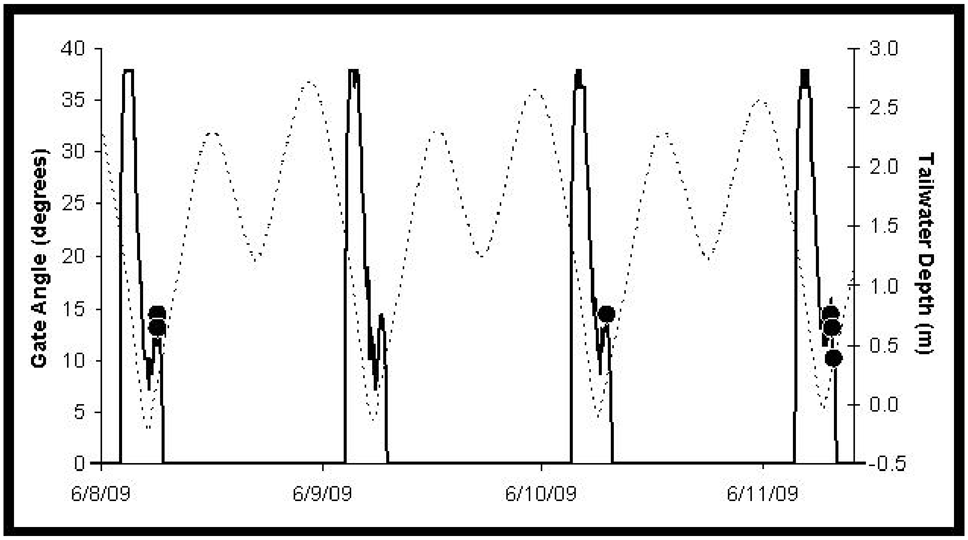

Figure 2.6: Subyearling coho salmon passage upstream timing at a top-hinged gate during a period of spring tides in June, 2009. Solid line= gate angle (each peak represents a gate open period, ∼4 hrs), dotted line= tailwater depth, black circle = upstream passage event.

2.4 Discussion

The results of this study indicated that tide gates have the potential to restrict smolt and subyearling coho salmon movement. A larger proportion of the detected smolt population at the non-gated channel passed upstream compared to the gated streams and individual smolts at the non-gated channel passed upstream more frequently than smolts at either gated stream. Therefore, we rejected our hypothesis that there is no difference in upstream and downstream passage frequency among the three streams. Because smolt and subyearling coho salmon both selected a specific range of angles and tailwater depths when passing through both tide gates, we rejected our hypothesis that juvenile coho salmon would not favor any particular range of these variables for passage.

The disparity in percentages observed to pass downstream between the gated systems and the non-gated system has multiple possible causes. The total number of coho smolts at the gated arrays is partially composed of individuals who are detected on the bay side of the tide gates but never pass upstream and are therefore unavailable to contribute to the number of individuals passing downstream. Furthermore, since many emigrating smolts in the non-gated system passed the antenna array multiple times, they had more opportunities to be recorded in at least one "confirmed" passage event. Finally, smolts could have died in the tide gate reservoirs or residualized and therefore would not be counted passing downstream. The differences among sites in percentages of smolts observed to pass upstream was not affected by these factors. Although we lacked antenna efficiency data for the non-gated array, the only consequence would be an underestimate of the true number of smolt upstream passage events and therefore makes our estimates conservative.

Coho salmon smolts passed downstream more frequently during greater gate angles and tailwater depths than the average available at both a top-hinged and a side-hinged gate. Kemp et al. (2005) found that chinook salmon smolts rejected downstream passage in a constricted channel at three times the rate they did so in an open channel. They speculated that the constricted channel induced behavioral avoidance by creating an "abrupt local acceleration of flow", a phenomenon that has been observed in other studies (Enders et al., 2009; Kemp et al., 2008). At tide gates, lower gate angles may be associated with localized acceleration and increased overhead cover, which also inhibits downstream passage (Kemp et al., 2008). Assuming this is what the juvenile coho salmon are responding to, side-hinged gates are less likely to cause passage avoidance because their sideway-opening doors create limited cover and their wide opening angles reduce localized velocity increases. Surprisingly, coho smolts preferred a significantly higher range of angles at the side-hinged gate than would be expected by chance. It is possible that the flow constriction created by the side-hinged gate, albeit minimal compared to that at the top-hinged gate, still created a sufficient water velocity increase to trigger avoidance by many coho salmon smolts.

Our findings are in agreement with previous studies that reported fish avoiding downstream passage through shallow channels or over submerged structure (Haro et al., 1998; Castro-Santos and Haro, 2003; Kemp and Williams, 2009). The phenomenon of shallow water acting as a partial barrier could easily be resolved at tide gates by ensuring that the invert elevation of the culvert is sufficiently low to minimize tailwater depths shallow enough to induce avoidance by fish. Although the invert elevation at the side-hinged gate in our study is over one meter lower in elevation than the invert at the top-hinged and never experienced a perched condition, coho smolts passing downstream still showed significant preference for greater tailwater depths at the side-hinged gate. Regardless of this preference, we expect that downstream passage is available for a greater portion of the gate open period at the side-hinged gate than at the top-hinged gate because a perched condition never occurs there.

The fact that subyearling coho salmon passed upstream more frequently at certain gate angles and tailwater depths at the top-hinged gate resulted in limited passage opportunities during each gate opening cycle. During spring tides, when the gate opened only once per day, the upstream passage of subyearlings was restricted to the last hour of the gate open period. At this time the tailwater depth approached the headwater depth and the gate angle increased slightly. We recorded velocities of approximately 0.6 m/s during this period. When the outflow of the tide gate becomes a waterfall, as it is prior to the above mentioned period, upstream passage by subyearling fish is very unlikely. Mueller et al. (2008) found that juvenile hatchery coho salmon (FL 60 - 135 mm) were capable of leaping into culverts with a 12-26 cm outfall drop (tailwater depths of -0.05 to -0.19 m by our terms), 7 cm water depth inside the culvert and culvert water velocities of 70 cm/s. In the case of the top-hinged tide gate, the gate door would likely physically obstruct the culvert opening and restrict leaping opportunities for the fish. Furthermore, water velocity at our top-hinged gate commonly exceeded 0.70 m/s for more than 75% of the gate open period for openings when the invert was perched. In contrast, subyearlings passed upstream through the side-hinged gate during the entire gate open period. They were detected moving through this gate multiple times in a single open period and holding in the gate doorways, possibly using the constriction of the channel created by the tide gate box as a feeding station. It seems that low water velocities, the lack of physical obstruction by the doors, and the consistently adequate depths for passage enabled subyearling coho salmon to pass upstream during the entire open period without having to wait for specific conditions.

More than half of a group of 67 subyearling coho salmon PIT tagged downstream of the top-hinged gate in early June moved upstream of either the top-hinged or side-hinged gate soon after tagging. Few of these individuals were seen at the gates again and half were detected at a PIT antenna array 3 km upstream of the top-hinged gate. Interestingly, of 42 subyearling chinook salmon PIT tagged at the same time and location for another study, only one was detected upstream of either tide gate. This suggests that subyearling coho salmon were highly motivated to return upstream of tide gates in June, potentially due to increasing salinities. The top-hinged gate allowed a small window of opportunity for passage on a daily basis; it is unclear what happened to subyearling coho salmon that were unable to pass upstream. If they suffer mortality as a result, tide gates could suppress the expression of the nomad life history strategy. While the contribution of coho nomads to the spawning population has not been well evaluated, it is likely that nomads contribute by: acting as a source of colonizers, providing a "bet hedging" strategy during years of poor stream conditions, and increasing the total production of a watershed (Koski, 2009). Given the expected consequences for a subyearling coho salmon that has difficulty move upstream compared to those for a smolt, we speculate that tide gates may prove most restrictive to coho nomads (without considering non-salmonid estuarine dependent fish species). If future research supports this hypothesis, tide gates should be designed to meet requirements for passage of subyearlings.

Selecting a location for a "reference" antenna array in Winchester Creek was complicated by the fact that tide gate installations alter the surrounding stream chemistry and morphology. We installed the non-gated PIT antenna array at the most representative location in Winchester Creek that we could access given logistical constraints including antenna array maintenance and recreational boat access. Miller and Sadro (2003) reported that acoustic tagged coho smolts in Winchester Creek resided in the upper estuary reach (where our antenna array was located) for an average of 11.6 days and half that time in the lower estuary. We recorded frequent upstream and downstream smolt movement at the non-gated array but saw no indication of such behavior at a PIT antenna array located 3 km upstream of the top-hinged gate nor either tide gate antenna array. Although we can not determine whether this frequent movement is specific to Winchester Creek or suppressed by the presence of tide gates, it appears that this behavior does not occur in the tide gated streams. We believe that regardless of where we installed the non-gated array in the Winchester Creek upper estuary, we would still observe greater occurrence of upstream and downstream movement of the smolt population compared to that observed at the tide gated streams.

To create the best conditions for fish passage short of removing a tide gate completely, we suggest combining the low velocity and deep tailwater conditions found at the side-hinged gate with the reservoir replenishing leaks, an accidental and not necessarily typical feature of any tide gate, that maintained more frequent and longer gate opening periods at the top-hinged gate at Palouse Creek. Manufacturers have accomplished this with simple mechanisms that keep tide gates open into the flood tide and allow the upstream reservoir to fill. These “self regulating tide gates”, or SRTs, may also benefit a multitude of organisms by allowing estuarine water upstream to create an environment more similar to that of a non-gated tidal slough.

This study provided the first evaluation of fine-scale salmonid movement through tide gates. We demonstrated that PIT antenna arrays could be employed for this purpose. Future research using PIT antennae or other tools is required to answer the many questions concerning design and operation of tide gates. Due to our small number of sites, our work should be considered a series of case studies, and application of findings to a certain tide gate should be made cautiously. Replication of these methods across a larger geographic range, multiple designs of tide gates, and years would provide greater inferential ability. Improvements to PIT antenna arrays including greater coverage of the water column would enhance data quality and quantity. We were unable to cover the majority of the water column downstream of the tide gate and therefore could not determine how frequently individuals approached the tide gates but failed in passing. Reducing the physical profile of antenna arrays, perhaps by using half duplex installations with recently introduced 12 mm tags, could reduce effects of the antenna arrays on fish behavior. From video recorded at the tide gates, it appears that some individuals utilized hydraulic refugia immediately behind the 11 cm diameter PVC tube that housed our antennae. It is unclear how this behavior effected the occurrence of upstream or downstream passage. Finally, more focus on subyearling coho salmon behavior at tide gates is required as we suspect this is the life stage most affected by tide gate presence due to limitations imposed by their swimming ability and physiological status.

Chapter 3 – Environmental Variables Influenced by Tide Gates and Their Effects on Coho Salmon Smolt Likelihood of Emigration

3.1 Introduction

Multiple studies of anadromous salmonids have acknowledged the existence of a migratory "smolt window", the duration and characteristics of which are determined by external factors (i.e., food availability, predation pressure, and environmental conditions) and internal factors (i.e., disease, parasites, and smolt physiology) (Hansen and Jonsson, 1989; Staurnes et al., 1993; McCormick et al., 1998; Scheuerell et al., 2009). Although the smolt window may shift annually, natural selection ensures that a population's peak emigration date will stabilize around the long-term optimum date (Quinn, 2005). While successful emigration requires synchrony with the smolt window, the onset of emigration is thought to be partially controlled by triggering factors in freshwater, especially temperature (Spence, 1995; Roper and Scarnecchia, 1999). Once emigration has commenced, physical features and environmental conditions along a downstream trajectory can influence migratory rate (Castro-Santos and Haro, 2003; Sykes et al., 2009). Anthropogenic changes to salmonid habitat can result in alterations to the conditions that determine migratory initiation and rate, resulting in emigration outside the smolt window (Kennedy and Crozier, 2010).

Upper estuary dikes and their tide gates are examples of anthropogenic changes to a watershed that may influence migration timing directly through physical interference and indirectly through alteration of environmental factors (Giannico and Souder, 2004, 2005). Where tidal marshlands are converted into agricultural or residential land, tide gates are employed to drain diked areas while preventing tidal flooding by brackish water. Tide gates are simple hinged doors at the mouth of a culvert or tide gate box that open and close depending on differences in water level (known as hydraulic head differential) and, therefore, pressure between the stream and the bay side. Among the many different tide gate designs that exist (see Giannico and Souder, 2005), top-hinged tide gates are the simplest and most commonly used. Because of their heavy weight and hinge position, these doors tend to open narrowly and create high water velocities and turbulent conditions expected to inhibit fish passage. This has led to the development of so-called “fish friendly” designs including side-hinged gates and self-regulating gates (Giannico and Souder, 2005). Side-hinged gates require less hydraulic head differential to open and therefore open wider than top-hinged gates with lower water velocities across a greater range of tidal levels. Although no studies have assessed fish passage through tide gates, channel constrictions, shallow structure, suddenly increasing water velocities and overhead cover are known to delay downstream smolt movement (Castro-Santos and Haro, 2003; Kemp et al., 2005, 2008; Enders et al., 2009). These conditions are all present at tide gates and are likely to influence smolt behavior and consequently their migratory timing.

Regardless of design, tide gates are closed for most of each day and therefore create upstream impoundments of low-velocity water (hereafter referred to as "reservoirs"). A tide gate's opening characteristics and level of disrepair determine how much its reservoir is influenced by the estuary. Old and leaky tide gates create reservoirs with muted tide cycles that are occupied by estuarine flora and fauna, whereas well sealed gates maintain freshwater habitat further downstream of its historic extent. Stagnant and sun exposed tide gate reservoirs are prone to rapid increases in temperature. Rising water temperature is correlated with increased smolt emigration for Atlantic salmon, *Salmo salar*; brown trout, *Salmo trutta*; coho salmon, *Oncorhynchus kisutch*; and chinook salmon *Oncorhynchus tshawytscha* (McMahon and Hartman, 1989; Whalen et al., 1999; Carlsen et al., 2004; DeVries et al., 2004; Zydlewski et al., 2005; Jonsson and Jonsson, 2009). Although many studies have highlighted the importance of a salinity gradient to emigrating salmonids, suggesting that fish prefer slow acclimation to direct entry into high salinity waters (Iwata and Komatsu, 1984; Handeland et al., 1996; Linley, 2001), few have documented the influence of salinity on smolt emigration due to the difficulties of simultaneously monitoring smolt movement and salinity concentrations in large estuaries.

In this study, we sought to test whether environmental and hydraulic conditions affected by tide gates have the potential to influence the likelihood of coho salmon smolt emigration. Our first objective was to describe salinity and temperature patterns upstream of two tide gates and in a non-gated stream. Our second objective was to determine whether temperature and salinity are associated with migratory rate in three streams and within multiple reaches of one stream. We hypothesized that temperature would not be assoicated with the likelihood of smolt emigration. We also hypothesized that salinity would not be associated with the likelihood of smolt emigration. Our third objective was to determine whether a combination of hydraulic and environmental factors at a tide gate were associated with passage delay. We hypothesized that no factors would influence the likelihood that a smolt passes downstream through the top-hinged gate or rejects passage.

3.2 Methods

3.2.1 Study Site

Three creeks that drain into Coos Bay, a 13 km^2 estuary on the southern Oregon coast, were used for this study. Palouse Creek has a top-hinged tide gate at its mouth, Larson Creek has a side-hinged tide gate, and Winchester Creek has no tide gate and was used as a reference system (for study site details, see Sections 2.2.1 and Figure 2.1). All three creeks have spawning populations of coho salmon; peak smolt emigration generally occurs during the month of May.

3.2.2 Effect of Tide Gates on Temperature and Salinity

We measured temperature and salinity every 15 min in Palouse and Larson Creeks using continuous data loggers (Star-Oddi DST CT, Reykjavik, Iceland). The loggers were positioned in the reservoirs 0.5 km upstream from the tide gates and were suspended 1 m below a float on the water's surface. Another logger intended to capture the bay conditions was positioned 1 m below the surface, attached to the floating antenna array immediately downstream of the Palouse tide gate. At Winchester Creek, a similar logger was also attached to the floating antenna array at the same depth. Salinity and temperature data were also recorded every 15 min 1 km downstream of the Winchester antenna array by a probe (YSI 6600 EDS, Yellow Springs, Ohio) installed by the South Slough Estuarine Research Reserve. Temperature was also measured every 30 min at each rotary screw trap (for RST locations see Section 3.2.3) by a continuous data logger (Hobo Water Temp Pro V2, Onset, Bourne, MA). Salinity and temperature measurements were averaged for each day and graphed together for visual comparison.

3.2.3 Factors Influencing Emigration Likelihood in the Lower Sections of Palouse, Larson, and Winchester Creeks

Stationary PIT tag antennae arrays were used to monitor coho salmon smolt movement through the top-hinged gate at Palouse Creek, the side-hinged gate at Larson Creek, and Winchester Creek's non-gated channel. Coho salmon smolts of 73 to 142 mm in fork length (FL) were tagged with 12 mm PIT tags (12.5 x 2.07 mm, 0.102 g; TX1411SST, Biomark, Boise,ID) between April 1 and May 28, 2009. All smolts were trapped at rotary screw traps that were located above tidal influence in each system (6 km above tide gates in Palouse and Larson Creeks and 1.5 km above the antenna array in Winchester Creek). Stationary antennae and antenna array layouts are described in Section 2.2.3. Although our goal was to assess the effects of salinity and temperature on emigration likelihood, we also recorded precipitation, fish fork length at tagging and date of tagging because each might influence migratory rate. Precipitation driven stream discharge is expected to increase smolt emigration rate. Multiple studies have shown that larger sized smolts emigrate more rapidly than smaller individuals (Hansen and Jonsson, 1985; Bohlin et al., 1996; Quinn, 2005). Finally, date of tagging was considered because individuals passing the smolt trap later in the year would be under greater pressure to emigrate since conditions favorable for emigration decline in June. Salinity and temperature data were recorded by the loggers positioned 0.5 km upstream of the tide gates and the logger positioned at the Winchester antenna array. Precipitation for the tide gated streams was measured at a rain gauge (Hobo U-30, Onset) maintained by the Coos Watershed Association and located approximately 11 km east of the tide gates. Precipitation for the non-gated array was measured at a rain gauge (Geonor T-200B series, Milford, PA) maintained by the South Slough Estuarine Research Reserve and located 0.4 km south of the antenna array.

Survival analysis has recently gained popularity for quantifying fish passage delay and identifying variables that cause delay at migratory barriers (Castro-Santos and Haro, 2003; Caudill et al., 2007; Anderson, 2009). Previous analysis methods biased results by only considering individuals that successfully passed a barrier. In contrast, survival analysis allows the inclusion of “censored observations”, which are individuals lost from the “risk set” (sample population for a given time interval) due to tag detection failure or mortality but able to contribute some information prior to their disappearance. We used Cox proportional hazards regression to determine how the explanatory variables influenced fish travel time through the antenna arrays at three streams (PROC PHREG SAS v. 9.2, SAS Institute Inc., Cary, North Carolina) because it does not require a known distribution of the data and can assess the effect of time varying explanatory variables on the likelihood of event occurrence. The Cox model assumes that for every unit increase in a continuous covariate, the likelihood of an event changes proportionally (the proportional hazards assumption). If the proportional hazards assumption holds, effects of parameters can be determined without knowing the distribution of the baseline hazard function. At each site we tested the model:

$$\lambda_i(t) = \lambda_0(t)e^{(\beta_1 X_{1i}+\beta_2 X_{2i}+\beta_3 X_{3i}(t)+\beta_4 X_{4i}(t)+\beta_5 X_{5i}(t))}$$

Where:

$\lambda_i(t)$ = The "hazard" of passage for individual i at time t

λ_0 = The unspecified nonnegative baseline hazard function

β_1 = Fork length at tagging (mm)

β_2 = Date of tagging (Julian day)

β_3 = Temperature (°C) defined as the average of temperatures recorded over a 24 hr period prior to a given time interval

β_4 = Salinity (ppt) defined as the average of salinities recorded over a 24 hr period prior to a given time interval

β_5 = Precipitation (cm) defined as the cummulative sum of precipitation recorded over a 48 hr period prior to a given time interval

Because our model includes three explanatory variables that change over time (temperature, salinity and precipitation) and coho smolts entered the risk set across a range of dates, we used the counting process format for data entry (Therneau and Grambsch, 2000). Upon their first detection at an antenna array individual smolts were considered to have entered the risk set; this is their time 0. Each 24 hr period after time 0 was an interval and the time dependent variables were averaged across each interval for each individual. Individuals that were never seen again after time 0 were censored at time 0 and therefore had no impact on the evaluation of the explanatory variables. An individual was also censored if its last detection occurred upstream of the tide gate when the gate was closed. An individual's last upstream detection when the gate was open was considered to be a passage event. If an individual was detected downstream of the gate without a prior passage detection, it was censored at the time of its last upstream detection.

To determine the most parsimonious combination of explanatory variables, we used the stepwise selection function in the SAS 9.2 PHREG procedure (significance level for entry = 0.25, significance level to stay = 0.05). We tested the goodness of fit of the resulting models by creating a model with 10 dummy variables, grouping the data in similarly sized bins based on the ranked values of the vector of estimated explanatory variables (similar to the Hosmer-Lemeshow test for logistic regression, suggested for survival analysis by Hosmer and Lemeshow, 1999). We used a likelihood ratio test to determine whether the model with the dummy variables fit the data significantly better than our selected model. To determine functional form of the explanatory variables (whether or not transformation is required), we visually assessed plots of smoothing splines as described in Therneau and Grambsch (2000). To test the proportional hazards assumption we visually assessed plots of Schoenfeld residuals regressed over time; slopes significantly different from zero suggest a violation of the assumption (Therneau and Grambsch, 2000). SAS v. 9.2 was used for the goodness of fit test, Splus 8.1 was used for testing functional form and proportional hazards. To provide summary statistics of time to emigration for each site (including mean and median time to emigration) we used PROC LIFETEST in SAS v. 9.2.

3.2.4 Factors Influencing Emigration Likelihood in Three Sections of Palouse Creek

Stationary PIT antennae were used to monitor coho salmon smolt movement from their tagging location at a rotary screw trap (Rkm 6), into the reservoir (Rkm 3), and through the tide gate (Rkm 0) (Figure 3.1). Data from the Palouse antenna array and smolts tagged at the rotary screw trap, as described in Section 3.2.3, were used for this analysis. We also incorporate data from an additional 2 x 1 array (to allow monitoring of directional movement) of 3.05 m x 1.22 m antennae positioned at the start of the reservoir section (Figure 3.1). For the survival analysis, a smolt's time 0 was the time of its release at the screw trap after being tagged, and emigration from the stream section occurred upon first detection at the reservoir antenna. Individuals recaptured by seining or at the rotary screw trap followed by

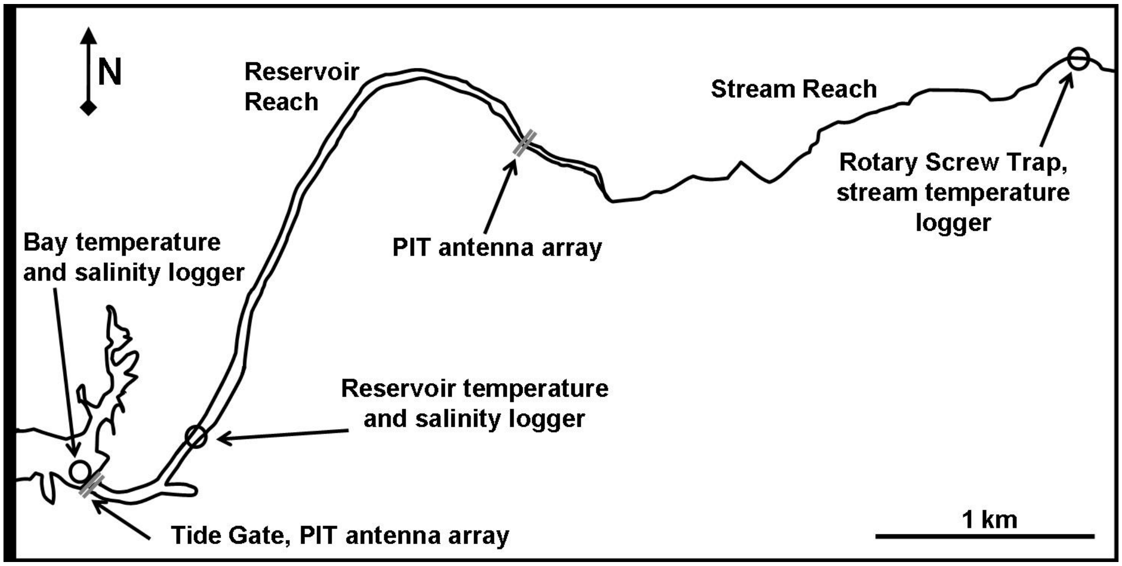

Figure 3.1: Map of lower reaches of Palouse Creek showing location of data loggers and stationary PIT antennae arrays used to monitor coho salmon smolt movement.

a lack of detection at the reservoir antenna were censored at their last sighting. Individuals never recaptured or detected after release or detection at the reservoir antenna were censored at time 0. An individual's first detection at the reservoir array was also their time 0 for the reservoir section. Upon first detection at the tide gate antenna, a smolt was considered to have emigrated from the reservoir section. If an individual was not detected at the tide gate but was recaptured by seining or detected at the reservoir antenna at least 24 hours after first detection there, it was censored. Censoring at the tide gate was determined as described in Section 3.2.3. The proportional hazards analysis was identical to that described in Section 3.2.3 except that for the stream section, there was no salinity measurement.

3.2.5 Hydraulic and Environmental Factors Influencing Coho Salmon Smolt Downstream Passage at a Top-Hinged Tide Gate

We used logistic regression to determine what variables influence coho smolt passage downstream through the top-hinged tide gate at Palouse Creek. An insufficient sample size at the side-hinged gate prevented a similar analysis for that site. Coho smolts encountering the tide gate from the upstream side were divided into two groups, pass and reject. Individuals in the pass group passed through the tide gate on their first encounter with the open gate after tagging. This was determined by a "confirmed" directional detection as described in Section 2.2.6. A reject individual was detected at the tide gate during an open period but did not pass downstream during the same open period in which its first detection occurred.

Explanatory variables tested for their effect on likelihood of passage included tagging location, date of event, salinity, temperature, gate angle, and tailwater depth. Since coho salmon tagged both as smolts in 2009 and subyearlings in 2008 were included in this analysis, fork length was not used as an explanatory variable. Tagging location and date of event were included as potentially confounding variables. Tagging location was a dichotomous variable; fish were either tagged in the stream portion of the system (Rkm 3 and greater) or the reservoir (Rkm 0 to 3). Date of event was the Julian day that a pass or reject behavior was recorded. Salinity was an average of the salinity measurements recorded for the 24 hours prior to the detection event, recorded as described in Section 3.2.2. Temperature was parameterized similarly and recorded concurrently with salinity. The closest measured gate angle and tailwater depth (recorded at 5 min intervals), measured as described in Section 2.2.4, was matched to each detection time.

We used AIC model selection to determine the combination of explanatory variables that best explained passage behavior (Burnham and Anderson, 2002). Since no data exist on the factors effecting downstream passage of fish through tide gates, we took an exploratory approach and generated AIC values for all 4, 3, 2, and 1 variable combinations of the explanatory variables. Models within two AIC values of the top model were considered competing. We assessed collinearity of explanatory variables to avoid fitting models with collinear variables. We evaluated deviance residuals to test for overdispersion and performed a Hosmer Lemeshow test for goodness of fit (Allison, 1999). Analyses were performed using PROC LOGISTIC in SAS v. 9.2.

3.3 Results

3.3.1 Effect of Tide Gates on Temperature and Salinity

Daily average salinity 0.5 km upstream of the well sealed side-hinged tide gate did not exceed 5 ppt from April through June, the main period of smolt emigration (Figure 3.2). Estuarine intrusion through the leaky top-hinged tide gate at Palouse Creek was revealed by how close salinities in the reservoir tracked those in the bay, although reservoir salinity is consistently 4-5 ppt lower (Figure 3.2). Daily average temperatures during a period of frequent solar warming, high air tempera-

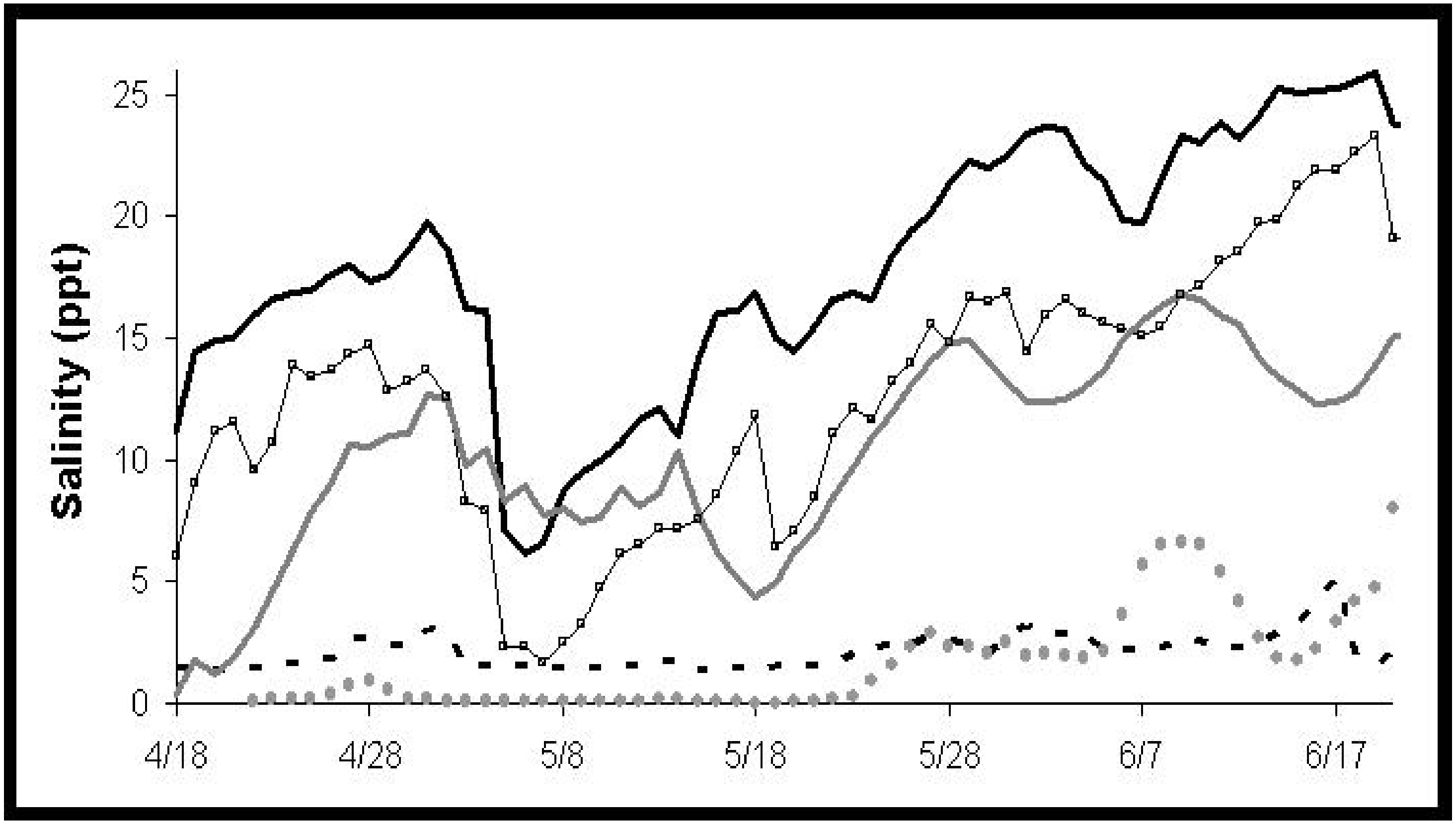

Figure 3.2: Daily average salinity for three streams from April 18th to June 20th, 2009. Thick gray line = salinity measured 1 Rkm downstream of the Winchester antenna array. Gray circle line = measured at the Winchester array. Thick black line = bay, measured immediately downstream of the Palouse gate. Thin black line with boxes = Palouse reservoir, measured 0.5 Rkm upstream of the tide gate. Dashed black line = Larson reservoir, measured 0.5 Rkm upstream of the tide gate.

tures, and little freshwater input (July to October) show that water temperatures upstream of tide gates were higher than bay temperatures (Figure 3.3). The effect of bay waters entering the Palouse reservoir through the leaky gate is evident in the temperature similarities between the bay and Palouse reservoir temperatures (Figure 3.3). Temperature peaks in the Larson reservoir occurred during periods when the gate opened less than one hour per day and substantially exceeded the bay temperatures. During the period of smolt emigration, daily average reservoir temperatures rarely rose above bay temperature (Figure 3.4). However, when reservoirs were drained on warm days, reservoir water temperature some times rapidly spiked and exceeded bay temperature (see Appendix A).

3.3.2 Factors Influencing Emigration Likelihood in the Lower Sections of Palouse, Larson, and Winchester Creeks

Nearly 40% of the 38 coho smolts that entered the risk set at Larson Creek were censored while only 1.3% of 78 smolts and 11.2% of 125 smolts were censored at Winchester and Palouse, respectively (Table 3.1). Approximately 50% of the coho smolts that approached both tide gates emigrated in less than one minute after their first approach while at the non-gated array, approximately 24% of individuals behaved similarly (Table 3.1, median days).

A likelihood ratio goodness of fit test indicated that a model with ten dummy variables fit the data significantly better than the selected, reduced model (explanatory variables = fork length and salinity) at Palouse Creek. This means

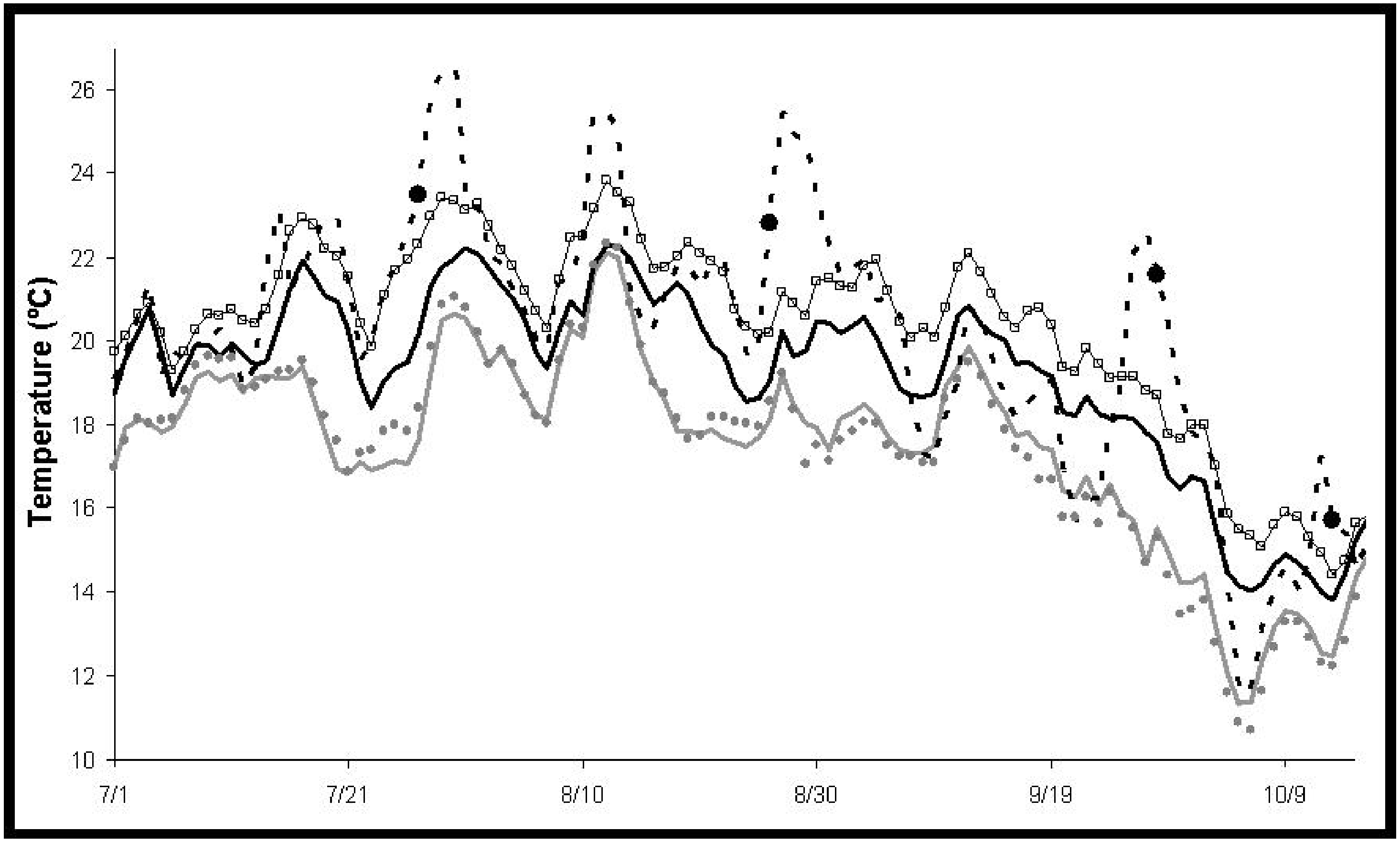

Figure 3.3: Daily average temperatures for three study streams from July 1st to October 15th, 2009. Thick gray line = temperature measured 1 Rkm downstream of the Winchester antenna array. Gray circle line = measured at the Winchester array. Thick black line = bay, measured immediately downstream of the Palouse gate. Thin black line with boxes= Palouse reservoir, measured 0.5 Rkm upstream of the tide gate. Dashed black line = Larson reservoir, measured 0.5 Rkm upstream of the tide gate. Black circles = days when the Larson tide gate did not open.

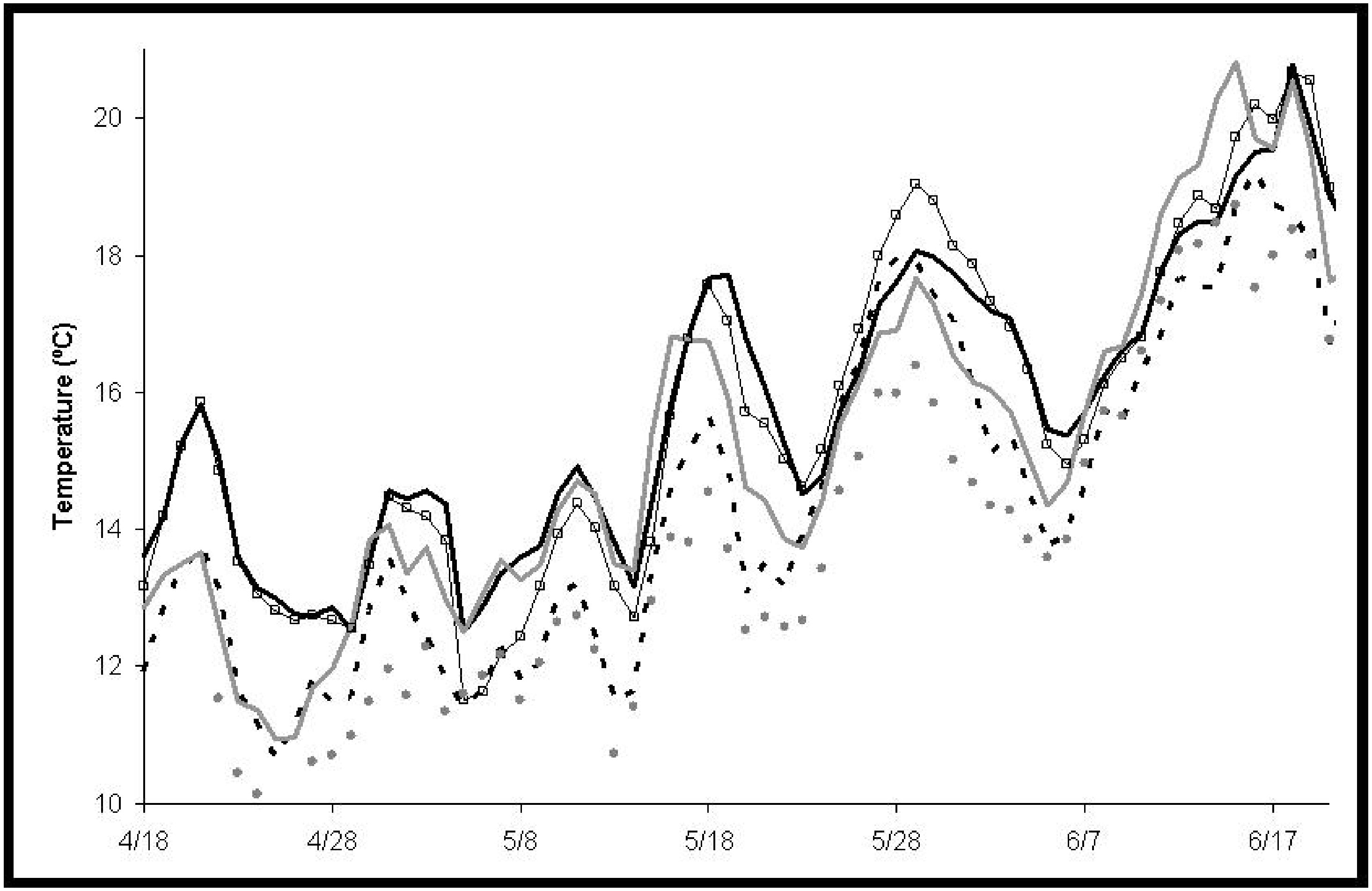

Figure 3.4: Daily average temperatures for three streams from April 18th to June 20th, 2009. Thick gray line = temperature measured 1 Rkm downstream of the Winchester antenna array. Gray circle line = measured at the Winchester array. Thick black line with boxes= bay, measured immediately downstream of the Palouse gate. Thin black line with boxes= Palouse reservoir, measured 0.5 Rkm upstream of the tide gate. Dashed black line = Larson reservoir, measured 0.5 Rkm upstream of the tide gate.

Table 3.1: Summary statistics for survival analysis in three study streams. Mean and median days represent the amount of time smolts spent in each risk set.

Site	N	% Censored	Mean Days	Median Days (95% C.I.)
Winchester	78	1.3	7.63	1.23 (0.32-3.22)
Larson	38	39.5	3.42	0.0002 (0.00-1.76)
Palouse	125	11.2	4.07	0.0013 (0.00-0.04)

that: the proportional hazards assumption is violated, explanatory variables require transformation, or the explanatory variables are inadequate. No violations of the proportional hazards assumption was indicated by residual plots and the need for data transformations was not indicated by graphs of smoothing splines (Appendix C). Therefore, all of the explanatory variables, regardless of their significance, were kept in the model (Table 3.2) since the goodness of fit test indicated that the full model fit the data better than the ten dummy variable model. This did little to change the influence of the significant explanatory variables on likelihood of downstream passage. For Larson Creek, smoothed spline plots and plots of Schoenfeld residuals suggested that functional form was appropriate and the proportional hazards assumption was supported. In Winchester Creek, Schoenfeld residuals indicated a violation of the proportional hazards assumption but removal of 4 visible outliers in the plot resulted in a non-signficant test result and the Hazard Ratios were not changed (Appendix C). For Palouse Creek some of the explanatory variables in the final model were collinear, most noteworthy temperature and salinity (Pearson $r^2 = 0.72$). Temperature and salinity were positively correlated in all models and temperature and precipitation were negatively correlated in all models.

The per unit effect of an explanatory variable in proportional hazards regression is inferred by subtracting 1 from that variable's odds ratio (Table 3.2). At both the top-hinged tide gate and the non-gated stream, each increase of 1 mm in fork length resulted in an increase in the likelihood of passage for any given time interval (a 3% increase at the top-hinged gate: $p = 0.01$, 95% C.I. = 1-5%; and a 5% increase at the non-gated channel: $p = 0.001$, 95% C.I. = 2-8%, table 3.2). At the top-hinged gate, the likelihood of passage decreased by 6% for every 1 ppt increase in salinity ($p = 0.03$, 95% C.I. = 1-11%). At the side-hinged gate, each 1 cm increase in cummulative rainfall over a 48 hr period increased the likelihood of passage by 33% ($p = 0.01$, 95% C.I. = 8-64%). At the non-gated channel, for each 1°C increase in temperature, the likelihood of downstream passage increased by 29% ($p = 0.001$, 95% C.I. = 11-49%). These results led us to reject our null hypotheses that both temperature and salinity have no effect on coho salmon smolt emigration likelihood.

Table 3.2: Final models, determined by Cox regression, of variables associated with likelihood of emigration for coho salmon smolts in three study streams.

Site	Variable	$\beta(SE)$	P value	Hazard Ratio (95% C.I.)
Palouse Creek (Top-Hinged Gate)	Temperature	0.14 (0.10)	0.17	1.15 (0.94 - 1.14)
	Fork Length	0.03 (0.01)	0.01	1.03 (1.01 - 1.05)
	Precipitation	0.01 (0.17)	0.97	1.01 (0.72 - 1.40)
	Tag Date	-0.01 (0.01)	0.41	0.99 (0.97 - 1.01)
	Salinity	-0.06 (0.03)	0.03	0.94 (0.89 - 0.99)
Larson Creek (Side-Hinged Gate)	Precipitation	0.28 (0.11)	0.01	1.33 (1.08 - 1.64)
Winchester Creek (Non-gated)	Temperature	0.25 (0.08)	0.001	1.29 (1.11 - 1.49)
	Fork Length	0.05 (0.01)	0.001	1.05 (1.02 - 1.08)

3.3.3 Factors Influencing Emigration Likelihood in Three Sections of Palouse Creek

This analysis includes 257 PIT tagged smolts released at the Palouse Creek smolt trap. Some of the individuals used in the gate analysis were not available for the reservoir analysis because the salinity and temperature loggers were not installed yet when they entered the reservoir. Of the three sections of Palouse Creek, smolts spent the most time in the reservoir (Table 3.3). Note that the analysis for the Tide Gate is identical to the analysis for Palouse Creek in Section 3.3.2.

Table 3.3: Summary statistics for survival analysis in three sections of Palouse Creek. Mean and median days represent the amount of time coho salmon smolts spent in each risk set.

Analysis	N	% Censored	Mean Days	Median Days (95% C.I.)
Palouse Gate	125	11.2	4.07	0.0013 (0.00-0.04)
Palouse Reservoir	145	26.9	11.49	8.95 (6.21-11.15)
Palouse Stream	257	39.7	4.34	1.67 (1.47-2.23)

As before, we found collinearity among explanatory variables in the three sections of Palouse Creek. The reduced model for the stream section was determined to be inadequate by the goodness of fit test. A test of functional form for the stream section suggested that temperature required transformation; however log, square root, and reciprocal transformation did not improve the functional form according to the smoothed spline plots so the variable was left untransformed. A Schoenfeld plot indicated that the proportional hazards assumption may be violated; however, the slope across time was very slight and removal of two visible outliers resulted in a non-singificant slope (Appendix C). Due to these diagnostic

Table 3.4: Final models, determined by Cox regression, of variables associated with likelihood of emigration for coho salmon smolts in three sections of Palouse Creek.

Section	Variable	$\beta(SE)$	P value	Hazard Ratio (95% C.I.)
Stream	Temperature	0.22 (0.06)	0.0001	1.25 (1.12 - 1.40)
	Fork Length	0.02 (0.01)	0.004	1.02 (1.01 - 1.04)
	Precipitation	0.09 (0.08)	0.28	1.10 (0.93 - 1.29)
	Tag Date	0.002 (0.01)	0.77	1.00 (0.99 - 1.02)
Reservoir	Temperature	0.26 (0.05)	<0.0001	1.30 (1.17 - 1.45)
	Fork Length	0.08 (0.01)	<0.0001	1.08 (1.06 - 1.11)
Tide Gate	Temperature	0.14 (0.10)	0.17	1.15 (0.94 - 1.14)
	Fork Length	0.03 (0.01)	0.01	1.03 (1.01 - 1.05)
	Precipitation	0.01 (0.17)	0.97	1.01 (0.72 - 1.40)
	Tag Date	-0.01 (0.01)	0.41	0.99 (0.97 - 1.01)
	Salinity	-0.06 (0.03)	0.03	0.94 (0.89 - 0.99)

problems, all explanatory variables were kept in the model. For each 1 mm increase in fork length, coho smolts in all sections were 2-8% more likely to emigrate at any given time interval (Stream:p = 0.004, 95% C.I. = 1-4%; Reservoir:$p = < 0.0001$, 95% C.I. = 6-11%; Tide Gate:p = 0.01, 95% C.I. = 1-5%; Table 3.4). Each 1°C increase in temperature caused a 25% and 30% increase in stream and reservoir emigration likelihood, respectively (Stream:p = 0.0001, 95% C.I. = 12-40%; Reservoir:$p = < 0.0001$, 95% C.I. = 17-45%). In the resevoir, tagging date was marginally significant; smolts tagged later were more likely to leave at any given time interval (p = 0.05, 95% C.I. = 0-4%). As reported in section 3.3.2, increasing salinity at the tide gate lowered the likelihood of emigration.

3.3.4 Hydraulic and Environmental Factors Influencing Coho Salmon Smolt Downstream Passage at a Top-Hinged Tide Gate

The model that best predicted whether, after being tagged, a coho salmon smolt passed downstream or rejected passage upon first approaching a tide gate, consisted of the explanatory variables gate angle, tagging reach, and salinity (Table 3.5). This led us to reject our null hypothesis that no factors would be associated with the likelihood that a smolt passes downstream through the top-hinged gate or rejects passage. The model with the lowest AIC value included these parameters and diel period (which was marginally significant, $p = 0.05$). To maintain parsimony, we chose the model without diel period which was within two AIC units of the model including it. A Hosmer Lemeshow goodness of fit test indicated that our model fit the data well. The evaluation of deviance indicated no evidence of overdispersion. There was no collinearity (Pearson's $r^2 > 0.40$) among the variables used in the final model. Salinity was correlated with temperature (Pearson's $r^2 = 0.57$) but temperature was not included in the final model. Furthermore, temperature (when tested) had a positive effect on downstream passage and in models with both parameters temperature was insignificant. When keeping the other variables in the model constant, likelihood of passing downstream at first gate approach increased by 6% for each degree increase in gate angle ($p = <0.0001$, 95% C.I. = 3-9%). Smolts tagged in the reservoir were 2.4 times more likely to pass than those tagged above Rkm 3.0 ($p = 0.005$, 95% C.I. = 1.30-4.55 times). For each 1 ppt increase in salinity (averaged for the 24 hrs prior to the detection event), smolts were 13% less likely to pass (p = 0.0002, 95% C.I. = 6-20%; (Table 3.5).

Table 3.5: Results from logistic regression comparing coho salmon smolts that pass immediately through a top-hinged gate to those that reject passage.

Parameter	$\beta(SE)$	P value	Odds Ratio (Wald 95% C.I.)
Intercept	1.31 (0.64)	0.04	
Gate Angle	0.06 (0.01)	<0.0001	1.06 (1.03 - 1.09)
Tagging Reach	-0.90 (0.32)	0.005	0.41 (0.22 - 0.77)
Salinity	-0.14 (0.04)	0.0002	0.87 (0.80 - 0.94)

3.4 Discussion

We found that environmental variables (i.e., temperature and salinity) that are influenced by tide gates were associated with emigration rates of coho salmon smolts in two coastal Oregon streams. As reported for other species of salmonids, the likelihood of emigration for coho salmon smolts increased as fork length (at tagging) increased. Increasing water temperature was also associated with increasing likelihood of emigration. Salinity was negatively associated with likelihood of smolt emigration. To our knowledge, this is the first time such a finding has been reported. We believe that this can be attributed to the unique features of our study sites and our monitoring system (i.e., full duplex PIT tag antennae that operate in brackish environments). We also found that hydraulic conditions at tide gates affect downstream passage. Coho salmon smolts were more likely to pass downstream at large gate angles.

The finding that fish fork length was positively correlated with likelihood of emigration agrees with what other studies have reported (Hansen and Jonsson, 1985;

Bohlin et al., 1996; Quinn, 2005). Several authors have found that body size of smolting salmonids is related to osmoregulatory ability, with larger smolts surviving salinity challenges more than smaller individuals (McCormick and Saunders, 1987; Bjerknes et al., 1992; Shrimpton, 1996). If this were the case in the current study, larger smolts may not need to decrease their rate of migration upon contact with increasing salinities to the same degree as smaller individuals. Smolt size has also been positively associated with survival (Reimers, 1971; Ward and Slaney, 1988; Holtby et al., 1990) and it may be that smaller smolts reside in freshwater longer to increase body size before entering environments with higher predation risks. Finally, body size is correlated to swimming speed and larger fish may be actively migrating at a greater rate than smaller fish (Glova and McInerney, 1977; Miller and Sadro, 2003).

The positive association we found between water temperature and coho salmon smolt emigration at multiple sites was also reported in other studies (Sandercock, 1991; Spence, 1995). By limiting estuarine influence and stagnating upstream freshwater for extended periods, tide gates cause reservoir water temperatures to surpass bay water temperatures. At our study sites during the period when smolts emigrated, this phenomenon primarily occurred following significant drainage of the reservoir accompanied by rapid heating from solar radiation and was therefore only episodic. Regardless, short periods of rapid temperature increase can stress salmonid smolts that are already physiologically challenged by osmoregulatory adjustments (Richter and Kolmes, 2005). The potential impact of early emigration caused by increasing temperatures was well demonstrated by Kennedy and Crozier

(2010), who studied Atlantic salmon smolt emigration in an Irish river. As river temperatures have increased over the past 30 years the onset of migration has become earlier, resulting in a mismatch of peak migration with ideal ocean conditions, thus reducing the survival of salmon during their first year at sea. Kennedy and Crozier (2010) found that for each day the onset of migration was delayed for a given cohort, there was almost a 2% increase in marine survival. Since tide gate reservoirs are vulnerable to rapid heating and coho smolts are more likely to emigrate as temperatures increase, a similar phenomenon could occur in systems like those that we studied.

Tide gates have the potential to significantly alter the salinity regimes of upstream habitats. The installation of a tide gate reduces the spatial extent of the local salinity gradient, the freshwater-estuarine ecotone that lessens the osmotic stress to anadromous fishes caused by the transition from fresh to salt water (Thorpe, 1994; Jobling, 1995; Linley, 2001). At the side-hinged gate, emigrating coho smolts often move from freshwater into salinities exceeding their internal salinity concentration over a short distance. This abrupt and potentially premature transition may be harmful, especially for those individuals that are less physiologically prepared for abrupt changes in salinity (Virtanen et al., 1991). Iwata and Komatsu (1984) reported that the hatchery reared juvenile chum salmon they released into an estuary held in the low salinity surface lens and did not swim deeper in the water column where salinities were higher. Handeland et al. (1996) found that, compared to acclimated groups, Atlantic salmon smolts placed directly in saltwater exhibited decreased predator avoidance response and schooling behavior which led to significantly higher predation rates by cod.

At the older Palouse Creek tide gate that allows substantial estuarine water upstream, we observed that coho salmon smolts were less likely to emigrate after encountering higher salinity water. At the newer and better sealed Larson Creek tide gate, the range of average salinities (1.3 - 3.2 ppt) in the reservoir may have represented too weak a signal to elicit a similar response. In our reference stream, Winchester Creek, the absence of a salinity effect on the likelihood of smolt emigration may have been an artifact of the position of our antenna array. Salinities at the non-gated antenna array were similar to those upstream of the side-hinged gate while salinities 1 Rkm downstream were more similar to those that were recorded in the Palouse reservoir. Interestingly, in this stream we detected many individuals passing upstream and downstream through the antenna array daily. Using acoustic tags in Winchester Creek, Miller and Sadro (2003) recorded smolts covering distances of 4 km in less than two hours, suggesting that smolts making daily movements have the ability to travel throughout the salinity gradient. It is possible that the back and forth behavior we detected in Winchester Creek represents coho salmon smolts using the far ranging natural salinity gradient to acclimate to higher salinities.

To the best of our knowledge, no other study has reported reduced smolt emigration rates in response to increased salinities. In fact, Martin et al. (2009) found the opposite reaction in Atlantic salmon smolts, which increased their seaward migration rate upon encountering increasing salinities. By using radio and ultrasonic telemetry, complemented by spot measurements of salinity, Moser et al. (1991)

found no effect of changing salinities on the migration rate of coho salmon smolts. The uniqueness of our findings may be a result of our tagging and data collection methods and the unusual study setting caused by a leaky tide gate. Past studies have utilized radio and acoustic tags which require a large body size (the minimum body size tagged by Moser et al., 1991 was 163 mm FL, 20 mm greater than the largest fish used in our study), whereas we PIT tagged emigrating juvenile coho salmon as small as 73 mm. Hence, if smaller smolts are less physiologically prepared to osmoregulate at high salinities than larger fish, then they are more likely to slow emigration when detecting increased salinity.

We were able to use PIT tags because tide gates provided spatial constraints capable of funneling smolts through a small area for detection by our PIT antennae arrays (which, unlike conventional PIT antennae, operated in saltwater). The top-hinged gate allowed substantial estuarine influence so that we could detect fish responses to salinities that would have been very difficult to observe at a larger spatial scale. Since we only found salinity affecting the likelihood of emigration in one of our three streams, replication of our approach across several years and sites is warranted. Recent technologies including smaller acoustic tags, archival tags, and spatial salinity modeling may allow more in depth analysis of the effects of tide gates and salinity on smolt behavior (Martin et al., 2009; McMichael et al., 2010).

In our logistic regression analysis we found further support for our conclusion, present in Section 2.3 of this thesis, that coho salmon smolts showed preference for large gate opening angles when passing downstream through a top-hinged gate.

Researchers working on the Columbia river have recently demonstrated that localized water acceleration resulting from channel constrictions and overhead cover causes pacific salmon smolts to delay downstream migration (Kemp et al., 2005, 2008; Enders et al., 2009). Since tide gates are only open for a short period each day, what would only be a temporary delay at a typical culvert may easily become a delay of days. Since it identified salinity as a variable negatively associated with the likelihood of downstream passage, our logistic regression analysis was in agreement with the results from the Cox proportional hazards regression at the Palouse tide gate. Our logistic regression analysis also showed that smolts tagged in the reservoir were over two times more likely to pass downstream than smolts tagged in the stream reach, which may further support our findings concerning salinity. Smolts tagged in the reservoir are more likely to have experienced brackish water than smolts tagged in the stream reach and are therefore less likely to slow emigration due to salinity tolerance. Alternatively, smolts tagged in the reservoir could have learned how to pass through the tide gate from multiple encounters prior to tagging while smolts tagged in the stream were naive to the structure.

Although in this study we found that water salinity and temperature affected the likelihood of coho salmon smolt emigration, we were unable to verify if this had a harmful effect on the fish. However, since tide gates tend to modify temperature and salinity and smolts respond to these factors during emigration, some tide gate installations are very likely to alter the timing of this movement. To determine whether this effect is actually deleterious for the fish would require actual test of estuarine and smolt to adult survival, a clear next step in tide gate research. Additionally, this study was limited to two tide gates and the effects these structures have on the aquatic environment and fish passage seems to be context dependent. Therefore, increasing the number and variety of gates for future studies is advised.

Chapter 4 – General Conclusion

For estuarine dependent salmonids and other organisms, tide gates present a physical barrier capable of restricting habitat access, altering nursery habitat conditions, and influencing migratory rate. To our knowledge, this study is the first to provide data on fine scale juvenile salmonid movement patterns at two types of tide gates. Coho salmon smolts passed upstream through both a side-hinged and a top-hinged tide gate but a larger percentage of the smolt population passed upstream through an open channel in a non-gated reference stream. Individually, coho salmon smolts at the non-gated channel moved back and forth through the antenna array more times than individuals at either gated creek. During the coho salmon smolt migration period, the top-hinged and side-hinged gates were open an average of 6.6 and 5.1 hrs per day, respectively, and neither gate was ever open more than half of the day. Therefore, the more frequent upstream-downstream movement at the non-gated channel should not be surprising since the tide gates were usually closed and passage opportunities were limited when the gates were open.

At both the side-hinged and the top-hinged gate, smolt downstream passage occurred across a distribution of gate angles and tailwater depths that indicated a non-random selection from the available conditions. Smolts showed preference for greater angles and deeper tailwater depths than those available on average. Approximately 0.5 hr after a tide gate opens, these two variables (as well as water velocity) reach their maximum for each gate open period. At the top-hinged gate, smolts showed a clear tendency to pass downstream early in the gate open period, whereas no clear pattern existed at the side-hinged gate. This suggests that smolts do not necessarily congregate above the gate before it opens. More likely, high velocities early in the open period force fish to pass downstream. Velocities at the top-hinged gate were considerably higher than at the side-hinged gate where the pattern of early downstream passage was not observed. Unfortunately, a high margin of error in our back-calculations of velocities (using gate angles and tailwater depths) prevented the use of velocity data in any statistical analyses. A final explanation for the early downstream passage pattern observed at the top-hinged tide gate is that smolts may approach the tide gate throughout the open period but many avoid downstream passage unless conditions are appropriate. Emigrating salmonid smolts tend not to pass downstream over shallow obstacles, through tight constrictions, under overhead cover, or where there are sudden increases in velocity (Haro et al., 1998; Kemp et al., 2005, 2008; Enders et al., 2009). As the top-hinged gate open period progresses, the gate opening narrows, water depth above the tide gate floor shallows, and a zone of sudden acceleration is created as tailwater decreases. Therefore, conditions for downstream passage may be best early on in the opening cycle. In contrast, the side-hinged gate doors open wider than the top-hinged for a similar hydraulic head differential, the tide gate floor is always submerged at least 1 m, and the small difference between headwater and tailwater depths creates little flow acceleration. Thus, conditions for downstream passage are adequate across a longer period and no pattern of early passage exists.

The tide box structure and the gate doors at the side-hinged gate created less overhead cover than was the case at the top-hinged gate.

Due to the turbulence created by the flowing top-hinged gate, we expected that juvenile coho salmon would select a specific range of gate angles and tailwater depths for upstream passage. While smolts did not behave as expected, subyearlings preferred a range of small gate angles and a narrow range of tailwater depths. During the lower daily low tide these conditions were limited to the last 0.5 - 1.0 hr of the gate open period. During the higher daily low tide, subyearlings could pass upstream throughout a greater proportion of the open period because tailwater depth did not drop as low and gate angles (as well as velocities) were not as great as during the lower tide. As a result, during spring tide cycles (characterized by very low tides and a large tidal exchange) conditions conducive to upstream passage by subyearling coho were present only for a small portion of the single daily open period. During neap tide cycles (moderate low tides and a minimal exchange) the top-hinged gate opened twice per day with low angles and no waterfall condition allowing more than 3 hrs for subyearling upstream passage. We assumed that subyearlings could pass upstream throughout the side-hinged gate open periods recorded in June. Therefore, during spring tides more upstream passage time was available at the side-hinged gate than the top-hinged gate. During neap tides the opposite was true. Maintaining gate opening at each low tide will maximize passage opportunities for juvenile salmonids and is best accomplished by allowing the reservoir to replenish by estuarine backflow.

Our results indicate that the Larson side-hinged tide gate offers more suitable juvenile fish passage conditions than the Palouse top-hinged gate. From a landowner perspective, side-hinged gates with low invert elevations are likely to be considered more effective than top-hinged, shallow gates. Since they open to greater angles than top-hinged gates, side-hinged gates are less likely to jam with woody debris. Unfortunately, side-hinged gates generally cost more to install and "do-it-yourself" constructions are impractical. Low tide gate invert elevations are also desirable to landowners since they drain the reservoir more thoroughly and reduce siltation. However, while lower inverts may allow more opportunity for fish passage, they may also reduce beneficial nursery habitat by draining the reservoir more efficiently and leaving juvenile salmonids exposed in small pockets of shallow water. Hence, maintaining habitat complexity with large wood structure and increased channel diversity may provide refuge to fish during low water periods.

To survive acclimation to the estuary, subyearling coho salmon "nomads" must be able to access habitats that provide appropriate salinities, temperatures, oxygen concentrations and food abundance. The small size of young fish limits their swimming capability and tide gates that create high water velocities and outlet waterfalls will prove impassable for a large proportion of individuals during most of each open period. In June, nomads in the estuary appeared to be highly motivated to move upstream of the tide gates we monitored; there may have been negative consequences for those that failed to pass. If the nomad life history strategy observed in coastal coho salmon is expressed by a particular gentoype, then tide gates may exert a selective force against it. Alternatively, if this strategy is one of various expressions of a flexible phenotype and is condition dependent (e.g., stream flow or fry density), tide gates may simply reduce the abundance of a particular cohort and its subsequent contribution to the population size. Regardless of the mechanisms behind it, this estuarine based life history may serve as a bet hedging strategy that supports the population in years when stream conditions are poor. Bottom et al. (2005a) found that removal of dikes and restoration of salt marshes in the Salmon River estuary (Oregon) resulted in the reappearance of an estuarine life history strategy among juvenile chinook salmon. In the fall of 2009 we detected 9 coho salmon jacks PIT tagged as subyearling reservoir residents in spring 2008, suggesting that coho nomads do contribute to the spawning population. As demonstrated by Koski (2009), coho nomads can act as a source population capable of colonizing available nursery habitat. As a result of this dispersal behavior, nomads may have a propensity to stray from their natal stream as spawners, providing gene flow between populations. By affecting coho salmon nomads to a greater extent than other life history types, tide gates may reduce the potential productivity boost and resilience that this life history may contribute to natal and neighboring populations.

By disconnecting upstream aquatic habitat from estuarine influence, tide gates alter reservoir temperature and salinity regimes. We assessed the effect of selected environmental variables on coho salmon smolt emigration in three systems and found that changes in temperature and salinity affect the likelihood of emigration. In the stream and reservoir sections of Palouse Creek as well as at the antenna array in Winchester Creek, increasing temperatures were associated with a higher likelihood of smolt emigration. At the Palouse Creek tide gate (which allows some estuarine influence), increasing salinity concentration was associated with a decreasing likelihood of smolt emigration. At the Larson Creek tide gate (which is well sealed), neither of these two factors showed any influence on emigration but increases in precipitation during the previous 48 hrs were associated with an increase in smolt emigration likelihood.

Premature smolt emigration due to temperature has been linked to a detrimental mismatch with ocean conditions (Kennedy and Crozier, 2010). Under certain conditions, tide gate reservoirs can rapidly warm. Estuarine water, if allowed to partially flood the reservoir, may reduce high reservoir temperatures. A low tide gate invert elevation will rapidly drain a reservoir, creating room for cooler water from forested stream reaches. Shade from riparian vegetation can also improve temperature conditions in the tide gate reservoir.

Smolts migrating downstream through a tide gated system with no salinity gradient above the dike may exit the tide gate, abruptly experience high salinities, and be unable to move back upstream. By contrast, smolts in a non-gated system may migrate back and forth between the upper estuary and the lower reaches of the stream to gradually adjust to increasing salinity. In fact, coho salmon smolts in a non-gated stream moved upstream and downstream through a PIT antenna array many more times than smolts in the tide gated systems. One smolt that left Palouse Creek in early April was detected at the Winchester antenna array 12 days later. It spent over two weeks in Winchester Creek, behaving very similarly to smolts from that system by moving upstream and downstream once daily at similar times each day. Although anecdotal evidence, this smolt may have been unprepared for the open ocean and temporarily returned to lower salinities to slowly acclimate. By maintaining a salinity gradient in the reservoir, tide gates that permit some estuarine intrusion allow smolts more time to acclimate to brackish conditions before passing downstream.

In addition to positively effecting the temperature and salinity regimes in reservoirs, allowing estuarine influence to tide gates will have other benefits. Studying tidal wetland ecosystems in northern California, Ritter et al. (2008) found that plant and animal communities with moderately restricted tidal exchange were similar to those with full exchange while those with extremely restricted exchange were markedly different. Water quality characteristics determined by tidal restriction strongly influence patterns of species presence or absence. The leaky top-hinged gate at Palouse Creek allows an estuarine ecosystem to persist in the reservoir. Large beds of eelgrass, *Zostera marina*, are found here and in Winchester Creek but not upstream of the well-sealed side-hinged gate at Larson Creek. Eelgrass provides excellent nursery habitat for salmonids (Semmens, 2008) and a variety of other estuarine fish and organisms. Maintaining some salinity in the reservoir may also prevent the establishment of invasive freshwater invertebrates, fish and plants.

This study did not address the issue of predation, likely a problem at tide gates (but see appendix D). Dikes spatially constrain tide channels so that water is funneled through tide gates, creating a small area that predators may exploit (Mather, 1998). Since tide gates open at most twice per day, emigrating salmonids will exit in predictable pulses that predators may learn to anticipate. The rapid transition from freshwater to higher salinities created by tide gates may reduce salmonid ability to evade predators (Handeland et al., 1996; Kennedy et al., 2007). Passage through hydraulic features created by tide gates might break up schools, leaving individuals more vulnerable. Birds, fish, and marine mammals might utilize tide gates as feeding stations. Anecdotally, we did observe avian predation downstream of the tide gates although we were unable to identify prey items. On April 6, 2009 we counted over 50 double crested cormorants, *Phalacrocorax auritus*; 10 caspian terns, *Hydroprogne caspia*; 40 great egrets, *Ardea alba*; and a great blue heron, *Ardea herodias*, simultaneously feeding within 100 m downstream of the top-hinged tide gate. This large aggregation of piscivorous birds was not present prior to the tide gate opening. Harbor seals, *Phoca vitulina* were sighted downstream of the tide gates during smolt outmigration and adult return (california sea lions, *Zalophus californianus*, were reported during adult return as well). Returning adults often hold downstream of tide gates and must pass through a constriction where they are vulnerable to predation, similar to steelhead entering fish ladders at Ballard Locks in Washington that were heavily preyed upon by sea lions (Gearin et al., 1988). Because some tide gate styles and installations may be easier for predators to exploit than others and the degree of predation around tide gates is currently unknown, research on this topic is needed.

The repair, upgrading, and installation of tide gates is complicated by the fact that their location, design, and purpose varies considerably between sites. Tide gates may drain into a wide spectrum of environments from polyhaline lower estuaries to tidally influenced coastal streams. Habitat upstream of tide gates may include streams with spawning habitat for salmonids or brackish lagoons that only receive freshwater input from rain. Lagoons can provide beneficial nursery habitat for juvenile salmonids during winter months but act as a high temperature, anoxic death trap in summer months. All of these factors will determine whether a tide gate that permits fish passage and estuarine intrusion is appropriate. However, the complexities of creating tide gate standards should not overwhelm regulatory efforts. Tide gates that do not allow adequate fish passage or negatively alter nursery habitat prevent estuaries and surrounding habitat from reaching their full potential as productive salmon habitat. Among Oregon's 17 largest estuaries, close to 70% of tidal wetland was disconnected from the estuary from 1870 to 1970 (Good, 2000). In many locations, removal or alteration of tide gates could return some connectivity and increase the functional area of the estuary. Worldwide, an estimated 70% of the world's coastal wetlands could be lost by 2080 due to anthropogenic alterations coupled with sea level rise (Nicholls et al., 1999). To ensure that estuaries continue to provide important ecosystem functions for estuarine dependent organisms, it is essential that we maintain connectivity through tidally influenced habitats.

APPENDICES

Appendix A – Water Temperatures in Tide Gate Reservoirs

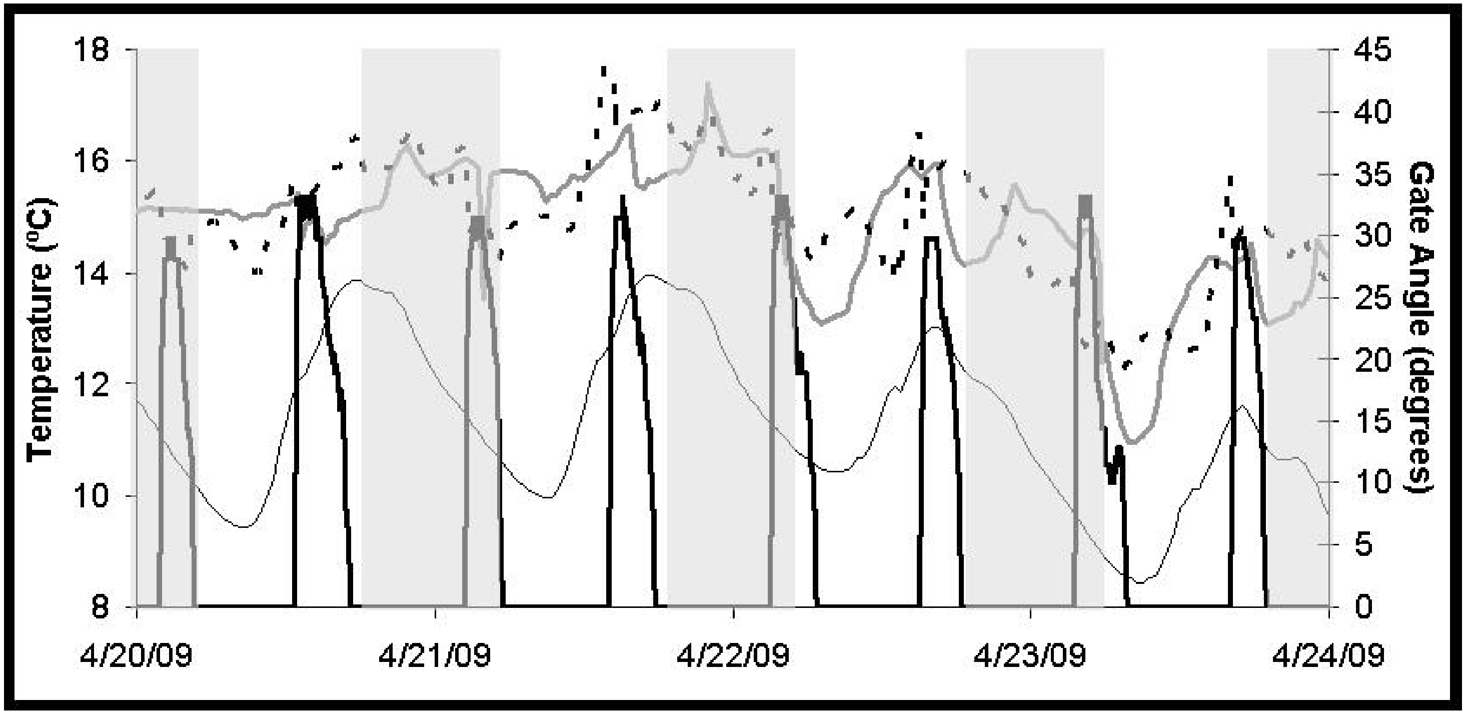

Figure A.1: Water temperatures for the Palouse reservoir (thick gray line), bay (dashed line), and Rkm 6 (thin black line). Gate open periods are indicated by the gate angle (thick black line). Gray shaded areas represent night time (sundown to sunrise). This period represents typical conditions during the smolt emigration period (April-June), reservoir and bay temperatures were often similar.

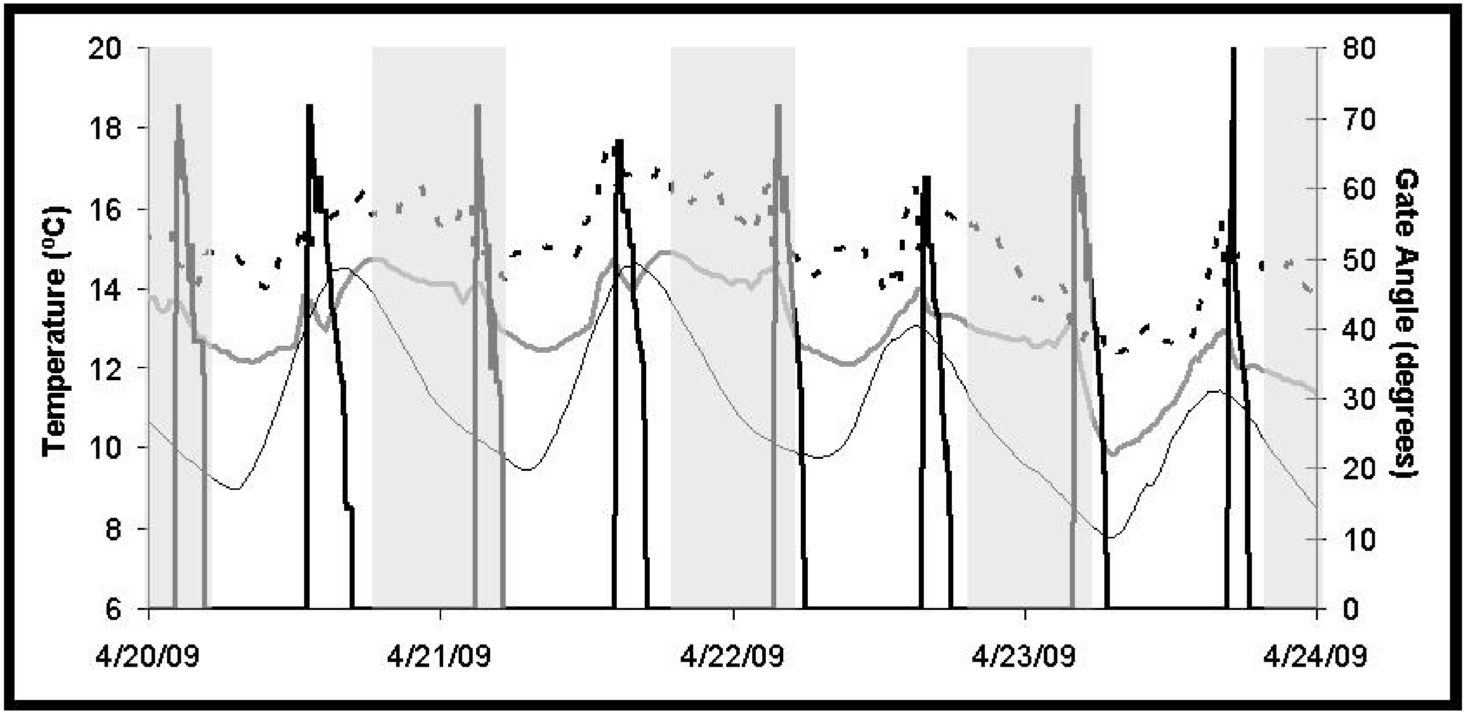

Figure A.2: Water temperatures for the Larson reservoir (thick gray line), bay (dashed line), and Rkm 6 (thin black line). Gate open periods are indicated by the gate angle (thick black line). Gray shaded areas represent night time (sundown to sunrise). This period represents typical conditions during the smolt emigration period (April-June), the Larson reservoir was often several degrees cooler than the bay.

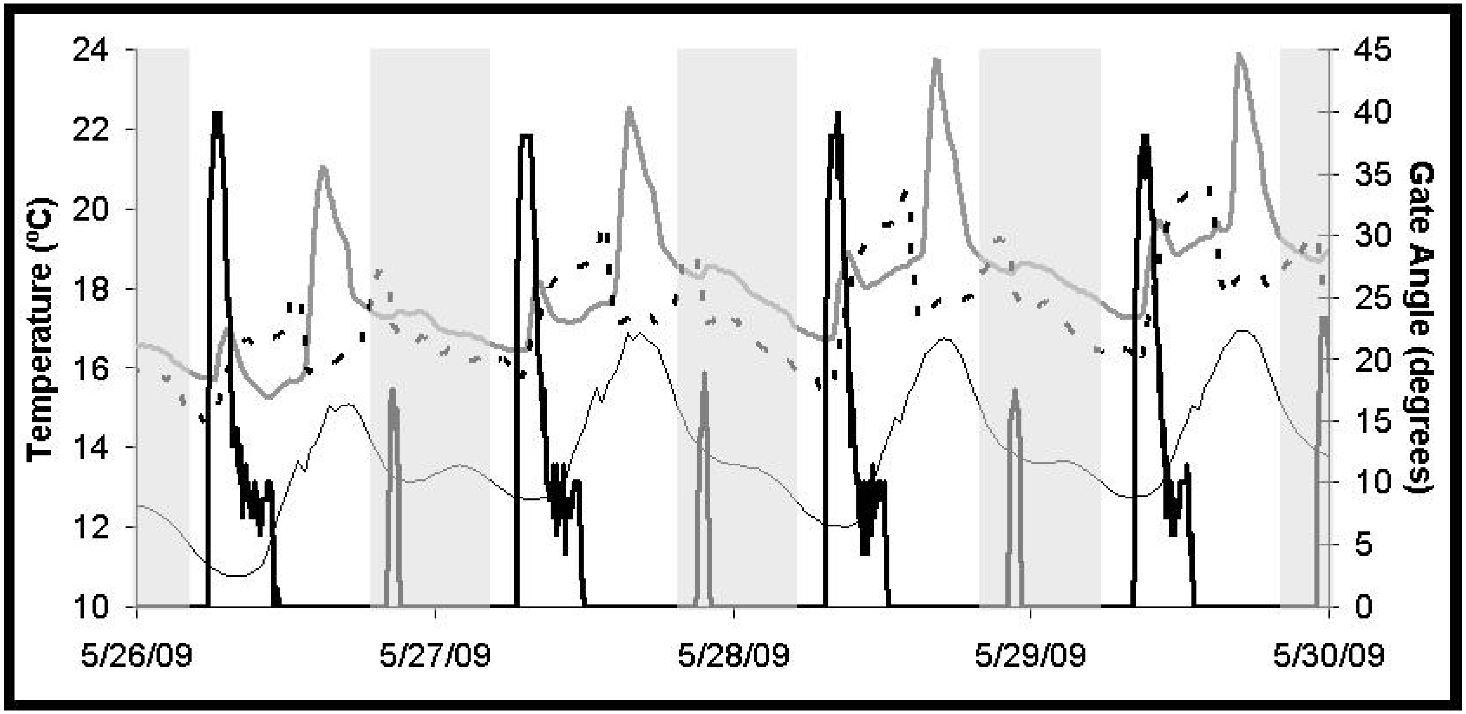

Figure A.3: Water temperatures for the Palouse reservoir (thick gray line), bay (dashed line), and Rkm 6 (thin black line). Gate open periods are indicated by the gate angle (thick black line). Gray shaded areas represent night time (sundown to sunrise). This period represents abnormally high temperatures in the reservoir. Long gate open periods followed by high mid day temperatures caused the reservoir temperature to spike until it was reduced by bay water flooding through the leaky gate.

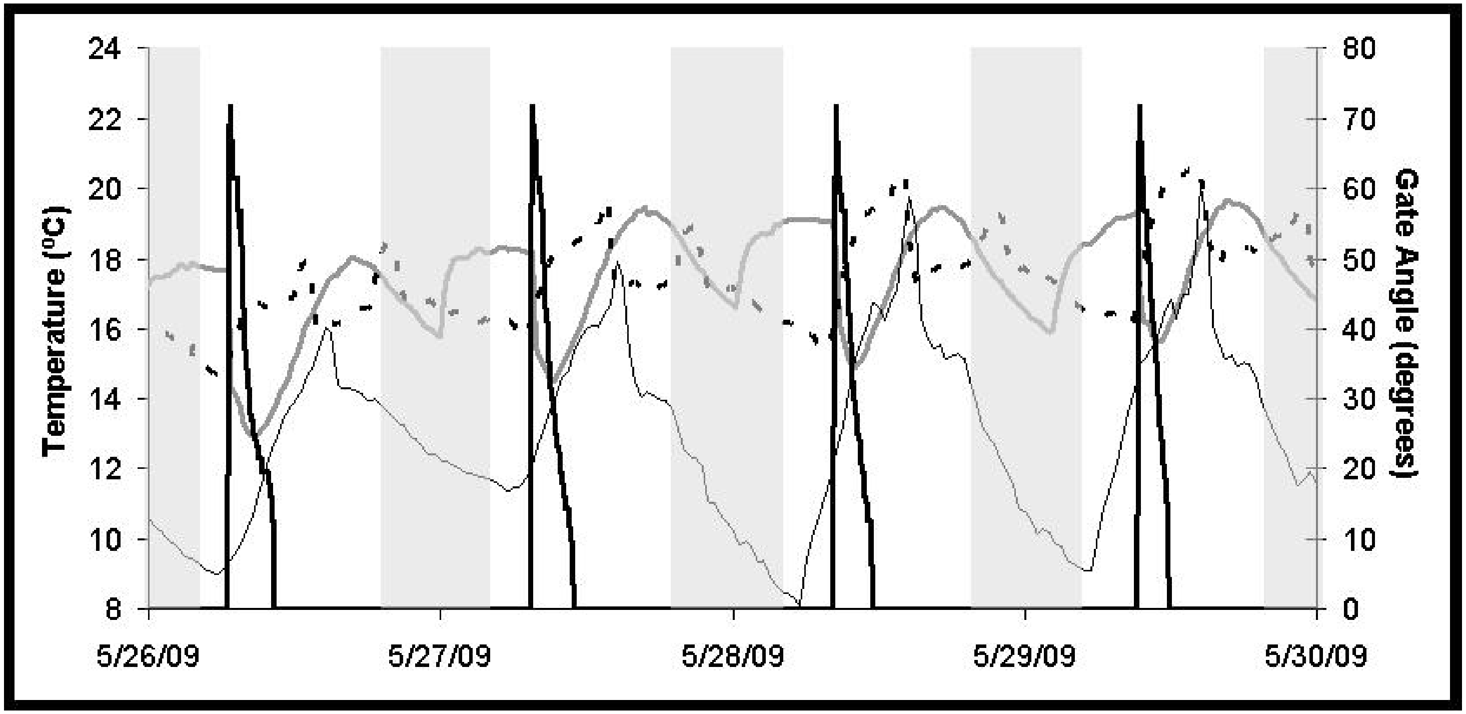

Figure A.4: Water temperatures for the Larson reservoir (thick gray line), bay (dashed line), and Rkm 6 (thin black line). Gate open periods are indicated by the gate angle (thick black line). Gray shaded areas represent night time (sundown to sunrise).This period represents abnormally high temperatures in the reservoir. The cause of the trough in reservoir temperature occurring during night periods is unknown.

Appendix B – Water Velocities Recorded at Tide Gates and a Non-Gated Stream

For water velocity measurement methods, see Section 2.2.5.

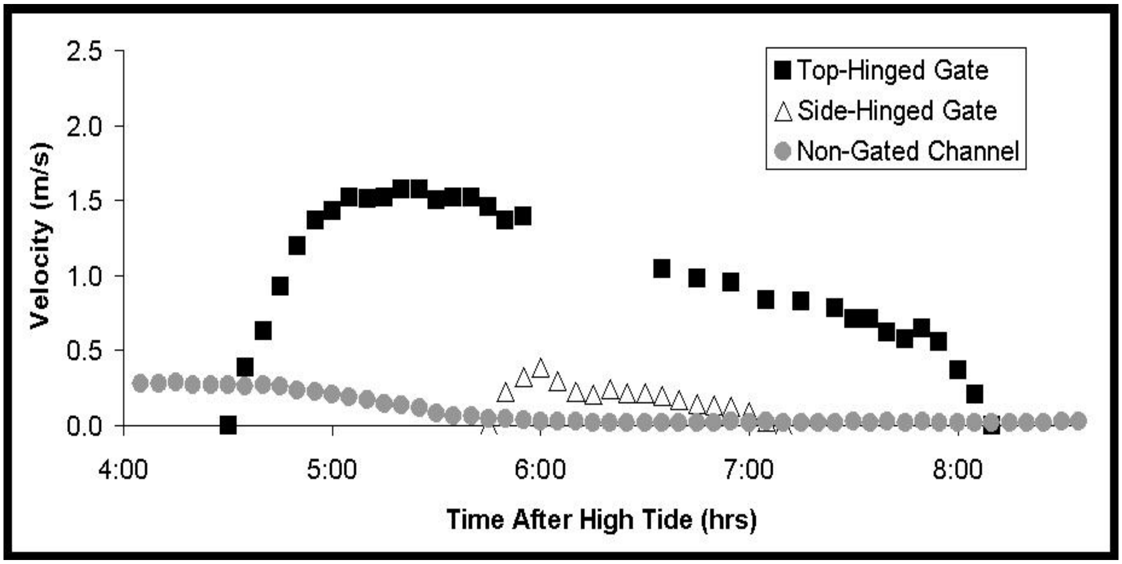

Figure B.1: Water velocities recorded during low flow conditions at a top-hinged tide gate (10/6/09), a side-hinged gate (10/8/09), and a non-gated channel (10/12/09). Measurements at the tide gates were recorded with a portable flow meter, measurements at the non-gated channel were recorded with an acoustic doppler velocity meter.

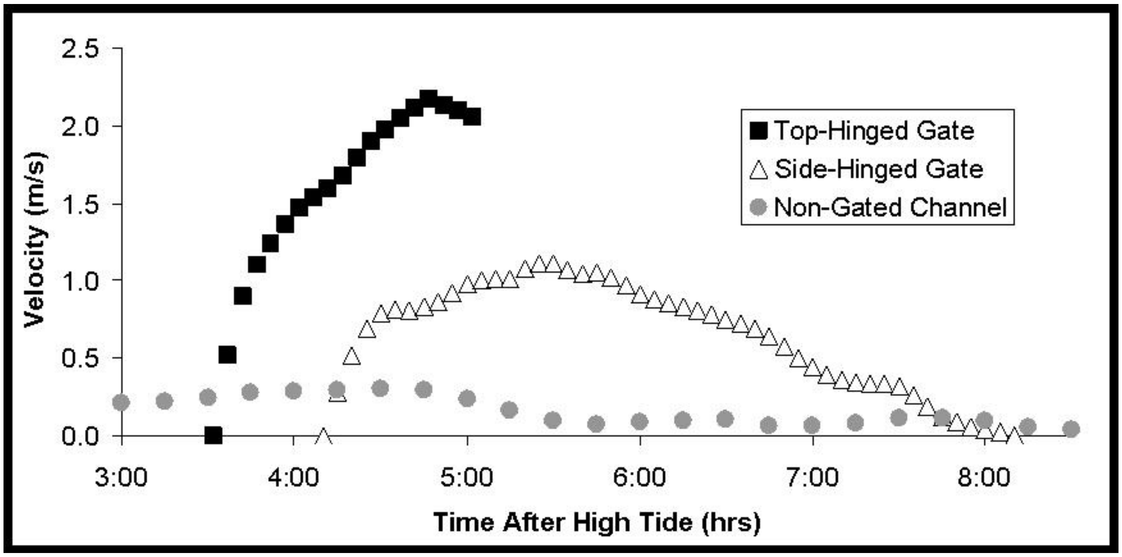

Figure B.2: Water velocities recorded during high flow conditions at a top-hinged tide gate (11/17/09), a side-hinged gate (12/2/09), and a non-gated channel (11/28/09). Measurements at all sites were recorded with an acoustic doppler velocity meter. Approximately 5 hr after the high tide, the water depth inside the top-hinged tide gate was too shallow for the velocity meter to properly operate.

Appendix C – Diagnostics for Cox Proportional Hazards Regression

Table C.1: Results of likelihood ratio goodness of fit tests for all sites using Cox proportional hazards regression. All results are for reduced models selected by stepwise regression. LRT is the likelihood ratio test statistic (chi-square).

Model	LRT	DF	*P* value
Larson Gate	11.72	7	0.11
Winchester Array	15.09	9	0.09
Palouse Stream	21.69	9	0.01
Palouse Reservoir	9.22	9	0.42
Palouse Gate	13.26	9	0.15

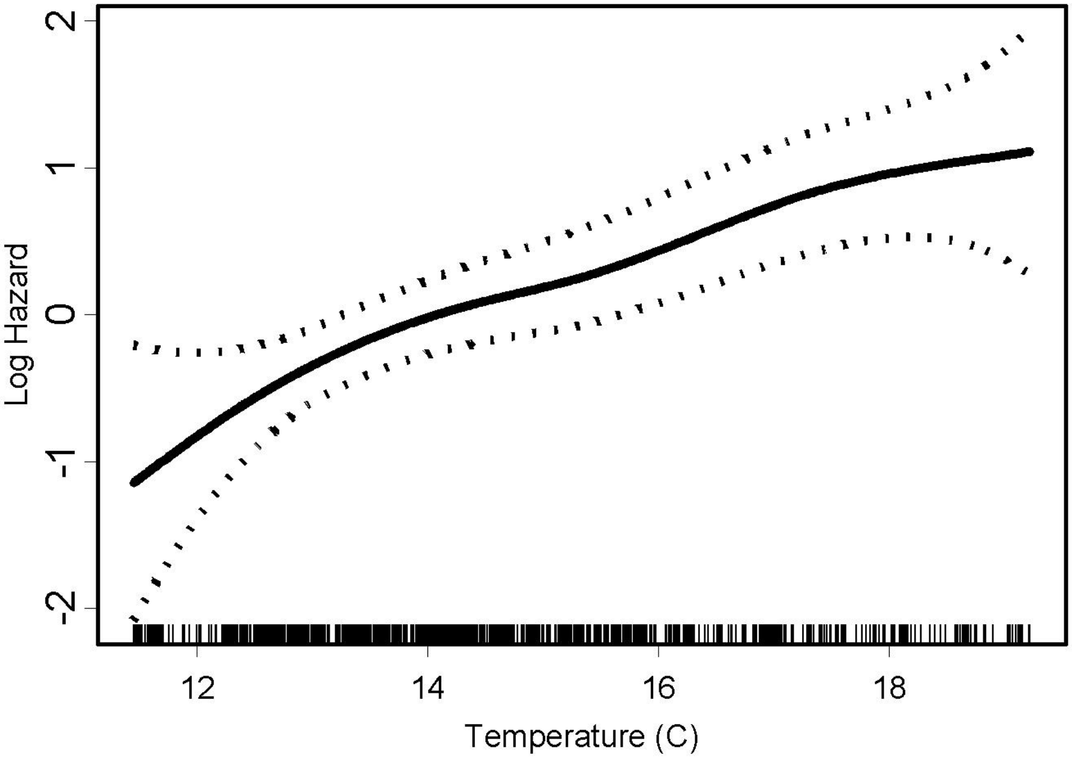

Figure C.1: Smoothing spline fit for temperature in the Palouse reservoir section. The log of the fitted hazard is the black line. The dotted lines are the 95% confidence interval. A straight line can be drawn through the confidence intervals, suggesting that no transformation of this variable is required.

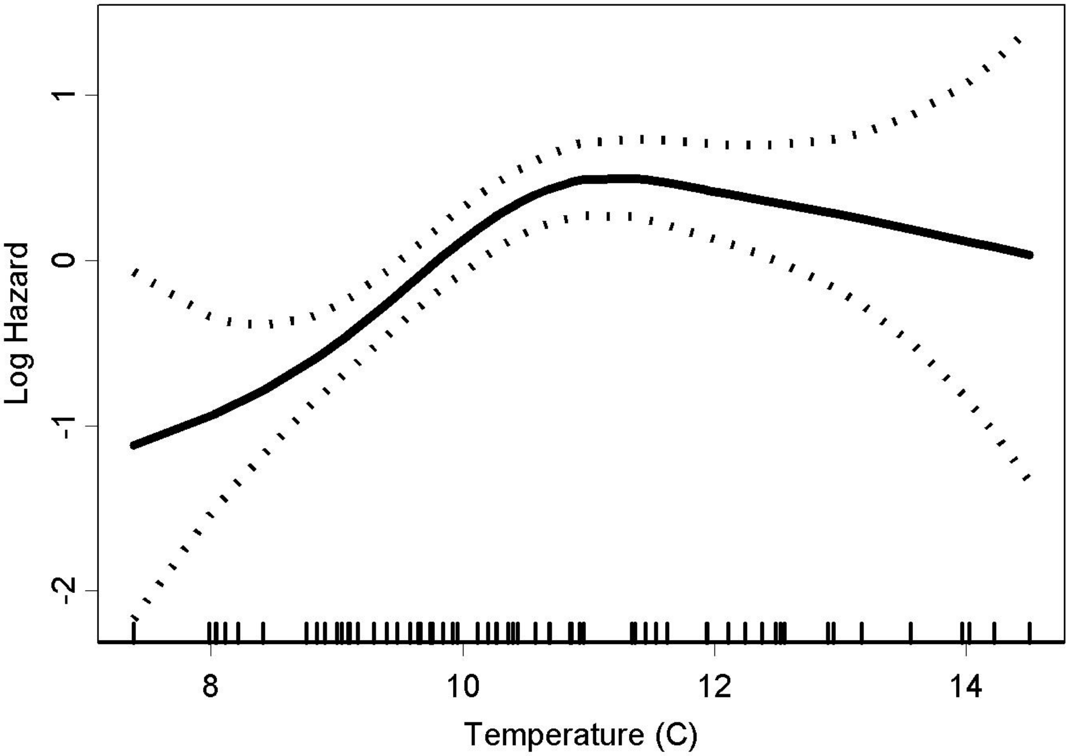

Figure C.2: Smoothing spline fit for temperature in the Palouse stream section. The log of the fitted hazard is the black line. The dotted lines are the 95% confidence interval. A straight line cannot be drawn through the confidence intervals, but transformations did not improve the spline. The shape of this spline is relatively linear aside from the sudden increase in the log hazard from 10 to 12 °C. Researchers have suggested that most coho smolt emigrate before 12°C, that may explain the sudden increase in log hazard.

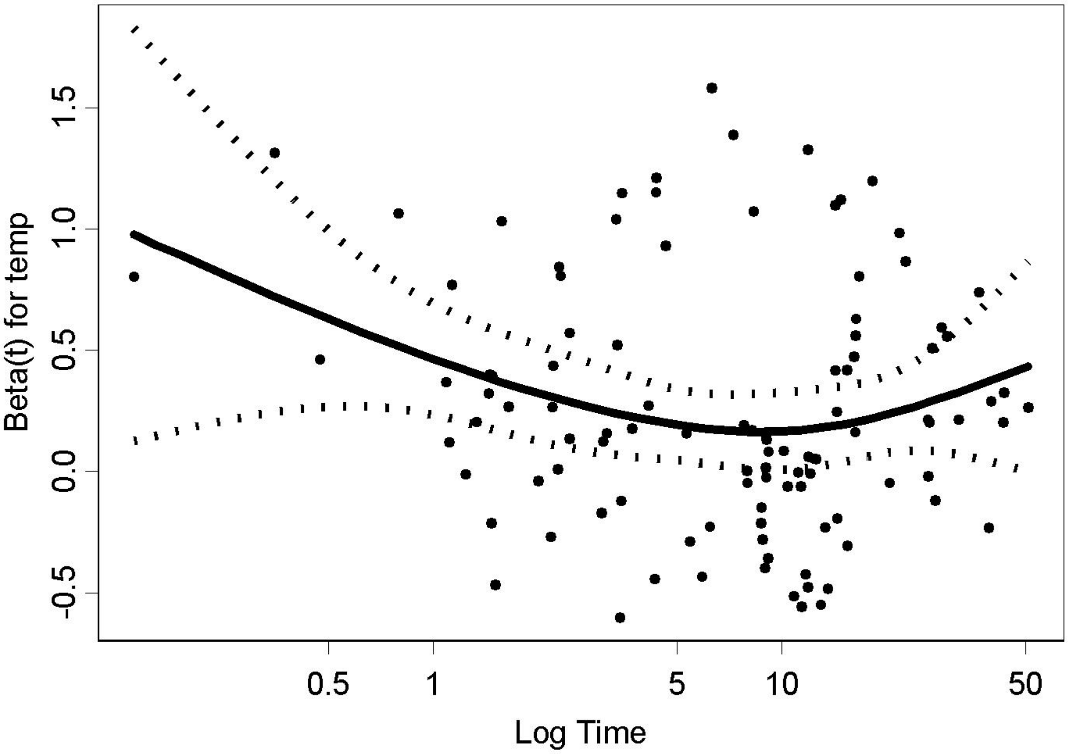

Figure C.3: Plot of scaled Schoenfeld residuals for temperature in the Palouse reservoir over the log of time. The black line is the least squares fit and the dotted lines represent a 95% confidence interval. If the slope of the fit is significantly different from 0, there may be a violation of the proportional hazards assumption (here $p = 0.19$). Time is log transformed to stretch out the data which would otherwise be very right-tailed. A Schoenfeld residual exists for each passage event and its distance from 0 indicates whether an individual passed early (negative) or late (positive) based on the model fit of the predictor variable, in this case temperature.

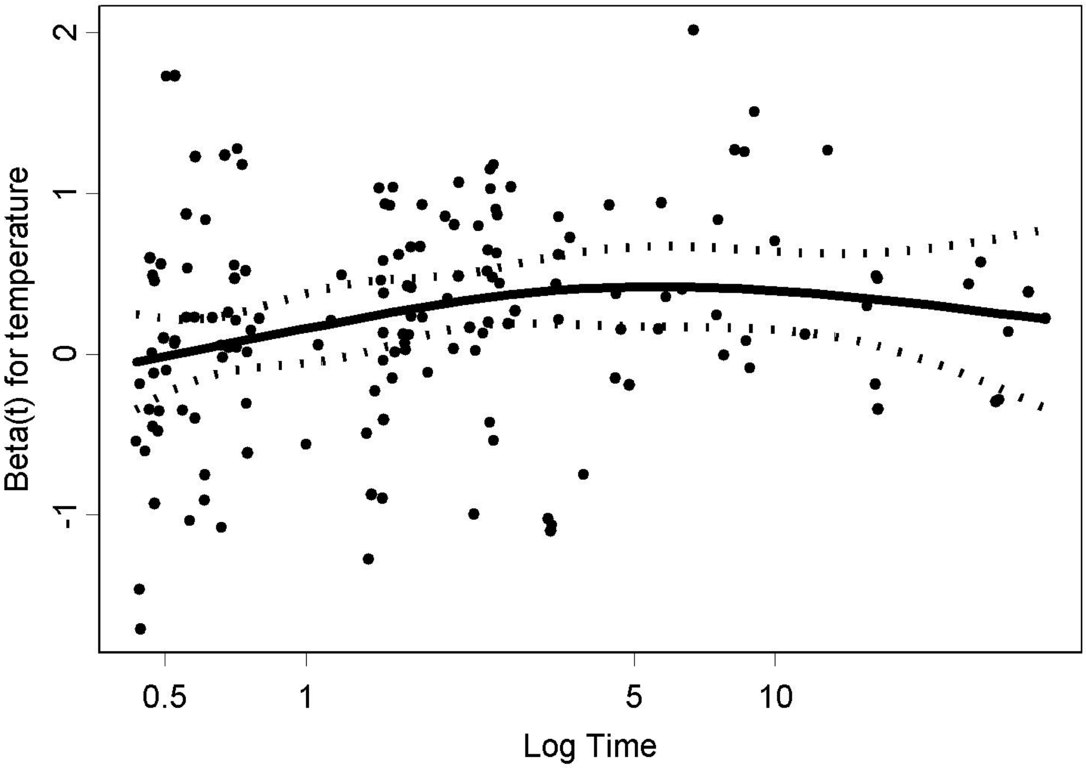

Figure C.4: Plot of scaled Schoenfeld residuals for temperature in the Palouse stream reach over the log of time. The black line is the least squares fit and the dotted lines represent a 95% confidence interval. In this instance, the fit is significantly different from 0 ($p = 0.04$). However, the line barely deviates from 0 and removing 4 potential outliers in the bottom left corner (they are stacked) resulted in a non-singificant slope.

Table C.2: Test of Proportional Hazards Assumption

Site	Variable	Pearson R	Chi-Sq	*P*
Palouse Stream	Temperature	0.19	4.42	0.04[1]
	Fork Length	-0.09	1.16	0.28
	Precipitation	-0.08	0.56	0.46
	Origin	0.13	2.59	0.11
	Global	–	7.75	0.10
Palouse Reservoir	Temperature	-0.14	1.72	0.19
	Fork Length	0.09	0.81	0.37
	Global	–	2.80	0.25
Palouse Tide Gate	Temperature	0.21	2.38	0.12
	Fork Length	0.009	0.004	0.95
	Precipitation	-0.19	3.11	0.08
	Origin	-0.23	3.00	0.08
	Salinity	0.18	2.07	0.15
	Global	–	3.00	0.04[2]
Larson Tide Gate	Precipitation	-0.38	2.43	0.12
Winchester Creek	Temperature	0.40	7.85	0.005[3]
	Fork Length	-0.03	0.03	0.87
	Global	–	8.30	0.02[3]

[1]After removing 4 outliers, this was no longer significant

[2]Although the global test is significant, the variables of interest in the model (salinity and fork length) met the proportional hazards assumption

[3]After removing two outliers from the temperature plot, this was no longer significant

Appendix D – PIT Tag Detections at a Double Crested Cormorant Colony

We observed a large number of double crested cormorants, *Phalacrocorax auritus*, foraging downstream of the tide gates, especially when they were open. Since we were unable to identify their prey by direct observation, we scanned the ground under a nearby colony (3 km southwest of tide gates, at the mouth of Haynes Inlet) for PIT tags. The vegetation strip where the cormorants roost between the bay and the road is approximately a 35,000 m^2 area. We scanned approximately 10,000 m^2 of the colony although many areas were difficult to access due to thick vegetation. Birds roost and nest primarily in large firs. Nests were visible and roost locations were evident from bird feces. We used Destron Fearing 2001F transceivers (St. Paul, MN) with a portable antenna system (Biomark, Boise, ID). So that we could measure our tag detection efficiency, a technician who did not participate in scanning sowed 26 12 mm and 12 8 mm PIT tags in the portion of the colony that we scanned.

We detected 18 and 3 of the 12 and 8 mm test tags, respectively. Therefore, our detection efficiency for 12 mm tags was 69% and 25% for 8 mm tags. In total, we detected 33 PIT tags from fish in the cormorant colony. We detected 5 tags that were not from our project (Table D). All but one of the 28 tags from our project that we detected were from coho salmon. While we can not determine exactly when and where the fish were taken, tagging and array detection dates indicate that coho salmon were predominately captured in their smolt stage.

Table D.1: Tagging and antenna array detection information for PIT tags recovered at a cormorant colony at the mouth of Haynes Inlet.

Tagcode	Species	FL @ Tagging (mm)	Tag Date	Tag Site	Date Last Detected	Site Last Detected
3D9.1BF11B4AC2	*O. kisutch*	125	2/20/03	Pendelton, OR	5/8/03	Bonneville Dam, OR
3D9.1BF18FC10C	*O. kisutch*	?	2/?/03	West Fork Smith River, OR	–	–
3D9.1BF203D48E	–	–	–	–	–	–
3D9.1BF207F16B	?	?	2005?	Zarembo Island, AK?	–	–
3D9.1BF20BA51A	?	?	2005?	Zarembo Island, AK?	–	–
3D9.1C2CBC1402	*O. kisutch*	115	4/21/09	Larson Rkm 0	4/23/09	U/S Larson TG
3D9.1C2CBC2E07	*O. kisutch*	66	9/24/08	Palouse Rkm 11	–	–
3D9.1C2CBC7487	*O. kisutch*	84	4/10/08	Palouse Rkm 6	–	–
3D9.1C2CBC74D6	*O. kisutch*	111	4/13/08	Palouse Rkm 6	5/2/08	U/S Palouse TG

Tagcode	Species	FL @ Tagging (mm)	Tag Date	Tag Site	Date Last Detected	Site Last Detected
3D9.1C2CBC77F3	*O. kisutch*	112	4/18/08	Palouse Rkm 6	–	–
3D9.1C2CBC7BAA	*O. kisutch*	95	5/2/08	Palouse Rkm 6	–	–
3D9.1C2CBD4654	*O. kisutch*	100	4/29/08	Palouse Rkm 6	5/16/08	U/S Palouse TG
3D9.1C2CBD5A1E	*O. kisutch*	84	8/6/08	Palouse Rkm 2.7	–	–
3D9.1C2CC30C19	*O. kisutch*	88	4/6/08	Palouse Rkm 6	–	–
3D9.1C2CC30C60	*O. mykiss*	83	4/6/08	Palouse Rkm 6	–	–
3D9.1C2CC3CD27	*O. kisutch*	88	4/6/08	Palouse Rkm 6	4/20/08	U/S Palouse TG
3D9.1C2CC3D03B	*O. kisutch*	116	4/24/08	Palouse Rkm 0	4/25/08	U/S Palouse TG
3D9.1C2CC3D366	*O. kisutch*	72	6/11/08	Palouse Rkm 1.8	5/3/09	U/S Palouse TG
3D9.1C2CC3DDB7	*O. kisutch*	86	4/21/08	Palouse Rkm 6	–	–
3D9.1C2CC401A7	*O. kisutch*	92	4/21/08	Palouse Rkm 6	–	–
3D9.1C2CC402D1	*O. kisutch*	81	9/24/08	Palouse Rkm 11	5/2/09	U/S Palouse TG
3D9.1C2CC4057A	*O. kisutch*	104	4/13/08	Palouse Rkm 6	4/17/08	U/S Palouse TG
3D9.1C2CC408D6	*O. kisutch*	86	4/11/08	Palouse Rkm 6	–	–

Tagcode	Species	FL @ Tagging (mm)	Tag Date	Tag Site	Date Last Detected	Site Last Detected
3D9.1C2CC40D00	*O. kisutch*	108	4/24/09	D/S Palouse TG	5/7/08	D/S Palouse TG
3D9.1C2D09FD21	*O. kisutch*	71	7/22/09	Larson Rkm 1.3	–	–
3D9.1C2D0A0B76	*O. kisutch*	120	5/13/09	Larson Rkm 0	–	–
3D9.1C2D0AFB4A	*O. kisutch*	109	4/4/09	Palouse Rkm 6	4/24/09	D/S Palouse TG
3D9.1C2D0B02E0	*O. kisutch*	115	4/8/09	Larson Rkm 0	4/10/09	D/S Larson TG
3D9.1C2D0B501E	*O. kisutch*	94	3/22/09	Larson Rkm 6	5/3/09	U/S Larson TG
3D9.1C2D0B9F26	*O. kisutch*	120	4/6/09	Palouse Rkm 0	5/3/09	D/S Palouse TG
3D9.1C2D0C0512	*O. kisutch*	105	4/7/09	Palouse Rkm 2.9	5/15/09	U/S Palouse TG
3D9.1C2D10A386	*O. kisutch*	105	4/8/09	Larson Rkm 0	–	–
3D9.1C2D23FC7D[1]	*O. mykiss*	54	5/30/09	Larson Rkm 0	7/9/09	U/S Larson TG

[1] This was the only 8 mm PIT tag (aside from test tags) detected.

Bibliography

Acolas, M. L., Roussel, J. M., Lebel, J. M., and Bagliniere, J. L. (2007). Laboratory experiment on survival, growth and tag retention following PIT injection into the body cavity of juvenile brown trout (*Salmo trutta*). *Fisheries Research*, 86(2):280–284.

Allison, P. (1999). *Logistic regression using the SAS system: theory and application.* SAS Publishing.

Anderson, M. (2009). Migratory behavior and passage of redband trout (Oncorhynchus mykiss) in the Donner und Blitzen River, Oregon.

Anisfeld, S. C. and Benoit, G. (1997). Impacts of flow restrictions on salt marshes: An instance of acidification. *Environmental Science and Technology*, 31(6):1650–1657.

Anisfeld, S. C., Tobin, M. J., and Benoit, G. (1999). Sedimentation rates in flow-restricted and restored salt marshes in long island sound. *Estuaries and Coasts*, 22(2):231–244.

Bates, K. and Powers, P. (1998). Upstream passage of juvenile coho salmon through roughened culverts. *Fish Migration and Fish Bypasses.*, pages 192–202.

Bjerknes, V., Duston, J., Knox, D., and Harmon, P. (1992). Importance of body size for acclimation of underyearling Atlantic salmon parr (*Salmo salar*) to seawater. *Aquaculture*, 104(3-4):357–366.

Bohlin, T., Dellefors, C., and Faremo, U. (1996). Date of smolt migration depends on body-size but not age in wild sea-run brown trout. *Journal of Fish Biology*, 49(1):157–164.

Bond, M. H., Hanson, C. V., Baertsch, R., Hayes, S. A., and MacFarlane, R. (2007). A new (low-cost) instream antenna system for tracking passive integrated transponder (PIT)-Tagged fish in small streams. *Transactions of the American Fisheries Society*, 136(5):562–566.

Bottom, D., Jones, K., Cornwell, T., Gray, A., and Simenstad, C. (2005a). Patterns of Chinook salmon migration and residency in the Salmon River estuary (Oregon). *Estuarine, Coastal and Shelf Science*, 64(1):79–93.

Bottom, D., Simenstad, C., Burke, J., Baptista, A., Jay, D., Jones, K., Casillas, E., and Schiewe, M. (2005b). Salmon at river's end: the role of the estuary in the decline and recovery of Columbia River salmon. *NOAA Technical Memorandum NMFS NWFSC*, 68.

Brown, R., Cooke, S., Anderson, W., and McKinley, R. (1999). Evidence to challenge the 2% rule for biotelemetry. *North American Journal of Fisheries Management*, 19:867–871.

Burnham, K. and Anderson, D. (2002). *Model selection and multimodel inference: a practical information-theoretic approach*. Springer Verlag.

Burrows, R., Ockleston, G. A., and Ali, K. H. M. (1997). Flow estimation from flap-gate monitoring. *Journal of the Chartered Institution of Water and Environmental Management*, 11(5):346–356.

Carlsen, K., Berg, O., Finstad, B., and Heggberget, T. (2004). Diel periodicity and environmental influence on the smolt migration of Arctic charr, *Salvelinus alpinus*, Atlantic salmon, *Salmo salar*, and brown trout, *Salmo trutta*, in northern Norway. *Environmental Biology of Fishes*, 70(4):403–413.

Castro-Santos, T. and Haro, A. (2003). Quantifying migratory delay: a new application of survival analysis methods. *Canadian Journal of Fisheries and Aquatic Science*, 60:986–996.

Caudill, C., Daigle, W., Keefer, M., Boggs, C., Jepson, M., Burke, B., Zabel, R., Bjornn, T., and Peery, C. (2007). Slow dam passage in adult Columbia River salmonids associated with unsuccessful migration: delayed negative effects of passage obstacles or condition-dependent mortality? *Canadian journal of fisheries and aquatic sciences*, 64(7):979–995.

Charland, J. (1998). Tide gate modifications for fish passage and water quality enhancement. *Tillamook Bay National Estuary Project, Garibaldi, Oregon.*

DeVries, P., Goetz, F., Fresh, K., and Seiler, D. (2004). Evidence of a lunar gravitation cue on timing of estuarine entry by pacific salmon smolts. *Transactions of the American Fisheries Society*, 133(6):1379–1395.

Easton, C. and Marshall, A. (2000). Control of acidic drain-water-breeding mosquitoes in New South Wales, Australia, by installing controlled leakage holes in tidal flap gates. *Journal of the American Mosquito Control Association*, 16(1):19–21.

Enders, E. C., Gessel, M. H., and Williams, J. G. (2009). Development of successful fish passage structures for downstream migrants requires knowledge of their behavioural response to accelerating flow. *Canadian Journal of Fisheries and Aquatic Science*, 66:2109–2117.

Flagg, T. and Smith, L. (1981). Changes in swimming behavior and stamina during smolting of coho salmon. In Brannon, E. L. and Salo, O., editors, *Proceedings of Symposium on Salmonid Migration*, pages 191–195, Seattle. School of Fisheries, University of Washington.

Gearin, P., Pfeifer, R., Jeffries, S., DeLong, R., and Johnson, M. (1988). Results of the 1986-87 California sea lion–steelhead trout predation control program at the Hiram M Chittenden Locks. *Northwest and Alaska Fisheries Center Processed Report*, pages 88–90.

Giannico, G. and Souder, J. (2004). The effects of tide gates on estuarine habitats and migratory fish. *Sea Grant Publication ORESU-G-04-002. COAS, Oregon State University, Corvallis, OR.*

Giannico, G. and Souder, J. (2005). Tide gates in the Pacific Northwest: operation, types, and environmental effects. *Sea Grant Publication ORESU-T-05-001. Oregon State University, Corvallis, OR*, pages 05–001.

Glova, G. J. and McInerney, J. E. (1977). Critical swimming speeds of coho Salmon(Oncorhynchus kisutch) fry to smolt stages in relation to salinity and temperature. *Journal of the Fisheries Research Board of Canada*, 34:151–154.

Good, J. (2000). Summary and current status of Oregons estuarine ecosystems. *The Oregon state of the environment report*.

Groot, C. and Margolis, L. (1991). *Pacific salmon life histories*. University of British Columbia Press, Vancouver, BC.

Handeland, S., Jarvi, T., Ferno, A., and Stefansson, S. (1996). Osmotic stress, antipredatory behaviour, and mortality of Atlantic salmon (*Salmo salar*) smolts. *Canadian Journal of Fisheries and Aquatic Sciences*, 53(12):2673–2680.

Hansen, L. and Jonsson, B. (1985). Downstream migration of hatchery-reared smolts of Atlantic salmon (*Salmo salar L.*) in the River Imsa, Norway. *Aquaculture*, 45(1-4):237–248.

Hansen, L. and Jonsson, B. (1989). Salmon ranching experiments in the River Imsa: effect of timing of Atlantic salmon (*Salmo salar*) smolt migration on survival to adults. *Aquaculture*, 82(1-4):367–373.

Haro, A., Odeh, M., Noreika, J., and Castro-Santos, T. (1998). Effect of water acceleration on downstream migratory behavior and passage of Atlantic salmon smolts and juvenile American shad at surface bypasses. *Transactions of the American Fisheries Society*, 127:118–127.

Healey, M. C. (1982). Juvenile pacific salmon in estuaries: the life support system. *Estuarine comparisons: proceedings of the sixth biennial international estuarine research conference, Gleneden Beach, Oregon, 1981*, pages 315–341.

Holtby, L. B., Andersen, B. C., and Kadowaki, R. K. (1990). Importance of smolt size and early ocean growth to interannual variability in marine survival of coho salmon (*Oncorhynchus kisutch*). *Canadian Journal of Fisheries and Aquatic Science*, 47:2181–2194.

Hosmer, D. and Lemeshow, S. (1999). *Applied survival analysis: regression modeling of time to event data*. John Wiley & Sons, Inc. New York, NY, USA.

Iwata, M. and Komatsu, S. (1984). Importance of estuarine residence for adaptation of chum salmon(*Oncorhynchus keta*) fry to seawater. *Canadian Journal of Fisheries and Aquatic Sciences*, 41(5):744–749.

Jobling, M. (1995). Osmotic and ionic regulation-water and salt balance. *Environmental biology of fishes. In: Jobling, M., Padstow, Cornwall, Great Britain: TJ Press*, pages 211–249.

Jonsson, B. and Jonsson, N. (2009). Migratory timing, marine survival and growth of anadromous brown trout, *Salmo trutta*, in the River Imsa, Norway. *Journal of Fish Biology*, 74(3):621–638.

Kemp, P. S., Gessel, M. H., and Williams, J. G. (2005). Fine-scale behavioral responses of pacific salmonid smolts as they encounter divergence and acceleration of flow. *Transactions of the American Fisheries Society*, 134:390–398.

Kemp, P. S., Gessel, M. H., and Williams, J. G. (2008). Response of downstream migrant juvenile pacific salmonids to accelerating flow and overhead cover. *Hydrobiologia*, 609:205–217.

Kemp, P. S. and Williams, J. G. (2009). Illumination influences the ability of migrating juvenile salmonids to pass a submerged experimental weir. *Ecology of Freshwater Fish*, 18:297– 304.

Kennedy, B., Gale, W., and Ostrand, K. (2007). Relationship between smolt gill Na+, K+ ATPase activity and migration timing to avian predation risk of steelhead trout (*Oncorhynchus mykiss*) in a large estuary. *Canadian Journal of Fisheries and Aquatic Sciences*, 64(11):1506–1516.

Kennedy, R. and Crozier, W. (2010). Evidence of changing migratory patterns of wild Atlantic salmon, *Salmo salar*, smolts in the River Bush, Northern Ireland, and possible associations with climate change. *Journal of Fish Biology*, 76(7):1786–1805.

Kennish, M. (2002). Environmental threats and environmental future of estuaries. *Environmental Conservation*, 29(01):78–107.

Koski, K. V. (2009). The fate of coho salmon nomads: the story of an estuarine-rearing strategy promoting resilience. *Ecology and Society*, 14(1):4.

Linley, T. (2001). Influence of short-term estuarine rearing on the ocean survival and size at return of coho salmon in southeastern Alaska. *North American Journal of Aquaculture*, 63:306–311.

Martin, F., Hedger, R., Dodson, J., Fernandes, L., Hatin, D., Caron, F., and Whoriskey, F. (2009). Behavioural transition during the estuarine migration of wild Atlantic salmon(*Salmo salar L.*) smolt. *Ecology of Freshwater Fish*, 18(3):406–417.

Mashiko, K., Sumita, M., Asakura, M., Muranaka, M., and Yamamoto, A. (1970). Large mortalities of fishes resulted from the reclamation of LakeImae-gata. *Annual Report Noto Marine Laboratory.*

Mather, M. (1998). The role of context-specific predation in understanding patterns exhibited by anadromous salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, 55(S1):232–246.

McCormick, S., Hansen, L., Quinn, T., and Saunders, R. (1998). Movement, migration, and smolting of Atlantic salmon (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Sciences*, 55(S1):77–92.

McCormick, S. and Saunders, R. (1987). Preparatory physiological adaptations for marine life of salmonids: osmoregulation, growth, and metabolism. In *Common strategies of anadromous and catadromous fishes: proceedings of an International Symposium held in Boston, Massachusetts, USA, March 9-13, 1986*, volume 1, pages 211–229. Amer Fisheries Society.

McMahon, T. E. and Hartman, G. F. (1989). Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (*Oncorhynchus kisutch*). *Canadian Journal of Fisheries and Aquatic Sciences*, 46(9):1551–1557. Incl. bibliogr.: 41 ref.

McMichael, G., Eppard, M., Carlson, T., Carter, J., Ebberts, B., Brown, R., Weiland, M., Ploskey, G., Harnish, R., and Deng, Z. (2010). The juvenile salmon acoustic telemetry system: A new tool. *Fisheries*, 35(1).

Miller, B. A. and Sadro, S. (2003). Residence time and seasonal movements of juvenile coho salmon in the ecotone and lower estuary of Winchester Creek, South Slough, Oregon. *Transactions of the American Fisheries Society*, 132(3):546–559.

Mitchell, S. B., Burgess, H. M., Pope, D. J., and Theodoridou, A. (2008). Field studies of velocity, salinity and suspended solids concentration in a shallow tidal channel near tidal flap gates. *Estuarine*, (2):385–395.

Moore, M., Berejikian, B., and Tezak, E. (2010). Early Marine Survival and Behavior of Steelhead Smolts through Hood Canal and the Strait of Juan de Fuca. *Transactions of the American Fisheries Society*, 139:49–61.

Moser, M., Olson, A., and Quinn, T. (1991). Riverine and estuarine migratory behavior of coho salmon (*Oncorhynchus kisutch*) smolts. *Canadian Journal of Fisheries and Aquatic Sciences*, 48(9):1670–1678.

Mueller, R. P., Southard, S. S., May, C. W., Pearson, W. H., and Cullinan, V. I. (2008). Juvenile coho salmon leaping ability and behavior in an experimental culvert test bed. *Transactions of the American Fisheries Society*, 137(4):941–950.

Myers, K. and Horton, H. (1982). Temporal use of an Oregon estuary by hatchery and wild juvenile salmon. In *Estuarine comparisons: proceedings of the Sixth Biennial International Estuarine Research Conference, Gleneden Beach, Oregon, November 1-6, 1981*, page 377. Academic Pr.

Nicholls, R., Hoozemans, F., and Marchand, M. (1999). Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. *Global Environmental Change*, 9:S69–S87.

Otto, R. (1971). Effects of salinity on the survival and growth of pre-smolt coho salmon (*Oncorhynchus kisutch*). *Journal of the Fisheries Research Board of Canada*, 28(3):343–349.

Portnoy, J. (1991). Summer oxygen depletion in a diked New England estuary. *Estuaries and Coasts*, 14(2):122–129.

Quinn, T. (2005). *The behavior and ecology of Pacific salmon and trout*. University of Washington Press.

Raposa, K. (2002). Early responses of fishes and crustaceans to restoration of a tidally restricted New England salt marsh. *Restoration Ecology*, 10(4):665–676.

Reimers, P. E. (1971). The length of residence of juvenile fall chinook salmon in sixes river, oregon.

Richter, A. and Kolmes, S. A. (2005). Maximum temperature limits for chinook, coho, and chum salmon, and steelhead trout in the pacific northwest. *Reviews in Fisheries Science*, 13(1):23–49.

Ritter, A. F., Wasson, K., Lonhart, S. I., Preisler, R. K., Woolfolk, A., Griffith, K. A., Connors, S., and Heiman, K. W. (2008). Ecological signatures of anthropogenically altered tidal exchange in estuarine ecosystems. *Estuaries and Coasts*, 31(3):554–571.

Roper, B. B. and Scarnecchia, D. (1999). Emigration of age-0 chinook salmon (*Oncorhynchus tshawytscha*) smolts from the upper south umpqua river basin, oregon, U.S.A. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(6):939–946.

Sandercock, F. (1991). Life history of coho salmon (*Oncorhynchus kisutch*). In *Pacific salmon life histories*, pages 395–446. University of British Columbia Press.

Scheuerell, M., Zabel, R., and Sandford, B. (2009). Relating juvenile migration timing and survival to adulthood in two species of threatened Pacific salmon (*Oncorhynchus spp.*). *Journal of Applied Ecology*, 46(5):983–990.

Semmens, B. (2008). Acoustically derived fine-scale behaviors of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) associated with intertidal benthic habitats in an estuary. *Canadian Journal of Fisheries and Aquatic Sciences*, 65(9):2053–2062.

Shrimpton, J. (1996). Relationship between size, gill corticosteroid receptors, Na+-K+ ATPase activity and smolting in juvenile coho salmon (*Oncorhynchus kisutch*) in autumn and spring. *Aquaculture*, 147(1-2):127–140.

Simenstad, C. A., Fresh, K. L., and Salo, E. O. (1982). The role of puget sound and washington coastal estuaries in the life history of pacific salmon: an unappreciated function. *Estuarine comparisons*, 539:343–364.

Spence, B. (1995). Geographic variation in timing of fry emergence and smolt migration of coho salmon (*Oncorhynchus kisutch*).

Staurnes, M., Lysfjord, G., Hansen, L., and Heggberget, T. (1993). Recapture rates of hatchery-reared Atlantic salmon (*Salmo salar*) related to smolt development and time of release. *Aquaculture*, 118(3-4):327–337.

Sykes, G., Johnson, C., and Shrimpton, J. (2009). Temperature and Flow Effects on Migration Timing of Chinook Salmon Smolts. *Transactions of the American Fisheries Society*, 138:1252–1265.

Therneau, T. and Grambsch, P. (2000). *Modeling survival data: extending the Cox model*. Springer Verlag.

Thorpe, J. (1994). Salmonid fishes and the estuarine environment. *Estuaries and Coasts*, 17(1):76–93.

Tschaplinski, P. J. (1982). Aspects of the population biology of estuary-reared and stream-reared juvenile coho salmon in carnation creek: a summary of current research. *Proceedings of the Carnation Creek Workshop*, 307:289.

Virtanen, E., Soderholm-Tana, L., Soivio, A., Foreman, L., and Muona, M. (1991). Effect of physiological condition and smoltification status at smolt release on subsequent catches of adult salmon. *Aquaculture*, 97(2-3):231–257.

Ward, B. and Slaney, P. (1988). Life history and smolt-to-adult survival of Keogh River steelhead trout(*Salmo gairdneri*) and the relationship to smolt size. *Canadian Journal of Fisheries and Aquatic Sciences*, 45(7):1110–1122.

Webster, S. J. and Dill, L. M. (2006). The energetic equivalence of changing salinity and temperature to juvenile salmon. *Functional Ecology*, 20(4):621–629.

Wetzel, P. and Kitchens, W. (2007). Vegetation change from chronic stress events: Detection of the effects of tide gate removal and long-term drought on a tidal marsh. *Journal of Vegetation Science*, 18(3):431–442.

Whalen, K. G., Parrish, D. L., and McCormick, S. D. (1999). Migration timing of atlantic salmon smolts relative to environmental and physiological factors. *Transactions of the American Fisheries Society*, 128(2):289–301.

Winn, R. N. and Knott, D. M. (1992). An evaluation of the survival of experimental populations exposed to hypoxia in the savannah river estuary. *Marine Ecology Progress Series*, 88(2):161–179.

Zydlewski, G., Haro, A., and McCormick, S. (2005). Evidence for cumulative temperature as an initiating and terminating factor in downstream migratory behavior of Atlantic salmon (Salmo salar) smolts. *Canadian Journal of Fisheries and Aquatic Sciences*, 62(1):68–78.

Zydlewski, G. B., Horton, G., Dubreuil, T., Letcher, B., Casey, S., and Zydlewski, J. (2006). Remote monitoring of fish in small streams: A unified approach using PIT tags. *Fisheries*, 31(10):492–502.