

AN ABSTRACT OF THE THESIS OF

Nathan Kobun Truelove for the degree of Master of Science in Fisheries Science
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Title: Effects of Estuarine Circulation Patterns and Stress on the Migratory Behavior
of Juvenile Salmonids (*Oncorhynchus sp.*)

Abstract approved:

Carl B. Schreck

For the first objective of this thesis, we attempt to understand the role of water flow and directionality in determining steelhead (*Oncorhynchus mykiss*) and spring/summer and fall Chinook (*O. tshawytscha*) migration patterns within the Columbia River Estuary and plume by integrating recent advances in biotelemetry and environmental observation and forecasting systems (EOFS). The underlying methodology included analysis of the spatial and temporal movements of juvenile outmigrant salmonids with hydrological data from the CORIE modeling system (<http://www.ccalmr.ogi.edu/CORIE>). The CORIE modeling system, an EOFS for the Columbia River and nearshore environment, integrates a real-time sensor network,

data management system and advanced 3-dimensional numerical models. Numerical simulations of key physical variables (water level, velocities, and directionality) were generated for the precise time and location that individual juvenile salmonids implanted with radio transmitters were present in the Columbia River Estuary. Five general behavioral trends were evident from these simulations: i) passive movement (drifting) during ebb tides, ii) active swimming with the current during ebb tides, iii) active swimming against the current during flood tides, iv) active swimming cross current during flood tides, and v) passive drifting during flood tide. Direction of water flow had a significant effect on fish velocity. All fish types showed a positive relationship between fish velocity and simulated drifter velocity with outgoing water flow. During slack water flow (< 0.25 m/s), this relationship was only observed in barged fall Chinook. With incoming water flow, spring/summer and fall Chinook fish types showed no relationship, whereas steelhead did. Analysis over a three-year period suggested that data from the CORIE modeling system corresponded well with juvenile salmonid migratory behavior and that the model may be a useful tool for evaluating the impact of different hydrological regimes on fish movement.

The secondary objective of this thesis evaluated the effects of both acute and chronic crowding stressors on the migratory behavior of hatchery reared juvenile steelhead released into Abernathy Creek, a tributary of the Columbia River Estuary, Washington. The acute stress treatment consisted of surgical implantation of a NanoTag® radio transmitter (Lotek Wireless, Canada), followed by 6 hours of crowding immediately prior to release. The chronic stress treatment consisted of surgical implantation of a PIT-tag (Digital Angel Corporation), 36 days of

acclimation, followed by 3 weeks of crowding in low water conditions prior to release. Short-term migratory success of steelhead that received the acute stress treatment was determined by radio telemetry. Numbers of migrating fish that received experimental stress treatments and their speed was determined by both mobile radio telemetry and stationary PIT-tag and radio-tag interrogation systems already established on Abernathy Creek. Acute and chronic stress treatments both significantly delayed migration by 2 to 10 days, respectively, compared to controls. Furthermore, the acute stress treatment significantly decreased the both the rate of migration and numbers of juvenile steelhead that successfully migrated out of Abernathy creek.

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Effects of Estuarine Circulation Patterns and Stress on the Migratory Behavior of
Juvenile Salmonids (*Oncorhynchus sp.*)

by

Nathan Kobun Truelove

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APPROVED:

Major Professor, representing Fisheries Science

Head of Department of Fisheries and Wildlife

Dean of 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.

Nathan Kobun Truelove, Author

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I would like to thank my major professor Dr. Carl Schreck for his tremendous encouragement and support throughout my history as a graduate student. I would also like to thank Dr. Antonio Baptista for his invaluable knowledge as a scientist and for providing direction on how to integrate the CORE Modeling System into this thesis. I extend these thanks to all the members of my committee, including Dr. Mike Kent and Dr. Michael Wing.

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CONTRIBUTION OF AUTHORS

Dr. Schreck and Dr. Clements were involved in the design, analysis, and editing of both manuscripts. Dr. Baptista was involved in the design, analysis, and editing of the first manuscript. Mark Karnowski was involved in field assistance, data analysis, and editing of the first manuscript. Sarah Lobser and Charles Seaton performed data analysis, and were involved the editing of the first manuscript. Dr. Gayle Zydlewski was involved in the design, analysis, and editing of the second manuscript.

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DEDICATION

I dedicate this thesis to the loving memory of my mother Vivian Balsam. Her love and support will forever guide me through my travels.

BODY OF TEXT: MANUSCRIPT DOCUMENT FORMAT

Effects of Estuarine Circulation Patterns and Stress on the Migratory Behavior of Juvenile Salmonids (*Oncorhynchus sp.*)

INTRODUCTION

This masters thesis contains two chapters. Chapter 1, entitled “Modeling the Migratory Behavior of Juvenile Salmonids (*Oncorhynchus sp.*) in the Columbia River Estuary: Integrating Biotelemetry with Environmental Observation and Forecast Systems”, describes the role of hydrology (*i.e.*, water level, velocities, and direction of flow) in determining steelhead, *Oncorhynchus mykiss*, and spring/summer and fall Chinook, *O. tshawytscha*, migration patterns within the Columbia River Estuary. The migratory routes of free-swimming downstream oriented juvenile salmonids were determined using radio telemetry (during 2002-2004). Geolocations of fish migration routes (from radio telemetry datasets) were then integrated with simulated oceanographic data from the CORIE (Columbia River Estuary) modeling system, an environment observation and forecast system (EOFS) for the Columbia River Estuary and near-shore ocean environments. The CORIE modeling system integrates a real-time sensor network, data management system and advanced 3-dimensional numerical models (Baptista *et al.* 2005). A series of CORIE simulations were used to determine if the migratory behavior of juvenile salmonids was active, passive, or both within the Columbia River Estuary. Furthermore, this study is a novel test of the movement of juvenile salmonids and establishes direct links of salmonid behavior to riverine and oceanographic processes in the estuary.

Chapter 2, entitled “Stressors disrupt the in-stream migration of juvenile hatchery steelhead (*Oncorhynchus mykiss*)”, describes the effects of a single, severe stress event (electronic tag implantation followed by a crowding stressor) and a chronic stressor (10 day crowding stressor) during smoltification on the downstream migration of juvenile hatchery steelhead. Here, we show how these two stress events disrupted the migratory behavior and ultimately the survival of juvenile steelhead. This study was conducted at the Abernathy Fish Technology Center, WA, in conjunction with the center’s annual hatchery release of steelhead. The downstream migration of all experimental fish was monitored using both radio telemetry and passive integrated transponder (PIT) tag technology.

Chapter 1

Modeling the Migratory Behavior of Juvenile Salmonids (*Oncorhynchus sp.*) in the
Columbia River Estuary: Integrating Biotelemetry with Environmental Observation
and Forecast Systems.

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Abstract

We examined the flow and direction of water in determining juvenile steelhead (*Oncorhynchus mykiss*) and spring/summer and fall Chinook (*O. tshawytscha*) migration patterns within the Columbia River Estuary and plume by integrating biotelemetry and environmental observation and forecasting systems (EOFS). The underlying methodology included analysis of the spatial and temporal movements of juvenile outmigrant salmonids with hydrological data from the CORIE modeling system (<http://www.ccalmr.ogi.edu/CORIE>). The CORIE modeling system, an EOFS for the Columbia River and nearshore environment, integrates a real-time sensor network, data management system and advanced 3-dimensional numerical models. Numerical simulations of key physical variables (*i.e.*, water level, velocity, and direction of flow) were generated for the precise time and location that individual juvenile salmonids implanted with radio transmitters were present in the Columbia River Estuary. Five general behavioral trends were evident from these simulations; i) passive movement (drifting) during ebb tides, ii) active swimming with the current during ebb tides, iii) active swimming against the current during flood tides, iv) active swimming cross current during flood tides, and v) passive drifting during the flood tide. Direction of water flow effected fish velocity. Spring/summer and fall Chinook and steelhead transported from the Snake River system in barges or those that migrated past Bonneville Dam from upper watersheds showed a positive relationship between fish velocity and simulated drifter velocity with outgoing water flow. During low water velocity (< 0.25 m/s), this relationship was only observed in barged fall Chinook. With incoming water flow, this relationship was also found with steelhead,

but not found with spring/summer and fall Chinook. Analysis over a 3-year period suggested that data from the CORIE modeling system corresponded well with juvenile salmonid migratory behavior and that this methodology may be a useful tool for evaluating the impact of different hydrological regimes on fish movement.

Introduction

The life history, ecology, and ultimately survival of Pacific Salmon, *Oncorhynchus spp.*, are dominated by their extraordinary migrations (Dittman and Quinn 1996). When juvenile salmonids reach a certain size-related developmental stage in freshwater, they leave their rearing tributaries and begin a migration that will take them downriver, through estuaries, and potentially hundreds or thousands of kilometers to oceanic feeding areas (McCormick *et al.* 1998). This downstream migration of juvenile salmonids is a critical stage in their life history, during which significant morphological, physiological, and behavioral changes occur to prepare them for life in the ocean (Hoar 1988).

Substantial resources have been dedicated towards improving survival and understanding the freshwater phase of juvenile salmon migration. Research towards understanding the basic mechanisms that control estuarine migration, however, have been relatively scarce (Beamish *et al.* 2005; Brodeur *et al.* 2004; Lacroix *et al.* 2004; Moore *et al.* 1998; Welch *et al.* 2004). The estuarine, coastal, and open-ocean environments continue to be a “black box” where juvenile salmon enter and some smaller percentage return as adults (Brodeur *et al.* 2000). This lack of information is particularly important because the greatest mortality of juvenile salmonids is thought to take place during the first few months after the juvenile salmon leave freshwater (Jonsson *et al.* 2003).

Spatial and temporal patterns of movement must be identified to understand the life history of salmonids and develop competent management strategies (Brodeur *et al.* 2000; Kareiva *et al.* 2000). Behavioral changes in salmonid movement and

their ability to disperse are critical factors determining their persistence in the face of habitat loss and fragmentation (Rothermel 2004). Furthermore, it is critical to identify the biophysical variables that juvenile salmonids associate with during their migration from fresh water to the ocean. Few methods exist, however, to study the movement patterns, dispersal, and other biophysical variables that can affect juvenile salmon as they migrate through estuaries.

The estuarine and ocean aquatic environments change with abiotic and climatic surroundings on differing spatial and temporal scales (Hinke *et al.* 2005). Salmon populations respond to these changes in the physical environment, from meso- to regional-scale climate (McFarlane *et al.* 2000; Welch *et al.* 2000; Mantua *et al.* 1997), as well as micro-climate and fine scale localized effects (Lacroix *et al.* 2005). Linking the movement and behavior of salmonids to changes in the aquatic environment through use of electronic tags and measured and modeled oceanographic data can provide important insight into the biology and ecology of these migratory species. Clearly, accurate knowledge of the fishes location is needed to successfully integrate this methodology (Teo *et al.* 2004). For example, the high resolution, continuous tracking of electronically tagged juvenile salmonids during their ocean migration has been difficult to obtain due to the limited resolution of existing technologies for studying juvenile fish.

Recent advances in biotelemetry and environmental observation and forecasting systems (EOFS), however, have allowed for the integration of high resolution spatial and temporal movements of juvenile outmigrant salmonids with physical oceanographic and riverine data. The CORIE modeling system

(<http://www.ccalmr.ogi.edu/CORIE>), an EOFS for the Columbia River and nearshore ocean environment, integrates a real-time sensor network, data management system, and advanced 3-dimensional numerical models (Baptista *et al.* 2005).

The objective of this study was to investigate of the role of hydrology (water level, velocities, and direction of flow) in determining steelhead and spring/summer and fall Chinook migration patterns within the Columbia River Estuary by integrating biotelemetry and EOFS. Radio transmitters were implanted between 2002-2004 to examine the migratory behaviors and dispersal of 3 races (spring/summer Chinook, fall Chinook, and steelhead) of juvenile salmonids. A series of CORIE simulations that reflect spatially and temporally the conditions when fish were present were used to examine the biophysical factors that affect movement and dispersal of juvenile salmonids within the Columbia River Estuary. This methodology provided a novel test of whether the movements and behaviors of juvenile salmonids can be linked directly to riverine and oceanographic processes in the estuary.

Methods

STUDY AREA

Annual cycles of river discharge strongly influence many characteristics of the estuary. From late fall to early spring the monthly average Columbia River discharge ranges 100,000 – 500,000 cubic feet per second (cfs) at Bonneville Dam and is primarily affected by surface runoff from the western region of the watershed (Fox *et al.* 1984). The complex geomorphology of the Columbia River strongly affects water circulation patterns throughout the estuary, which is characterized by an intricate

series of channels, tidal flats, sand bars, and shallow bays (Figure 1.1). Channels rarely exceed 18 m in depth and tidal flats are exposed at low tide (Fox *et al.* 1984). Moreover, the process of sediment deposition and erosion continually alters the geomorphology of this estuarine environment. Water circulation patterns throughout this estuary are determined by interactions among river flow, tidal cycle, wind, bathymetry, ocean salinity, and ocean currents, to name a few. However, the primary factors that control water circulation patterns in the Columbia River Estuary are river flow and tidal cycle. The interaction between river discharge and tidal strength determines the spatial and temporal variability among ebb, flood, and slack currents in the estuary.

FISH

Transported fish: Transported fishes we studied were collected from those destined for transport from Lower Granite Dam on the Snake River to a release site just below the lowermost dam on the Columbia River as part of routine fish management (Budy *et al.* 2002; Karieva *et al.* 2000; Schreck *et al.* 2006). Fish collection spanned the smolt “season” from early May through July during 2002, 2003, and 2004.

Transported (barged) fall Chinook, spring/summer Chinook, and steelhead were collected from 2 sources at Lower Granite Dam: either from the National Oceanic and Atmospheric Administration Fisheries PIT-tagging sample (in which fish were collected passively through the separator over the previous 24 hours) or directly from the separator (using a dip net). Barge transportation from Lower Granite Dam to Bonneville Dam typically takes 36 h and spans ~510 river km. All radio-tagged transported fish (2002, 350 steelhead, 104 fall Chinook; 2003, 558 steelhead, 266 fall

Chinook; 2004, 594 spring/summer Chinook) were released from the barge just below Bonneville Dam (river kilometer 235).

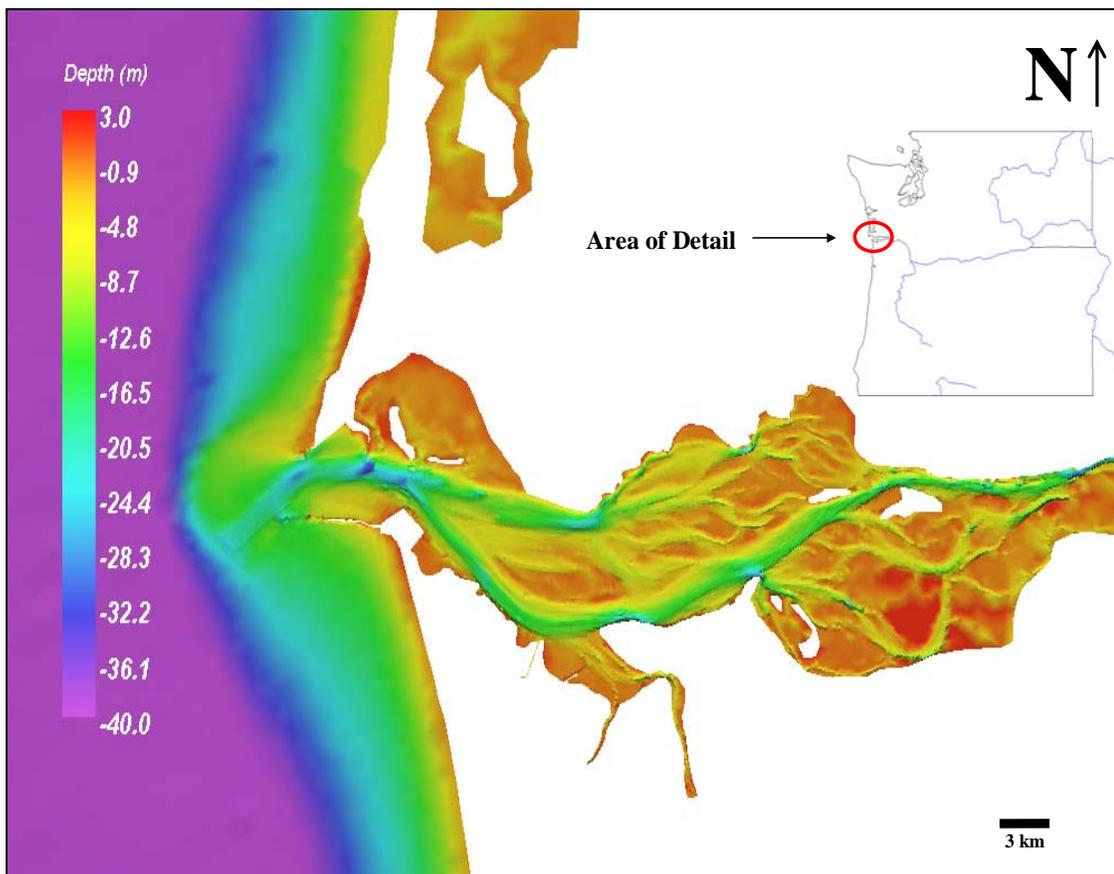


Figure 1.1 Bathymetric map of Columbia River Estuary and near-shore ocean. The Northern Washington Channel and the Southern Navigation Channel were the 2 main channels of the estuary. A complex network of shallow side channels were present throughout the estuary.

Run of the River fish: Fish collection spanned the smolt “season” from early May through July. Fish that migrated on their own were also collected at the Bonneville Dam 2nd Powerhouse Juvenile Monitoring Facility (BJMF2). All fish were held overnight in large flow through tanks or raceways prior to tagging. All radio-tagged

run of the river fish (ROR; 2002, 115 steelhead, 123 fall Chinook; 2003, 270 steelhead, 263 fall Chinook) were released into the Columbia River immediately downstream of BJMF2.

Fish Quality: The existing Lower Granite Dam (LGR) fish collection facility had previously experienced variable mortality rates throughout the smolt season for fall Chinook. Smith *et al.* (2003) showed that high temperatures were inversely correlated with survival at LGR for fall Chinook. Prolonged exposure to temperatures above 20°C can disrupt fall Chinook growth, smoltification, and downstream movement (Connor *et al.* 2003). Our observations also suggested that fall Chinook may have been stressed prior to tagging. Hence, there was some uncertainty associated with the transported and ROR fall Chinook because water temperatures could have exceeded 21°C at LGR during July-August. Steelhead (2002 barged, 2002 ROR, 2003 barged, 2003 ROR) and spring/summer Chinook (2004 barged) were collected earlier in the smolt season (May-June) and did not experience water temperatures > 21°C. In general, we consider fish behavior from all steelhead and spring/summer Chinook groups representative of healthy *in situ* fish. Due to potential exposure to higher than desirable temperatures however, we do not have the same level of confidence in transported and ROR fall chinook.

RADIO TELEMETRY

The migratory behavior and dispersal of juvenile salmonids in the Columbia River Estuary were monitored using radio telemetry. Juvenile spring/summer Chinook, fall Chinook, and steelhead were tagged with digitally encoded radio

transmitters (NTC-3-1 NanoTag®; 0.85 g in air, 149 – 150 megahertz, 2.9 – 3.1 second burst rate, ~11 day battery life, Lotek Wireless Inc., Canada). Prior to tagging, fish were anesthetized in 50 mg l⁻¹ tricane methanesulfonate (MS-222) buffered with 125 mg l⁻¹ NaHCO₃. Each NanoTag® was surgically implanted into the body cavity using a modified technique from Moore *et al.* (1990). Fish were placed ventral side up in a wetted foam insert to hold them in place. Commercially available Stresscoat® (Aquarium Pharmaceuticals Inc., USA) was applied to the foam surface to minimize mucus and scale loss. Anesthetic was perfused over the gills using a squeeze bottle to maintain oxygen to the gills while keeping the fish anesthetized. A 1 – 1.5 cm incision was made into the ventral body wall anterior to the pelvic girdle. The tag was inserted and the incision closed with 2 sutures. During the implantation of the radio transmitters and prior to closing the incision wound, a needle that encased the wire antennae was guided through the incision and pushed through the body wall, posterior to the incision and anterior to the pelvic girdle. Preliminary trials at Oregon State University's Fish Performance and Genetics Laboratory indicated that this method was most effective at minimizing tissue damage and fin abrasion around the antenna exit (Jepsen *et al.* 2001). After surgical tagging, fish recovered for a minimum of 20 h in large flow-through holding tanks. For more detail on these fish and the tagging procedures see Schreck *et al.* (2006). All fish were within suitable tag size to-body weight ratios (Jepsen *et al.* 2005).

ACTIVE RADIO TRACKING

In the estuary, detailed behavioral data from individual juvenile salmonid migrants were collected using boats fitted with radio-telemetry tracking equipment and a Global Positioning System (GPS). Two 7 m boats, each equipped with one 4-element Yagi antenna and a Lotek receiver (SRX 400) were used to continuously monitor the behavior of individual fish as they migrated through the estuary. Tracking was conducted continuously over a 24 h period for several days when tagged fish were known to be in the estuary (~ 2 – 6 d post release). A boat would traverse the estuary, monitoring all frequencies, then, when a signal was detected, the operators would stop scanning and only track the specific detected frequency. Once tracking began the boat was kept as close to the fish as possible by using the gain function on the Lotek receivers. At approximately 10-min intervals, the location of the fish was determined with the GPS unit (Garmin GPSMAP 2010) utilizing the Wide Area Augmentation System (WAAS) that generally has an error of < 10 m. A fish was tracked until it moved into water too shallow for the boat, the signal was lost and could not be re-acquired after set search limits, or other factors, such as when weather made continued tracking unsafe.

CORIE MODELING SYSTEM

The CORIE modeling system simulated key physical variables in the aquatic environment (*i.e.*, tidal height, horizontal and vertical flow velocities) at the precise time and location that individual juvenile salmonids implanted with radio transmitters were present in the Columbia River Estuary. Vector analysis of fish movement and

orientation, simulated surface velocities, and simulated fish swimming speeds were calculated using a software package (IDL v 6.0, Research Systems Inc., Boulder, Colorado).

Swimming behavior by fish was analyzed by incorporating *in situ* fish tracking geolocations with CORIE modeling system Lagrangian passive drifter simulations. Lagrangian passive drifter simulations were generated for all fish tracks greater than 2 h. A unique simulation was generated for each individual fish track (N = 64). The CORIE modeling system allowed for both free floating (3-dimensional) and fixed depth (2-dimensional) drifter simulations. However, preliminary comparisons showed that the fixed depth drifter simulations corresponded better with the movements of the radio-tagged fish than did the free floating drifter simulations. The shallow bathymetry of the Columbia River Estuary further constrained the simulations to depths of < 3 m. Furthermore, depth tag data (Schreck, unpublished data), PIT tag trawl data (Emmett *et al.* 2004) and avian predation by Caspian terns, *Sterna caspia* (which cannot dive deeper than 0.75 m, Collis *et al.* 2001), suggested that fish were near the surface. Hence, a grid of 25 simulated virtual drifters (5 x 5 m grid, with 5 m spacing) were released at each of the following fixed depths: 0.1 m, 1 m, and 3 m. The center particle of each grid corresponded to the precise GPS location from the start of the fish track. Simulated drifters were also released at the beginning of each fish track and allowed to passively drift for a time period equal to the duration of the entire fish track. Over the course of several hours, small differences between movements of the tracked fish and the

simulated drifters sometimes caused erroneous data that resulted in the virtual drifters traveling through a different network of channels than the tracked fish.

The differences between observed and simulated fish movements at each geolocation were analyzed to better understand fish behavior. A single surface drifter, released at each geolocation, was allowed to drift only for the time period between corresponding fish observations (~ 10-min). If a fish was passively drifting, surface drifter and fish geolocations would be similar. Animations of all drifter simulations were generated in 2- and 3-dimensional space using CORIE visualization software (Oregon Health and Science University).

Results

MIGRATION ROUTES

A total of 62 juvenile salmonids, consisting of steelhead, spring/summer Chinook, and fall Chinook, were actively tracked (geolocations recorded ~10 min) by radio telemetry in the Columbia River Estuary for periods ranging from 2-26 hours. The migratory routes of juvenile salmon corresponded well to channel location (Figure 1.2). All actively tracked salmon spent a portion of their migration in the dredged shipping channel, while a majority moved from deep shipping channel through numerous shallow side channels, and into the deep northern channel.

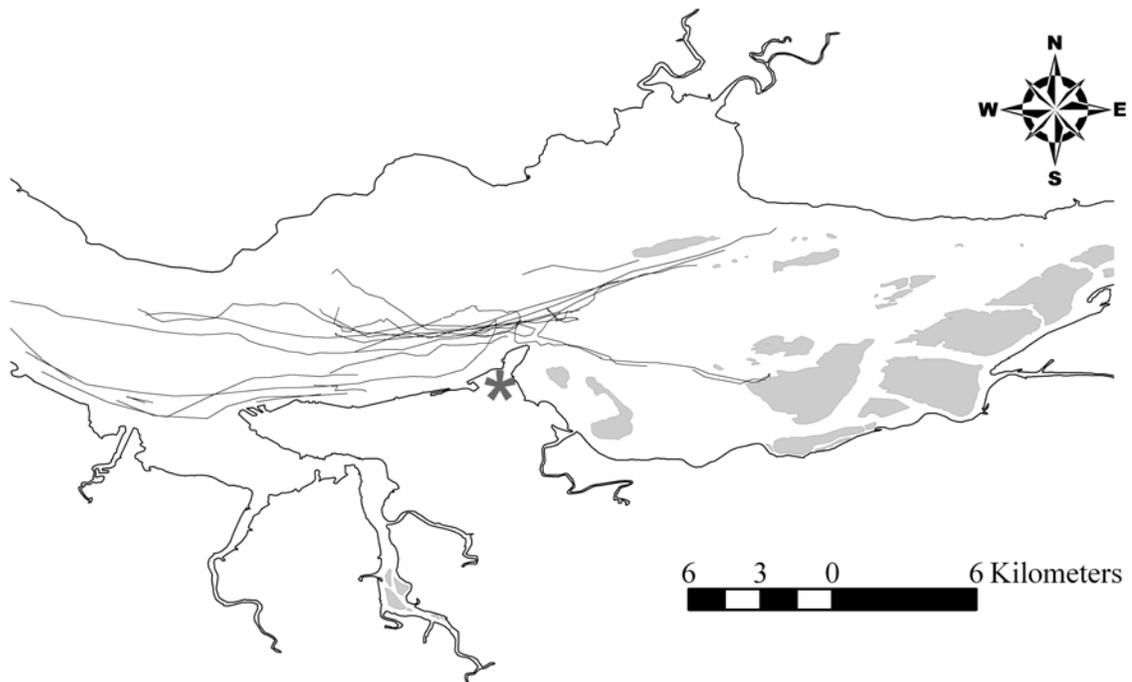
(a)

Figure 1.2. Individual estuarine migration routes of steelhead (N = 21) (a), and fall Chinook (N = 26) (b) from May 7 to July 20, 2002. Individual spring/summer Chinook (N = 17) (c) migration routes were collected from May 7 to June 3, 2004. Downstream is to the left. Tongue Point, located above *, corresponds to River km 29.

(b)



(c)

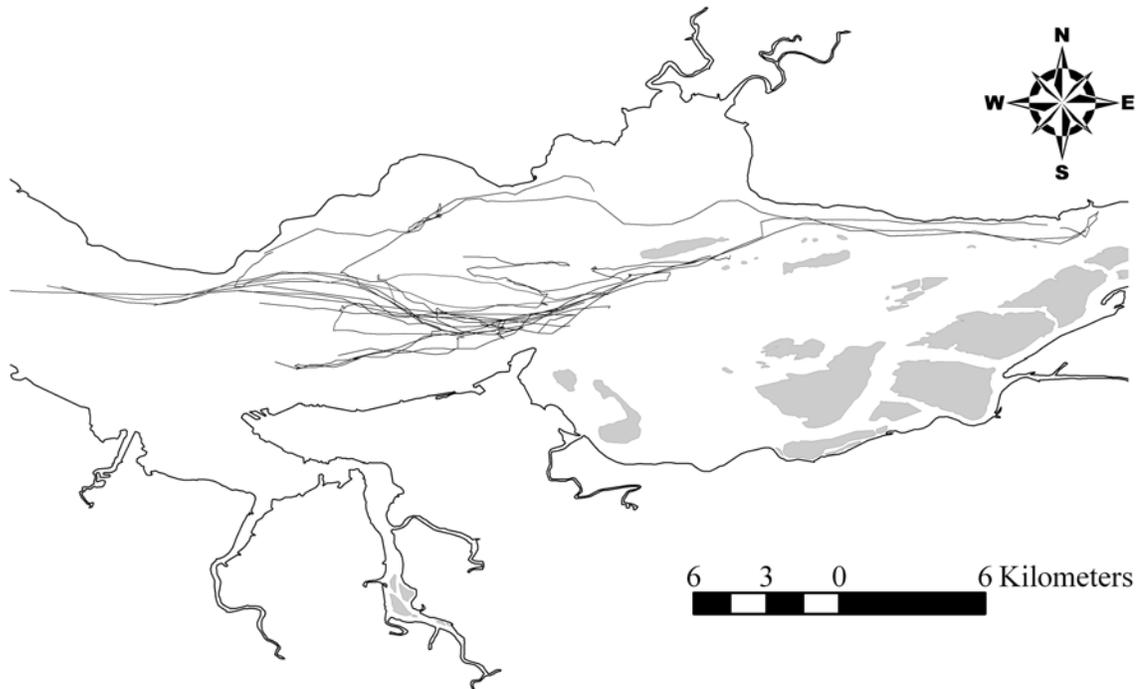


Figure 1.2. Continued

DRIFTER ROUTES

A GPS linked drifter (2 m fixed depth) was released in the lower Columbia River Estuary during flood tide on March 3, 2004 from 10:24 through 17:10 PST. CORIE drifter simulations were generated for the same release site, time, and fixed depth as the real drifter (Figure 1.3). In general, only small ($< 0.1 \text{ m s}^{-1}$) deviations in overall velocities and direction of travel were present between the simulated drifter and GPS linked drifter over short time scales (< 15 -min). Over the course of nine hours however, these small deviations were additive, and became compounded into larger errors resulting in the simulated drifter traveling through a different network of channels than the real drifter.

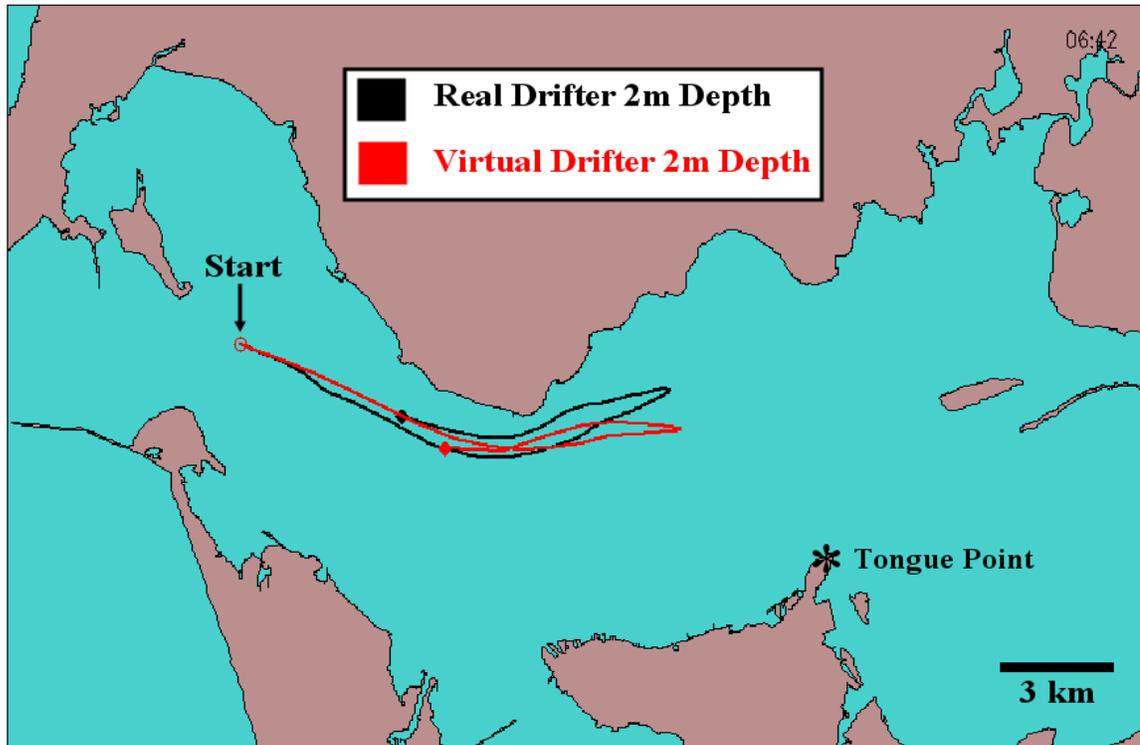


Figure 1.3 Routes of a real drifter at 2 m fixed depth (black) and CORIE model virtual drifter simulation for 2 m fixed depth (red). Virtual drifter simulation corresponded to the exact time and release site as the real drifter (March 4, 2003, 10:24 am PST). Downstream is to the left. Tongue Point (*) corresponds to river kilometer 29.

FISH SWIMMING BEHAVIOR

Five general behavioral trends were made evident through comparisons between movements of the observed fish and their simulated passive drifters (Figure 1.4): i) Passive movement (drifting) during ebb tides, ii) active swimming with the current during ebb tides, iii) active swimming against the current during flood tides, iv) active swimming cross current during flood tides, iv) active swimming against the current during flood, and v) passive drifting during the flood tide. Furthermore, over the course of multiple tidal cycles these behavior patterns resulted in several km

distances between migratory fish and simulated drifters at the end of each observational period (Figure 1.4f).

During their migration through the Columbia River Estuary, juvenile salmonids encountered a complex network of interconnected side shallow channels that divert flow away from the two main channels (Navigation Channel and Washington Channel) of the estuary (Figure 1.1). Some juvenile steelhead remained in the large shipping channel while simulated drifters moved into shallow side channels (*e.g.*, Figure 1.5 a, c). However, when one passive drifter was released at each geolocation of the same steelhead tracks and allowed to drift only for the time period between steelhead geolocations (~ 10 min), more detailed analysis of swimming behavior was possible (*e.g.*, Figure 1.5 b, d).

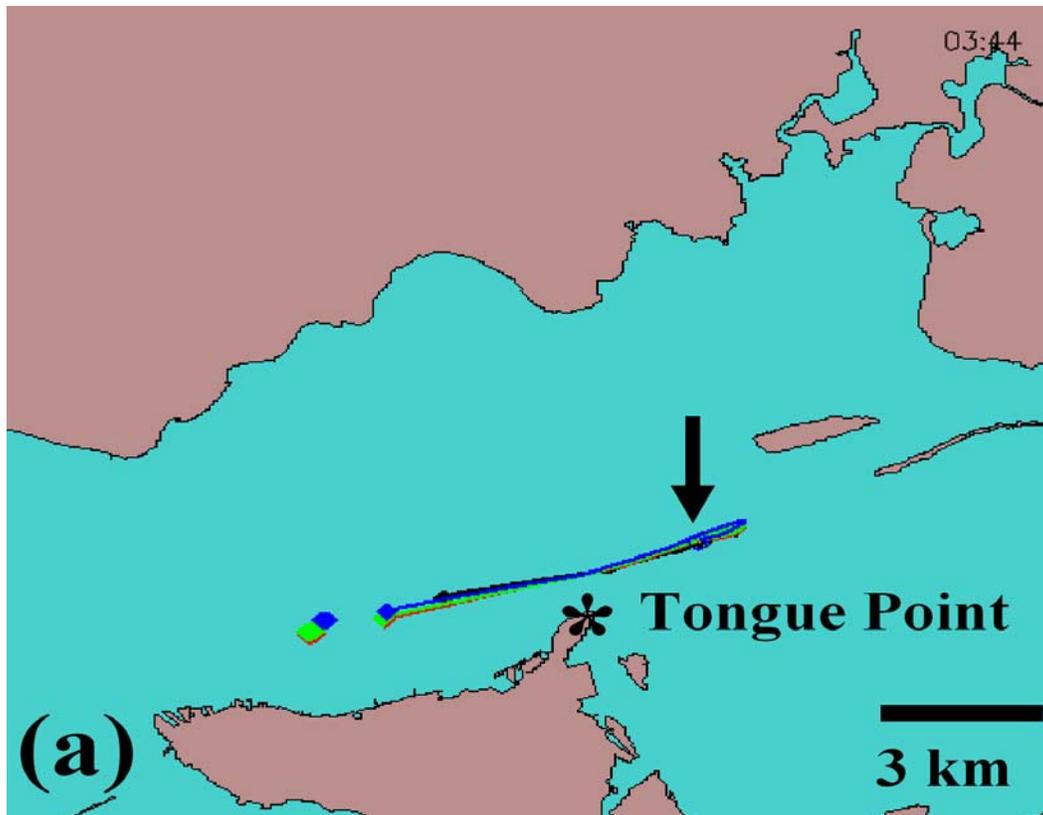


Figure 1.4. Typical behavioral trends selected from juvenile salmonid migration routes ($N = 64$). Fall Chinook (a), steelhead (b), fall Chinook (c), steelhead (d), fall Chinook (e), and spring/summer Chinook (f). Virtual drifter simulations, 0.1m (red), 1m (green), and 3m (blue) depth released at starting time and location of actual fish observations in the Columbia River Estuary (black). Ebb tide simulations correspond to panels (a- c). Flood tide simulations correspond (d – f). Tongue Point (* Panel a), river kilometer 29, is a point of reference for all panels. Black arrows indicate start location. Downstream is to the left (west).

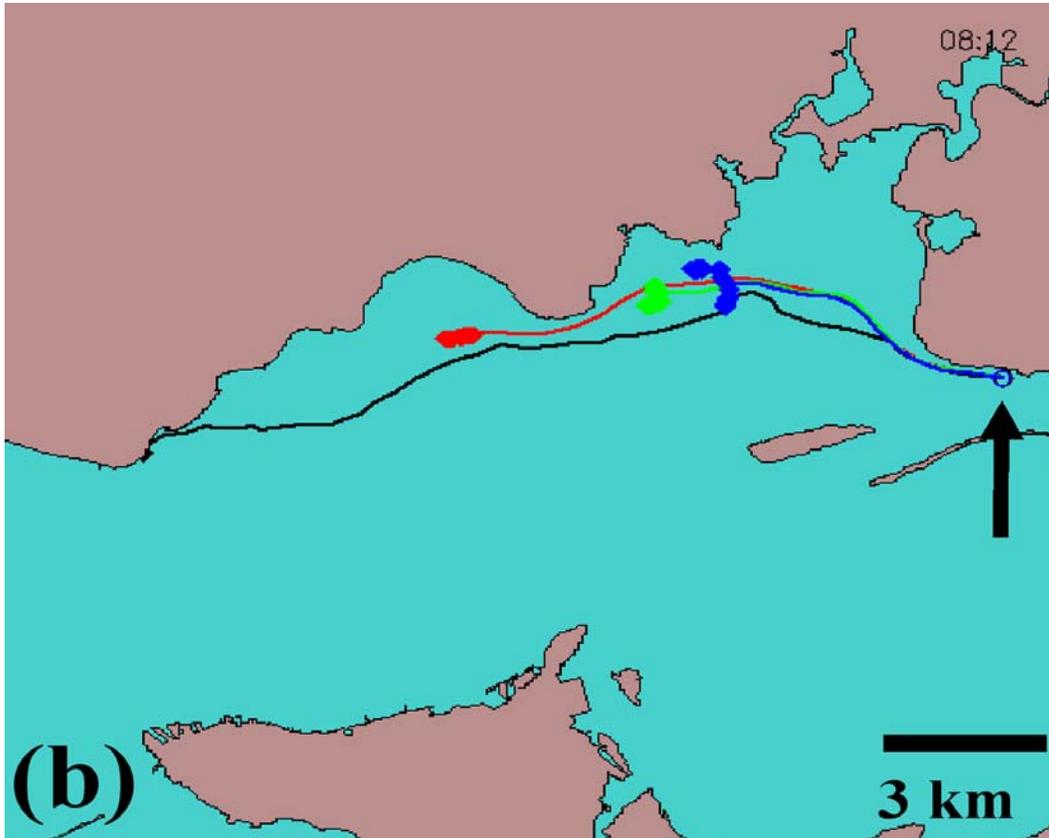


Figure 1.4. Continued

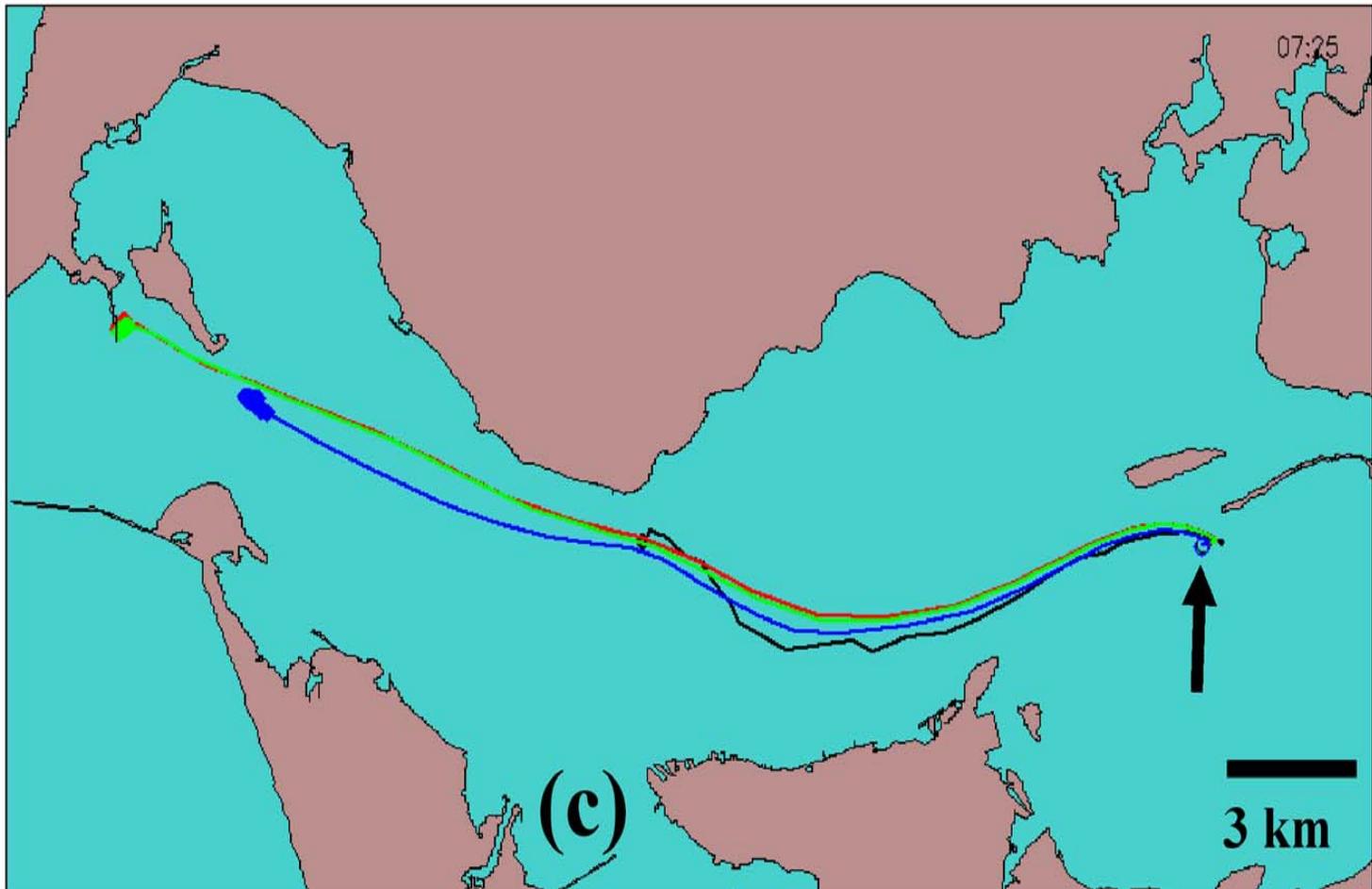


Figure 1.4. Continued

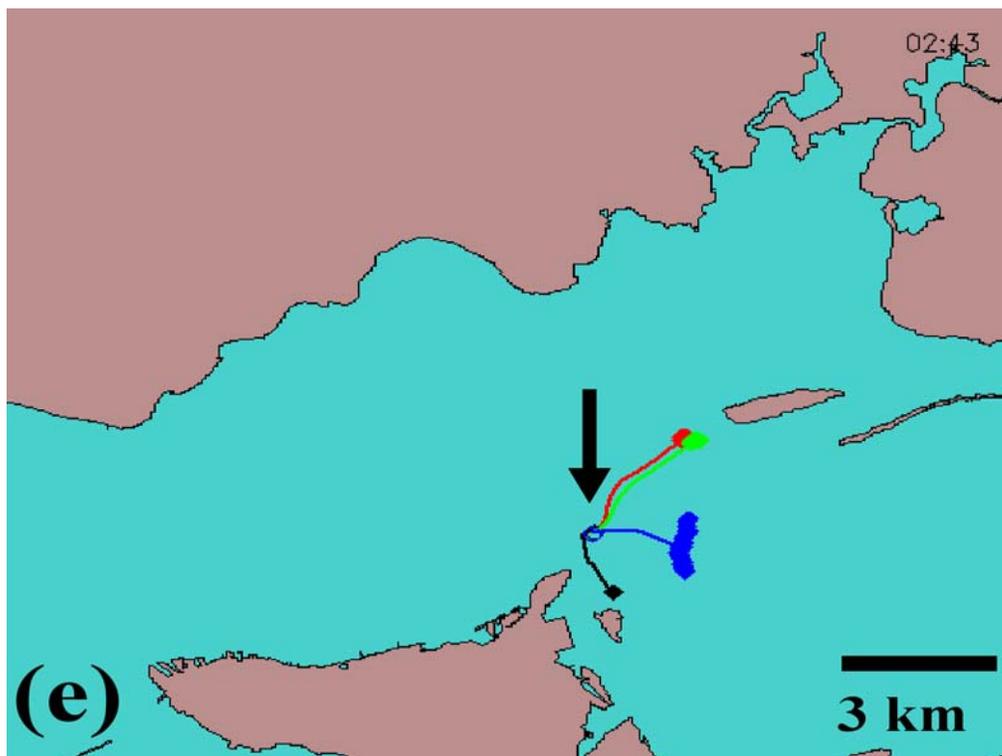
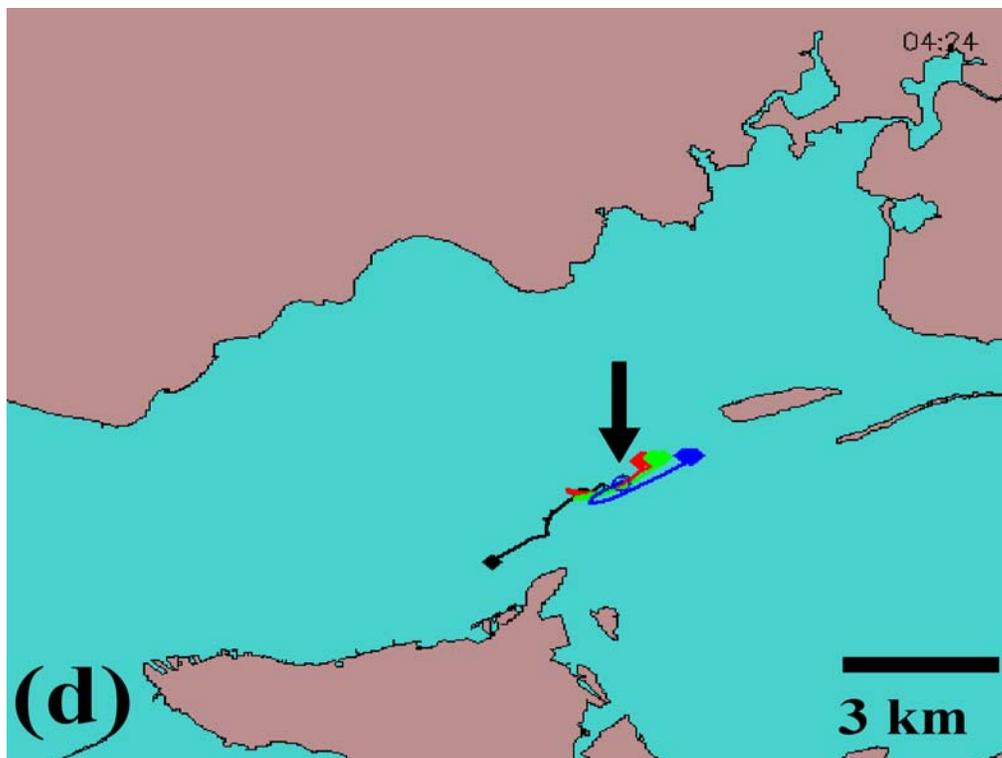


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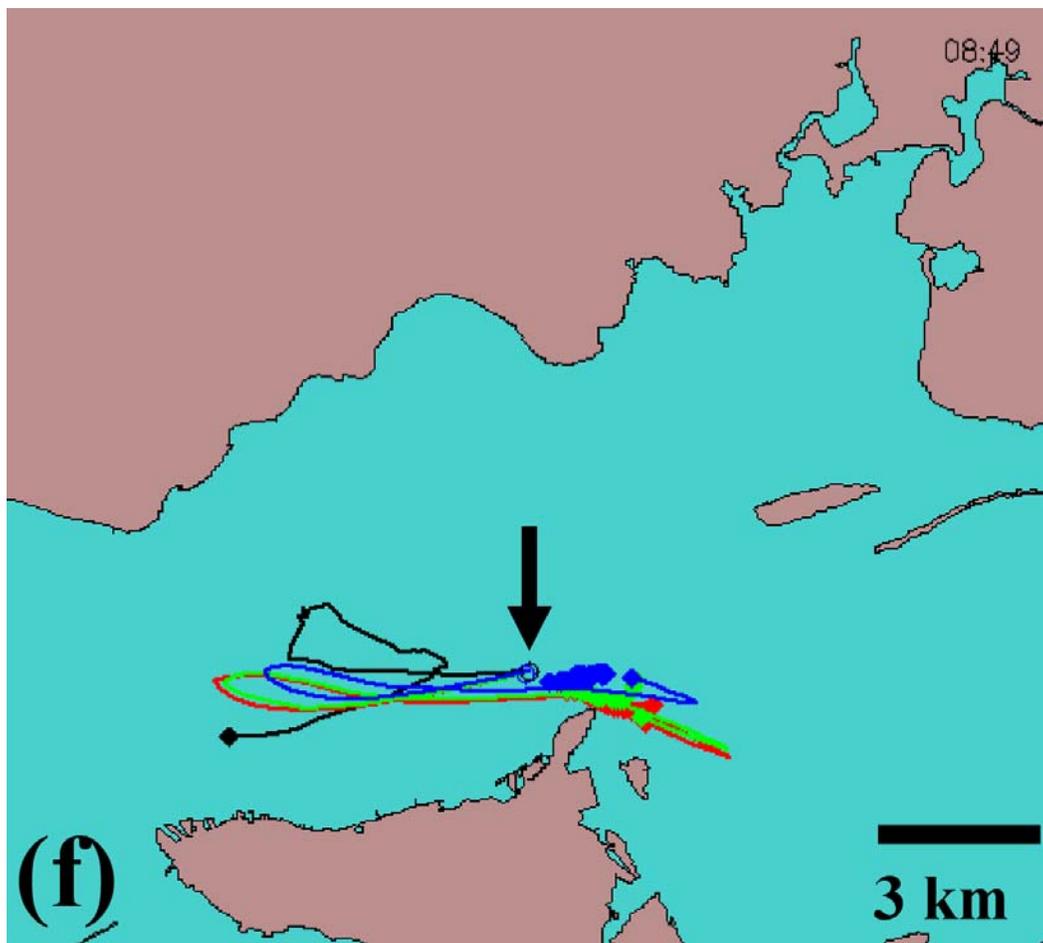


Figure 1.4. Continued

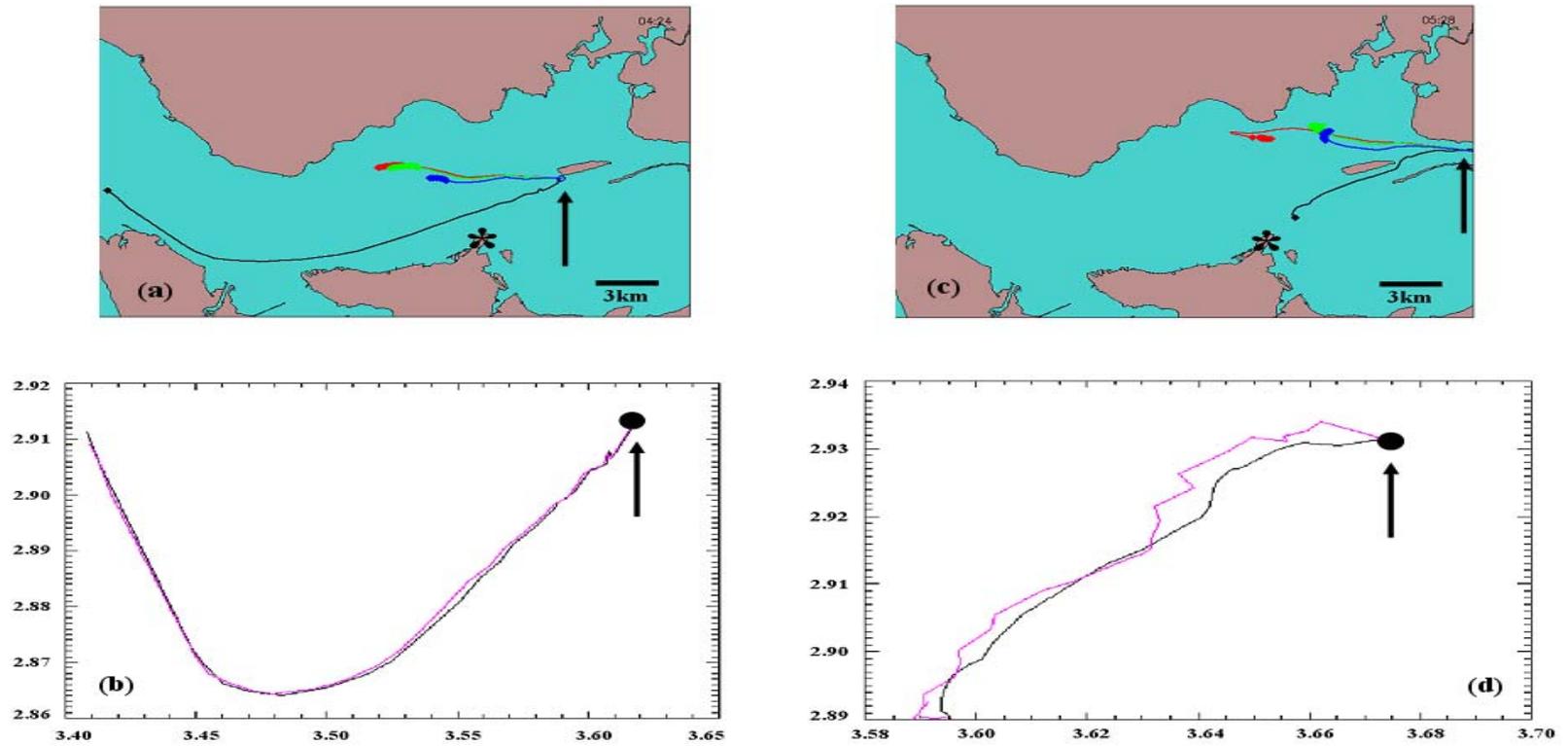


Figure 1.5 Drifter simulations (panels a and c), 0.1m (red), 1m (green), and 3m (blue) depths, released at starting time and location of observed fish in from the Columbia River Estuary (black). All drifters were simulated for the same period as that of the actual fish track. Drifter simulations (panels b and d) were made at each geolocation for the same period of time as the actual tracked fish (~ 10-min). Units for panels (b) and (d) are latitude and longitude (Oregon State Plane North Projection NAD 1927 meters $\times 10^5$). The purple line connects end point locations of virtual drifter simulations. The black line connects all geolocation endpoints of the observed fish. Black arrows indicate the start location. Tongue Point (*), corresponds to river km 29.

For example, if the movement of observed steelhead were passive, each consecutive steelhead geolocation would be identical to the simulated drifter location. Analysis of simulated drifters showed that brief periods of steelhead swimming (during periods of high surface flow velocity) resulted in large differences (several km) between actual fish locations and simulated drifter locations in a relatively short period of time (< 1 h). These data also showed that steelhead can drift or passively migrate for long periods of time (Figure 1.5 panel b), and can also spend long periods of time actively swimming (*i.e.*, the deviation between the observed fish and drifter tracks, Figure 1.5 panel d).

Temporal changes in the behavior of the observed fish occurred during tidal phase changes. These results were also consistent with data from the simulated drifters (Figure 1.2). Four responses in behavior to tidal changes were consistent in all observed species: (i) from flood to ebb tide, fish and simulated particle velocities increased (Figure 1.6); (ii) during flood tides, fish and simulated particle velocities were often equal (indicating passive swimming behavior), or the observed fish velocities were less than simulated particle velocities (*i.e.*, fish swimming against the current or that fish traveled in a zig-zag pattern too small to be detected by fish tracking methodology); (iii) during ebb tides, fish velocities were greater than—or equal to particle velocities (indicating fish swimming with the current); and (iv) during periods of high ebb tide currents, fish velocities were often slower than particle velocities when flows were $> 2 \text{ m s}^{-1}$. These patterns occurred regardless of the diurnal cycle of light and dark (*i.e.*, day or nighttime activity).

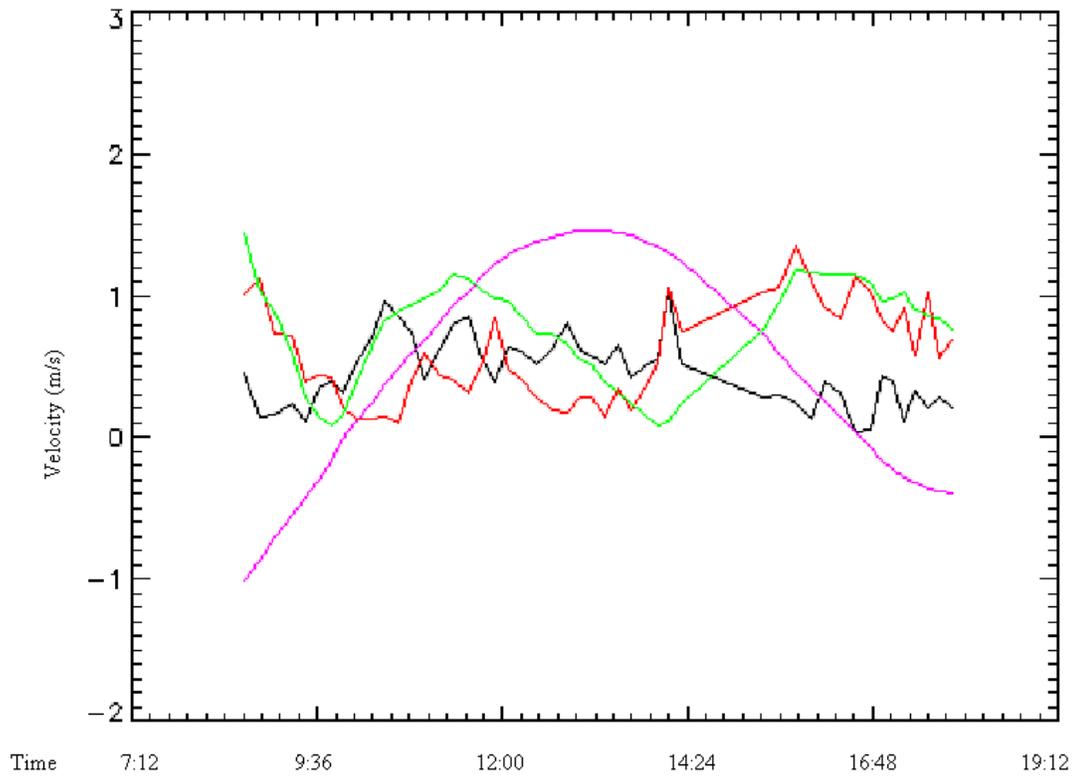


Figure 1.6 An example of tidal influenced changes in behavior from a single spring/summer Chinook. The behavior from this fish was representative in all fish species. Velocity and tidal height were recorded at each geolocation ($\Delta t = 10$ -min). X-axis (time), Y-axis (tidal height in meters; velocity in m s^{-1}). Fish velocity (red), simulated particle velocity (green), difference between simulated particle geolocation and fish geolocation (black), and tidal height (purple) are displayed.

The effect of water velocity on the velocity of observed fish varied by species and mode of transport (Table 1.1). Comparison of slopes (Sokal and

Table 1.1 Regression statistics comparing fish and real drifter velocity to simulated drifter velocity. Fish were grouped by race, year, transportation, and local current direction (in, out, and slack). Pair-wise comparison of slopes was used to determine statistical significance among groups. Significant results (p-value < 0.05) are in bold, and an * indicates significant differences among slopes. No data indicates no significant difference.

<i>Fish Type</i>	<i>Tracks (N)</i>	<i>Transportation</i>	<i>Current</i>	<i>p-value</i>	<i>R² (%)</i>	<i>Waypoints (N)</i>	<i>Slope</i>
<i>Drifter</i>	<i>1</i>	<i>None</i>	<i>In</i>	<i>0.001</i>	<i>48.62</i>	<i>17</i>	<i>0.47</i>
<i>Drifter</i>	<i>1</i>	<i>None</i>	<i>Out</i>	<i>0.000</i>	<i>96.94</i>	<i>10</i>	<i>1.35</i>
Spring Chinook	12	Barged	In	0.988	0.00	122	0.00
Spring Chinook	17	Barged	Out	0.000	23.26	266	0.36
Spring Chinook	16	Barged	Slack	0.624	0.28	88	0.19
Steelhead	6	ROR	In	0.039	14.39	48	0.77
Steelhead	6	Barged	In	0.000	22.77	52	0.59
Steelhead	12	ROR	Out	0.000	8.98	231	0.38
Steelhead	9	Barged	Out	0.000	9.32	160	0.22
Steelhead	10	ROR	Slack	0.614	0.66	41	0.42
Steelhead	8	Barged	Slack	0.825	0.10	51	0.13
Fall Chinook	9	ROR	In	0.363	1.17	72	0.18
Fall Chinook	5	Barged	In	0.658	0.41	50	0.14
Fall Chinook	13	ROR	Out	0.000	26.43	309	0.51
Fall Chinook	11	Barged	Out	0.004	3.38	245	0.20
Fall Chinook	12	ROR	Slack	0.031	6.32	73	0.60
Fall Chinook	6	Barged	Slack	0.218	6.24	26	0.98
Steelhead vs. Steelhead	12	Barged vs. ROR	In	0.513	65.17	100	
Steelhead vs. Steelhead	21	Barged vs. ROR	Out	0.119	8.74	391	
Steelhead vs. Steelhead	33	Combined	In vs. Out	0.001	22.34	491	*
Steelhead vs. Spring Chinook	38	Combined	Out	0.446	13.74	657	
Fall Chinook vs. Fall Chinook	24	Barged vs. ROR	Out	0.000	14.70	554	*

Table 1.1 Continued

<i>Fish Type</i>	<i>Tracks</i>	<i>Transportation</i>	<i>Current</i>	<i>p-value</i>	<i>R2 (%)</i>	<i>Waypoints (N)</i>	<i>Slope</i>
Fall Chinook vs. Steelhead	32	Barged vs. Combined	Out	0.226	7.91	635	
Fall Chinook vs. Spring Chinook	28	Barged	Out	0.033	10.84	511	*
Fall Chinook vs. Steelhead	34	ROR vs. Combined	Out	0.005	17.09	700	*
Fall Chinook vs. Spring Chinook	30	ROR vs. Barged	Out	0.018	24.90	575	*
Steelhead vs. Drifter	22	Combined vs. None	Out	0.005	11.73	401	*
Spring Chinook vs. Drifter	18	Barged vs. None	Out	0.000	28.85	276	*
Fall Chinook vs. Drifter	12	Barged vs. None	Out	0.004	7.33	255	*
Steelhead vs. Drifter	13	Combined vs. None	In	0.613	64.36	110	
Drifter	1	None	Combined	0.000	76.64	27	0.70
Spring Chinook Barged	17	Barged	Combined	0.000	31.68	518	0.36
Steelhead	21	Combined	Combined	0.000	21.45	554	0.45
Fall Chinook ROR	14	ROR	Combined	0.000	37.06	454	0.56
Fall Chinook Barged	12	Barged	Combined	0.000	11.01	320	0.03
Steelhead 2002 vs. Steelhead 2003	21	Combined	Combined	0.966	23.63	554	
Steelhead vs. Steelhead	21	Barged vs. ROR	Combined	0.693	22.05	554	
Fall Chinook 2002 vs. Fall Chinook 2003	26	Combined	Combined	0.535	11.40	320	
Fall Chinook vs. Fall Chinook	26	Barged vs. ROR	Combined	0.000	25.87	774	*
Spring Chinook vs. Steelhead	38	Barged vs. Combined	Combined	0.185	28.80	1044	
Fall Chinook vs. Steelhead	33	Barged vs. Combined	Combined	0.013	17.60	874	*
Fall Chinook vs. Steelhead	35	ROR vs. Combined	Combined	0.036	28.46	1008	*
Fall Chinook vs. Spring Chinook	31	ROR vs. Barged	Combined	0.001	35.12	972	*
Fall Chinook vs. Spring Chinook	29	Barged	Combined	0.030	23.99	838	*
Spring Chinook vs. Drifter	18	Barged	Combined	0.030	23.20	554	*
Steelhead vs. Drifter	22	Combined	Combined	0.087	34.80	545	*
Fall Chinook ROR vs. Drifter	15	ROR	Combined	0.043	38.50	454	*
Fall Chinook Barged vs. Drifter	13	Barged	Combined	0.068	14.56	347	

Rohlf 1981) was used to determine these differential effects. Four key distinctions may be inferred from this analysis. First and foremost, a nearly one-to-one relationship between real and simulated velocities, indicating passive drifting, was only observed for the real drifter when current was moving out of the estuary (Figure 1.7). The slopes of the regression lines in all fish groups were significantly different from that of the real drifter (Table 1.1). In general, the slopes of all fish groups were less than the slope of the real drifter, indicative of overall active swimming against the current. Second, the slopes in the steelhead and spring/summer Chinook groups were significantly greater than the slopes in the fall Chinook groups ($p < 0.05$, comparison of slopes). Third, the slopes in the barged fall Chinook groups were significantly less than those in the ROR fall Chinook groups ($p < 0.05$, comparison of slopes). This distinction was not observed in steelhead ($p > 0.05$, comparison of slopes). The comparison could not be made for spring/summer Chinook, because there were no ROR spring/summer Chinook. Finally, no differences were observed among years in any group. Unfortunately, spring/summer Chinook were only monitored for one year, and this comparison could not be made. It should also be noted that there was large variation in behavior among individual fish within each group.

Direction of water flow had a significant effect on fish velocity (Table 1.1; Figure 1.7). All fish types showed a positive relationship between fish velocity and simulated drifter velocity with outgoing water flow. During slack water flow ($< 0.25 \text{ m s}^{-1}$), this relationship was only observed in barged fall Chinook. There

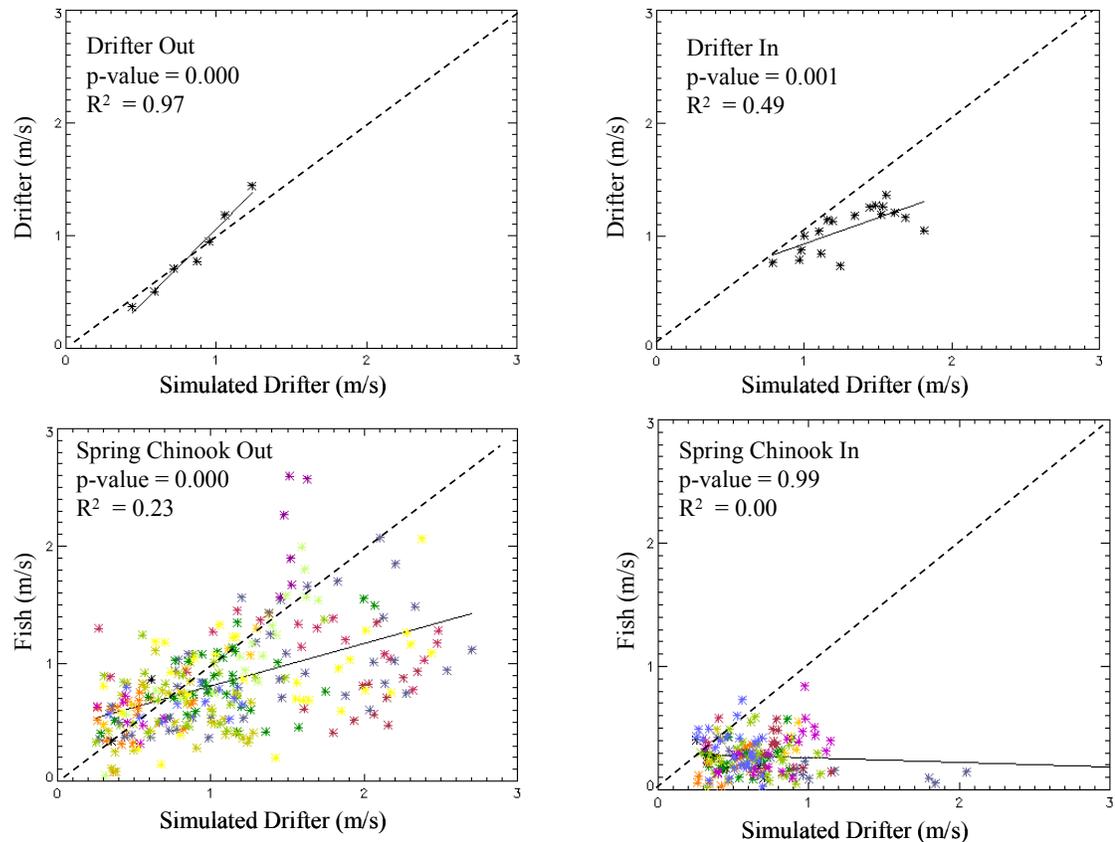


Figure 1.7 Regressions that compare the velocity (m s^{-1}) between spring/summer Chinook and simulated and actual drifters (for spring/summer Chinook). Spring/summer Chinook and real drifter velocities were grouped by current direction (In = water moving into the estuary, Out = water moving out of the estuary). The unique color of each symbol corresponds to an individual spring/summer Chinook actively tracked in the Columbia River Estuary. The solid black line corresponds to either the average slope of all individual spring/summer Chinook or the slope of the real drifter. The dotted black line is equivalent to the slope of a passive drifter (with drifter and simulated drifter error = 0).

was no relationship between incoming water flow and spring/summer and fall Chinook. There was however, a positive relationship between incoming water flow and steelhead. Vector analysis illustrated significant differences between the movement of juvenile steelhead and real drifters in the Columbia River Estuary (Figure 1.8). Velocity (m s^{-1}) and orientation vector analysis of fish geolocations,

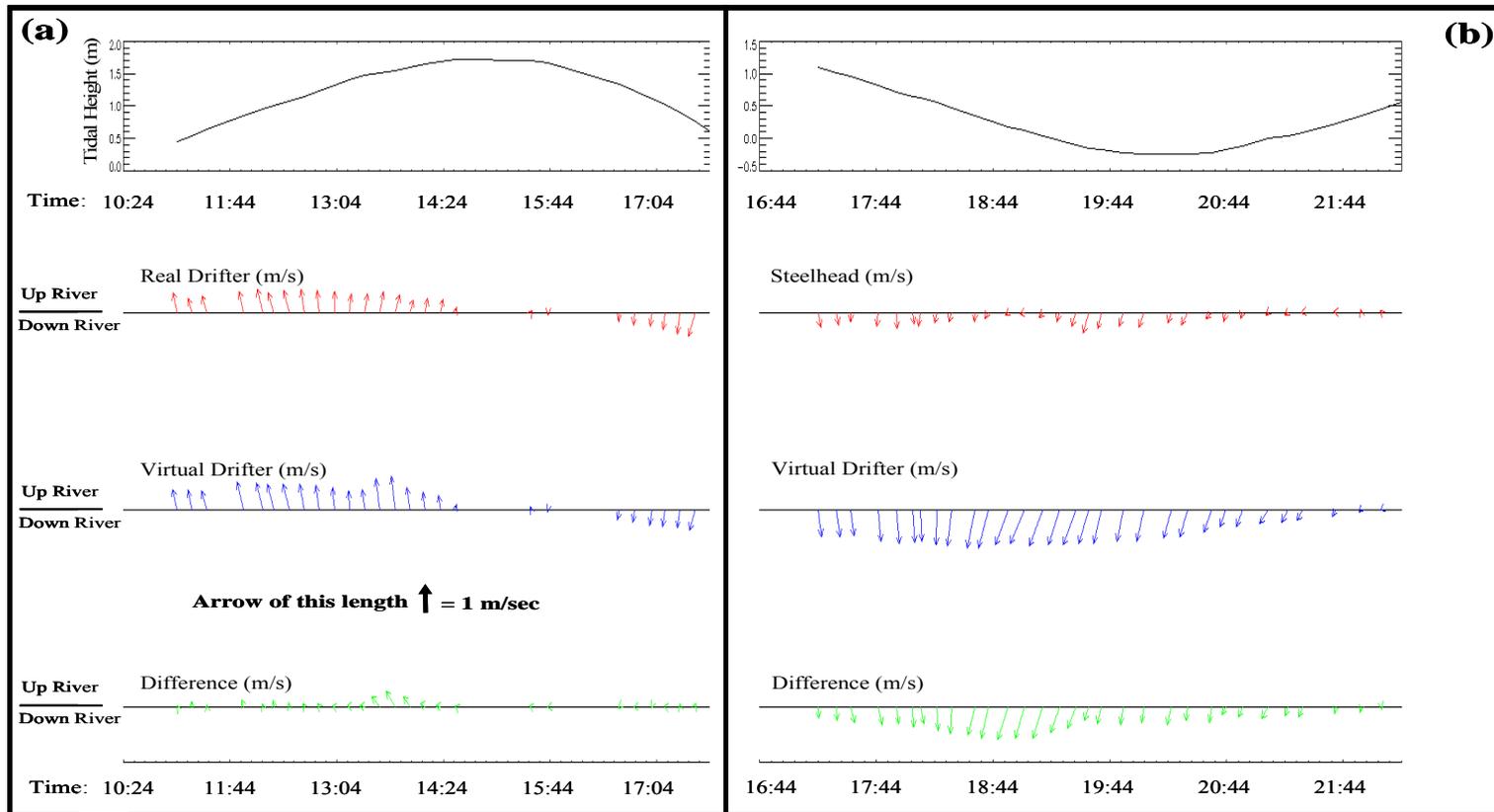


Figure 1.8 Vector analysis comparing travel direction and velocity (m s^{-1}) for a real drifter track (panel a) and a single steelhead track (panel b). Data in both panels are representative of the fish behavior found in this study. This figure represents the vector traveled over time of observed data (red), simulated data (blue), and the difference between them (green). Tidal height (top of both panels) corresponded to CORIE model tidal height at steelhead and real drifter geolocations. An arrow pointing up corresponds to travel up river (generally eastward), and an arrow pointing down corresponds to down river travel (generally westward). The more an arrow leans to the left, the more direction of travel is towards the south. The more an arrow leans to the right, the more direction of travel is towards to the north. Arrow length corresponds to velocity (m s^{-1}).

surface drifters simulations (released at each fish geolocation), and the difference between fish locations and final simulated surface drifters locations were measured in approximately 10-min intervals (difference between fish geolocations from the field) for the duration of active tracking in each study fish.

During ebb tide steelhead (representative of a typical fish in this study) depicted in Figure 1.8 (top panel) migrated in the same direction as the surface currents. During slack and flood tide, vector orientation and magnitude differed from that of the surface drifter simulation. Furthermore, the vector magnitude of steelhead was consistently less than that of the simulated surface drifter throughout the analysis. During both the ebb and flood tides the real surface drifter typically moved in the same direction (with a similar velocity) as the simulated surface drifter. During slack tide both velocity and direction differed between the real surface drifter and the simulated surface drifter. Vector analysis of all fish tracks (for both species and races) in this study showed that juvenile salmonids typically oriented themselves against the current during flood tides, and for all tidal stages, observed fish velocities were generally lower than the simulated surface velocities.

Discussion

This novel analysis of fish movement within the context of real time simulated current direction and velocity data provided new insights into juvenile salmonid behavior and ecology. First and foremost, we found that juvenile

salmonids exert control over their location and mobility. Moreover, a response in swimming behavior to the direction of current flow (*i.e.*, moving out of the estuary and into the ocean or moving from the ocean into the estuary) was observed in all fish types. Generally, all fish types swam more passively when the current was moving out of the estuary and more actively during slack current. When the current was moving into the estuary however, steelhead were the only fish to exhibit passive swimming behavior, while spring/summer and fall Chinook swam actively against the current.

The velocities of observed steelhead, spring/summer Chinook, and fall Chinook were all positively correlated with simulated current velocities (Figure 1.7). In general, fish moved slower in the current than simulated drifters, implying that the fish are swimming against the current. However, the degree of response differed by race/size and transportation type. In general, larger races of fish (steelhead and spring/summer Chinook) moved relatively faster (*i.e.*, greater slope shown in the regression analyses) with increasing water velocities than smaller fall Chinook.

An alternative explanation is that fish did not travel in a straight line between measurement points, but rather in a zigzag pattern too small to detect during our observational period. In either case, this behavior extended the relative time to travel a horizontal distance. Because observations were continually recorded over ~ 10-min period, this type of subtle behavior would otherwise go undetected by our tracking methodology. If juvenile salmonids were moving in

these zig-zag patterns, fish velocities would have been under estimated, because the distance traveled by the fish would also have been under-estimated.

Among individuals, substantial spatial variability in fish location and movement as well as substantial variability in the time fish moved from one location to the next (Table 1.1; Figure 1.7) was observed. For example, one individual spring/summer Chinook moved faster than the simulated drifters for the entire observational period, while another spent the entire period moving slower than the simulated drifters (Figure 1.7). A slope of 1 for any fish group in Table 1.1 indicates passive drifting behavior.

A slope of < 1 (*i.e.*, 0.49; Figure 1.7), however, for an actual surface drifter compared to the simulated surface drifter during in-coming current was evidence of uncertainty between the CORIE modeling system and the real drifter in the estuary (Zhang *et al.* 2004). During out-going current, the uncertainty between the CORIE modeling system and the real drifter was relatively low (*i.e.*, slope = 1.35, $R^2 = 0.97$). Since only one real drifter was used in this comparison, future studies are required to identify the relative uncertainty between the CORIE modeling system and real drifters in the Columbia River Estuary.

A majority of fish observations occurred during outgoing current where the uncertainty of CORIE modeling system drifter simulations was believed to be the lowest. Unfortunately, relatively few steelhead and fall Chinook were recorded during slack and incoming currents, which was reflected in low R^2 values, increasing the relative uncertainty in these specific comparisons. Furthermore, low R^2 values increased the uncertainty among species specific

comparisons of transportation type and annual variation on the swimming behavior of juvenile salmonids.

There are other external factors that may have contributed towards variation in migratory behavior among fish types. In addition to transportation, lack of sufficient recovery time from stressors encountered in the upper basin could have affected the migratory behavior of barged fall Chinook. Barged fall Chinook collected during July-August in both 2002 and 2003 appeared to be in poorer condition than unbarged fish. This was reflected in significant mortality rates of fish collected at LRG, perhaps associated with high water temperatures (above 20 °C). Furthermore, the survival of barged fall Chinook that were released below Bonneville dam (river km 236) to the entrance of the Columbia River Estuary (Stella, WA; river km 89) decreased as the smolt season continued (Schreck *et al.* 2003; Schreck *et al.* 2005). This may reflect both poor condition and insufficient recovery time from stressors that these fish encountered during their migration to LGR in association with collection, transportation, and temperature, among others. The trend of decreased survival as the smolt season continued was not observed in steelhead or spring/summer Chinook within this study. We speculate that the ROR fall Chinook were potentially in better condition than the barged group since they had the fitness to migrate to Bonneville Dam.

Although the effects of stressors in the upper-Columbia basin need to be addressed, we found the effects of dynamic estuarine currents could not be ignored by migrating juvenile salmonids. Several studies have suggested that

water velocity and direction are the major factors affecting seaward migration of salmonid smolts within estuaries (Moser *et al.* 1991; Moore *et al.* 1998; Lacroix *et al.* 2004). For instance, in the Bay of Fundee (an open marine environment with extreme tides), Lacroix *et al.* (2005) found that tidal currents influenced the swimming behavior of post-smolt Atlantic Salmon (*Salmo salar*). Post smolts moved out of the bay during ebb tides, and moved into the bay during flood tides or during a change from ebb to flood. In contrast, in a fjord system with weak tidal currents Atlantic salmon exhibited strong swimming behavior with no apparent response to either the velocity or direction of tidal currents (Finstad *et al.* 2005). Residence times of juvenile steelhead and coho (*Oncorhynchus kisutch*) salmon migrating through the Nehalem River Estuary (a small Oregon estuary with strong tidal currents), tended to be less than a day and corresponded well with tidal currents (Schreck *et al.* 2002). In contrast to previous studies in Grays Harbor, Washington, where extensive periods of holding (several days in low velocity water) were observed in juvenile coho salmon (Moser *et al.* 1991), no extended periods of holding were observed in juvenile salmonids within the Columbia River Estuary.

Water flow and direction in the complex channels of the Columbia River Estuary (Fig 1.1) change with tides, regulated river discharge, and coastal winds. In turn, the velocity and direction of surface currents change with depth and from one channel to the next. Hence, the economy of short periods of active swimming at the confluence of two channels, could exert the largest control on the dispersal of juvenile salmonids within the Columbia River Estuary (Figures 1.4 and 1.5).

This study also suggests that juvenile salmon moved into channels not traveled by simulated drifters by active swimming and not by passive drifting.

We did not measure depth at the geolocations of the observed juvenile salmonids. CORIE drifter simulations showed that juvenile steelhead, spring/summer Chinook, and fall Chinook were consistently in surface current flow, regardless of channel depth. Emmett *et al.* (2004) also found juvenile salmon inhabit the surface of the water column in the Columbia River. Radio-tags used in this study were rarely detected at depths > 3 m, suggesting that we captured the all the salmonid behavior regardless of depth, although this should be confirmed by future studies.

The behavioral trends of juvenile salmonids described above demonstrate the utility of this methodology and provide insight for future research. The incorporation of animal telemetry with environmental data can be applied in a wide variety of aquatic environments such as rivers, lakes, estuaries, coastal, and open-ocean. Future studies within the Columbia River Estuary should incorporate acoustic transmitters (radio signals cannot be detected in salt water) to monitor migratory behaviors of juvenile salmonids in the lower estuary and coastal ocean. Species-specific interactions such as schooling, interactions with avian, marine mammal, and fish predators, and interactions with large volume of estuarine boat traffic within the Columbia River Estuary, could all be addressed using similar methodology.

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CHAPTER 2

Stressors disrupt the in-stream migration of juvenile hatchery steelhead

(*Oncorhynchus mykiss*)

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Abstract

We evaluated the effects of both acute and chronic crowding stressors on the migratory behavior of hatchery reared juvenile steelhead (*Oncorhynchus mykiss*) released into Abernathy Creek, a tributary of the Columbia River Estuary, Washington. The acute stress treatment consisted of surgical implantation of a NanoTag® radio transmitter (Lotek Wireless, Canada), followed by 6 hours of crowding immediately prior to release. The chronic stress treatment consisted of surgical implantation of a PIT-tag (Digital Angel Corporation), 36 days of acclimation, followed by 3 weeks of crowding in low water conditions prior to release. Short-term migratory success of steelhead that received the acute stress treatment was determined by radio-telemetry. Numbers of migrating fish that received experimental stress treatments and their speed was determined by both mobile radio telemetry and stationary PIT tag and radio tag interrogation systems already established on Abernathy Creek. Acute and chronic stress treatments both significantly delayed migration by 2 to 10 days, respectively, compared to controls. Furthermore, the acute stress treatment significantly decreased the both the rate of migration and numbers of juvenile steelhead that successfully migrated out of Abernathy creek.

Introduction

Considerable evidence suggests that disruption to migratory pathways in both juveniles and adults is contributing to the decline of salmonid populations (Williams 1989; Raymond 1998; Rivinoja *et al.* 2001; and Wilson 2003). Migration corridors (mainstems of rivers and estuaries) have been heavily impacted by anthropogenic stressors, such as pollution, dams, and habitat destruction, which may be directly lethal or increase mortality by delaying or inhibiting smolt migration (McCormick *et al.* 1998). Handling and transport stressors associated with common fisheries management strategies are also of particular concern since they are known to cause severe physiological stress in juvenile salmonids (Schreck *et al.* 1989). Physiological reactions such as elevated levels of circulating cortisol initiate a cascade of events that appear to hinder essential performance characteristics of juvenile salmonids including disease resistance (Maule *et al.* 1989), seawater tolerance (Redding *et al.* 1984), rate of downstream migration (Specker and Schreck 1980), and increased mortality during migration (Koed *et al.* 2002). Furthermore, stress related disruption of downstream migration in juvenile salmonids includes extended holding in areas of high predation (Snelling and Schreck 1993).

The downstream migration of juvenile salmonids is a critical life history stage, during which significant physiological, morphological, and behavioral changes occur to prepare fish for life in seawater (Hoar 1988). We currently have a general understanding of the endocrine control of the parr-smolt transformation and several hormones have been identified as stimulatory or inhibitory regulators

(Agustsson *et al.* 2001; Specker *et al.* 2000). However, relatively little information is available concerning the interaction between physiology and behavior that influence downstream migration of juvenile (Iwata 1995). Previous studies have demonstrated high predation on recently released juvenile hatchery salmon, presumably through a prey density effect (Shively *et al.* 1996; Koed *et al.* 2002). Therefore, an increased understanding of the interaction among anthropogenic stressors, juvenile salmon migratory behavior, and predation is critical for current management efforts towards maximizing the survival of declining salmon stocks.

It has been suggested that handling stress increases the river and marine mortality of smolts after their release (Schreck *et al.* 1989). In contrast, the use of stress-reducing methods, especially recovery after transport and handling, can improve the migratory behavior and marine survival of smolt releases (Finstad *et al.* 2003). The aim of the present study was to determine if either chronic (10 day) or acute (6 hour) handling and crowding stressors can disrupt the migratory behavior, and ultimately reduce the survival of juvenile hatchery steelhead.

Methods

FISH REARING

Abernathy Fish Technology Center (ATFC) Hatchery Steelhead

The ATFC hatchery steelhead were progeny of native Abernathy Creek broodstock. Raceways were covered with bird netting and had partial overhead cover. Fish had continual access to demand feeders and were handfed daily. *Renibacterium salmoninarum*, present in most salmonid stocks (Mesa *et al.* 1999), was observed in ATFC steelhead at a rate typical for Columbia River salmon hatcheries.

CONTROL FOR ACUTE STRESS TREATMENT

A total of 26 fish for the control treatment group were sampled via dip net from a single hatchery raceway (AFTC raceway 2) that contained approximately 5000 AFTC steelhead. Starting, April 10th, 2003, one week prior to release, radio-tags were surgically implanted, and fish were placed back into their original raceway (to provide sufficient acclimation to the radio-tag implantation stressor). This was the only stressor for this group (other than standard hatchery practices).

ACUTE RADIO TAG IMPLANTATION AND CROWDING TREATMENT

Starting April 17th, 2003, a total of 76 steelhead were collected from AFTC hatchery raceway 3, which contained 5000 AFTC steelhead. Starting 6 hours prior to release, fish were surgically implanted with either radio-tags (N=26) or PIT-tags (N=50). After surgical implantation, fish were placed in a net-

pen that blocked the final meter of the bottom end of the raceway from which they were originally selected. All fish remained in the net pen for 6 hours prior to release to simulate a crowding stressor. The time and method of release was the same for experimentally stressed fish as it was for AFTC hatchery fish.

CHRONIC CROWDING STRESS TREATMENT

Starting on February 1st, 2003, two months prior to release, juvenile steelhead (N=228) were collected from AFTC raceway 3 and surgically implanted with a PIT-tag. Fish were randomly assigned to one of 2 treatment groups (chronic stress or control). Replication of tanks occurred in triplicate for chronic stress and control treatment types. Fish were placed into 2 m circular tanks at a density of 38 fish per tank. Well water at 11°C was supplied to the tanks at 3 l min⁻¹. Fish were fed daily with BioOregonTM at a total ration of 0.8% of body weight. Starting March 27th, 2003, three weeks prior to release, the chronic stress treatment group was exposed to a continuous low water crowding stressor until release. Tank water level was lowered to the minimal amount required for fish to maintain themselves upright, with dorsal fins unexposed. The control/minimal stress treatment group did not receive the low water crowding stressor. Starting, April 17th, 2003, on the day of AFTC steelhead release, all chronic stress and control treatment fish were released into Abernathy Creek. The release of all experimentally stressed fish occurred in conjunction with the AFTC steelhead release (5:15 pm PST). A brief (5-min) transport stressor occurred immediately prior to release for fish that received the chronic stress and control treatments. All

fish were netted out of their respective tank and transported via a 19 l bucket approximately 100 m from the tank location, to the AFTC release site in Abernathy Creek (Figure 2.1). This netting and release stressor was the only stressor that the control treatment experienced.

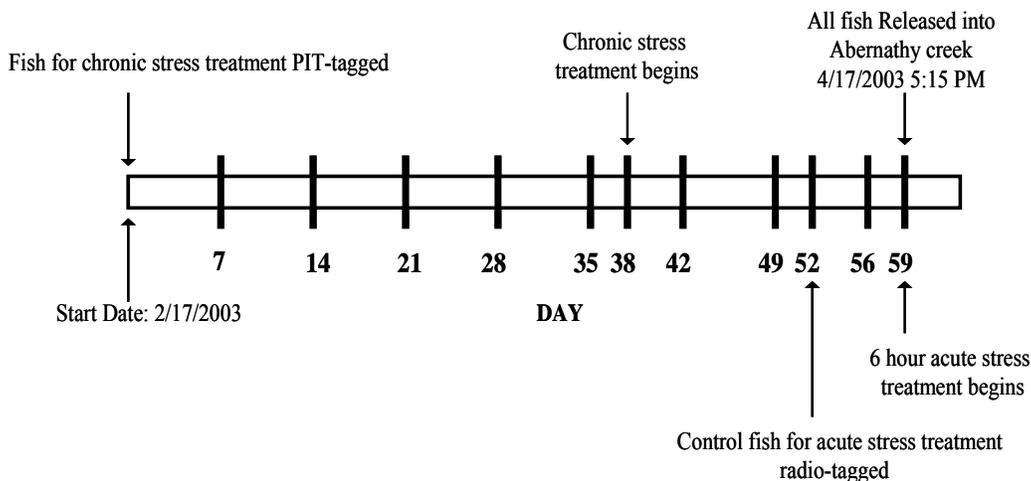


Figure 2.1 Timeline of acute and chronic stress treatments prior to AFTC steelhead release on April 1st, 2003.

FISH TAGGING

Juvenile steelhead were tagged with either digitally encoded radio transmitters (NTC-3-1 NanoTag®; 0.85 g in air, 149 – 150 megahertz, 2.9 – 3.1 second burst rate, ~11 day battery life, Lotek Wireless, Canada) or PIT-tags (Digital Angel Corporation, Full Duplex Technology, 0.6 g in air, 23mm by 3.4mm). Prior to tagging, fish were anesthetized in 50 mg l⁻¹ tricaine methanesulfonate (MS-222) buffered with 125 mg l⁻¹ NaHCO₃, measured, and weighed. Each NanoTag® was surgically implanted into the body cavity using a

modified technique from Moore *et al.* (1990). Fish were placed ventral side up in a wetted foam insert to hold them in place. Commercially available Stresscoat® was applied to the foam surface to minimize mucus and scale loss. Anesthetic was perfused over the gills using a squeeze bottle to maintain oxygen to the gills while keeping the fish sedated.

PIT-tags were inserted via a 3 mm incision into the ventral body wall anterior to the pelvic girdle. Radio tagged steelhead received a 1 – 1.5 cm incision into the ventral body wall anterior to the pelvic girdle. The tag was inserted and the incision closed with 2 sutures. During the implantation of the radio transmitters and prior to closing the incision wound, a needle that encased the wire antennae was guided through the incision and pushed through the body wall, posterior to the incision and anterior to the pelvic girdle. Preliminary trials the Oregon State University Fish Performance and Genetics Laboratory indicated that this method was most effective at minimizing tissue damage and fin abrasion around the antenna exit. Jepsen *et al.* (2001) have shown that radio-tagging is indeed stressful for salmon smolts but that the presence of the tags is not chronically stressful because levels of cortisol, glucose, and lactate return to normal (control) levels after a few days.

FISH TRACKING

Movement of all radio-tagged fish was monitored using radio telemetry (Lotek, SRX 400). Starting on April 16th, one day prior to ATFC release, a fixed radio telemetry station was established at the confluence of Abernathy Creek and

the Columbia River Estuary, 4 km downstream from the point of release (Figure 2.2). Starting on April 17th, 2003, a geolocator sweep (active radio-tracking) covering Abernathy Creek 1 km above the release site to the confluence of the Columbia River, occurred immediately following release of experimentally stressed fish at 5:15 pm. The geolocations of all radio tagged fish encountered were recorded with a handheld GPS unit (Garmin GPS Map 60). Active radio-tracking continued daily until April 21st, 2003, 4 days post AFTC release.

Numbers of migrating PIT-tagged fish and their speed was monitored using stationary PIT-tag interrogation systems already established on Abernathy Creek (Zydlewski *et al.* 2001). Systems were designed to report all detected PIT-tag codes with a time stamp. Two systems were functional during the time of this study. One was located at AFTC (upstream of the hatchery release site) and one was located approximately 1 km downstream of AFTC (downstream the hatchery release site) (Figure 2.2). Abernathy Creek, a tributary to the Columbia River, in Longview, WA, USA, is a small, third order stream with a drainage area of approximately 110 km².

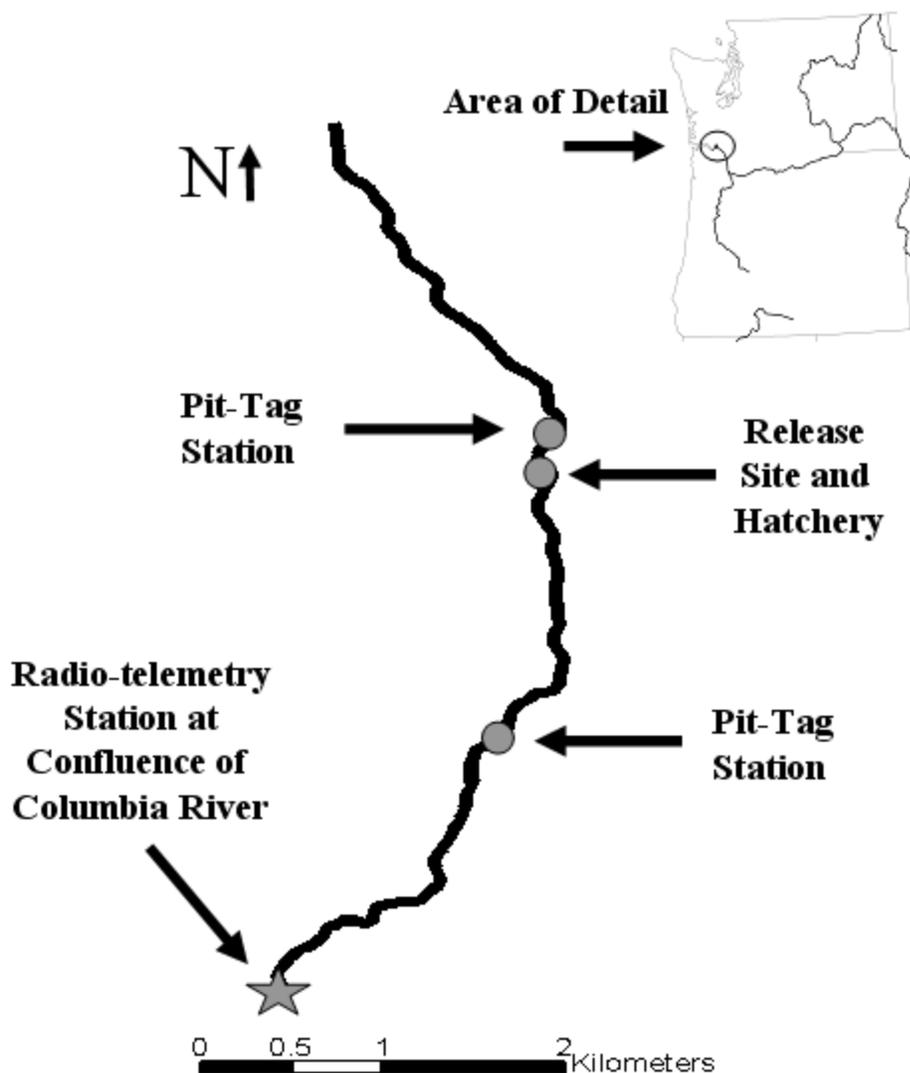


Figure 2.2 Map of Abernathy Creek (black) and confluence with the Columbia River (star). Geolocations of fish release site, fixed PIT-tag stations, and fixed radio-telemetry station are identified.

Results

Post-release migration profiles for PIT-tagged fish are suggestive of a stress dependent delay of migration (Figure 2.3). Treatment type (acute or chronic) did not affect the number of fish that migrated to the fixed PIT-tag

detection station (2 km downstream from the release site). A total of 230 (46%) raceway control, 52 (45%) chronic stress, 52 (45%) of the controls for the acutely stressed group (recall these fish received a brief liberation stressor), and 24 (45%) acute stress treatment fish were detected by the fixed PIT-tag detection station. A total of 2 fish from the acute stress treatment (4%) were detected by the fixed PIT-tag array 100 m upstream from the release site. No fish from the other treatments were observed by the fixed PIT-tag array upstream of release site. Acute and chronic stress treatments both significantly delayed migration by 2 to 10 days, respectively ($p < 0.05$, Kolomogorov-Smirnov test of distributions).

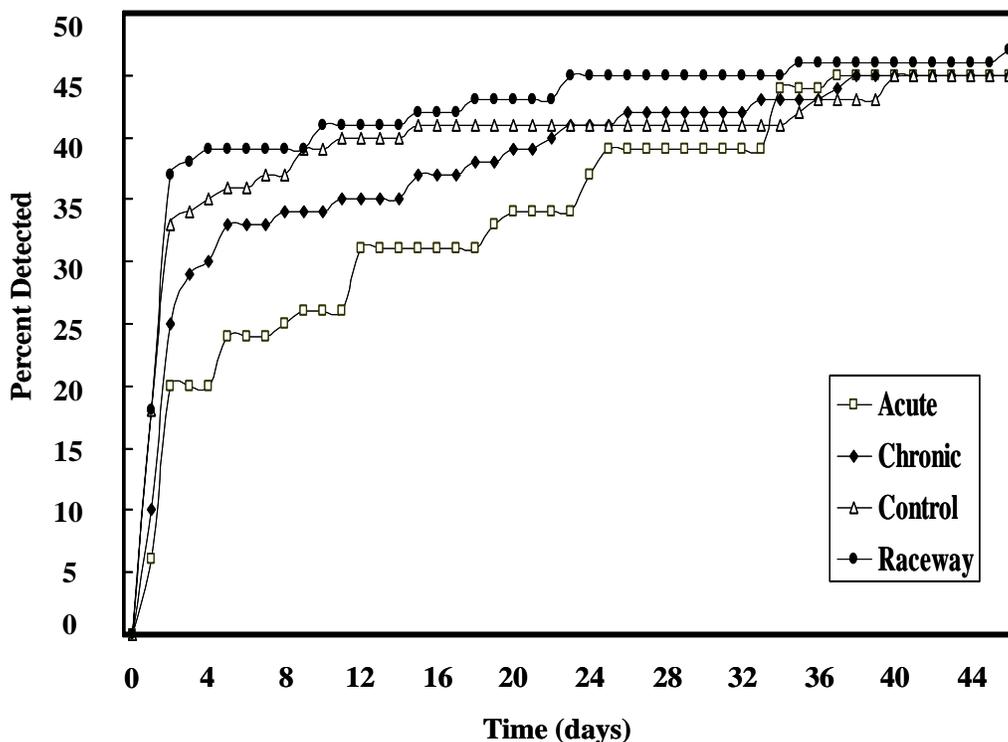


Figure 2.3 Percent of PIT-tagged fish recorded by a fixed PIT-tag reading station 2 km downstream from the release site. Acute crowding and PIT-tagging stress treatment (box), chronic crowding stress treatment (black diamond), control (triangle), and fish reared by a standardized Abernathy Fish Technology Center protocol (black circle) were all released at the same time and location.

The acute radio-tag implantation and crowding stress treatment significantly decreased the migratory success of radio-tagged juvenile steelhead (Figure 2.4). Active in-stream radio tracking from the moment of release until 4

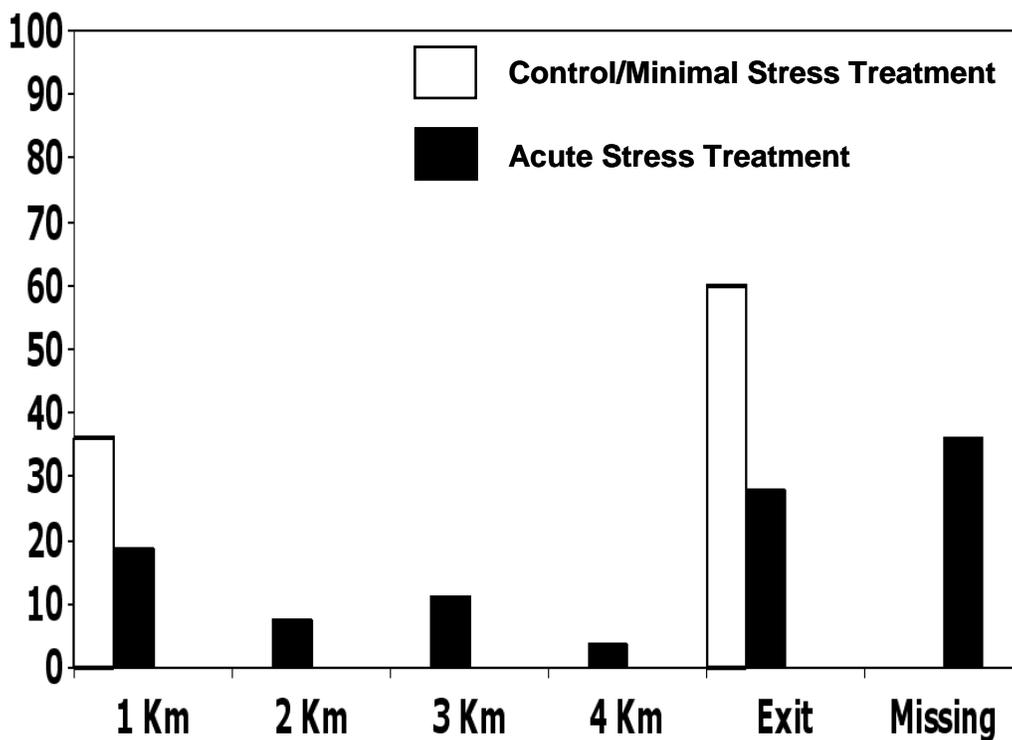


Figure 2.4 Migratory success of radio-tagged juvenile steelhead 4 days post-release. Percentages of acute stress treatment (N=25) fish are indicated in black and the control (N=27) treatment in white. Bars represent the percent of fish released that were detected in the first km (1 km), second km (2 km), third km (3 km), and fourth km (4 km) downstream of the release site, those that exited into the Columbia River (Exit), and the percentage of fish that were not detected anywhere (Missing). Total percentage of fish that exited Abernathy creek was determined by a fixed radio-telemetry station. All fish from the control treatment were detected.

days post-release revealed a 3-fold increase in migratory success for the control group relative to the acute stress treatment ($p < 0.005$, rank-sum permutation). Similarly, a 2-fold increase in holding near the release site was observed in the acute stress treatment ($p < 0.005$, rank-sum permutation). Of particular importance, 9 (36%) fish from the acute stress treatment were missing from the Abernathy Creek study site 4 days post-release, while all fish from the control treatment were accounted for.

Discussion

The results of this study are consistent with the hypothesis that insufficient recovery time from a severe stressor could be detrimental to the migratory success and ultimately the survival of juvenile steelhead. This study provides suggestive evidence that both acute and chronic stress treatments can disrupt the downstream migratory behavior of juvenile hatchery reared steelhead. Furthermore, the acute stress treatment increased holding behavior near the release site, and reduced the migratory success of juvenile steelhead from their natal tributary to the Columbia River. In contrast, the recovery of coho salmon (*Oncorhynchus kisutch*) transported as juveniles that were allowed sufficient recovery were more likely to survive to adulthood than those released directly into the wild following a transport stressor (Schreck *et al.* 1989).

Behavioral alteration generally occurs after the end of a stressor (Olla *et al.* 1995), while physiologically it may require minutes to weeks to return to their pre-stress state (Schreck *et al.* 1997). Similarly, significant departures from

behavioral norms may decrease the probability of survival in the wild (Schreck *et al.* 1997). Therefore, alterations in fish behavior induced by stressors such as handling (Sharpe *et al.* 1998), crowding (Patiño *et al.* 1986), and tagging without acclimation (Sharpe *et al.* 1998) may disrupt activities essential for survival (Olla *et al.* 1995), including food acquisition, predator avoidance, aggression, learning, and habitat selection (Schreck *et al.* 1997).

Several species of avian and mammalian predators were observed near the AFTC on the day of fish release. Blue herons (*Ardea herodias*), merganser ducks (*Mergus merganser*), bald eagles (*Haliaeetus leucocephalus*), and river otters (*Lutra Canadensis*) were all observed in Abernathy Creek, and seals (*Phoca vitulina*) congregated at the confluence of Abernathy Creek with the Columbia River. However, no direct measure of predation was observed in the 36% of acutely stressed fish that were not detected in Abernathy Creek 4 days post-release. Since all fish from the control treatment were accounted for, it is unlikely that tracking error could explain the missing fish. Besides predation, other scenarios for the fate of the missing acutely stressed fish include possible migration to areas not covered by active tracking, such as connective tributaries of Abernathy Creek or migration of 2 km upstream of the hatchery release site. The two tributaries that flow into Abernathy creek below the release site contain waterfalls that could act as fish barriers near their confluence with Abernathy Creek; it is therefore unlikely that fish actually left Abernathy creek proper. However, 2 PIT-tagged fish from the severe stress treatment were detected by the PIT-tag interrogation system upstream of the release site. Unfortunately, long-

term monitoring of acutely stressed (radio-tagged) juvenile steelhead was not possible, since the battery life of the radio-tags was approximately 2 weeks. Similarly, we were unable to collect survival data to the Columbia Estuary for PIT-tagged fish. High winter and spring flow conditions within Abernathy Creek have made it logistically difficult to maintain a permanent PIT-tag reader at the entrance of the Columbia River Estuary (Bill Gayle, Personal Communication).

Our results from Abernathy Creek, Washington, suggested that long-term monitoring of stress-induced behavioral alterations in juvenile steelhead is critical for understanding the mechanisms that affect the migratory behavior and the ultimately survival of steelhead trout during their seaward migration. The current study provides further evidence that stress-induced holding behaviors in areas where predators are present contributes to decreased migratory success in juvenile steelhead.

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GENERAL CONCLUSIONS AND SPECULATIONS

The first chapter of this thesis provided new insights into the environmental cues used by migratory fish and the sensory systems underlying their sophisticated patterns of behavior. This was the first study that provided high resolution long-term (May-August; 2002-2004) monitoring of swimming speeds, orientation, and migratory behaviors of juvenile salmonids in relation to tidal and surface currents in a large estuary. The present study provides evidence that juvenile salmonids exert control over their movement and location by active and passive swimming behaviors in response to variation in tidal phase, surface current velocity, and surface current direction.

Detailed analysis of migratory behavior revealed common patterns related to CORIE modeling system simulations of tidal height and surface currents within the complex network of channels in the Columbia River Estuary. We found that the tracked velocity of steelhead, spring/summer Chinook, and fall Chinook were all positively affected by simulated current velocity (Figure 1.7). In general, the fish moved slower in the current than a real drifter, implying that the fish are swimming against the current. However, this response varied by race/size and transportation type. Pair-wise regression analysis showed that, in general, larger races of fish (steelhead and spring/summer Chinook) moved proportionally faster (greater slope) to increasing water velocity than smaller fall Chinook. Though not intuitively obvious, this suggests that fall Chinook generally fought the current more than their counterparts.

A behavioral response to current direction was observed in all fish types. In general, the swimming behavior of all fish types was more passive when the current was outgoing. However, when the current was in coming, passive swimming behavior was only observed in steelhead. Spring/summer and fall Chinook displayed more active swimming behavior during incoming current. In general, during slack current, fish behavior was active.

In the second chapter, we provided suggestive evidence that both acute and chronic stress treatments can disrupt the downstream migratory behavior of juvenile hatchery reared steelhead. Furthermore, the acute stress treatment increased holding behavior near the release site, and reduced the migratory success of juvenile steelhead from their natal tributary to the Columbia River. In contrast, the recovery of coho salmon transported as juveniles that were allowed sufficient recovery time were more likely to survive to adulthood than those released directly into the wild following a transport stressor (Schreck *et al.* 1989).

Our results from Abernathy Creek, Washington, suggested that long-term monitoring of stress-induced behavioral alterations in juvenile steelhead is critical for understanding the mechanisms that affect the migratory behavior and ultimately the survival of steelhead trout during their seaward migration. The current study provided further evidence that stress-induced holding behaviors in areas where predators are present contributes to decreased migratory success in juvenile steelhead.

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