Salmon Habitat Use of Tidal-fluvial Habitats of the Columbia River Estuary, 2010-2013. Final Report

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Executive Summary

In 2010 we initiated an integrated study program to better understand the contribution of the Columbia River estuary to the spatial structure and life history diversity of salmon stocks and the implications for strategic estuary restoration. Research encompassed both an estuary-wide evaluation of Chinook salmon genetic variability across an array of habitats, as well as focused studies at tidal-fluvial and saline-estuarine reaches. Tidal-fluvial reaches are environments that have been undersampled to date, while our saline-estuarine site comprises a 13-year baseline study. We tracked salmon habitat use in several wetlands with PIT tag arrays, made comparative diet studies, and examined otolith microchemisty to evaluate the contribution of salmon life history diversity to adult returns. We conducted numerical modeling experiments to investigate salmon habitat opportunity as a function of salmon size and physical constraints. Although funding limitations after 2012 curtailed expected field activities, we have published results from analyses of the spatial scale of genetic diversity (Teel et al. 2014), and a summary of our first 2 years of study (Roegner et al. 2013). In this report, we focus on research completed since 2011, provide conclusions and management recommendations to date, and collate pertinent research manuscripts in preparatory and published form. Our research contributes to understanding salmon habitat use in the lower Columbia River and estuary and aids management decisions for recovery of federally listed stocks.

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Contents

Introduction and Study Objectives

The 2008 *Biological Opinion on Operation of the Federal Columbia River Power System* established estuary restoration goals that included 10-year survival improvements of 9% for ocean-type and 6% for stream-type ESUs (NMFS 2008). To support these goals, a qualitative assessment process (Columbia River Estuary Recovery Plan Module) was devised to identify limiting factors and to prioritize estuary restoration actions based on their presumed salmon survival benefits. This method ranks potential benefits of various restoration projects based on published results and professional judgments about their relative effectiveness. Empirical estimates of survival benefit are unavailable; however, the actual contributions of single or cumulative estuary actions to the survival goals in the biological opinion are unknown.

Today scores of wetland restoration projects have been undertaken in the estuary as a method to recover at-risk salmon populations throughout the Columbia River basin. These projects are based in part on the latest information about the role of the estuary as a productive nursery ground for juvenile salmon (Bottom et al. 2005, 2008, 2011; Roegner et al. 2008, 2010, 2012; Johnson et al. 2011). Recent genetic data collected in the estuary have shown evidence of important stock-specific differences in estuarine habitat use (Bottom et al. 2008; Teel et al. 2009), and to date, these findings have not been considered in the selection or design of restoration projects.

Moreover, the population response to estuary restoration remains poorly understood because research, monitoring, and evaluation (RME) programs have focused exclusively on the performance of estuarine-rearing juveniles rather than their ultimate contribution to adult returns. In 2010 we initiated an integrated study program to better understand the contribution of the estuary to spatial structure and life history diversity for Columbia River salmon stocks, and the implications of this contribution for strategic estuary restoration efforts. To achieve this long-term goal, we proposed four research objectives corresponding to each of the following questions:

1. How are genetic stock groups distributed throughout the estuary?
2. Do salmon life history, habitat use, and performance vary by stock?
3. Which juvenile life histories contribute to adult returns, and does estuarine habitat restoration benefit population resilience?
4. How much restoration is needed to ensure stock persistence?

In 2010-2012 we completed an estuary-wide survey of juvenile Chinook salmon stock distribution (Teel et al. 2014). These results directly address question 1 (above) and lay the foundation for higher-resolution studies to address questions 2 and 3. This final report summarizes our research findings and conclusions from 2010-2013, including data collected since the 2011 annual project report (Roegner et al. 2013). Here we present methods and results for:

- Salmon habitat use and genetic stock composition in the upper Columbia River estuary
- Temporal variations in fish community structure and salmon life histories near the estuary mouth
- Stock sources, travel times, and residency of PIT-tagged salmon in selected wetland tidal channels
- Chinook salmon diet composition and instantaneous ration in mainstem and back-channel habitats
- Juvenile Chinook life history contributions to selected Columbia River spawning populations
- The dynamics of shallow-water habitat opportunities for different size classes of juvenile salmon

Manuscripts reporting related project results, either in preparation or published since 2010, are summarized in Appendices A and B.

Methods and Results

This research addresses salmon ecology at multiple spatial scales (i.e., entire estuary, hydrogeomorphic reaches, and local habitats), which involve different sampling methods, locations, and time periods. During a 2010-2012 estuary-wide stock distribution survey (Teel et al. 2014), we sampled juvenile salmon bimonthly in each of three shallow-water habitats (mainstem, backwater, and confluence) in six estuary hydrogeomorphic reaches (reaches C-H) and at a single monitoring site near the estuary mouth (Point Adams Beach, reach A; Figure 1).

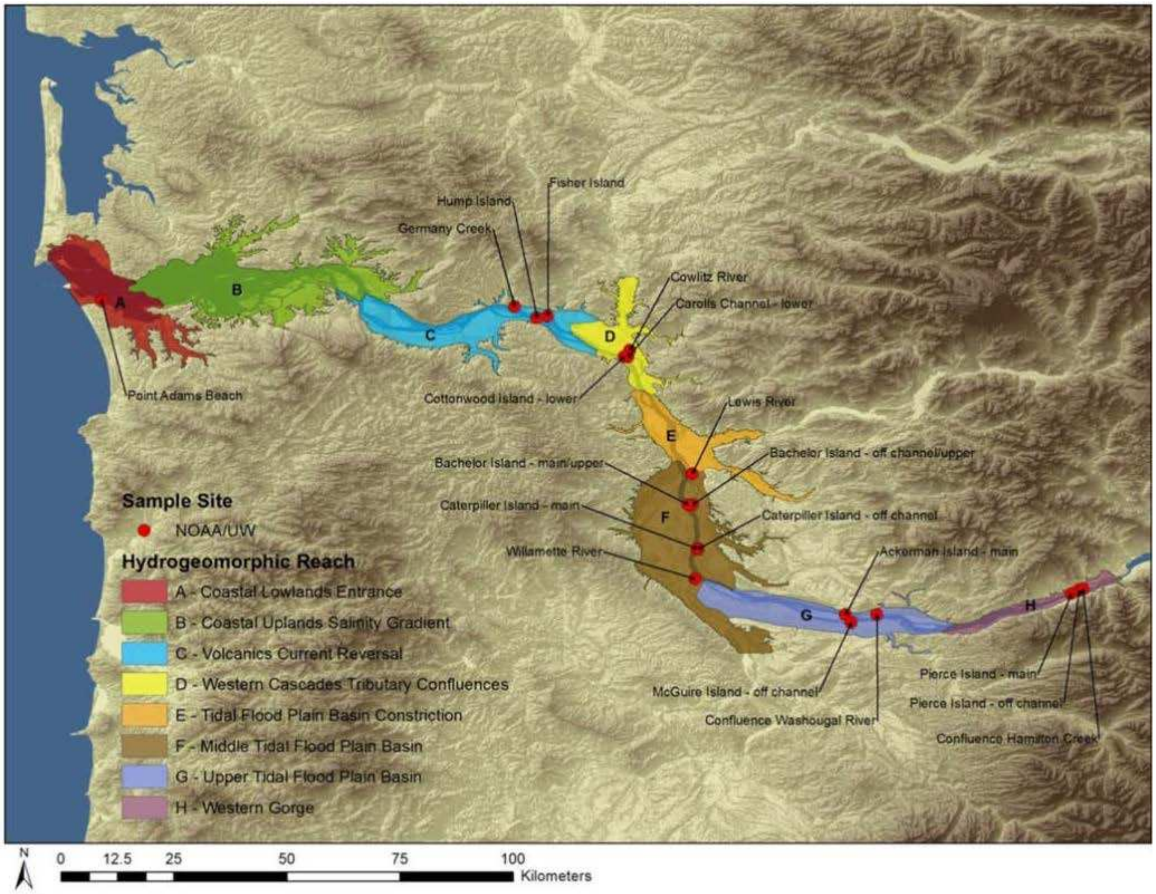


Figure 1. Map of genetic sampling sites in 2010-2012 by estuary reach (Teel et al. 2014). Many research activities reported here target particular reaches or habitats from the estuary-wide genetics survey. Reach designations A-H coincide with the eight hydrogeomorphic reaches designated by Simenstad et al. (2011).

Juvenile Chinook salmon collected during this survey were later subsampled to determine habitat-specific growth rates (Goertler et al. in prep, Appendix A) and to compare salmon diet composition among habitats in two estuary reaches. From 2010-2013 we continued monitoring fish assemblage composition and the abundance, life history, and stock diversity of migrant juvenile Chinook salmon at Point Adams Beach. We also increased the number of PIT detection sites for monitoring habitat use by tagged juvenile salmonids. Coverage was increased from one emergent wetland channel in reach B during 2008-2010 to as many as four emergent and forested wetland channels in reaches B, C, and F in 2013.

Finally, in 2012-2013 we initiated new fish surveys in reach F to investigate stock-specific habitat use and performance among a high diversity of Chinook stocks found in the area near Sauvie Island and the Willamette River confluence (Teel et al. 2014). The research studies summarized below describe methods and results for these activities and for additional life history analyses and simulation modeling completed in 2010-2013.

Reports of Research

Salmon habitat use and stock composition in tidal-fluvial floodplain wetlands

Susan Hinton, David Teel, and Dan Bottom

We selected representative floodplain, back-channel, and mainstem sites to investigate salmon habitat use. These sites were located between the confluence of the mainstem Columbia with the Lewis and Willamette Rivers (reaches E and F), and included Multnomah Channel on the back side of Sauvie Island. Roegner et al. (2013) reported results of preliminary sampling at selected sites in 2011, as well as test methods for beach seining and trapping. Their report summarized catches and genetic sources of salmon at selected back-channel and mainstem sites sampled in April and July. The following year we implemented a monthly (January-November) survey design for reaches E and F to determine fish species composition, habitat associations, and stock-specific habitat use by juvenile Chinook salmon.

Monthly sampling was discontinued the following year due to budget cuts. However, with assistance from the Oregon Department of Fish and Wildlife, we conducted two surveys in 2013 to test whether boat electroshocking could provide an alternative tool for collecting fish along debris-laden shorelines and secondary channels, where other methods cannot be used or have been ineffective. Here we summarize results from monthly surveys in 2012 and from test electrofishing and beach-seining collections in 2012.

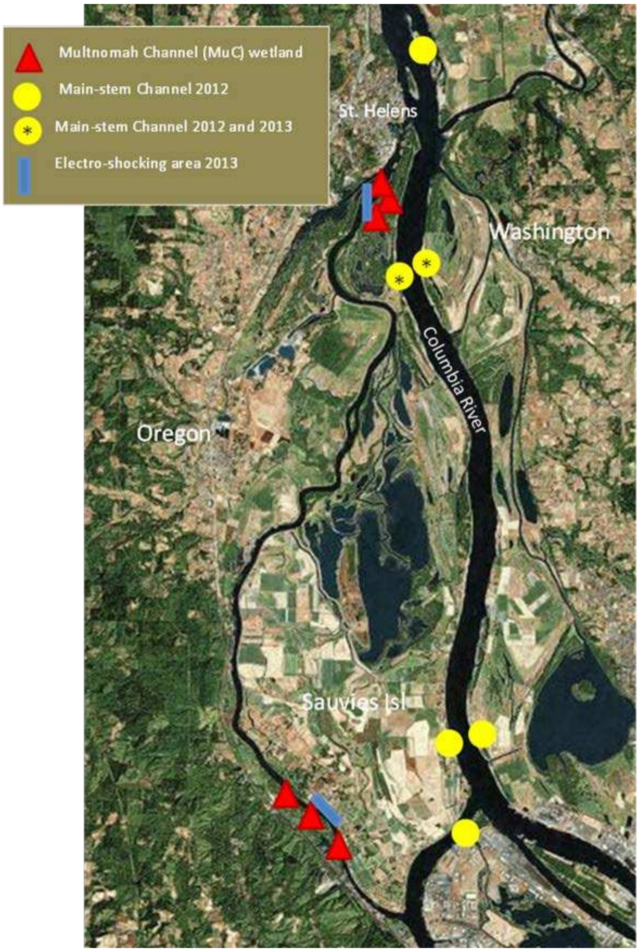


Figure 1. Reach E and F sampling sites, 2012-2013.

Methods

Fish Collections—From January to November 2012, we collected fish at six wetland-channel sites within upper and lower Multnomah Channel and six sites on the mainstem Columbia or Willamette River. Standard fish sampling methods followed those of Roegner et al. (2009) and Bottom et al. (2011). All mainstem sites were sampled with a 38-m bag seine, while wetland-channel sites were sampled with the bag seine or a fyke trap. Variations in water levels influenced the choice and effectiveness of sampling gear and thus prevented quantitative comparisons of fish abundances across sites or dates. Here we report fish species composition and Chinook salmon size distributions and genetic stock composition.

The first 30 of each salmon species collected at each site were weighed and measured, and tissue samples (i.e., caudal fin clip) were collected from juvenile Chinook salmon and preserved in ethanol for genetic analysis (described below). The next 70 individuals of each salmon species in a collection were counted and measured only. All salmon were examined for marks or tags. Subyearling and yearling age classes were determined by length and capture day (day of year).

Fry were defined as subyearlings 60 mm or less in fork length (FL) and fingerlings as subyearlings smaller than 60 mm. Generally, fish captured in winter exceeding 70 mm FL by January or 90 mm by March, and those captured in spring exceeding 120 mm by May, were considered yearlings. Smaller size classes and individuals captured July through November were considered subyearlings. All fish species were released except tagged Chinook salmon, which were preserved to retrieve the codes from coded wire tags (CWTs).

During April and May 2013, in conjunction with NMFS bag seining at mainstem sites, staff of the Oregon Department of Fish and Wildlife used an electroshocking boat to collect fish along the brushy margins and in several secondary channels of Multnomah Channel. Within each sample location, fish were captured with a boat electrofisher by two persons with nets positioned on the bow to retrieve fish rising near the surface. Each boat electrofishing run was 200-m in length, sampled in a downstream direction approximately 4-10 m from shore at 1-4 m water depths. Fish collections during these surveys were processed as described above.

Genetic Analysis—For juvenile Chinook salmon sampled in 2012 at wetland and mainstem sites, caudal fin clips were analyzed for proportional stock composition using standard methods of genetic stock identification and individual assignment (reviewed by Manel et al. 2005). Chinook salmon were genotyped using the methods described by Teel et al. (2009). Data were collected for 13 microsatellite loci that have recently been standardized among several West Coast genetics laboratories (Seeb et al. 2007).

Genetic mixture analysis and the relative probability of stock origin of each sample were estimated using the genetic stock identification computer program ONCOR (Kalinowski et al. 2007). Confidence intervals of the mixture proportions were estimated using ONCOR by re-sampling mixture and baseline data 100 times. Population baseline data were from the multi-laboratory standardized Chinook salmon genetic database described by Seeb et al. (2007). Mixture proportions and assignment probabilities for individual baseline populations were summed to 11 Columbia River Basin stock groups. Additional details about the genetic mixture analysis are provided by Teel et al. (2014).

Results

2012 Fish Survey—A total of 31 fish species were collected in 2012 at the six mainstem channel and six Multnomah Channel wetland sites (Table 1). Threespine stickleback represented 97% of all mainstem fish and 93% of all Multnomah Channel fish e collected. More than half of the species captured in the two areas of reach F were introduced (12 of 23 species at mainstem sites; 17 of 28 species at Multnomah Channel sites). Threespine stickleback accounted for 97% of all individuals collected in mainstem sites and 93% of fish sampled in Multnomah Channel.

After removing threespine stickleback from the total, 52% of the remaining mainstem catch (3,765) and 86% of the Multnomah catch (3,824) was contributed by introduced species. Chinook salmon was the dominant salmonid in both mainstem and Multnomah Channel sites, but of the six salmonid species captured overall, five were found in the mainstem and three in Multnomah Channel. Discounting threespine stickleback from the total, Chinook salmon accounted for 33% of the catch in the mainstem and ~5% of the catch in Multnomah Channel.

Length frequencies of fish from mainstem and Multnomah Channel habitats in 2012 included a wide range of size classes (fry through yearlings) January-March, with fry most common January through June (Figure 2). By August-November all fish ranged 80 to >120 mm FL. The proportion of fingerlings peaked in April and May, when about half of all salmon (and most 70- and 80-mm FL size classes) were known hatchery fish (i.e., marked with fin clips). However, some marked salmon were present in the system throughout the year. Despite lower catches, the size range for fingerlings and yearlings and the proportions of marked fish in Multnomah Channel were similar to those observed in the mainstem. However, fewer fry were captured in Multnomah Channel compared with mainstem sites.

Table 1. Fish species captured in Reach E/F of the Columbia River mainstem and in upper Multnomah Channel, 2012.

Species	Common Name	Mainstem	Upper Multnomah Channel
Oncorhynchus tshawytscha	Chinook salmon	1,243	201
Oncorhynchus kisutch	Coho salmon	7	1
Oncorhynchus keta	Chum salmon	5	
Oncorhynchus mykiss	Steelhead trout	2	
Oncorhynchus nerka	Sockeye salmon	2	
Oncorhynchus clarki clarki	Coastal cutthroat trout		1
Alosa sapidissima	American shad*	206	203
Rhinogobius brunneus	Amur goby*	10	6
Fundulus diaphanus	Banded killifish*	22	45
Pomoxis nigromaculatus	Black crappie*	18	15
Ameiurus nebulosus	Brown bullhead*		74
Acrocheilus alutaceus	Chiselmouth		1
Cyprinus carpio	Common carp*	1	192
Notemigonus crysoleucas	Golden Shiner*	2	760
Carassius auratus auratus	Goldfish*		1
Micropterus salmoides	Largemouth bass*	1	31
Catostomus macrocheilus	Largescale sucker	21	92
Ptychocheilus oregonensi	Northern pikeminnow	11	5
Mylocheilus caurinus	Peamouth	298	171
Cottus asper	Prickly sculpin	33	38
Lepomis gibbosus	Pumpkinseed*	7	265
Richardsonius balteatus	Redside shiner		15
Micropterus dolomieu	Smallmouth bass*	10	20
Platichthys stellatus	Starry flounder	184	11
Gasterosteus aculeatus	Threespine stickleback	116,073	42,158
Centrarchidae	Unidentified centrarchid*	11	117
Pomoxis sp.	Unidentified crappie*	7	22
Cyprinidae	Unidentified cyprinid*		218
Osteichthyes	Unidentified sp.*		9
Pomoxis annularis	White crappie*		1
Perca flavescens	Yellow perch*	1,664	1,383

* Non-native species

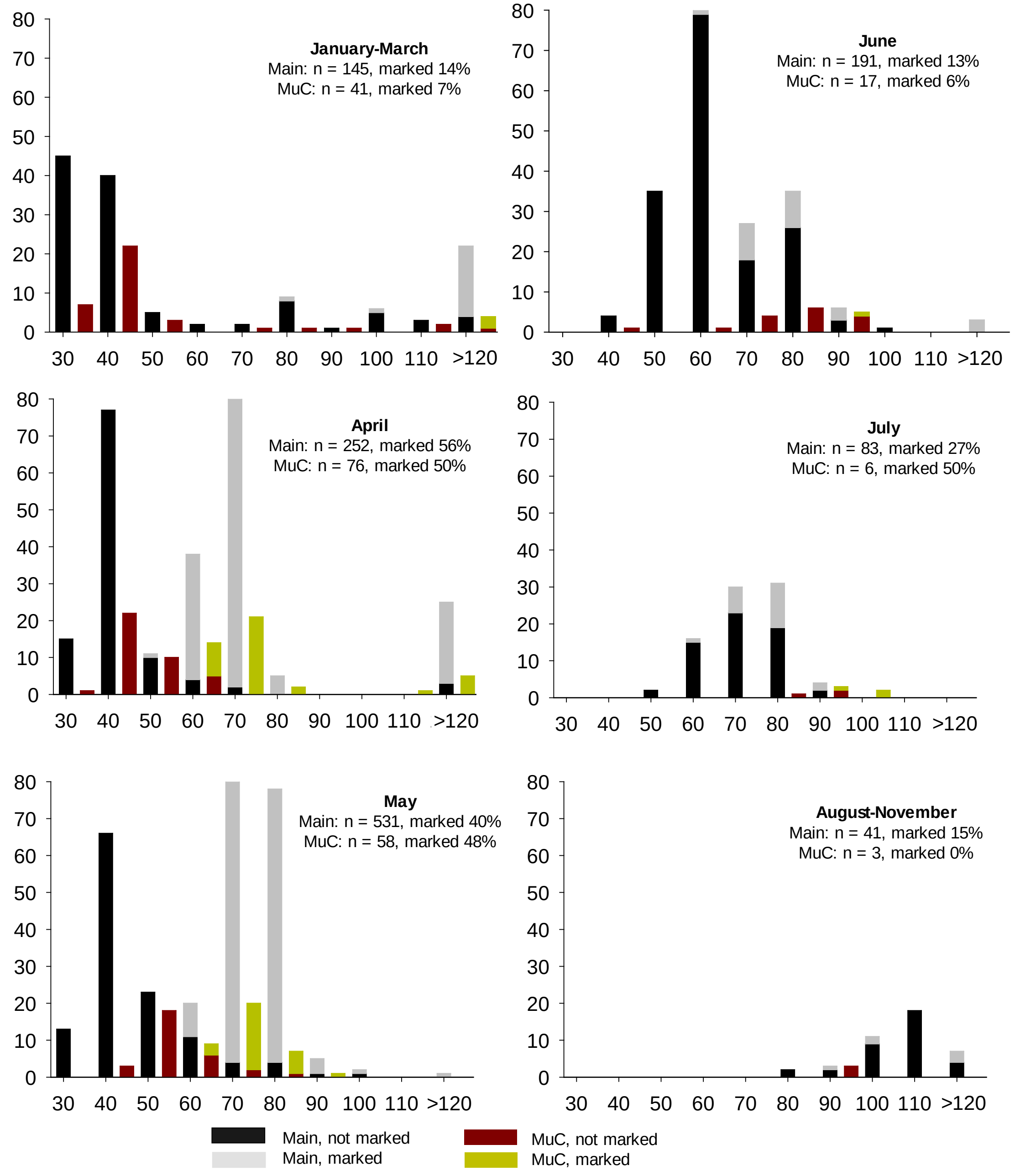


Figure 3. Length frequencies of marked and unmarked juvenile Chinook salmon captured at mainstem (Main) and Multnomah Channel (MuC) sites, January-November 2012.

Chinook salmon with CWTs were sampled throughout the year and included hatchery releases of subyearling fall and yearling spring Chinook salmon (Table 2). Willamette Basin tributaries were the predominant sources of tagged yearling spring Chinook. Growth of at-large tagged fish could not be readily estimated because CWT fish were not individually marked; thus lengths, if reported, were mean values for an entire release group. In most cases individual sizes at capture were similar to the mean size at release, although sizes were variable when multiple individuals were recovered from the same release group. For fall Chinook, the time between estimated release date and recapture ranged almost exclusively between 4-7 d, with one exception of 39 d. Spring Chinook exhibited a broader range 2-168 d, with the majority of fish recaptured 28-37 d after release.

Genotypic data were collected for a total of 952 juveniles sampled in wetland and mainstem habitats (Table 3). In reach E, samples were collected at mainstem river sites near Pile Dike Island, Bachelor Island, and lower Sauvie Island (lower mainstem) and at wetland sites in lower Multnomah Channel (lower Multnomah Channel). In reach F, samples were collected at mainstem river sites near upper Sauvie Island, upper Vancouver Lake, and the confluence of the Willamette River (upper mainstem) and at wetland sites in upper Multnomah Channel (upper Multnomah Channel).

Stock composition in Reach E/F in 2012 showed similar seasonal patterns as those reported by Teel et al (2014) but the monthly sampling design provided additional temporal resolution. Willamette River Spring Chinook were abundant January-March (yearling and fry), Spring Creek Group fall Chinook April and May (fry and fingerlings), and upper Columbia River Summer/Fall in June and July. Total Chinook salmon abundance in Reach E/F declined rapidly across all sites after July but increased again in November and December with the appearance of Willamette River Spring, West Cascade Fall, and Upper Columbia River Summer/Fall Chinook.

Table 2. Summary of coded wire tags recovered from fish collected in the Columbia River mainstem (Main) and Multnomah Channel (MuC), January-November 2012. Days between release and recapture (liberty) were determined using the last release date provided. F fall run, LF late fall run, Sp Spring run.

Location	State	Run	Date	Mean FL (mm)	Main (n)	MuC (n)	FL range (mm)	Days at liberty (d)
				Brood year 2010				
Clackamas River	OR	Sp	12-19 Mar 12		4		132-187	2, 28
Clackamas River	OR	Sp	15-Mar-12		2		150-177	6,34
Grande Ronde River 2	OR	Sp	16-Apr-12		1		207	41
Umatilla River	OR	LF	8-Mar-12		1		174	41
Detroit Res (Santiam)	OR	Sp	25-Jul-11		1		181	168
Mckenzie River 1	OR	Sp	3-Nov-11		2	1	128-183	36,37
Mckenzie River 1	OR	Sp	2-Feb-12			1	154	75
Mckenzie River 1	OR	Sp	2-Feb-12		1		148	47
Willamette R Cst Fork	OR	Sp	12-Mar-12		1	1	144-157	35, 37
				Brood year 2011				
Little White Salmon NFH	WA	F	13-Apr-12	83	4		70-78	4, 5
Little White Salmon NFH	WA	F	13-Apr-12	83	3		78-96	4, 39
Little White Salmon NFH	WA	LF	26-Jun-12	93	1		84	29
Spring Creek 29.0159	WA	F	11-13 Apr-12	76	1		83	4
Spring Creek 29.0159	WA	F	11-13 Apr-12	76	2		67-70	4, 5
Spring Creek 29.0159	WA	F	30-Apr-12	82	1		81	23
Tanner Cr (Bonneville)	OR	F	18-May-12		9	3	71-83	4,5,6,7
Santiam R & N Fork 1	OR	Sp	9-10 Aug-12		1		117	37
Clearwater at Lapwai Creek	ID	LF	8-30 May-12	91	1		79	3
Klickitat Hatchery (Ykfp)	WA	LF	18-21 Jun-12	80	2		74-82	6
Klickitat Hatchery (Ykfp)	WA	LF	18-21 Jun-12	80	1		82	7
Klickitat Hatchery (Ykfp)	WA	LF	18-21 Jun-12	80	2	1	72-86	6,7

Table 3. Sample sizes and estimated proportional composition of 7 genetic stock groups observed in samples of juvenile Chinook salmon collected in 4 sampling areas in reaches E and F during 2012. Range below each estimate shows a 95% CI derived from 100 bootstrap resamplings of baseline and mixed-stock genotypes. Four Chinook genetic stock groups were estimated to comprise less than 2% of all compositions and are not shown (Mid and Upper Columbia spring, Snake spring, Rogue, and Coast).

N	West Cascade Fall	West Cascade Spring	Willamette Spring	Spring Creek Group Fall	Upper Columbia Summer/Fall	Deschutes Fall	Snake River Fall
All samples							
952	0.20	0.04	0.16	0.28	0.24	0.02	0.05
	0.18-0.24	0.03-0.07	0.13-0.18	0.23-0.29	0.20-0.28	0.01-0.04	0.04-0.08
By area (all months)							
Lower Mainstem							
360	0.32	0.03	0.12	0.22	0.24	0.01	0.06
	0.25-0.37	0.02-0.09	0.08-0.14	0.16-0.24	0.19-0.30	0.00-0.05	0.02-0.10
Lower Multnomah Channel							
74	0.20	0.01	0.18	0.45	0.13	0.00	0.01
	0.08-0.29	0.00-0.06	0.08-0.25	0.31-0.52	0.08-0.24	0.00-0.05	0.00-0.07
Upper Multnomah Channel							
124	0.05	0.05	0.35	0.33	0.12	0.02	0.08
	0.01-0.13	0.01-0.13	0.26-0.44	0.23-0.39	0.06-0.21	0.00-0.05	0.01-0.13
Upper Mainstem							
394	0.15	0.04	0.15	0.29	0.29	0.02	0.05
	0.11-0.20	0.02-0.07	0.11-0.18	0.22-0.33	0.23-0.35	0.00-0.04	0.02-0.09
By month (all areas)							
Jan-Mar							
123	0.13	0.07	0.62	0.17	0.01	0.00	0.00
	0.06-0.19	0.03-0.15	0.53-0.71	0.09-0.22	0.00-0.05	0.00-0.01	0.00-0.02
April							
249	0.18	0.05	0.17	0.51	0.06	0.03	0.01
	0.13-0.25	0.03-0.11	0.11-0.20	0.40-0.55	0.03-0.11	0.00-0.05	0.00-0.03
May							
230	0.14	0.01	0.03	0.49	0.26	0.00	0.06
	0.09-0.21	0.00-0.04	0.01-0.05	0.39-0.54	0.18-0.33	0.00-0.05	0.01-0.11
June							
181	0.19	0.01	0.01	0.03	0.63	0.03	0.09
	0.12-0.25	0.00-0.04	0.00-0.02	0.00-0.04	0.54-0.70	0.01-0.08	0.05-0.17
July							
88	0.46	0.01	0.03	0.02	0.30	0.02	0.14
	0.28-0.54	0.00-0.06	0.00-0.06	0.00-0.06	0.19-0.46	0.00-0.12	0.04-0.20
Oct-Dec							
74	0.33	0.12	0.41	0.02	0.09	0.00	0.04
	0.15-0.46	0.06-0.30	0.25-0.51	0.00-0.08	0.03-0.16	0.00-0.05	0.00-0.08

2013 Test Electrofishing—Using electrofishing in April and May 2013, we successfully sampled fish along debris-strewn shorelines and secondary channels of Multnomah Channel that could not be sampled using other methods. Juvenile salmon as well as a diversity of non-native species occupied brushy shorelines and areas of large woody debris along the wetland margins of Multnomah Channel. These test fishing results suggest electrofishing will be a useful method for assessing the importance of woody debris, flooded shorelines, and riparian habitats for juvenile salmon. These habitats comprise key uncertainties for restoration efforts in the Columbia River estuary (ERTG 2012).

Fish abundances obtained from beach-seine and electrofishing methods in 2013 are not directly comparable, and each method sampled different habitat types (i.e., mainstem beaches vs. off-channel wooded shorelines). Nonetheless, species composition in 2013 was generally similar to the results reported for mainstem and Multnomah Channel habitats in 2012 (Tables 2 and 4). Of the five salmonid species captured in 2013, regardless of gear type and location, Chinook salmon was the most common (Table 4).

Table 4. Comparison of fish species captured in the Columbia River mainstem with a beach seine and in Multnomah Channel with an electrofishing boat, April and May 2013.

Species	Common name	Mainstem	Multnomah Channel
Oncorhynchus tshawytscha	Chinook salmon	231	69
Oncorhynchus kisutch	Coho salmon	2	16
Oncorhynchus keta	Chum salmon	8	
Oncorhynchus clarki clarki	Coastal cutthroat trout		2
Oncorhynchus mykiss	Steelhead trout	1	
Fundulus diaphanus	Banded killifish*	2	
Pomoxis nigromaculatus	Black crappie*		1
Ameiurus nebulosus	Brown bullhead*		1
Cyprinus carpio	Common carp*		2
Notemigonus crysoleucas	Golden Shiner*		1
Carassius auratus auratus	Goldfish*		1
Catostomus macrocheilus	Largescale sucker	1	35
Ptychocheilus oregonensi	Northern pikeminnow	3	
Misgurnus anguillicaudatus	Oriental Weatherfish*		1
Mylocheilus caurinus	Peamouth	4	1
Cottus asper	Prickly sculpin		10
Lepomis gibbosus	Pumpkinseed*		3
Micropterus dolomieu	Smallmouth bass*		3
Platichthys stellatus	Starry flounder	3	28
Gasterosteus aculeatus	Threespine stickleback	277	1,093
Cyprinidae	Unidentified cyprinid	13	
Perca flavescens	Yellow perch*	1	28

* Non-native species

In April 2013 yearling Chinook, dominated by fish marked at hatcheries, occurred simultaneously at beach-seine sites on the mainstem and at electrofishing sites in Multnomah Channel (Figure 4). Yearlings were not present in either area in May. A much greater proportion of fry were captured at mainstem than at Multnomah Channel sites, but it was not clear whether this represented a true difference in fry distribution or was an artifact of the sampling gear.

However, various types of net gear used in 2012 also collected a somewhat lower proportion of fry at Multnomah Channel sites relative to the mainstem beach-seine sites (Figure 3). Length-weight relationships for fish sampled in Multnomah Channel and on the mainstem were similar in 2013, suggesting no obvious difference in fish condition between back-channel and mainstem areas (Figure 5).

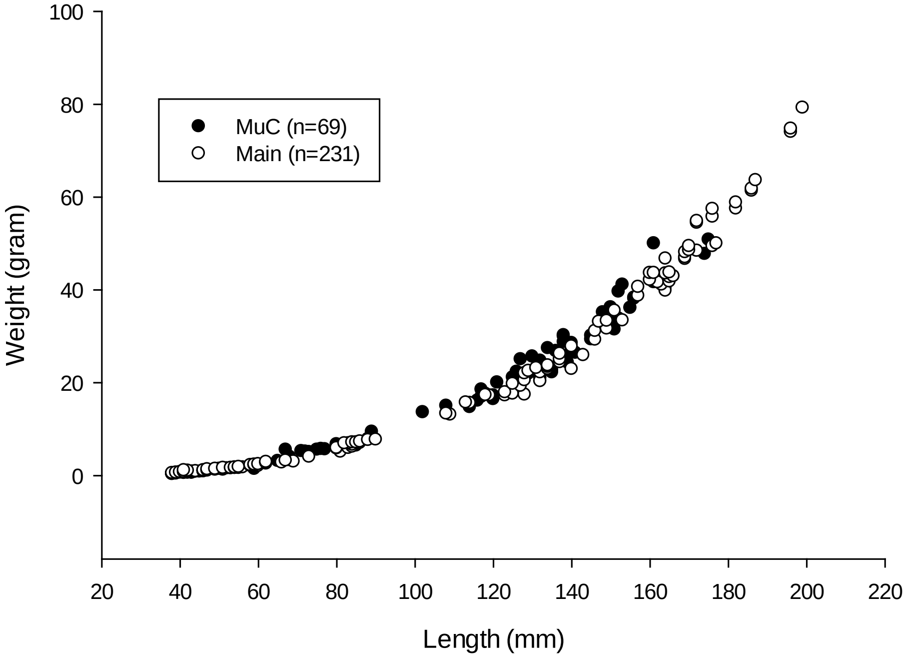
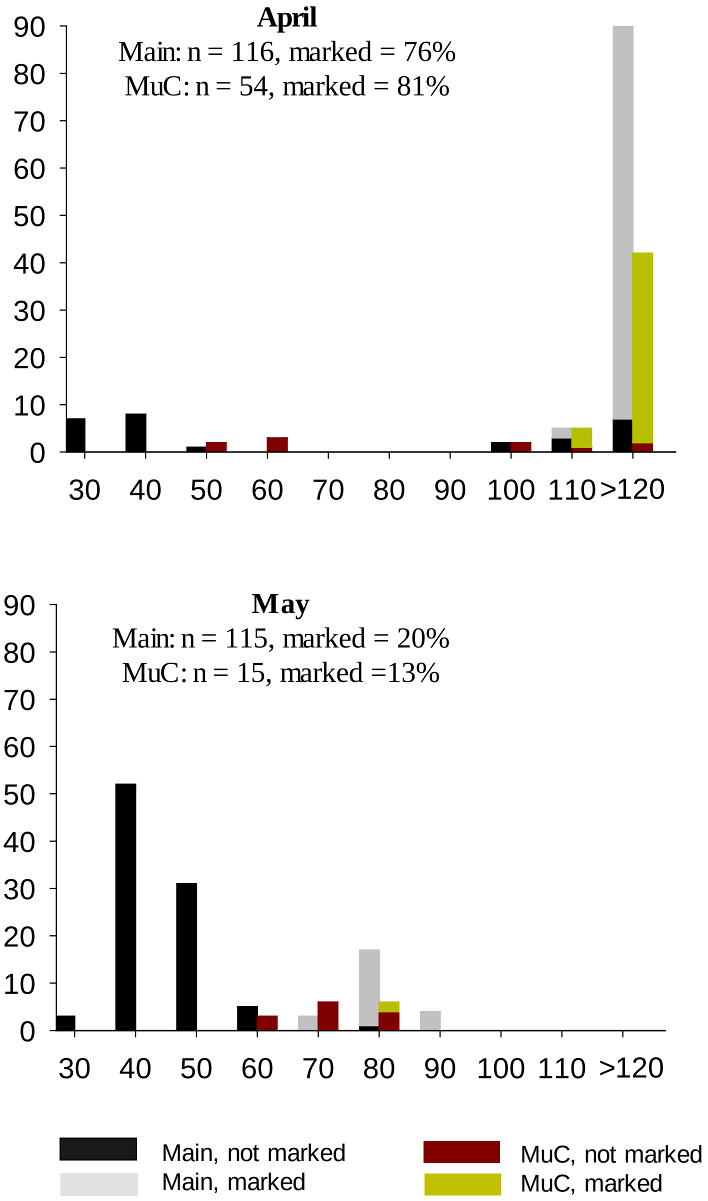


Figure 1. Length frequencies, marked and unmarked juvenile Chinook salmon captured in the Columbia River mainstem (Main) with a beach seine and in Multnomah Channel (MuC) with an electrofishing boat, April and May 2013.



April

Main: n = 116, marked = 76%

MuC: n = 54, marked = 81%

May

Main: n = 115, marked = 20%

MuC: n = 15, marked =13%

Figure 2. Length frequencies, marked and unmarked juvenile Chinook salmon captured in the Columbia River mainstem (Main) with a beach seine and in Multnomah Channel (MuC) with an electrofishing boat, April and May 2013.

Most of the 2013 CWT recoveries were collected in April from yearling spring Chinook salmon released from Willamette basin hatcheries (Table 5). On at least four occasions, fish from the same release group were sampled at both mainstem and Multnomah Channel areas. Most individuals were captured within approximately 2 months of release. For Chinook salmon captured from a single release group, size varied as much as 42 mm.

Table 5. Summary of coded wire tags recovered during beach seining in the Columbia River mainstem (Main) and boat electrofishing in Multnomah Channel (MuC), April and May 2013. Days between release and recapture were determined by using the last release date provided. Days between release and recapture (Liberty) were determined by using the last release date provided. F, fall run; LF. late fall run; Sp, Spring run.

			Capture					
	State	Run	Date	Ave FL	MuC (n)	Main (n)	FL range (mm)	Days at liberty (d)
Brood year 2012								
Spring Creek 29.0159	WA	F	2 May 2013	89		1	85	12
Brood year 2011								
Willamette R Mid Fork 1	OR	Sp	5 Mar 2013			1	134	30
Clackamas River	OR	Sp	7 Mar 2013		3	4	136-169	27, 28
Clackamas River	OR	Sp	14 Mar 2013		3		132-150	19, 20
Clackamas River	OR	Sp	11 Mar 2013		1	2	157-172	24, 25
Santiam R & N Fork 1	OR	Sp	18-19 Mar 2013			2	160-164	16
Santiam R & N Fork 1	OR	Sp	9-10 Aug-2012		1	1	114-125	237, 238
Mckenzie River 1	OR	Sp	8 Feb 2013			1	165	55
Mckenzie River 1	OR	Sp	8 Feb 2013			1	132	55
Bull Run River	OR	Sp	22 Mar-18 Apr 2013			4	157-199	*
Sandy River	OR	Sp	25 Feb-11 Apr 2013		1	1	174-176	*
Klickitat Hatchery (Ykfp)	WA	Sp	5-7 Mar 2013	127		1	140	27
Lewis R N Fork 27.0168	WA	Sp	1-15 Feb 2013		1		118	46
Lewis R N Fork 27.0168	WA	Sp	1-15 Feb 2013		1		102	46

* Release date ranged >28 d and concluded after these salmon were recaptured

Conclusions

- In reaches E and F, fish densities were higher in mainstem than back-channel habitats.
- Salmon size distributions were similar between mainstem and back-channel habitats (i.e., Multnomah Channel) except in 2012, when proportions of fry were less at Multnomah Channel sites.
- In reach E and F, stock diversity and evenness were high for juvenile Chinook salmon in 2012, reflecting a diverse mixture of Willamette River, lower basin, and interior stock groups. These findings were consistent with results of the estuary-wide genetics survey (Teel et al. 2014).
- Chinook salmon stock composition in reaches E and F followed distinct seasonal patterns in 2012, similar to those previously described by Teel et al. (2014) but at a finer resolution.
- Chinook stock composition at Multnomah back-channel sites was similar to that at mainstem sites. Exceptions included somewhat higher proportions of Spring Creek Fall Chinook stocks throughout Multnomah Channel and higher proportions of Willamette River Spring Chinook in Upper Multnomah Channel relative to the mainstem sites.
- Significant numbers of tagged spring Chinook from various Willamette River hatcheries occurred in mainstem and off-channel habitats of reaches E and F.
- Chinook salmon of a range of size classes use vegetated riparian areas, debris-strewn shorelines, and secondary channels of Multnomah Channel. Boat electrofishing provides a practical tool for sampling these habitats much of the year.

Temporal variation in fish community structure and life histories near the estuary Mouth

Curtis Roegner

Point Adams Beach serves as a long-term reference site for monitoring fish populations and juvenile salmon (Columbia River km 20; Figure 1). Surveys at this site since 2002 (excluding 2009) have also provided a baseline for comparison to fish assemblages sampled by purse seine at nearby main channel sites (Weitkamp et al. 2012; Roegner et al. submitted). In 2010-2013 we continued fish collections at Pt Adams Beach to track annual variations in species assemblage and trends in juvenile salmonid abundance and life histories, as well as Chinook salmon stock composition.

Methods

From 2010 through 2013, beach-seine sampling at Pt Adams Beach was conducted biweekly from January through July; sampling thereafter was conducted monthly. Seines were usually set within 2 h of low tide using standard sampling techniques (Roegner et al. 2009; 2012). All salmon were counted, and up to 70 were measured and released. Measured salmon were examined for marks and tags, and fish with coded-wire tags were retained for subsequent laboratory identification of origin.

It is important to note that estimates of hatchery origin were minimum estimates, since not all hatchery fish are marked. Fin clips of up to 30 fish per sample day were taken for genetic analysis, and representative Chinook salmon were retained monthly for otolith analysis. For non-salmonid species, a representative sample of up to 30 individuals was measured, and the remainder was counted and released. Total catch from the ~400 m^2 seine area was standardized (ind/100 m^2), with density computed as 0.25 × total CPUE.

For prevalent species (categorized by habitat use as “migratory salmonid,” “demersal,” or “pelagic”), population and life-history attributes were evaluated using size-frequencies and annualized time series of density and mean size (i.e. plotted by day of year, DOY). For comparative purposes, we also plotted density and size measurements from monthly samples taken at Pt Adams Beach during 2002-2008.

Interannual variation in community metrics was examined in several ways:

1. Standard diversity indices were calculated for each year and compared to overall diversity of the 4-year period as an anomaly.

2. For each sample day, fish community density and biomass were plotted as stacked bar time series. Biomass estimates (kg/100 m^2) were calculated using mean lengths and species-specific length-weight regression equations (from samples collected during 2002-2004).
3. Variation in abundance and diversity metrics among the 4 years were expressed as percent deviations from mean values as % = 100 × (N-Ň)/ Ň, where Ň is the average valued for 2010-2013.

Results

From 2010 through 2013 we made 110 beach seines over 30 dates and sampled over 83,000 fish (Table 6). Of the entire fish community during this period, threespine stickleback dominated the catch (81.9%), followed by Chinook salmon (6.1%), shiner perch (3.6%), surf smelt (3.0%), and English sole (1.4%). All other species comprised less than 1.0% of the overall sample. However, these combined annual percentages of the dominant species masked wide seasonal and annual fluctuations in the catch, both between years from 2010 through 2013 as well as among previous years.

Because of their numerical dominance, diversity and evenness indices were inversely related to stickleback abundance. For diversity and evenness, the highest values were observed in 2010, (year of minimum stickleback counts) and the lowest values in 2014 (year of maximum stickleback count). Removing variation in the stickleback counts resulted in much more similar values of total catch and higher and more similar values of diversity and evenness across years. Without stickleback, the highest values of diversity and evenness were in 2014 and the lowest in 2011. Interestingly, the number of species (S) was highest in 2014 due in part to the presence of sharpnose sculpin, pipefish, and saddleback gunnel, which was associated with increased eelgrass cover at the site.

Table 6. Comparison of species composition and diversity metrics of fish sampled at Pt Adams Beach 2010-2013. Calculations were also made with after excluding threespine stickleback. Ave/set; average abundance/set for all years.

Species	Common name	2010	2011	2012	2013	All	Ave/set
Oncorhynchus tshawytscha	Chinook salmon 0	342	2,250	1,892	571	5,055	46.0
Oncorhynchus tshawytscha	Chinook salmon 1	4	23	7	272	306	2.8
Oncorhynchus keta	Chum salmon	113	67	361	148	689	6.3
Oncorhynchus kisutch	Coho salmon	27	49	33	139	248	2.3
Gasterosteus aculeatus	Threespine stickleback	6,216	15,391	17,798	28,705	68,110	619.2
Cymatogaster aggregata	Shiner perch	423	470	1,101	1,035	3,029	27.5
Hypomesus pretiosus	Surf smelt	975	1,122	259	163	2,519	22.9
Parphrys vetulus	English sole	981	9	57	157	1,204	10.9
Leptocottus armatus	Pacific staghorn sculpin	144	81	342	230	797	7.2
Platichthys stellatus	Starry flounder	32	39	283	263	617	5.6
Pholis ornata	Saddleback gunnel	2	0	37	313	352	3.2
Alosa sapidissima	American shad*	8	52	67	7	134	1.2
Clinocottus acuticeps	Sharpnose sculpin	0	0	0	34	34	0.3
Psettichthys melanostictus	Sand sole	20	4	0	2	26	0.2
Clupea pallasii	Pacific herring	2	1	0	18	21	0.2
Syngnathus griseolineatus	Bay pipefish	0	0	0	17	17	0.2
Engraulis mordax	Northern anchovy	2	0	0	0	2	0.0
Lumpenus sagitta	Snake Prickleback	0	0	0	2	2	0.0
Fundulus diaphanus	Banded Killifish*	0	0	0	1	1	0.0
Pleuronichthys decurrens	Curlfin turbot	0	0	0	1	1	0.0
	N fish	9,291	19,558	22,237	32,078	83,164	756.0
	N seines	27	28	24	31	110	27.5
	All fish						
	Diversity (H')	1.19	0.79	0.83	0.56	0.82	0.84
	Number of species (S)	15	13	12	19	20	14.8
	Evenness (J)	0.44	0.31	0.33	0.19	0.28	0.32
	N fish	3,075	4,167	4,439	3,373	15,054	136.9
	N seines	27	28	24	31	110	27.5
	No stickleback						
	Diversity (H')	1.67	1.28	1.66	2.15	1.94	1.7
	Number of species (S)	14	12	11	18	19	13.8
	Evenness (J)	0.63	0.51	0.69	0.75	0.66	0.6

* Non-native species

Migratory Salmon—The Chinook salmon population was comprised of fry-sized (26.8%) or fingerling-sized (61.8%) subyearlings, with a smaller component of yearlings (11.4%). Migration timing conformed to earlier studies at Pt Adams Beach (Roegner et al. 2012), with yearlings found during March and April and subyearlings present year-round with a peak in June-July. Maximum densities were 158 ind/100 m^2 for subyearlings and 25 ind/100 m^2 for yearlings; 2011 and 2012 were high-density years for subyearlings, and 2013 was a high-abundance year for yearlings.

However, note that migration timing varied significantly with an early density peak in 2012 compared to most years. The annual frequency of occurrence (FO) ranged from 71.4 to 92.6% for subyearlings, but only 7.4 to 25.8% for yearlings. For subyearlings, size ranged 35 to 195 mm with dual peaks at 45 and 85 mm, while for yearling Chinook, size ranged 90-220 mm with a mode around 155 mm. Mean size increased linearly for subyearling Chinook, as is typically observed, but size trajectories varied substantially among years. For a given date from April through December, mean sizes ranged 40 to 70 mm.

Both 2011 and 2012 were high density years; however, the year 2011 exhibited larger overall mean sizes compared with 2012, which was near the lower range of the entire time series. Size by time for yearlings was not distinct due to the punctuated migration. Late autumn subyearling migrants could exceed sizes of spring yearling migrants. We caught more large autumn migrants in 2010 than in most years. Only 44% of the subyearlings were marked, reflecting in part the high number of small and presumably wild-origin fish, while 85% of the yearlings were marked. Marking rates are minimum estimates, and yearling timing and sizes in the estuary are likely driven by hatchery releases.

Table 7. Hatchey composition of measured salmon. Abbreviations: N number measured, H percent marked or tagged.

	2010		2011		2012		2013		All Years	
Salmonid	N	H (%)	N	H (%)	N	H (%)	N	H (%)	N	H (%)
Chinook 0	342	52.6	775	51.9	870	36.2	603	40.3	2,590	44
Chinook 1	4	75.0	22	100.0	7	28.6	299	84.9	332	85
Chum	70	0.0	66	0.0	166	0.0	288	8.7	590	4
Coho	27	85.2	47	70.2	23	47.8	92	83.7	189	76

Chum salmon were primarily fry-sized subyearling fish (80.4%) and had an overall size range of 35-80 mm. Migration timing ranged between January and June with peaks in March or April, with an annual FO ranging from 14.8 to 42.8%. Maximum density was 55 ind/100 m^2 and was observed during March 2012. Mean size tended to increase only slightly from January through March and accelerated through June. Chum juveniles were mostly unmarked, except those caught during a CWT marking experiment in May 2013. Overall patterns were consistent with previous observations.

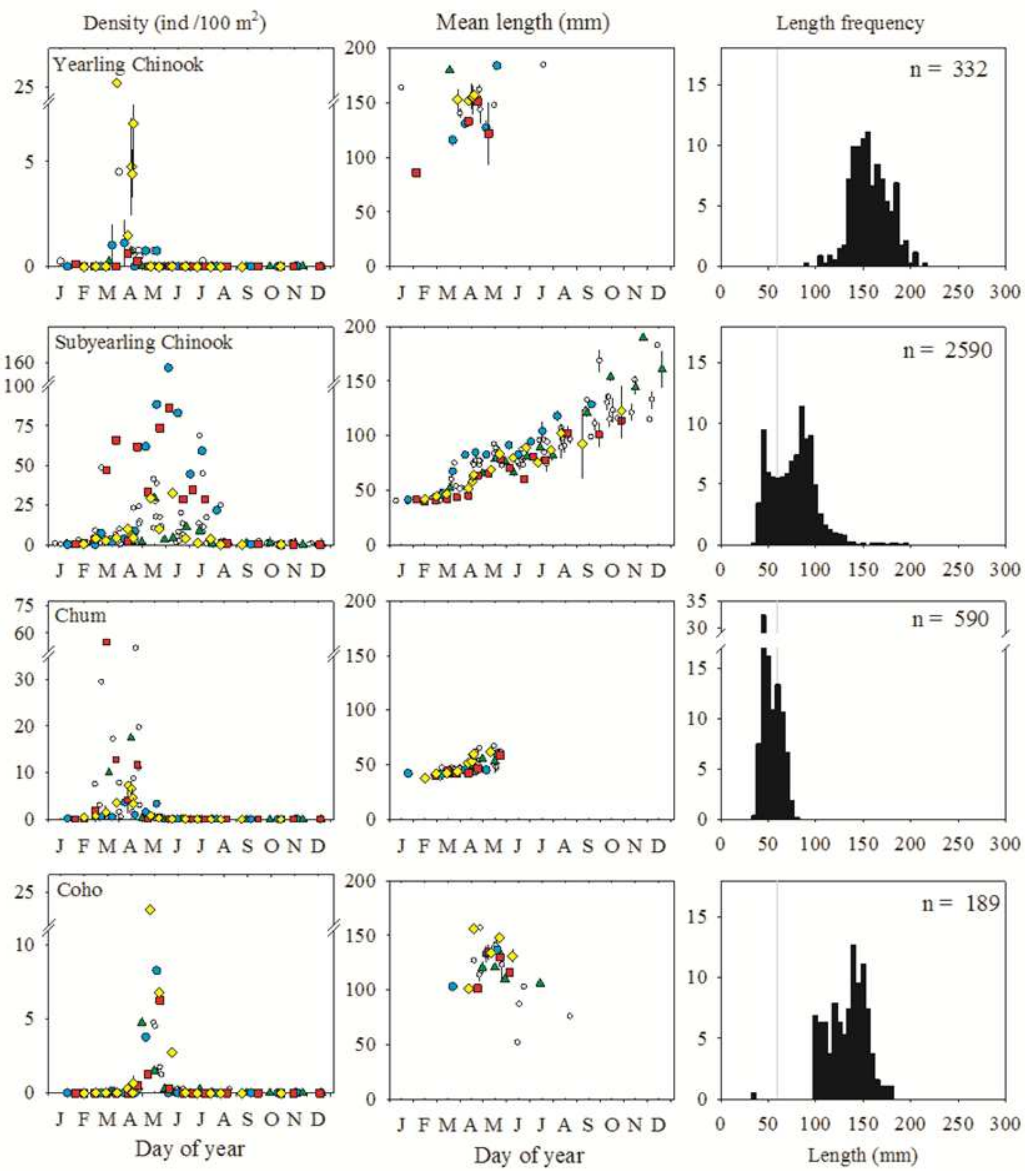


Figure 5. Time series of density (left) and mean length (center) and length-frequency (right) for salmon species/life history group. ▲ 2010; ● 2011; ■ 2012; ◆ 2013; ○ 2002-2008.

Coho salmon migration ranged from March through May but was concentrated in late April to mid-May. Coho were sampled at a relatively higher density (maximum 22 ind/100 m^2) and frequencies (FO = 10.7 to 19.3%) compared to previous years, likely due to a higher sampling rate within the migration window. Coho densities were generally higher than those of yearling Chinook, except in 2013. Sizes ranged from 100-185 mm except one fry, and size with time tended to peak in the middle of the run and decline thereafter. For coho, the overall marking rate was 76%, and like yearling Chinook salmon, abundance and size patterns were likely related to hatchery release patterns.

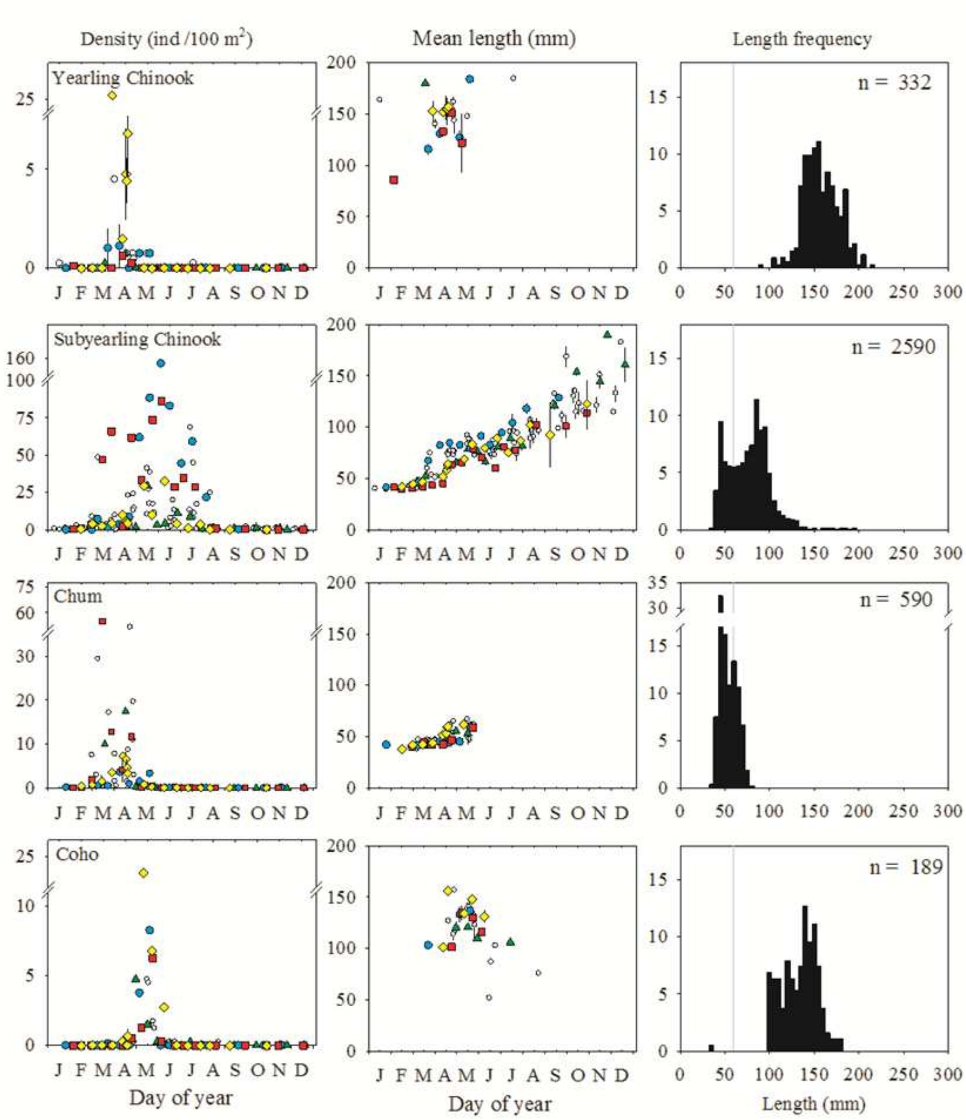


Figure 6. Time series of density (left) and mean length (center) and length-frequency (right) for selected demersal fish species. ▲ 2010; ● 2011; ■ 2012; ◆ 2013; ○ 2002-2008.

Other abundant fish—We investigated population characteristics of several other abundant demersal and pelagic fish captured at Pt Adams Beach. Main demersal species were English sole, starry flounder, and staghorn sculpin, and pelagic or water column species were surf smelt, shiner perch, and stickleback.

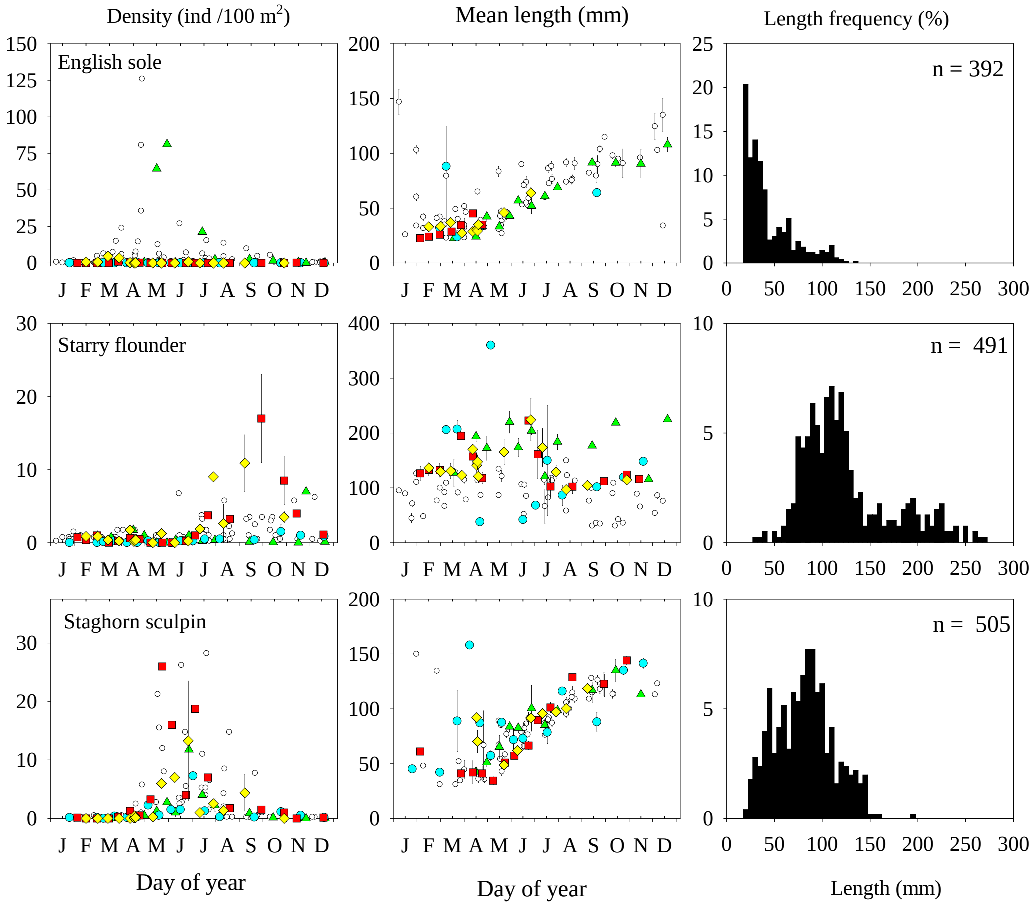


Figure 7. Time series of density (left) and mean length (center) and length-frequency (right) for selected pelagic fish species. ▲ 2010; ● 2011; ■ 2012; ◆ 2013; ○ 2002-2008.

English sole had a positively skewed frequency histogram and high density in spring, indicating spring recruitment events. Newly metamorphosed individuals were observed at Pt Adams Beach from January through April; Marko (2008) found English sole larvae in the water column from April through May. Mean sizes tended to increase linearly with time, but densities decreased as fish left the shallow area by summer of most years. Compared to previous years, English sole recruitment was poor during the recent survey, with only 2010 exhibiting high numbers of juveniles or persistence during the year. Sizes-at-date during 2010 also tended to be lower than previous observations.

Starry flounder was found year-round, with sporadic high abundances in summer/autumn. Starry flounder exhibited a wide size range for a given date, indicating the presence of multiple year classes. However, year classes were not very discernable in the size frequency distribution, which depicted few individuals less than 60 mm, a relatively large mode between 70–130 mm, and a more even distribution up to 275 mm. Mean size tended to decrease precipitously from ~200 to ~100 mm in June-July, indicating migration of juveniles into the site.

We have observed abundances of smaller (> 30 mm) starry flounder in tidal freshwater tributaries further upstream (Roegner et al. 2010), where larval settlement apparently occurs, and where Marko (2008) found pelagic larvae in March. Compared to previous observations, starry flounder density was very high during 2012 and 2013. Individuals were larger in the spring of all 4 recent years than in previous years.

Staghorn sculpin was captured year-round at Pt Adams Beach, with high densities from May to July at sizes of 40-100 mm. Mean sizes increased linearly with time, and the overall distribution was 20-195 mm, with a broad peak between 85 and 105 mm that suggested larval recruitment occurred in winter outside the sample site. This is consistent with larval presence in late autumn and winter (Marko 2008). Density and size of staghorn sculpin conformed to previous observations.

Pelagic species captured included surf smelt, shiner perch, and threespine stickleback. Like English sole, surf smelt have positively skewed frequency histograms and high abundances in April-June indicating recruitment events. Densities decreased as fish left the shallow area by summer (FO 46-63%; max density 156 ind/100 m^2). Size-frequency ranged 40-140 mm, with a wide mean size distribution per day of year, indicating several year classes were present at the site. We observed newly metamorphosed juveniles at Pt Adams Beach, while Marko (2008) found osmerid larvae only in December. Maximum densities were lower than previous years (except 2010) but mean sizes were within the observed range.

Shiner perch had a distinct occupancy period from June through October (FO 29-56%), and exhibited steep declines in mean size during early summer, indicative of reproductive events. High densities occurred during this time, with a maximum of 173 ind/100 m^2 in 2012. Shiner perch juveniles were initially ~40 mm in length (shiner perch are live-birthed) and increased in size linearly to ~80 mm through November; overall size range was 30-175 mm. Time series of densities during 2010 and 2011 were below typical values, but time series of mean sizes were very consistent between study periods.

Threespine stickleback was by far the most abundant (FO 100%) and most dense (max 1648 ind/100 m^2) species of the pelagic fish community. Sizes ranged from 35-70 mm and increased linearly until June-July, when mean size decreased corresponding to reproductive events. Stickleback is a brooder, whose young develops in benthic nests. Sizes conformed to earlier observations, but abundances in 2011-2013 were among the highest of the 11-year time series.

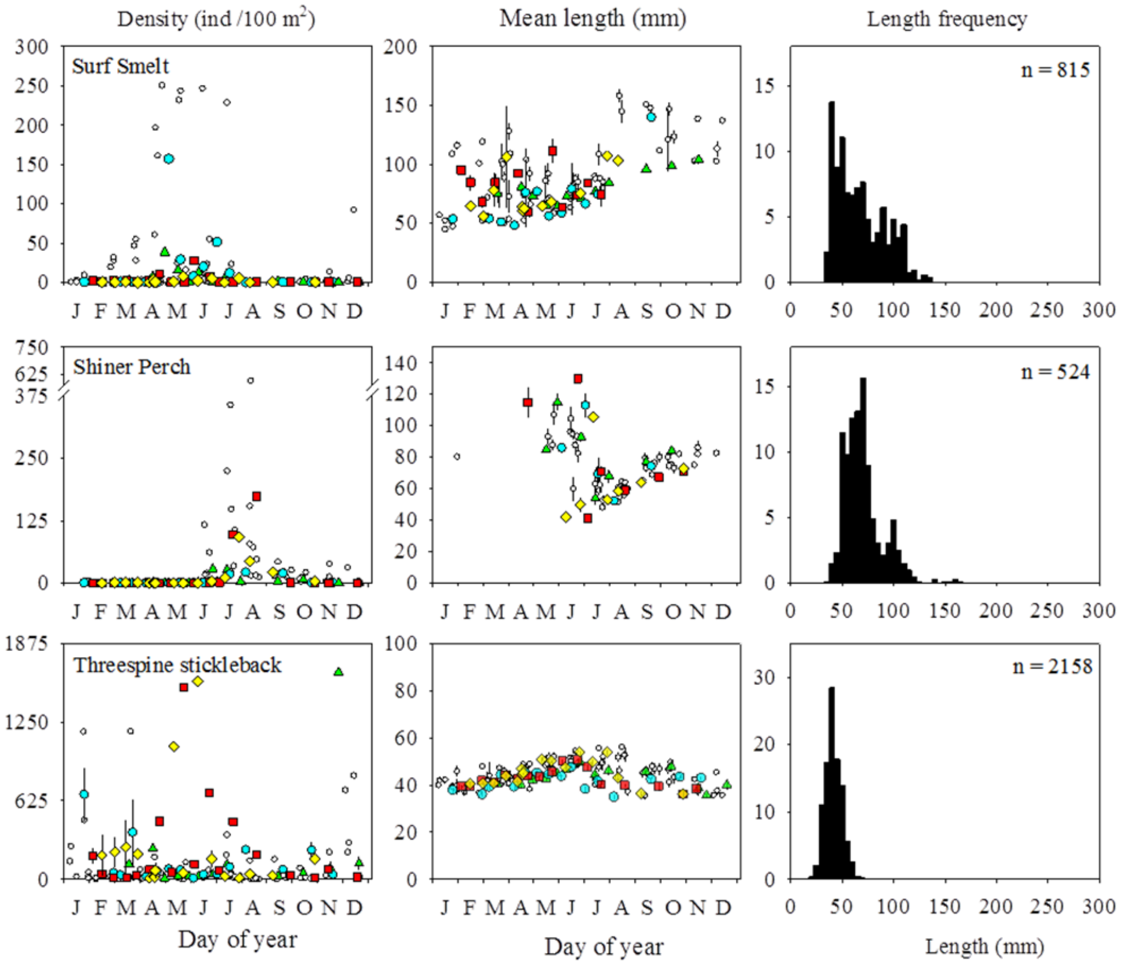


Figure 1. Time series of density (left) and mean length (center) and length-frequency (right) for selected pelagic fish species. ▲ 2010; ● 2011; ■ 2012; ◆ 2013; ○ 2002-2008.

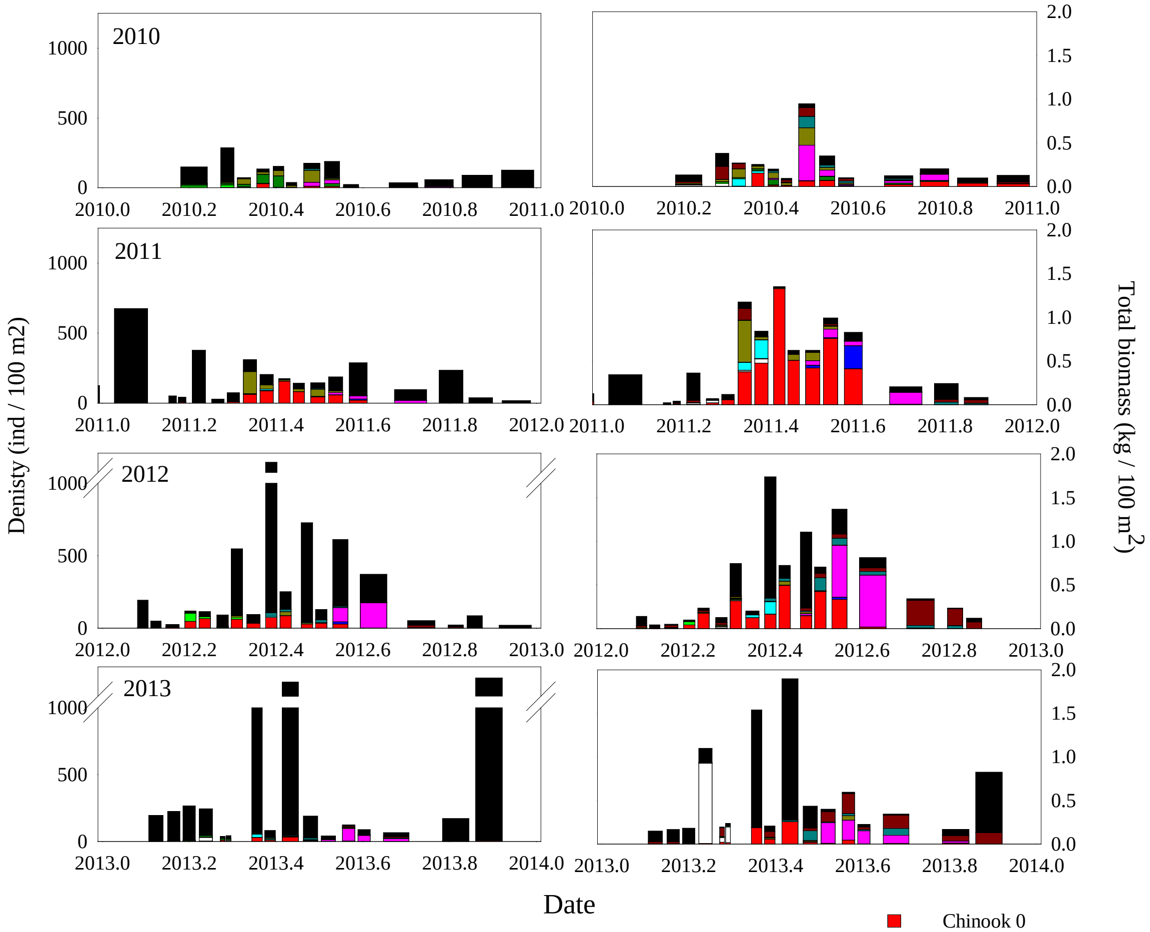


Figure 9. Annual patterns of species abundance (left column) and biomass (right column) for the years 2010-2013. Note axis breaks at high stickleback densities.

Interannual variation in proportional species composition and biomass varied across many scales over the 4-year period. Interannual patterns were driven in great part by the interaction of stickleback, subyearling Chinook salmon, and shiner perch. The year 2010 was one of low overall abundance, especially for stickleback, leading to the highest diversity and evenness indices of the study period (Table 6). As discussed above, diversity indices all years increased when stickleback were removed from the calculation.

Biomass measurements were affected by both density and mean fish size. When abundant, (2012 and 2013), stickleback biomass could exceed 1 kg/100 m^2. Shiner perch reached high biomasses during reproductive events in summer and were especially prevalent in 2012 and 2013. Perhaps most noteworthy was the contribution of subyearling Chinook salmon to population biomass. In both 2011 and 2012, subyearling Chinook densities were relatively high and corresponded to large biomasses (also exceeding 1 kg/100 m^2). During 2011, when stickleback were at low abundance, Chinook salmon were the dominate fish species by biomass. Biomass variation affects energy requirements and trophic interactions in as yet undetermined ways.

Conclusions

- Point Adams Beach serves as a time-series reference station for fish populations in the lower estuary. Survey data extend from 2002 to 2014, excluding 2009.
- Large variation in species composition and biomass occur on seasonal and interannual scales, with species-specific differences attributed to recruitment events and migration periods.
- Salmon migration patterns were largely consistent over time and narrow for subyearling runs of chum salmon and yearling runs of Chinook and coho salmon. In contrast, subyearling Chinook salmon was present year-round and exhibited more variability in peak migration timing.
- Yearling Chinook and coho salmon were primarily hatchery derived, while subyearlings were a mix of hatchery and wild-spawned fish. Most chum salmon was naturally produced.
- This shallow-water site serves as both nursery habitat for small fish and a migration corridor for juveniles of several species, including salmon.

Sources, travel time, and residency of tagged juvenile salmon in tidal wetland channels

Regan McNatt

The genetic survey design in 2010-2012 provided a coarse bimonthly “snapshot” of the estuary-wide distributions of Chinook salmon stocks (Teel et al. 2014; Figure 1). To investigate stock-specific patterns of estuary use at a finer temporal and spatial resolution, we deployed PIT detection arrays in a diversity of wetland-channel types and locations along the estuary tidal gradient. Detections at each array provided information about the upriver source, travel time, and habitat-scale residency of tagged individuals entering each tidal channel. This section summarizes detection results from four PIT-monitoring sites distributed among three hydrogeomorphic reaches of the Columbia River estuary.

PIT-tag detection sites—Since 2008 we have continuously monitored PIT-tagged salmonids entering selected marsh channels in the lower estuary at Russian Island, rkm 36 (Bottom et al. 2011). During 2011-2013 we expanded coverage to include three additional monitoring sites in other wetland habitats further upriver: Woody and Wallace Islands (rkm 47 and 80, respectively) and the lower end of Sauvie Island (rkm 139).

Figure 9. Locations and years of operation of PIT detection arrays in the Columbia River estuary.

Each site consisted of 5 or 6 antennas arranged in parallel transects across each tidal channel to measure the directional movement of tagged fish. Antennas either spanned the width of the channel or a block net was used to guide fish through the antennas. We used a 24-V DC-powered transceiver (Destron-Fearing FS-1001M) to read and store PIT tag codes. Detection sites were typically operated from March through September each year.

The Russian Island site is located in reach B, approximately 6 km from the mainstem channel in an emergent marsh complex comprised of intersecting tidal channels. To reach the detection array, fish must travel through a larger distributary channel and then up a secondary channel. Tidal influence is strong, and the experimental channel typically dewaters with each low tide. The Woody Island site is also located in Reach B, approximately 1 km from the mainstem channel in forested/scrub-shrub wetland. Tidal influence is also strong at this site, and access to the experimental channel is cut off during low tides by a shallow sill at the mouth.

The Wallace Island site is located in reach C, approximately 4.5 km from the mainstem channel in a forested/scrub-shrub wetland. This experimental channel is accessed from the back side of the island (an off-channel site). The channel retains approximately 0.5 m of water during low tides, but is often choked with submerged aquatic vegetation. The lower Sauvie Island site is located in reach F, off Multnomah Channel approximately 2 km upstream from the confluence of Multnomah Channel and the Columbia River. The PIT detector is located in a forested wetland channel, where water level is more dependent upon river elevation than tides.

Results

Detection rates for run-of-river fish that have already been PIT tagged varies with the number of fish tagged in the Columbia River Basin each year. The Pacific States Marine Fisheries Commission (www.ptagis.org) reported that 2.4-3 million fish were PIT-tagged each year from 2008 to 2012. This figure includes fish released outside of the Columbia River Basin; however, the number released outside of basin is typically negligible. Numbers of unique PIT detections in 2008-2012 averaged 11.5-28.5 per site (Table 8). In 2013 the number of PIT-tagged fish released in the Columbia River Basin decreased to 2.2 million, and average unique detections per site dropped to 5.5.

Table 8. Number of PIT-tagged fish detected at estuary detection arrays from 2008-2013 and average annual outflow at Bonneville Dam.

Site	PTAGIS code	2008	2009	2010	2011	2012	2013
Russian Island 1	RU1	10	24	25	---	---	---
Russian Island 2	RU2	13	33	28	20	22	6
Woody Island	WDI	---	---	---	11	11	4
Wallace Island	WAI	---	---	---	---	11	8
Lower Sauvie Island	LSI	---	---	---	---	34	4

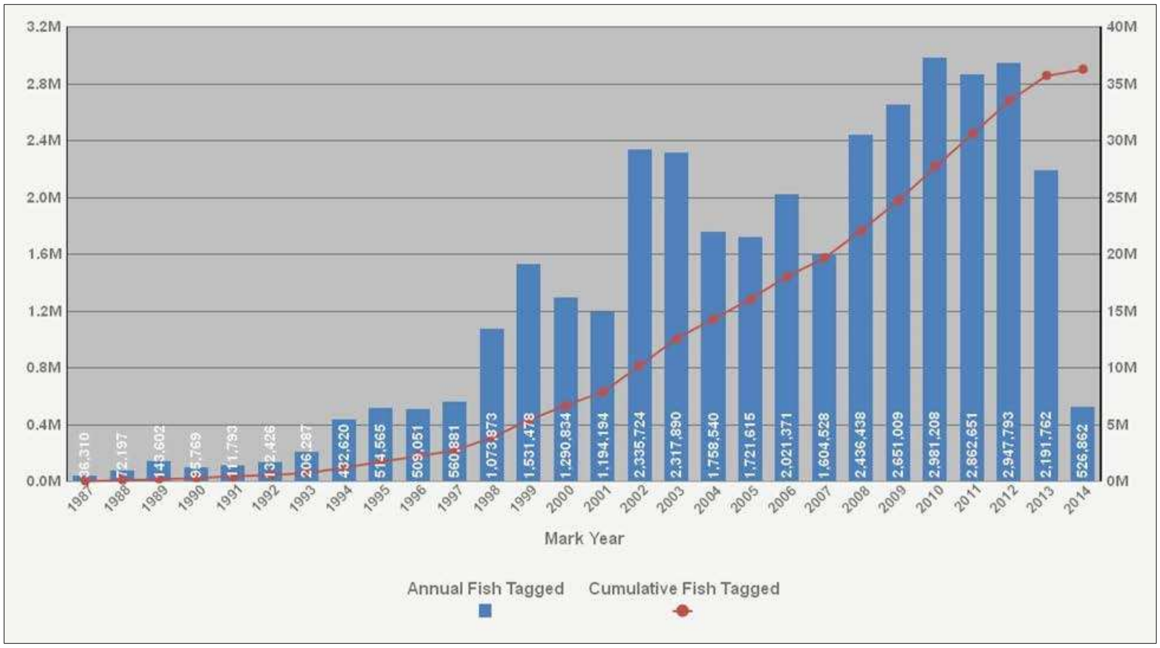


Figure 10. Annual and cumulative number of PIT-tagged fish released.

We grouped detected fish by evolutionarily significant unit (ESU) or distinct population segment (DPS). Hatchery-reared Chinook salmon that were not part of any particular ESU (HSRG 2009) are labeled here as "non-associated hatchery populations" and grouped with non-listed Chinook salmon ESUs, such as Middle Columbia River and Upper Columbia River summer/fall ESUs. We detected 19 different non-associated hatchery populations, ESUs, and DPSs, 10 of which were ESA-listed (Table 9).

Table 9. A list of evolutionarily significant units, distinct population segments, and non-associated hatchery populations detected by PIT arrays 2008-2013.

	Population code	ESA Status
Evolutionarily Significant Unit		
Lower Columbia River Chinook	LCR-Chin	Threatened
Upper Willamette River Chinook	UWR-Chin	Threatened
Middle Columbia River spring Chinook	MCR-Spr-Chin	Not listed
Snake River fall Chinook	SR-Fall-Chin	Threatened
Snake River spring/summer Chinook	SR-Spr/Sum-Chin	Threatened
Upper Columbia River summer/fall Chinook	UCR-Sum/Fall-Chin	Not listed
Upper Columbia River spring Chinook	UCR-Spr-Chin	Endangered
Lower Columbia River coho	LCR-coho	Threatened
Clearwater River coho	ClearR-coho	Not listed
Distinct Population Segment		
Southwest Washington steelhead	SWWA-sthd	Not listed
Upper Willamette River steelhead	UWR-sthd	Threatened
Middle Columbia River steelhead	MCR-sthd	Threatened
Snake River Basin steelhead	SRB-sthd	Threatened
Upper Columbia River steelhead	UCR-sthd	Threatened
Non-associated hatchery populations*		
Carson NFH spring Chinook		Not listed
Kooskia NFH spring Chinook		Not listed
Little White Salmon NFH fall Chinook		Not listed
IDFG Rapid River Hatchery spring Chinook		Not listed
Upper Mid Columbia R mainstem hatchery summer Chinook		Not listed

* As defined by the Hatchery Scientific Review Group

Release sites ranged from the Lower Columbia River (cumulative rkm 47) to the Methow Valley, Washington (cumulative rkm 930) to the interior Salmon River, Idaho (cumulative rkm 1442). ESA-listed interior stocks represented 10% of all salmonids detected. Data presented here are a review of salmonid detections from 2008-2013 and compare the lower estuary sites of 2008-2010 to the expanded estuary sites of 2011-2013.

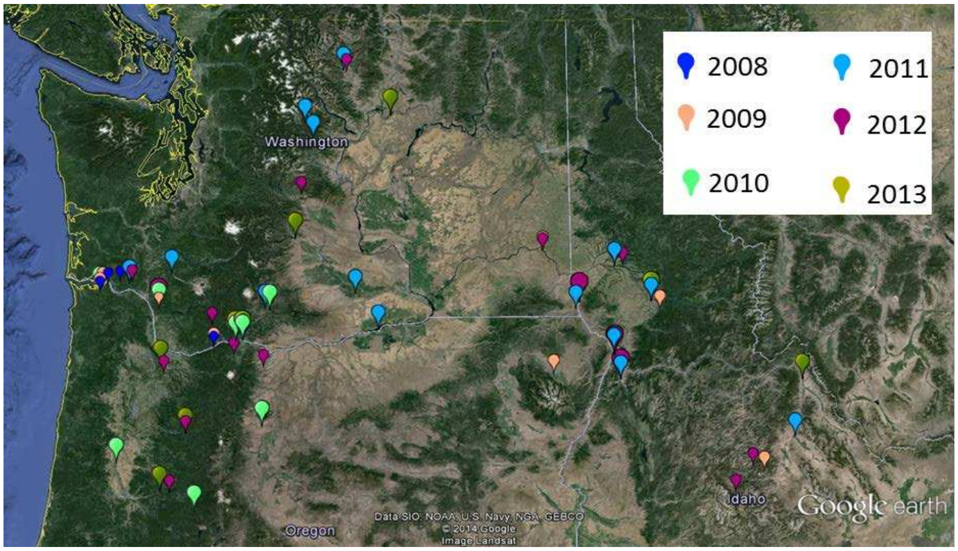
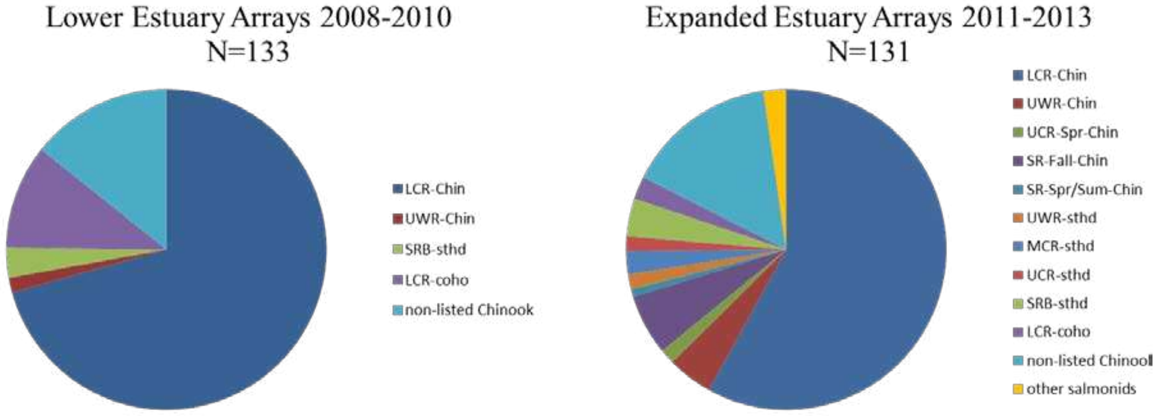


Figure 11. Locations of release sites or fish detected in estuary.

Diversity of Stocks—We detected a total of 264 individual salmonids in 2008-2013. Lower Columbia River Chinook salmon (LCR) accounted for 71 and 58% of detections during 2008-2010 and 2011-2013, respectively.


Lower Estuary Arrays 2008-2010
N=133

Expanded Estuary Arrays 2011-2013
N=131

Figure 12. Proportion of Chinook salmon stocks detected at estuary PIT detection arrays.

Among the minor contributors detected during 2008-2010 were Upper Willamette Chinook salmon, Snake River Basin steelhead, and lower Columbia River coho salmon. Non-listed stocks included representatives from the Middle Columbia River spring Chinook salmon ESU, and non-associated hatchery populations from Little White Salmon NFH (upriver bright fall Chinook salmon) and Kooskia NFH (spring Chinook salmon).

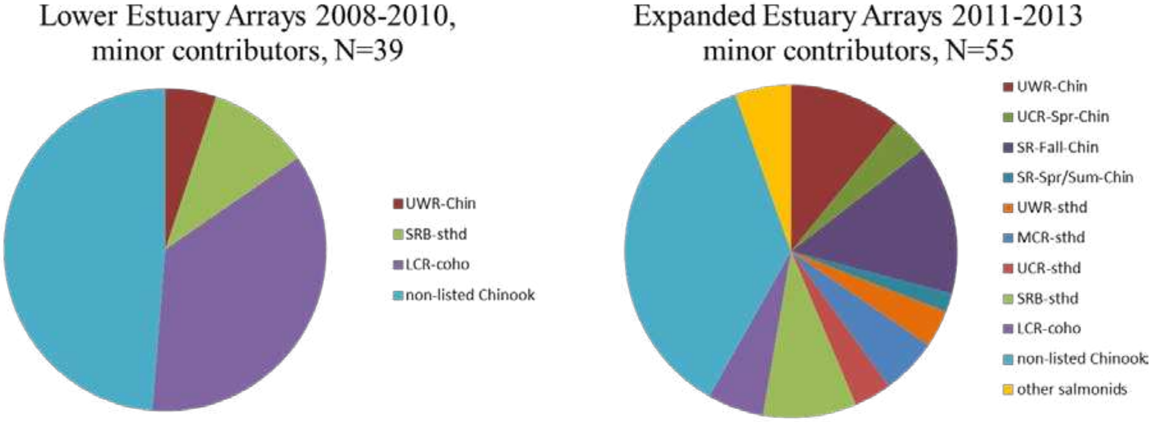


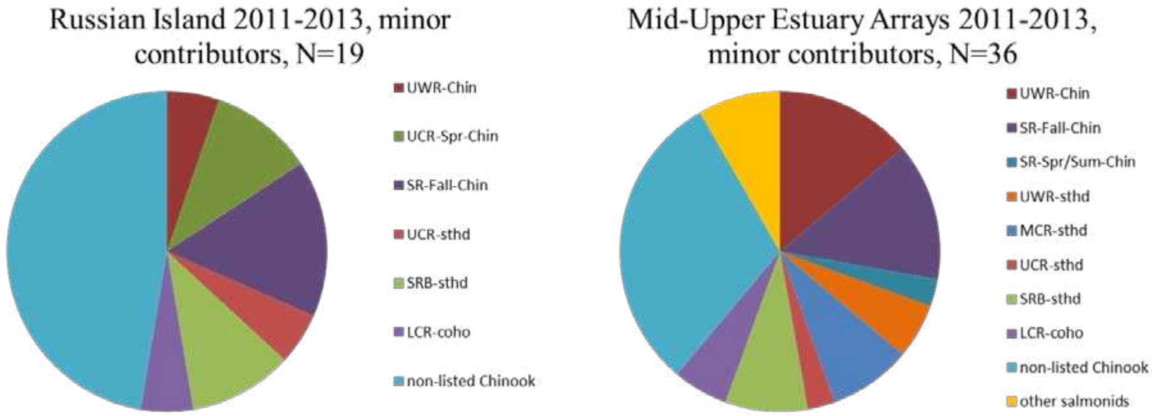
Figure 13. Proportion of minor contributors detected at estuary PIT detected arrays.

Stock diversity increased as the number of detection arrays expanded in 2011-2013. While lower Columbia River Chinook salmon was still the predominant stock, we also recorded new detections from the following ESUs/DPSs: Upper Columbia River spring Chinook salmon, Upper Columbia River summer/fall Chinook salmon, Snake River fall Chinook salmon, Snake River spring/summer Chinook salmon, Southwest Washington steelhead, Upper Willamette River steelhead, Middle Columbia River steelhead, and Upper Columbia River steelhead.

The number of non-associated hatchery stocks also increased to include the following: Carson Hatchery spring Chinook salmon, Rapid River Hatchery spring Chinook salmon, Upper Middle Columbia mainstem hatchery summer Chinook salmon, and Clearwater River coho salmon.

To determine whether the expanded number of PIT detection sites explained the increased diversity, we compared detections at Russian Island during 2011-2013 to those at the mid- and upper estuary sites during the same years. Four new ESUs/DPSs and non-associated populations were detected at Russian Island: Upper Columbia River spring Chinook salmon, Snake River fall Chinook salmon, Upper Columbia River steelhead, and Rapid River Hatchery spring Chinook salmon.

However, an even greater diversity of new stocks was recorded at the expanded estuary PIT detection sites, including five additional ESUs/DPSs (Snake River spring/summer Chinook salmon, Upper Columbia River summer/fall Chinook salmon, Upper Willamette River steelhead, Middle Columbia River steelhead, and Southwest Washington steelhead) and three additional non-associated populations (Carson hatchery spring Chinook, Upper Middle Columbia mainstem hatcheries summer Chinook salmon, and Clearwater River coho). One ESU that was detected at Russian Island and not at the expanded estuary arrays during 2011-2013 was the endangered Upper Columbia River spring Chinook salmon.


Russian Island 2011-2013, minor contributors, N=19

Mid-Upper Estuary Arrays 2011-2013, minor contributors, N=36

Figure 14. Proportion of minor contributors detected during 2011-2013 at Russian Island and the mid-upper estuary PIT detection arrays See Table 9 for abbreviations.

Travel Time and Travel Rate—For the purposes of this study, travel time was defined as the amount of time elapsed between release and first detection of a tagged fish on a PIT detection array. Fish in a particular ESU/DPS or non-listed group often originate from different release sites. To normalize for different distances traveled, we calculated a travel rate based on the distance from release site to the detection array divided by the travel time. Travel rate does not imply a swimming speed of a fish, since we had no knowledge of migration route, effects of barge transport, or other factors influencing the travel time of an individual to a particular site.

During both study periods (2008-2010 and 2011-2013), fish originating farthest from the estuary tended to have faster rates of travel than fish originating in the lower Columbia or Willamette River Basin (Tables 10 and 11). The same overall trend was evident among LCR stocks (Table 12). Chinook salmon released at Spring Creek NFH (rkm 269) traveled more quickly through the estuary than fish released at Kalama Falls (rkm 118) or Big Creek Hatchery (rkm 47). Likewise fish released from Kalama Falls

Table 10. Average travel rates and sample size (N) by ESU or DPS for 2008-2010. An asterisk indicates that at least one fish from the group was transported via barge to below Bonneville Dam.

	Average rate of travel			
	Russian Island 1		Russian Island 2	
	(km/d)	(N)	(km/d)	(N)
Lower Columbia River Chinook	3.6	41	5.5	53
Upper Willamette River Chinook	4.1	1	1.4	1
Snake River Basin steelhead*	43.7	2	73.1*	2
Lower Columbia River coho	4.5	7	1.9	7
Not listed	5.9	8	5.5*	11

* DPS

Table 11. Average travel rates (km/d) and sample size (N) by ESU/DPS for 2011-2013.

	Site							
	Russian Island 2		Woody Isl		Wallace Isl		Lower Sauvie Isl	
	(km/d)	(N)	(km/d)	(N)	(km/d)	(N)	(km/d)	(N)
Chinook								
Lower Columbia River	6.3	29	25.7	11	18.7	11	27.2	25
Upper Willamette River	4.1	1					3.5	5
Snake R spring/summer			42.1*	1				
Snake River fall	53.2*	3	23.3*	3			29.4*	2
Upper Columbia R spring	27.2	2						
Steelhead								
Upper Willamette River							0.1	2
Middle Columbia River			14.1	1			2.0	2
Snake River Basin River	71.4*	2	25.1*	2	1.6	1		
Upper Columbia River	51.1	1			60.8	1		
Coho								
Lower Columbia River	0.2	1			0.4	2		
Not Listed	8.1	9	13.4	7	5.9	4	10.4	2

* At least one fish from the group was transported via barge to below Bonneville Dam

Table 12. Sample size (N), travel time (d), and travel rate (km/d) of selected releases of LCR Chinook salmon, 2008-2010.

Site	Attribute	Big Creek (Oregon Dept Fish & Wildlife)	Kalama Falls WDFW	Spring Creek NFH
Russian Island 1	N	19	6	9
	Travel Time	16.8	29.9	33.2
	Travel Rate	1.0	3.8	8.0
Russian Island 2	N	17	13	15
	Travel Time	26.4	23.7	31.9
	Travel Rate	0.7	5.5	10.7

Hatchery traveled more quickly than those released from Big Creek Hatchery. Although Spring Creek hatchery fish had the fastest travel rate compared to the other releases of LCR Chinook salmon, they did not move quickly through the estuary. On average it took longer than 30 d for the Spring Creek release group to reach the lower estuary arrays at Russian Island.

Expanded estuary arrays in 2011-2013 allowed us to compare travel times of Spring Creek hatchery Chinook salmon to different sections of the estuary (Table 13). Travel rates of Spring Creek hatchery fish to the upper estuary site (Lower Sauvie Isl) and the site closest to the mainstem (Woody Isl) were faster than travel rates to the lower estuary (Russian Isl) or sites located further from the mainstem (Russian and Wallace Isl). These data suggest that Spring Creek hatchery Chinook salmon delay movement through the estuary or that arrays further from the mainstem are frequented by slower-moving individuals.

Residence Time—Residence time was estimated as time elapsed from first to last detection on a given array for an individual fish. Residence times reported here are minimal estimates because we do not know how long fish utilized habitat before and after detection. During 2008-2010, residence times in the lower estuary were stock dependent. Lower Columbia River Chinook and coho salmon had the longest average residence times, ranging 21.5-42.75 h (Table 14) with a maximum of 51 d for Chinook salmon and 4.3 d for coho.

Other ESU/DPSs had significantly shorter residence times. Lower Columbia River Chinook salmon again had the greatest residence time among stocks detected at the additional arrays during 2011-2013, with an average residence time of 36 h and a maximum of 47 d. Interior stocks had relatively short residence times but their abundance at all sites was not sufficient to compare residency among estuary locations.

Table 13. Sample size (N), travel time, and travel rate for selected releases of Lower Columbia River Chinook salmon, 2011-2013.

Site	Attribute	Spring Creek NFH	Big Creek (Oregon Dept Fish & Wildlife)
Russian Island 2	N	16	9
	Travel time (d)	28.6	11.4
	Travel rate (km/d)	9.2	1.4
Woody Island 1	N	10	
	Travel time (d)	14.8	
	Travel rate (km/d)	25.6	
Wallace Island 1	N	11	
	Travel time (d)	15.1	
	Travel rate (km/d)	18.7	
Lower Sauvie Island 1	N	25	
	Travel time (d)	8.6	
	Travel rate (km/d)	27.2	

Table 14. Average residence time (h) and sample size by ESU/DPS for 2008-2010.

	Lower Columbia R Chinook		Upper Willamette R Chinook		Snake R Basin steelhead		Lower Columbia R coho		Not listed	
	Time (h)	N	Time (h)	N	Time (h)	N	Time (h)	N	Time (h)	N
Russian Island 1	41.822	41	0.016	1	0.833	2	29.830	7	0.829	8
Russian Island 2	35.826	53	0.824	1	2.829	2	21.830	7	0.828	11

When we examined average residence times of all stocks throughout the expanded estuary arrays (2011-2013) average residence time appeared to decrease toward the mid-estuary, but average residence time at the upper most site, Lower Sauvie Island, surpassed that of the lowermost site, Russian Isl (Table 15). This indicates that site-specific residence time does not necessarily increase or decrease as a juvenile salmon migrates to the ocean, but may depend upon site-specific habitat attributes, for example, structural complexity and water level.

Table 15. Average residence time (h) and sample size (N) by site for 2011-2013.

	Russian Island 2		Woody Island 1		Wallace Island 1		Lower Sauvie Isl 1	
ESU/DPS	Time (h)	N	Time (h)	N	Time (h)	N	Time (h)	N
	Chinook							
Lower Columbia R	52.828	29	3.817	11	14.826	11	73.817	25
Upper Willamette R	4.821	1					2.826	5
Snake R spring/summer	---		0.003	1				
Snake R fall	0.829	3	1.818	3			1.833	2
Upper Columbia R spring	0.833	2						
	Steelhead							
Upper Willamette R							0.832	2
Middle Columbia R			0.002	1			1.826	2
Snake R Basin	0.012	2	2.823	2	0.828	1		
Upper Columbia R	0.819	1			0.824	1		
Lower Columbia R coho	1.824	1			0.828	2		
Not Listed	23.833	9	3.826	7	0.820	4	0.833	2

Adult Use—Adult hatchery steelhead were detected at all mid-upper estuary detection sites. At Lower Sauvie Island, two adult steelhead were detected returning to the Willamette River. Each had been released 2 years prior to detection on the Lower Sauvie array and each was subsequently detected at the Willamette Falls Adult Fishway (4 and 14 d later). Adult Snake River Basin steelhead were detected at Wallace and Woody Island arrays. Adult steelhead detected at Wallace Island had been released the previous year and were detected at Bonneville Dam adult ladder 7 d after detection at Wallace Island. The adult steelhead detected at Woody Island was a kelt returning to the ocean. It had been released from Kooskia Hatchery in spring 2010 and then barged from Lower Monumental Dam. During fall 2012 it was detected on adult ladders at Bonneville, McNary, Ice Harbor, and Lower Granite Dams. In spring 2013 it was observed at the Bonneville Dam corner collector; 8 d later it was detected at Woody Island.

We detected one jack Chinook salmon at Lower Sauvie Island that had been released from Rapid River Hatchery in March 2012 and was seen at juvenile fish bypass facilities at Lower Granite, Little Goose, and McNary Dams. Two months after detection at McNary Dam, it was detected at Lower Sauvie Island, and 2 d later it was seen at Bonneville Dam adult ladders. It subsequently passed McNary and Ice Harbor Dam fish ladders. Adults were detected only at mid- and upper estuary sites. This was likely because the three mid-upper estuary sites are adjacent to deep water, whereas Russian Island is surrounded by a vast expanse of shallow water and mudflats.

Conclusions

- Interior stocks of Chinook salmon and steelhead utilize off-channel shallow-water habitat throughout estuary reaches B, C, and F.
- Interior ESA-listed stocks represented 10% of the total salmonids detected.
- Snake River fall Chinook salmon and Snake River basin steelhead were the most abundant of interior stocks detected.
- Lower Columbia River Chinook tend to utilize off-channel shallow-water habitat to the greatest extent, as measured by number of fish detected and residence times.
- Diversity of stocks increased temporally but more so geographically. This trend supports results from genetic analyses showing increased diversity of stocks utilizing the upper estuary, especially reaches E and F.
- Fish released further upriver tended to move faster through the system, and Lower Columbia River Chinook may slow down as they migrate through the estuary.
- Lower Columbia River Chinook salmon demonstrated a wide range of site-specific residence times with a maximum of 51 d.
- Residence time was not related to a longitudinal estuary gradient, but instead seemed to be influenced by local site conditions, such as habitat complexity, water level, and tides. For example, fish sampled at Russian Isl had long residence times. This was likely because of the highly complex habitat structure with multiple entry/exit points, and because even though waters recede at low tide, there are a few deeper areas which likely serve as shallow water refuge.

  Fish occupying the lower Sauvie Isl site also had relatively long residence times. This pattern could reflect high water levels, abundant woody debris in the channel, and an expansive floodplain that is available (during high water levels, the channel opens into floodplain habitat). Fish entering the study channels at Woody and Wallace Islands had shorter residence times. These habitats have only one entry/exit point, do not intersect other channels or floodplains, and do not retain much water during low tides.
- Expansion of PIT detection capabilities into the mid- and upper estuary has provided unexpected documentation of adult steelhead use of tidal channels.

Chinook salmon diet composition in upper estuary reaches

Si Simenstad and Pascal Goertler

Previous beach-seining collections in 2002-2007 provided diet composition results for juvenile Chinook salmon in the lower 100 km of the estuary (Bottom et al. 2011). Prey assemblages and juvenile salmon diets were also reported for a diversity of lower-estuary wetland types (Lott 2004; Ramirez 2008; Bottom et al. 2011). As part of the present study, salmon diets were sampled from reaches above rkm 100 to the head of tide at Bonneville Dam during the estuary-wide stock distribution survey (Teel et al. 2014).

We sampled juvenile salmon bimonthly in each of three shallow-water habitats (mainstem, back channel, and confluence) in six estuary hydrogeomorphic reaches (C-H) and at a single monitoring site near the estuary mouth (Point Adams Beach, reach A). Juvenile Chinook salmon collected during this survey were later subsampled to determine habitat-specific growth rates (see Appendix A; Goertler et al. in prep) and to compare salmon diet composition among habitats in two estuary reaches. Here we report results from stomach content analyses of juvenile Chinook sampled from mainstem, back-channel, and confluence habitats in reaches D and H during 2010-2012.

Methods

The sampling design for juvenile Chinook diet composition (prey taxa and foraging intensity) was opportunistically embedded in the genetics study sampling design (Bottom et al. 2012; see *Salmon Habitat Use and Stock Composition in Tidal-Fluvial Floodplain Wetlands* for details and overall methods). Sites were stratified among the six freshwater tidal level 3-hydrologeomorphic reaches, defined by Simenstad et al. (2011) in the *Columbia River Estuary Ecosystem Classification*.

Three types of juvenile Chinook habitat were sampled within each reach: mainstem channel, backwater channel and confluence (junction of tributary and mainstem Columbia). Fish for diet analysis were selected from fish sacrificed for otolith analyses (Appendix A; Goertler et al. in prep). A total of 18 sites were sampled every other month for 2 years (March 2010-March 2012). Results from the broader sampling design, including life history and genetic stock and mark identification, were described by Teel et al. (2014) and in other sections of this report.

Supplemental funding was obtained to further analyze a subsample (n = 106) of the fish examined for otolith microstructure. These fish were assessed for diet composition and relative consumption rate. Samples were selected exclusively from collections at mainstem and back-channel habitat types in reaches D and H, but included samples from all representative size ranges, stock groups, and time periods within these collections (Table 16).

Table 16. Summary of samples for diet composition and relative consumption rate from reaches D-H, March 2010-September 2011.

Month and year	Reach	Habitat	N	Length range (mm FL)	Weight range (g)	Total prey categories	Mean unidentifiable mass (%)
May 2011	D	Back channel	6	44-84	0.6-5.5	11	16.9
May 2010	D	Back channel	6	38-75	0.5-3.7	8	0
May 2010	D	Mainstem	8	40-78	0.7-4.8	15	0.54
May 2011	D	Mainstem	8	42-81	0.9-5.5	22	24.2
May 2010	H	Back channel	10	44-90	0.8-7.4	27	1.0
May 2011	H	Back channel	10	49-86	1.0-6.4	23	15.7
May 2011	H	Mainstem	7	48-63	1.0-2.6	16	0.4
July 2010	D	Mainstem	7	51-87	1.9-6.4	16	9.5
July 2010	H	Mainstem	3	72-85	3.8-6.3	10	0.0
July 2011	D	Back channel	7	55-94	1.8-10.0	14	7.7
July 2011	D	Mainstem	8	41-78	0.4-4.7	35	10.7
July 2011	H	Back channel	8	66-92	3.1-8.0	26	0.2
July 2011	H	Mainstem	5	63-85	2.5-6.1	15	5.2
Sept 2011	H	Back channel	12	88-127	6.9-23.5	35	9.2

In the lab, fish were thawed and the stomachs were removed from the abdominal cavity, preserved in 10% buffered formalin, and retained for later determination of diet composition and relative consumption rate. This procedure entailed determining blotted dry wet weight of the whole fish and of prey items, which were also counted. Prey were counted and identified under a dissecting microscope to class, family, or order taxa groups, and prey groups were also weighed.

In general, where identifiable due to the state of digestion, crustaceans such as amphipods, copepods, and isopods were identified to species, while insects were identified to family and oligochaetes to order. Total weight of the stomach contents was obtained by adding the total weight of each prey taxa to the weight (by difference from the total fish weight) of the unidentified material. Total weight of the stomach contents was obtained after the blotting process to avoid damage to insects prior to identification.

Relative consumption rate, or "instantaneous ration," was calculated as the ratio of stomach content weight to predator weight (Terry 1977). We assessed the three basic metrics of prey composition: percent numerical composition, percent gravimetric contribution, and frequency of occurrence, as well as the contribution of each prey item group. Prey group contribution was measured using the non-dimensional index of relative importance, IRI (Pinkas et al. 1971; Bowen 1983), which is calculated using numerical composition (NC), gravimetric composition (GC) and frequency of occurrence (FO):

$$\mathrm{IRI} = \mathrm{FO} * [\mathrm{NC} + \mathrm{GC}].$$

Additionally, the stomach fullness index was determined using a qualitative ranking that ranged from 1 (empty) to 6 (distended).

We tested for significant differences in diet composition among months, years, reaches, habitats, and genetic stocks using non-metric multidimensional scaling (multivariate) analysis (PRIMER 6 software; Clarke and Warwick 2001). Diet data were also grouped into four length intervals to test for differences based on early life history stage. Numerical and gravimetric diet composition data were square-root transformed before analysis.

Results

Approximately 98 prey taxa were identified from among all 106 fish; general plant matter, algae, and rocks were also included in the diet. However, only 23 prey types occurred in more than 5% of total sample. Therefore, we confined our assessment of diet to these most representative prey taxa. Among frequently consumed prey, insects were the most predominant, particularly dipteran midges of the family Chironomidae, in terms of frequency of occurrence and total biomass (gravimetric contribution; Figure 15).

Midges of all life history stages were found in the diet, including emerging or teneral, pupal, and larval, as well as adult stages (Figure 16). The amphipods *Americorophium* spp. were also fed upon frequently and contributed considerably to diet biomass (primarily *A. salmonis* but also *A. spinicorne*).

Compared to these benthic-epibenthic prey (excepting the teneral chironomids, which may have been fed upon at the water surface), the planktonic cladocerans *Dapnia* and *Bosmina* sp. constituted the most numerically prominent prey. However, these were fed upon somewhat less frequently than the insects and amphipods.

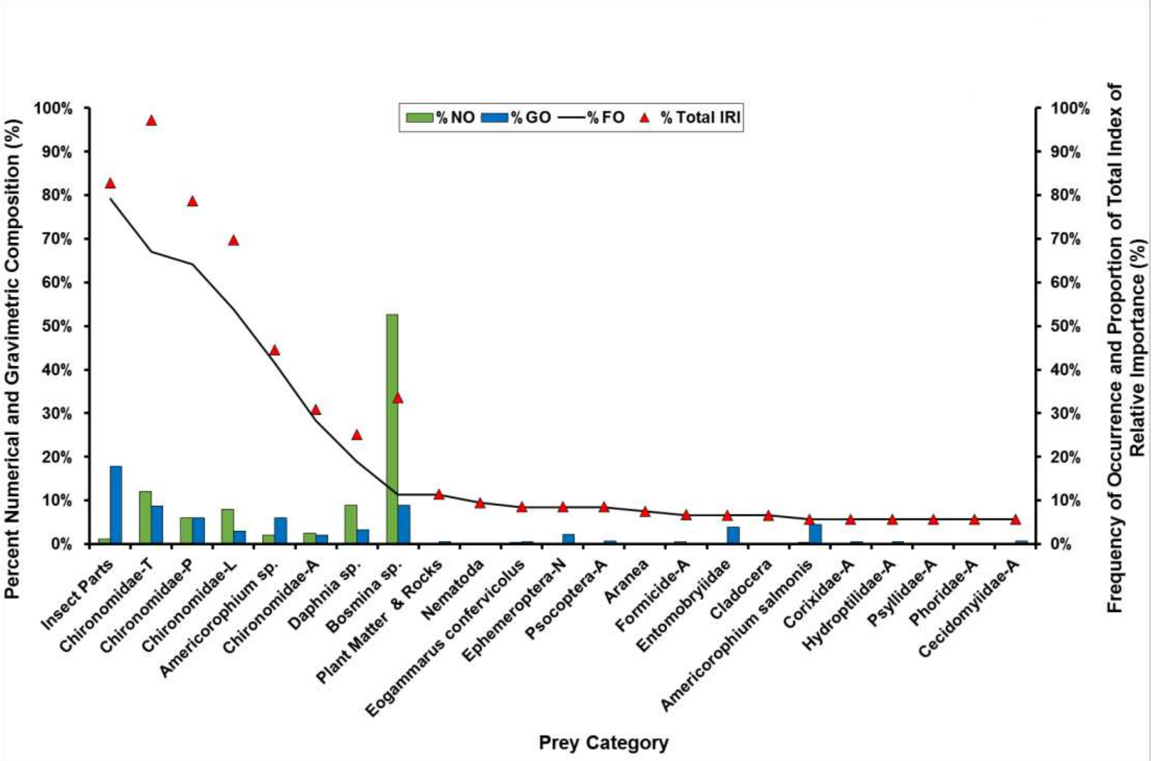


Figure 15. Dominant diet composition of 106 juvenile Chinook salmon sampled from Columbia River estuary reaches D and H, March 2010-September 2011. In the y axis, life stages are T teneral, P pupal, L larval, N nymph, or A adult.

Gravimetric analyses indicated that Chinook salmon foraged predominantly on chironomid midges of various stages, especially the emergent teneral stage, through most months, reaches, and habitats. However, the diet was often supplemented by amphipods *Americorophium* spp. Exceptions tended to occur in mainstem habitats where juvenile Chinook salmon had recently fed upon planktonic cladocerans (reaches D and H during May 2010) or terrestrial insects (reach D in July 2011). It is important to note that habitats in the analysis represent locations where fish were captured, not necessarily where they fed. For example, a fish could have fed in back-channel habitats just prior to capture in the mainstem.

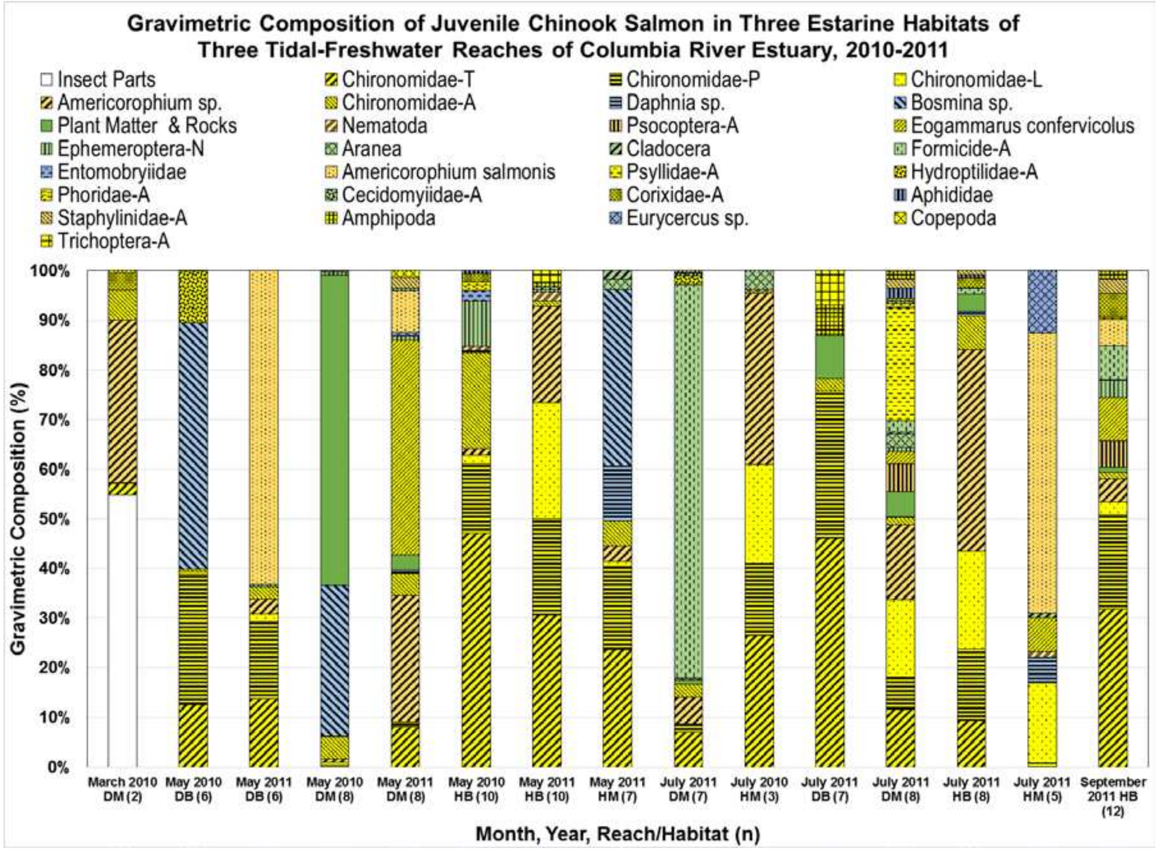


Figure 16. Gravimetric composition of juvenile Chinook salmon in three habitats of two reaches in the upper Columbia River estuary, March 2010-September 2011. Abbreviations: the first letter below each bar designates estuary reach and the second letter designates habitat, where M = mainstem and B = back channel. In the legend, life stages are T teneral, P pupal, L larval, N nymph, or A adult. All aquatic insects are displayed in yellow patterns, amphipods in orange, terrestrial insects in light green and planktonic crustaceans in blue.

Numerical composition data suggest that juvenile Chinook salmon often fed extensively on individual cladocerans, as was evident in mainstem and back-channel samples from reach D in May 2010 and in mainstem samples from reach H in 2011 (Figure 17). However, aquatic insects, and generally chironomids of all life history stages, still dominated in 11 of the 15 samples.

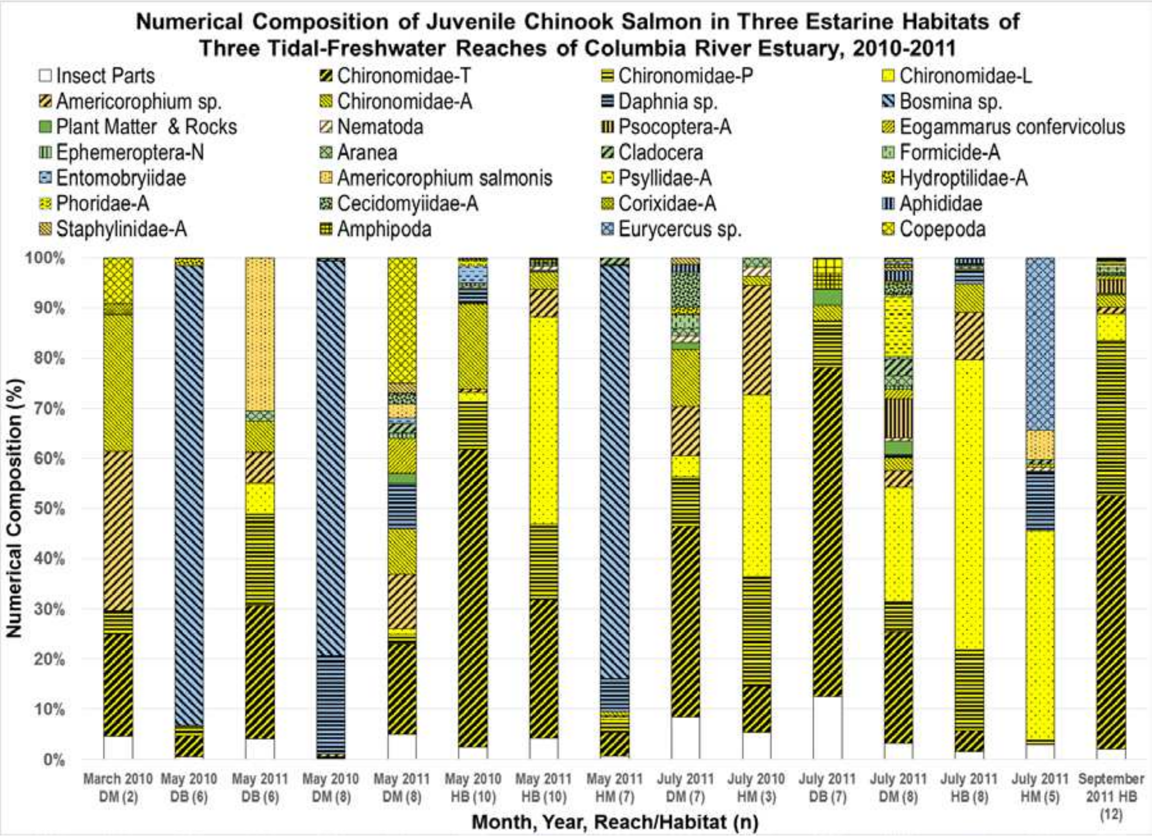


Figure 17. Numerical composition of juvenile Chinook salmon in three habitats of two reaches in the upper Columbia River estuary, March 2010-September 2011 (first letter designates estuary reach; second letter designates habitat, where M = mainstem and B = backwater). In the legend, life stages are T teneral, P pupal, L larval, N nymph, or A adult. All aquatic insects are displayed in yellow patterns, amphipods in orange, terrestrial insects in light green, and planktonic crustaceans in blue.

Because of the allometric relationship between fish size and stomach volume, comparisons of instantaneous ration (relative consumption rate) for individual fish from the two reaches and two habitats were grouped into four bins based on fork length (Figure 19). While there was no pervasive trend in consumption rate, it is interesting to note that fish captured in the mainstem habitat of reach D during July 2010 tended to have lower consumption for their size than fish captured in the same location during May 2010 and during May and July 2011. Similarly, fish from back-channel habitat in reach D during July 2011 also tended to have lower consumption than fish from the same location in May 2010 and 2011. There were no similar trends among fish from mainstem or back-channel habitats of reach H.

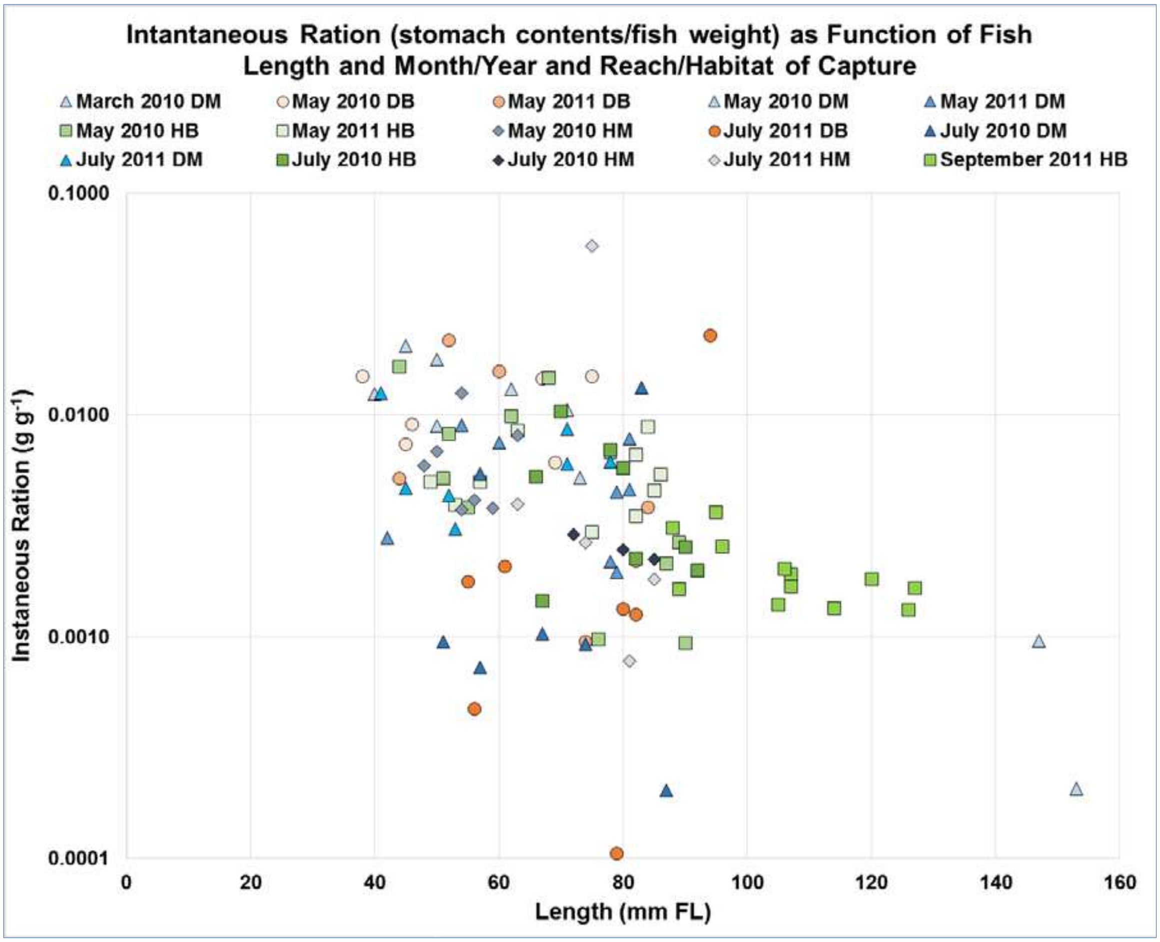


Figure 19. Instantaneous ration of individual juvenile Chinook salmon (each symbol is an individual fish) in three habitats of two reaches in the upper Columbia River estuary, March 2010-September 2011 (first letter designates estuary reach; second letter designates habitat, where M = mainstem and B = back channel).

Conclusions

- In Chinook salmon sampled from tidal-freshwater reaches of the Columbia River estuary, diet composition was generally comparable to that found in fish from lower reach habitats, despite differences in ecosystem structure (e.g., vegetation, flooding regime).

  Chironomid midges of all life history stages, but particularly the teneral (emerging adult) and amphipod *Ameriocorophium salmonis* forms were predominant in Chinook salmon diets. These prey suggest explicit linkages to benthic/epibenthic habitats.
- Planktonic cladocerans *Daphnia* sp., *Bosmina* sp. were numerically prominent, particularly from fish captured in mainstem channel habitats.
- There were no consistent trends in the variability of size-specific consumption rates among fish mainstem or back-channel wetland habitats or between reaches D and H. However, within some reaches, differences among years were found for the same habitats.

Juvenile life-history contributions to spawning populations of Columbia River Chinook salmon

Lance Campbell

From 2009 through 2011 we analyzed adult Chinook salmon otoliths to reconstruct the juvenile life histories contributing to adult returns in selected Columbia River tributaries (Bottom et al. 2011). During 2012-2013, we expanded these analyses to increase spatial diversity among studied populations and to characterize interannual variability in adult contributions among different juvenile life histories. Here we compare otolith results from spawning populations sampled from different areas of the basin during 2011-2013.

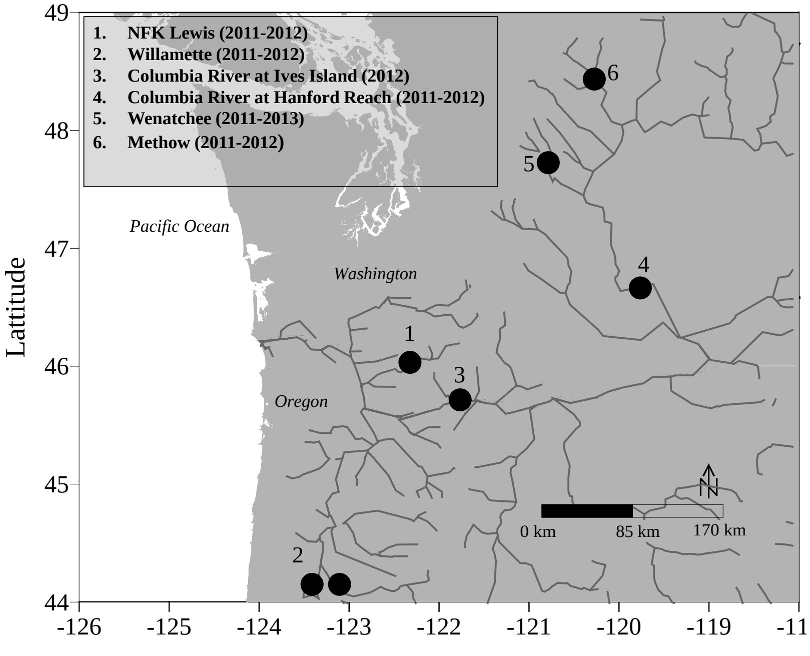


Figure 19. Location of adult otolith samples collected in selected mainstem and tributary sites of the Columbia River basin. Otoliths have been collected and analyzed from the six sites shown

Methods

Adult otolith samples were collected during spawning-ground surveys in four Columbia River tributaries and two mainstem sites (Figure 19). These sites were grouped into three categories: lower tributaries (Lewis and Willamette River), mainstem Columbia River (Hanford Reach, Ives Island), and upper tributaries (Methow and Wenatchee Rivers).

The eight spawning populations from these sites included spring, summer, and fall run stocks. We used the relationship between fish size and otolith size, as well as chemical data gathered from laser ablation inductively coupled mass spectrometry, to back-calculate size at estuary/ocean entrance (determined by contact with saline water). For further details see Campbell (2010) and Claiborne (2013).

Results

Preliminary results indicate that:

1. Juvenile sizes at estuary/ocean entry vary among spawning populations and among return years, and
2. Life histories of fry (<60 mm) contribute to adult returns in fall spawning populations from each of the three main regions (lower and upper tributaries and mainstem Columbia River; Figure 20).

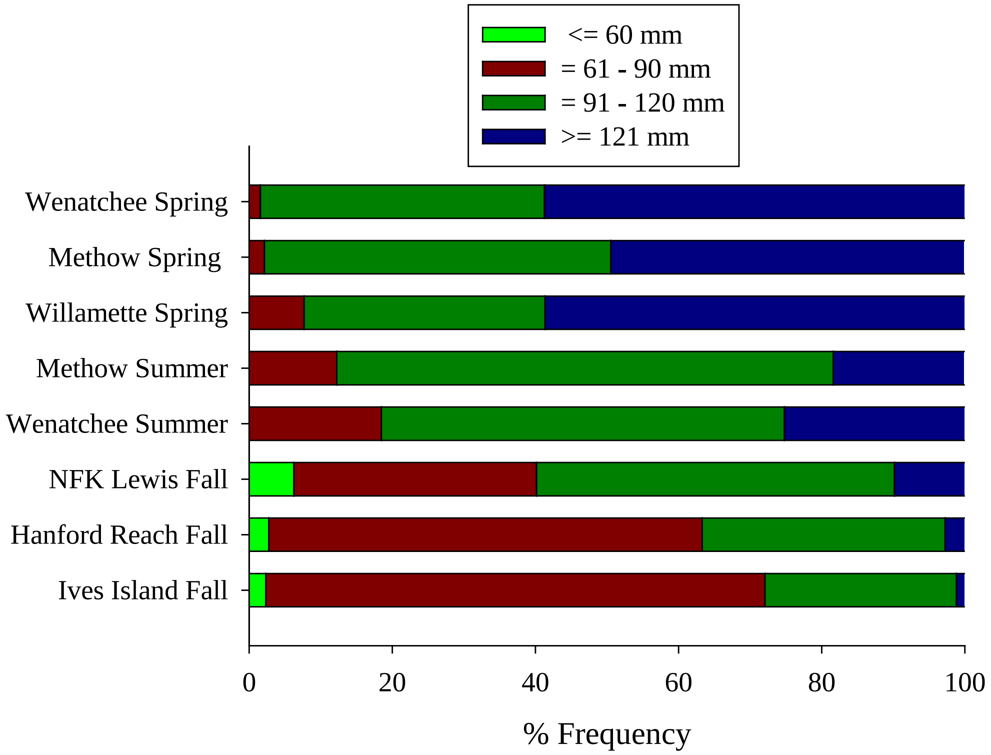


Figure 20. Frequency of juvenile life histories based on mean size at estuary/ocean entrance for selected spawning populations regardless of return year.

For all spawning populations sampled, mean size at estuary/ocean entry was 5-19 mm larger in 2012 than in 2011. On average, fall spawning populations had the smallest fork length at estuary entry (range 77-96 mm), followed by summer and spring spawning populations (range 101-120 and 115-132 mm, respectively). Interestingly, summer populations entered the estuary at a relatively large mean size, similar to that of yearling migrants from some spring spawning populations.

Spring-run Chinook from the Methow and Wenatchee Basins were predominately yearling spring migrants, while summer-run Chinook from these basins were classified as subyearling migrants (WDFW scale analysis; Table 17). The difference in size at estuary/ocean entry between fish with yearling vs. subyearling juvenile migration histories was relatively small in some years (~10 mm) despite different periods of ocean entry. We hypothesize that this small difference may be due to

1. An increase in growth potential for summer migrants in non-natal habitats (mainstem Columbia/reservoir/lower river and estuary), and/or
2. Subyearling Chinook may leave their natal habitat earlier than yearling conspecifics but spend similar amounts of time in the entire system (from tributary to estuary) before making their true seaward migration.

Table 17. Proportion of back-calculated size ranges at estuary/ocean entrance among adult Chinook salmon returning to selected Columbia River populations.

	Backcalculated FL at estuary/ocean entrance (mm)					Average	
	<60	61-90	91-120	>121	n	FL (mm)	SD
NFK Lewis FCk 2011	0.08	0.40	0.46	0.06	86	90	20.25
NFK Lewis FCk 2012	0.05	0.28	0.53	0.13	42	96	21.63
Willamette SpCk 2011	0.00	0.12	0.29	0.59	51	127	28.74
Willamette SpCk 2012	0.00	0.04	0.38	0.58	49	132	26.89
Ives Island FCk 2012	0.02	0.70	0.27	0.01	52	85	12.55
Hanford Reach FCk 2011	0.06	0.79	0.15	0.00	60	77	10.33
Hanford Reach FCk 2012	0.00	0.43	0.52	0.05	53	95	12.41
Wenatchee SuCk 2011	0.00	0.32	0.55	0.13	56	101	17.38
Wenatchee SuCk 2012	0.00	0.04	0.58	0.39	63	120	23.14
Wenatchee SpCk 2013	0.00	0.02	0.40	0.59	62	127	19.59
Methow SuCk 2011	0.00	0.12	0.69	0.18	57	107	18.58
Methow SpCk 2011	0.00	0.05	0.64	0.31	51	115	13.81
Methow SpCk 2012	0.00	0.00	0.35	0.65	53	129	15.29

Results to date indicate that in return years 2011 and 2012, fall spawners from the North Fork Lewis River and spring spawners from the Willamette River had the greatest variation in migration size and timing (Figure 21). For example, 5-8% of North Fork Lewis adults were smaller than 60 mm FL at estuary/ocean entry, while 6-13% were larger than 121 mm FL. Juveniles from the upper Willamette River spring ESU migrate to estuary/ocean waters as yearlings, and to a lesser extent as subyearlings (Myers et al. 1998).

A conservative estimate based on these results is that 4-12% of returning adults were likely subyearling migrants and entered estuary/ocean waters at sizes smaller than 90 mm (FL), which is consistent with our previous findings. Figure 21 suggests that among juveniles from the Methow spring and Hanford Reach fall populations, migration timing and size were more uniform relative to the other spawning population examined. In both return years Methow spring and Hanford Reach fall Chinook had the least variation in length.

These preliminary results demonstrate the value of otolith reconstruction for comparing life history variations within and among Columbia River ESUs. Further work is needed to evaluate

1. Juvenile life-history expression among adults for additional years and ages of return
2. Compare life-history expression among different Chinook races and spawning locations (i.e., mainstem, lower, or upper tributary etc.);
3. Contrast in migration timing and residency of experimental populations from the mainstem vs. lower Columbia River.

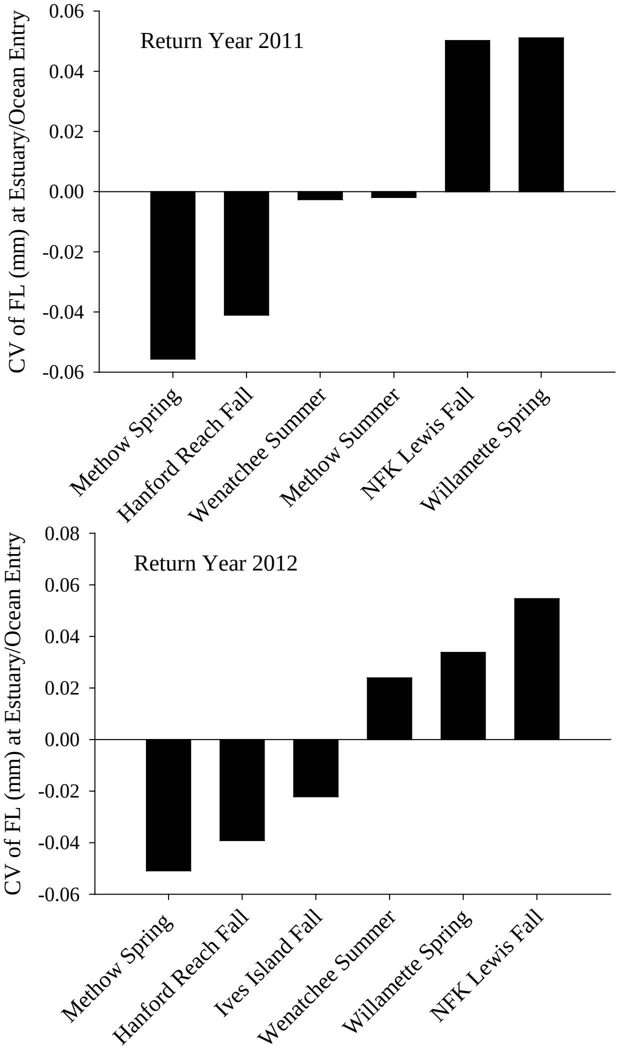


Figure 21. Anomaly of the coefficient of variation of fork length (mm) at estuary/ocean entry by population for adult Chinook returning in 2011 and 2012.

Conclusions

- Multiple juvenile life histories contribute to adult returns in lower, mid- and upper Columbia River, and Willamette ESUs.
- Juvenile size at salt-water entry is not a simple function of distance travelled from natal spawning and rearing areas.

Modeling shallow-water rearing opportunities for juvenile salmon

Antonio Baptista

Salmon habitat use in different estuary locales may be influenced by stock distributions as well as hydrological variables. Simulation modeling has demonstrated that for juvenile salmon in different lower-estuary regions, habitat opportunities respond independently to physical changes. These responses reflect unique interactions of local habitat features and regional landscapes with system-wide processes (e.g., tides and river flow) (Bottom et al. 2005; Burla et al. 2007). Thus the effectiveness of a given habitat restoration projects for salmon may vary, depending upon the reach or complex within which it is embedded. We characterized the dynamics of habitat opportunity for juvenile salmon at reach- and habitat-scales.

We used a hydrological model to simulate salmon habitat access in tidal-freshwater reaches of the estuary under varying flow, temperature, and climate-change conditions. These simulations utilized habitat-opportunity metrics proposed by Bottom et al. (2005) and modified based on recent estuary survey results (Roegner et al. 2008; Bottom et al. 2011). Original metrics included depth (0.5-2.0 m), velocity (≤ 30 cm s^{-1}), and temperature (<19°C). We further modified and expanded these metrics (as outlined below) to reflect results from new habitat-specific data collected during this study.

Methods

Model simulations examined the dynamics of habitat opportunities across all tidal-fluvial reaches (reaches C-H) and of focal habitats within one or more selected reaches. The characterization and analysis of shallow-water rearing opportunities for juvenile salmon in the Columbia River estuary has traditionally involved two key methodologies:

- Numerical simulation of 3D circulation for the estuary and adjacent waters over multiple years.
- Conversion of these simulations into integrative metrics of salmon habitat opportunity (SHO) and into contextual metrics of the estuary.

An additional methodology was recently developed that adds a practical capability with strong potential for application to management and operation:

- Fast "instantaneous" prediction of the response of habitat opportunity and other integrative metrics to river discharge.

Results

Methodological advances included the following:

Numerical simulations—Over the course of this project, we have updated our simulation circulation databases when a clear benefit in modeling skill was expected. In the last year, we created an improved version of the simulation circulation database (named “DB31” by contrast with the previous database “DB22”). We also extended the period of simulation coverage for both databases to 1 January 1999-31 December 2012. All simulations were based on the baroclinic circulation code SELFE (Zhang and Baptista 2008).

Model enhancements leading to DB31 were obtained primarily via refinements of the computational grid and reduction of computational steps rather than through algorithmic changes in code. Improvements to the representation of salinity intrusion were particularly noteworthy, although errors remain for high flows and low tidal ranges in particular.

Capturing salinity intrusion is key to representing estuarine circulation. Therefore we used a detailed dataset of lower estuary salinity and velocity fields obtained from a vessel and two autonomous underwater vehicles. Our dataset comprises a stringent benchmark designed to test, calibrate, and enhance circulation models. This benchmark is reported by Frolov et al. (in prep, Appendix A), with results based on a modified version of SELFE leading to further improvements over DB31; modifications refer to an algorithmic change (in the treatment of the bottom friction) and the improvements are sufficiently significant to suggest the desirability of developing a next-generation simulation database.

In addition, we developed and have begun applying a SELFE-compatible sediment transport model for the estuary. This model is in part a response to the frequent request to include turbidity as one of our salmon habitat metrics. A publication reporting on the development, calibration of the model, as well as early insights into the sediment dynamics in the lower estuary, is in preparation (Lopez et al., in prep.).

Integrative metrics—The concept of circulation-based habitat opportunity (HO) has been used for over a decade in support of regional management decisions for salmon (Bottom et al. 2008). However, past studies have not been stock or life-stage specific and have relied on a straightforward application of individual or combined thresholds for favorable water depth, velocity, salinity, and temperature. At the beginning of this project, favorable habitat opportunity within the eight hydrogeomorphic reaches (Simenstad et al. 2011) was defined as areas for which the following thresholds were met:

- Water depth: $0.5 \leq D \leq 2$ m
- Temperature: $T \leq 19$°C
- Salinity: $S \leq 5$ psu
- Velocity: $V \leq 0.35$ m/s

We then developed a simple variation of these criteria, keeping all other thresholds unchanged but using different velocity thresholds for fish of different sizes:

- Emergent fry (<45 mm): $V \leq 0.4$ m/s
- Fry (45-60 mm): $V \leq 0.5$ m/s
- Subyearling A (60-80 mm): $V \leq 0.6$ m/s
- Subyearling B (>80 mm): $V \leq 1.0$ m/s

Over the last year, we have conducted a sensitivity analysis (Rostaminia et al. in prep.) involving three other approaches. Each approach builds upon the previous, toward what we expect to be a progressively more realistic representation of estuarine habitat use by salmon. These approaches allow differentiation among life stages, but not directly among stocks. The first consists of a volumetric rather than area-based characterization of salmon habitat opportunity, which is obtained by applying the above criteria in an explicitly 3D manner. The second approach allows thresholds for favorable velocity to vary as a function of fish size while depth, salinity and temperature criteria remain unchanged.

The third approach embodies a more sophisticated understanding of estuary use by juvenile Chinook salmon. Favorable habitat is characterized first through depth thresholds, which are then adjusted via 3D modifiers associated with bioenergetics (via temperature) and environmental (via velocity and salinity) considerations. We are considering a fourth approach that would be both stock and life-stage specific. This fourth approach would combine the third (above) with specific knowledge from fisheries data about when different stocks occupy different reaches of the estuary.

Fast predictors—Core strategies for characterization of salmon habitat opportunity and contextual metrics were applied directly in early stage studies of estuarine impact. These strategies contributed to recommendations to the U.S. Department of State for improved provisions of the *Columbia River Treaty* (BPA and USACE 2013). However, the large number of scenarios (11) and long periods (70 years) for which numerical simulations were eventually required quickly rendered the approach unfeasible from a purely computational perspective: circa 10 years of simulation time would have been needed to run all of the scenarios.

To address this challenge, we developed fast alternative strategies to compute the integrative metrics on which the impact studies were based. Specifically, we developed multivariate linear correlations between all contextual integrative metrics and river flows, each with strong predictive skill (Baptista et al., in prep.). However, for salmon habitat opportunity (SHO), correlations did not show sufficient predictive skill.

Instead, we resorted to inexpensive model surrogates—trained on a limited set of numerical simulations—to replace the numerical simulations. We then computed habitat opportunity from the model surrogates. Fundamentals for the model surrogates were introduced by van der Merwe et al. (2007), but surrogates were algorithmically improved and retrained during and after the treaty review (Frolov et al., in prep., Appendix A).

Since conclusion of the treaty review process, we have explored the use of more sophisticated statistical techniques to obtain correlations between salmon habitat opportunity and river flow and temperature. Use of a generalized additive model has shown strong promise (Rostaminia et al., in prep.). Implications are that we now have two approaches that enable fast (nearly instantaneous) predictions as a function of river conditions for both SHO and salmon-relevant contextual metrics. These predictors could—if desired—be run in real time, and thus conceivably inform operation of the Federal Columbia River Power System.

Advances in understanding—Over the last year, we gained detailed understanding of the influence of river flow on the contextual estuarine dynamics relevant for salmon. This was accomplished primarily through data exploration of the simulation database DB31, and findings are being reported by Baptista et al. (in prep). Many of these findings confirm and refine classical understanding of the estuary and create a needed quantitative framework, which had been missing and which is contextually important to understand the use of the estuary by salmon and other fish, and perhaps birds. Other findings, however, offer fundamentally new windows into the dynamics of the estuary. For instance, we have identified what appear to be two fundamentally distinct mechanisms of frontogenesis in the estuary, and their dependence on river discharge.

We have also—and of essence to this project—gained new insight into salmon habitat opportunity in the estuary, from characterizing the spatial and temporal variability of SHO to beginning to understand salmon dependency on habitat opportunity in terms of life stage. Perhaps most significant, we have introduced a promising new definition of salmon habitat opportunity based upon depth thresholds and adjusted through consideration of bioenergetics (temperature) and environment (velocity and salinity). Over time, this new definition should replace the simpler concept pioneered by Bottom et al. (2005). These findings to date are reported by Rostaminia et al. (in prep).

Conclusions

- Our new definition of salmon habitat opportunity is based depth thresholds, adjusted through consideration of bioenergetics (temperature) and environment (velocity and salinity). This new definition should be further explored and refined and considered by the region as a possible new standard for impact studies.
- The fast predictors developed for SHO and other salmon-relevant metrics offer a potentially practical tool to guide aspects of an innovative, adaptive operation of the FCRPS, assuming one goal of FCRPS operation is optimization of environmental conditions—at daily and perhaps seasonal scales—relative to the timing of the use of the estuary by specific stocks and life stages. A pilot effort to explore this concept is recommended.

Summary and Conclusions

In 2010 we initiated an integrated research program to investigate habitat use and performance of juvenile Chinook salmon in selected tidal-fluvial reaches of the Columbia River estuary. The purpose of this research was twofold: 1) determine the estuary contribution to spatial structure and diversity of Columbia River salmon stocks, and 2) address critical uncertainties about tidal-fluvial habitat functions that limit estuary restoration and salmon recovery planning.

Due to funding reductions after 2012, our long-term research plan could not be fully executed, and the number and frequency of surveys in the upper estuary was limited. Nevertheless, we have made significant gains toward fulfilling many program objectives. Most notably, surveys since 2010 have provided new information about 1) the estuary distribution of Chinook salmon genetic stock groups; 2) stock-specific juvenile life histories, habitat use, and performance; and 3) the contribution of different juvenile life histories to adult returns for a variety of ESUs. From results during 2010-2013, we drew the following conclusions:

Estuary distribution of Chinook salmon genetic stock groups

- Chinook salmon stocks and life histories are not uniformly distributed through the lower Columbia River estuary, but exhibit broad seasonal and spatial patterns that are generally consistent between years. New juvenile salmon data from reaches E and F indicate high stock diversity and evenness, reflecting a diverse mixture of Willamette River, lower basin, and interior stock groups. Distinct seasonal patterns from 2013 confirmed early results by Teel et al. (2014) but at a finer resolution. Results from these tidal-fluvial habitats can now be compared to previously studied habitats in the lower river (Bottom et al. 2011).

- Chinook salmon stock composition at Multnomah Channel back-channel sites was similar to that found at mainstem sites. Exceptions included a somewhat higher proportion of Spring Creek fall Chinook stocks throughout Multnomah Channel and higher proportions of Willamette River spring Chinook in Upper Multnomah Channel relative to the mainstem sites. However, in reaches E and F, fish densities were higher in mainstem than in back-channel habitats, while salmon size distributions were similar between habitats except in 2012, when fry proportions were lower at Multnomah Channel sites.

- Timing of seasonally high flows relative to stock migration timing will determine which stocks/life history types can access floodplain habitats. River flows and water elevations may determine the number of fish that disperse from the mainstem Columbia River into Multnomah Channel and onto the seasonally wetted floodplain. Fish abundances on the lower Multnomah Channel floodplain were high following a peak flood event (flows >500,000 ft^3 at Bonneville). Throughout 2012, peak river flows were lower, and fish abundances were relatively low, even in spring, when water levels were sufficient to inundate the Multnomah Channel floodplains.

- Seasonal catches suggest that low flows and high temperatures may limit salmon use of upper-estuary habitats and off-channel areas in late summer and early fall. However, the upper estuary could provide overwintering habitat for life history types that enter tidal areas after fall rains have increased and peak water temperatures have moderated. However, flow changes limit the suitability and efficiency of particular fish sampling methods in the upper estuary. No single method can sample the full range of habitats available throughout the year. A variety of sampling methods is necessary to track year-round changes in fish composition and stock-specific habitat use.

- Fish population data from Point Adams Beach were analyzed to examine temporal variation in abundance, mean size, and biomass. Large variation in species composition and biomass were found occur on seasonal and interannual scales, with species-specific differences attributed to recruitment events and migration periods. However, salmon migration patterns were largely consistent over time and narrow for subyearling runs of chum salmon and yearling runs of Chinook and coho salmon. In contrast, subyearling Chinook salmon were present year-round and exhibit more variability in peak migration timing. Time series such as these are necessary to elucidate environmental change and species interactions.

- The proportion of marked hatchery Chinook salmon in beach-seine catches at the estuary mouth increases with each successive size class (i.e., fry, fingerling, yearling), suggesting a substantial hatchery influence on phenotypic variation in the estuary. Phenotypic selection by hatchery programs is particularly evident in the high proportions of marked individuals among larger subyearling and yearling Chinook salmon. Yearling Chinook and coho salmon were primarily hatchery derived, while subyearling Chinook salmon were a mix of hatchery and wild-spawned fish, and most chum were naturally produced. A substantial number of unmarked, wild fish are found in shallow systems; such habitats are clearly important for restoration and conservation.

- Size-dependent patterns of habitat use by juvenile Chinook salmon found throughout the habitats examined in this study are similar to patterns previously documented: greater proportions of small subyearlings (fry and fingerlings) and smaller proportions of large yearlings occupy shallow, near-shore habitats (sampled by beach seine) rather than deep-channel habitats (sampled by purse seine) of the lower estuary. However, more intensive sampling during salmon migration periods, as well as PIT-tag information has revealed habitat use by larger yearling coho, Chinook, and steelhead.

Stock-specific juvenile life histories, habitat use, and performance

- PIT tagged individuals from a diversity of species and stocks, including individuals from the interior basin, demonstrated use of emergent, scrub-shrub, and forested wetland habitats along the estuary tidal gradient. Listed interior stocks represented 10% of total salmonids detected, with Snake River fall Chinook salmon and Snake River basin steelhead being the most abundant of interior stocks detected.

  Significant numbers of tagged spring Chinook from various Willamette River hatcheries occurred in mainstem and off-channel habitats of reaches E and F. Although small unmarked fry and fingerlings are typically most abundant in shallow wetland channels, large subyearling and yearling salmon, including hatchery- reared individuals, also enter these habitats.

  Expansion of PIT-detection capabilities into the mid- and upper estuary has provided unexpected documentation of adult steelhead use of tidal channels.

- PIT tagged Lower Columbia Chinook salmon demonstrated a wide range of site-specific residence times, with a maximum residence of 51 d. Residence time was not related to a longitudinal estuary gradient, but instead seems to be influenced by local site conditions such as habitat complexity, water level, and tides. In general, fish released further upriver tended to move faster through the system, and lower Columbia Chinook may slow down as they migrate through the estuary

- There is a strong spatial gradient in percentage of non-native fish sampled in the lower estuary. Diversity and abundance of introduced fishes are very high in habitats such as Multnomah Channel, moderate in nearby mainstem habitats, and low in lower reaches of the river or estuary. Little is known of potential competitive or predatory interactions of these introduced fish with salmon or other native fauna

- Diet composition in wetlands of tidal-freshwater reaches is generally comparable to that found in lower reaches of the Columbia River estuary, despite differences in ecosystem structure (e.g., vegetation, flooding regime). All life history stages of chironomid midges, but particularly emerging adults, and the amphipod *Ameriocorophium salmonis* predominated in diets.

These prey suggest explicit linkages to benthic/epibenthic habitats. In mainstem channel habitats, planktonic cladocerans *Daphnia* sp., *Bosmina* sp. were numerically prominent.

- There were no consistent trends in the variability of size-specific consumption rates among fish from the two wetland habitat types (mainstem, back channel) or the two reaches studied (D, H). However, some differences were apparent among the same reaches and habitats in different years.

Contribution of different juvenile life histories to adult returns

- Otolith analyses indicate that multiple juvenile life histories contribute to adult returns for lower, mid, and upper Columbia River ESUs. Among surviving adults from different ESUs, juvenile size at salt-water entry is not a simple function of the distance travelled from natal spawning and rearing areas. Hydrologic modeling shows a strong influence of seasonal river flow and temperature criteria on habitat-opportunity for juvenile salmon in reach F. Further investigation is needed to explain an apparent threshold in modeled habitat opportunity at flows higher than 7,000 m^3/s.
- Modeling scenarios suggest that salmon habitat opportunities in the estuary could be sensitive to future sea-level rise because of increased salinity intrusion, particularly during summer and fall. In this case, habitat opportunity is defined by the availability of low-salinity habitat (<5 psu) in reach A, where subyearling migrants could gradually acclimate to salt water.
- Modeling suggests that physical habitat opportunities for particular salmon size classes (life histories) may be highly sensitive in some estuary reaches. Additional refinements in the opportunity criteria are needed to further explore stock-specific and size-specific changes in habitat opportunity.

Recommendations

- Results from this survey have increased the resolution of genetic stock information for reaches E and F and provided the development of protocols for sampling fish in a diversity of back-water habitats. However, a single-year (2012) study is not sufficient to answer many of the fundamental questions about the importance of the upper estuary to recovery of Columbia River salmon.

  Also, we still know very little about the function of these upper reaches for stocks that inhabit them. Additional upper-estuary surveys are needed to assess interannual variation in salmon distribution and habitat use, the effects of river flow dynamics on fish dispersal into backwater and floodplain habitats, and the factors influencing stock-specific salmon performance metrics, such as consumption, bioenergetics, residency, and growth.

- Fall-winter surveys may be particularly important to identify stocks and life histories that take advantage of late-season rearing opportunities in the upper estuary. Winter utilization of the upper reaches remains poorly understood. Occurrence of several stocks, especially the Willamette River spring stocks, suggests that there is likely significant entry to the estuary and potential rearing between November and March.

  Nevertheless, we as yet have no data for December and February and somewhat limited data for January. Given the extensive collaborative effort to provide information on Willamette River fish, it would be worthwhile to consider more intensive, complete sampling in reaches G-F from October to March.

  Assessment of these stocks would require more targeted research on occurrence and performance of individuals from these stocks across the diversity of habitats in the upper reaches through all seasons.

- Vegetated riparian areas, debris-strewn shorelines, and secondary channels of Multnomah Channel were used by Chinook salmon of various size classes. Other similar locales are likely used in a similar manner.

  Boat electrofishing offers a useful method to address key uncertainties about the role of large woody debris as habitat for salmon and salmon predators, particularly in slack-water forested sloughs with minimal tidal influence (ERTG 2012).

  A series of electrofishing transects could be surveyed to compare fish composition and salmon life histories among a diversity of upper-estuary microhabitats, including shorelines with flooded riparian vegetation and large woody debris, channel areas, and tributary junctions armored and not armored with riprap. Physical surveys should quantify varying amounts of wood or other substrate along each transect.

- Surveys of reach E and F have documented overlap in salmon habitat distributions, with a diverse assemblage of non-native species. However, little is known about the ecological interactions between salmon and non-native species. Initial studies should investigate potential dietary overlap and predatory interactions between salmon and other fishes in upper estuary locations where a persistent reservoir of non-natives exists. Risks and benefits of opening shallow habitats to salmon are not well studied.

- Studies of additional populations and return years are needed to understand life history variations that sustain adult returns in different Columbia River ESUs. Further work is needed to evaluate:

  1) Juvenile life-history expression among adults for additional years and ages of return
  2) Compare life-history expression among different Chinook races and spawning locations (i.e., mainstem, lower, or upper tributary etc.)
  3) Contrast migration timing and residency of experimental populations from the mainstem and lower Columbia River.

- Reed canarygrass *Phalaris arundinacea* dominates emergent vegetation throughout a substantial portion of reaches E and F, and many other tidal freshwater habitats. Little is known about the influence of this grass on detrital or insect transport or on salmon diets and food webs (ERTG 2012).

  A wide variety and sometimes conflicting array of management actions have been undertaken in response to reed canarygrass invasions, including removal and revegetation, installation of water control structures, removal of water control structures, and lowering of channel elevations. A systematic research effort will be needed to better understand the ecological functions of reed canarygrass, its costs or benefits to juvenile salmon, and ecological responses to alternative vegetative control measures.

- On the estuary scale, data is particularly limited on fish densities, residence, growth and foraging in all potential rearing habitats known for *O. tshawytscha*. At this point, we have moderately thorough coverage of most habitats in the lower reaches (reaches A-C). Nevertheless, coverage has focused mostly on emergent marsh tidal channels and shoreline habitats, while representation of tidal scrub-shrub and forested wetland habitats has been more limited.

  Comparable data from the upper tidal freshwater reaches (D-H), are generally limited to mainstem, confluence, or back-channel habitats, all three of which are on the margin of floodplains. There are numerous discrete floodplain habitats for which we have very little or no data: channels of different forms, connected lakes and ponds, emergent marshes, and tributary valleys. Despite a fundamental lack of data, all of these floodplain habitats are of particular interest for targeted juvenile salmon habitat restoration.

- The fast predictors developed for salmon habitat opportunity and other salmon-relevant metrics offer a potentially practical tool to guide aspects of innovative, adaptive management for the FCRPS. One goal of estuary management is to optimize environmental conditions—at daily and perhaps seasonal scales—relative to the timing of use by specific stocks and life stages. A pilot effort to explore this concept is recommended.

- The success of restoration actions in the upper estuary could depend on a variety of system-wide controls on ecological trajectories at the site scale. These include hydropower regulation, which limits the frequency and duration of floodplain inundation and therefore salmon access to floodplain habitats. The spread of invasive (native and non-native) plants and animals could also limit habitat capacities for juvenile salmon. Finally, large pulses of hatchery-reared salmon may alter the behavior and performance of naturally-produced juveniles in restored habitats. These effects are poorly understood and would benefit from further monitoring, experimentation, and modeling.

- Restoration projects in the LCRE are rarely strategically developed, and most projects are poorly monitored to ascertain expected benefits to migrating salmon. More effort should be made to target restoration projects to provide testable salmon performance metrics. Hypothesis-based research and monitoring should be developed at the initial planning stage of restoration projects.

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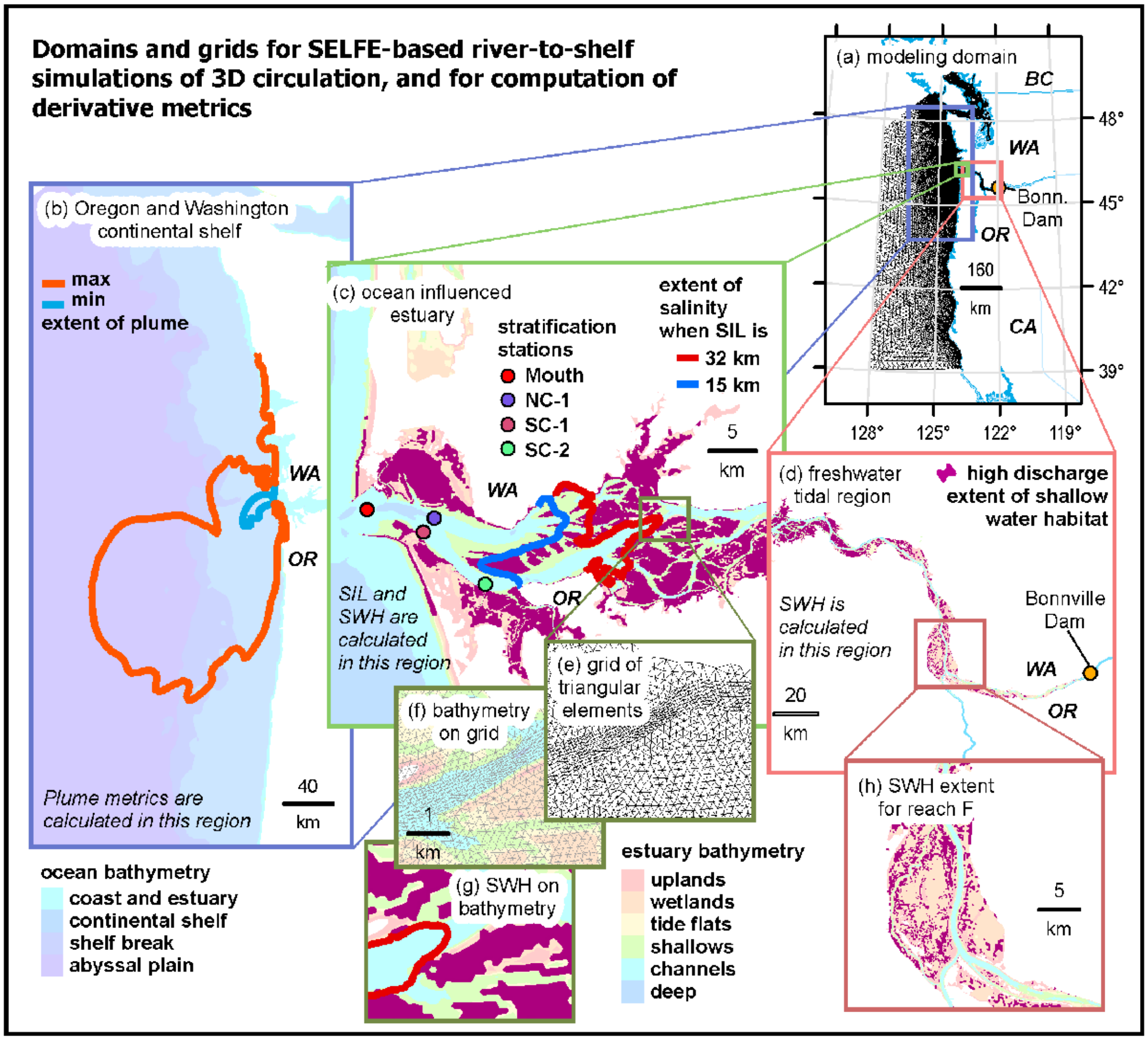
Appendix A: Manuscripts in Preparation

Flow influences on a river-dominated mesotidal estuary in an eastern boundary current

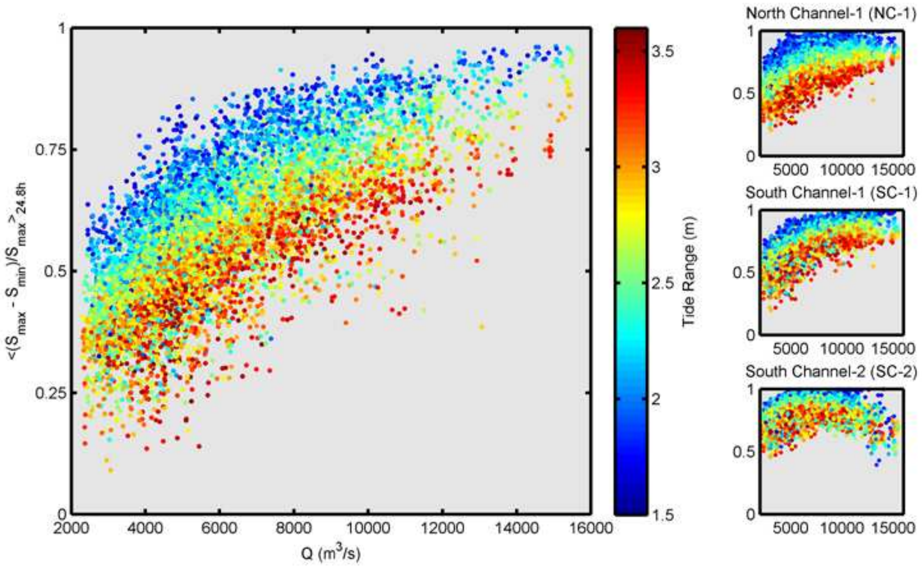
António M. Baptista, Charles Seaton, Tuomas Kärnä, and Paul J. Turner

Status: In preparation (June 2014 target date) for Limnology & Oceanography: Fluids & Environment; thematic issue on River-Dominated Estuaries as Bioreactors. Abstract, tables and figures are all provisional. Primary funding source is NSF. Corps co-funding will be acknowledged.

We conduct an *in silico* exploration of the often-dominant influence of river flows on a large mesotidal Eastern Boundary Current estuary regulated for hydropower production and flood protection. The analysis is anchored on a 14-year high-resolution circulation simulation database, which has been separately calibrated and skill-assessed. The outcome is an integrative view of physical metrics that offer important context for companion efforts aimed at understanding the estuary as a river-dominated bioreactor and as a productive ecosystem. The metrics characterize salt intrusion, stratification, estuary-shelf exchanges, residence times, and shallow water habitat. The response of the metrics to river flows is analyzed accounting for the strongly confounding effects of tides and the weaker effects of coastal upwelling, and contrasted against classical understanding of the estuary. Multivariate regressions on river flows, tidal range and coastal winds are shown to be fast and skilled predictors of the response of most metrics to change in forcing—and are thus valuable scientific and management tools. Of importance, the numerical simulations of circulation that anchor the analysis are imperfect representations of reality, with errors that respond—as does the estuarine dynamics—to river discharge and other forcing. The analysis and correlations would thus benefit from being updated when substantially more skilled simulation databases become available.

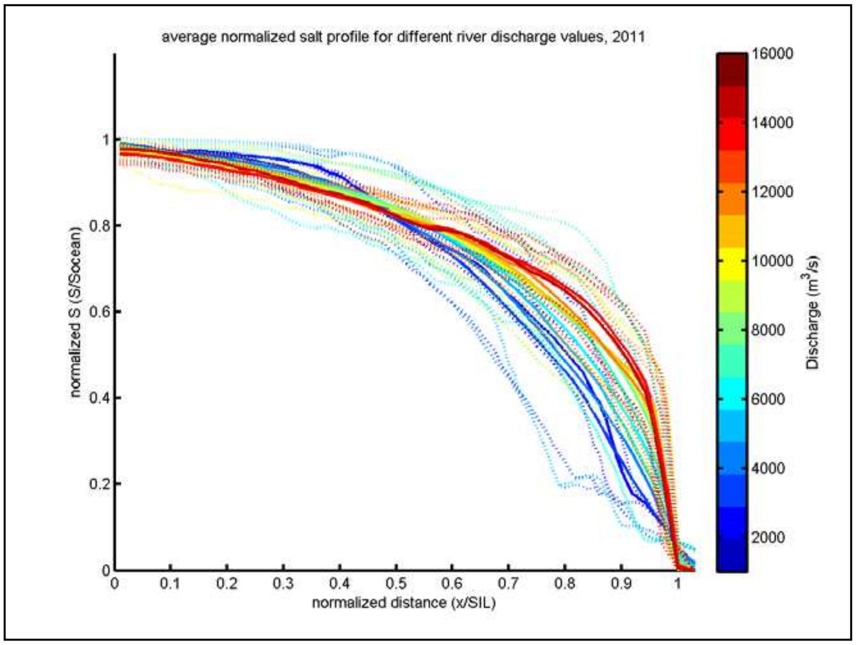


Appendix Figure A1. The metrics used in this study characterize salt intrusion, stratification, estuary-shelf exchanges, residence times, and shallow water habitat. This map provides geographical context for the metrics. SIL; salinity intrusion length. SWH, shallow water habitat.

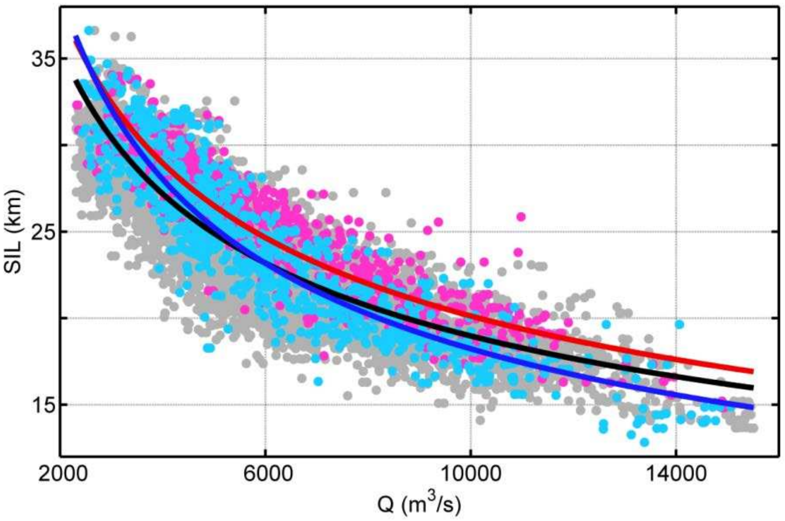


Appendix Figure A2.

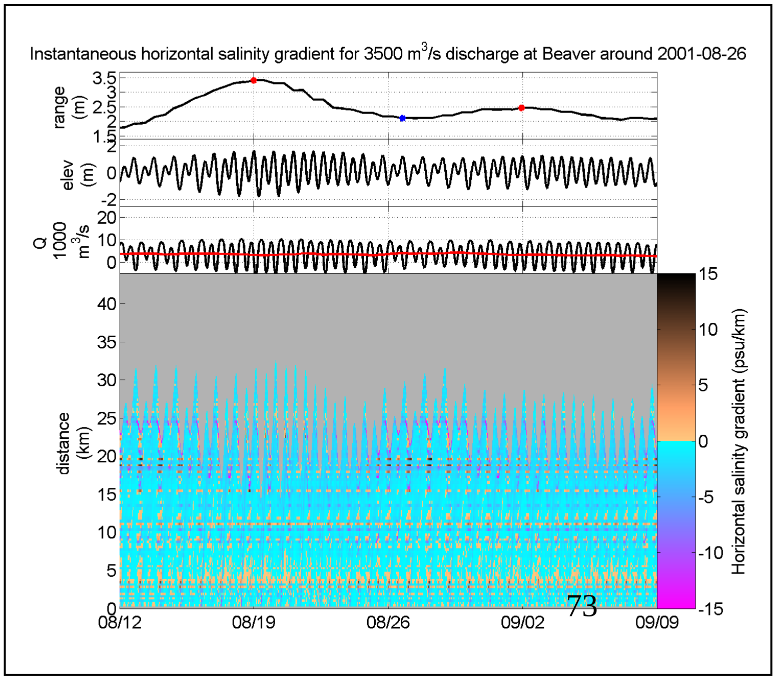
Most metrics of lower estuary physics respond quite strongly to river flow and tidal range, as illustrated here by the normalized stratification at the mouth of the estuary (main panel) and at stations along the North and South channels (later panels). However, that dependency can be complex and subject to flow thresholds, as illustrated in the panel relative to station SC-2.



Appendix Figure A3. Salinity Intrusion Length (SIL) scales many key behaviors of the estuary, as illustrated here by the longitudinal distribution of the maximum daily salinity along the South Channel. Both axes of the Figure are normalized: salinity is normalized by the ocean salinity, and longitudinal distance along the South Channel is normalized by SIL. Each solid line represents an average for a flow band of 1,000 m3/s (see color scale). Dashed lines represent corresponding maxima and minimal.



Appendix Figure A4. Dependency of salinity intrusion length (SIL) on discharge (Q) at Beaver Army, based on DB31 simulations. Grey circles are tidal daily values of SIL, for 1999-2012. Overlapping blue and red circles are SIL values restricted to small and large tides, respectively. Curves are the SIL∝ Q-y regressions obtained using all days (black) and days corresponding only to small (blue) and to large (red) tides, respectively. While both flows and tidal ranges influence SIL, the role of tidal range is complex, and itself dependent on river flows (e.g., note the relative position of the regression curves for small and large tides, as flows decrease).



Appendix Figure A5. Spring-neap variation of the horizontal gradients of bottom salinity along the longitudinal axis of the South channel, for a low flow condition. Among others, two important points can be drawn for this plot.

First, SIL does not respond to local tidal range only: there is a “memory effect” (visible, for instance, in the maximum intrusion around the neap) that is flow dependent (not shown). Second, there appear to be bottom salinity “fronts” (shown as horizontal “bands”) generated at/near fixed locations along the south channel, which coincide with sharp changes in bathymetry (bathymetry not shown); specifics of the generation mechanism need to be examined. The SIL “memory” affects directly salmon habitat opportunity for reaches A and B; the effect of “fronts” on salmon, their prey or predators, is unexplored.

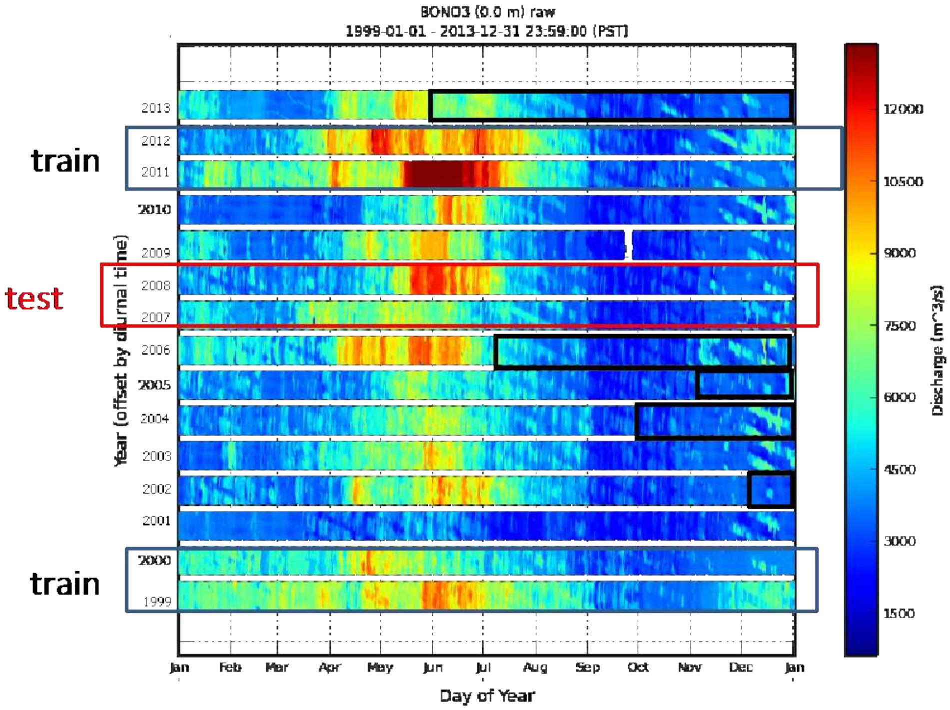
Fast model emulators for Columbia River circulation and habitat opportunity

Sergey Frolov, Tuomas Karna, Charles Seaton, Paul Turner, Jesse Lopez, António M. Baptista.

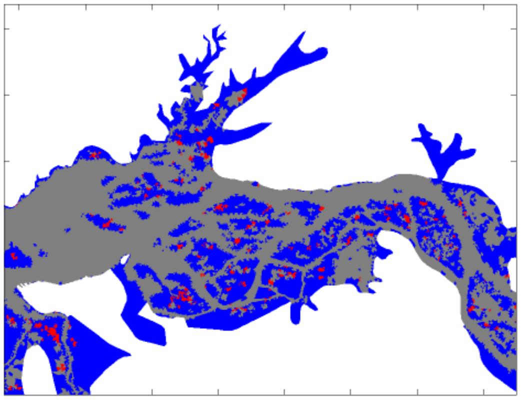
Status: In preparation (June 2014 target date) for *Water Resources Research*. Primary funding sources are National Science Foundation and Columbia River Treaty Review. Corps co-funding will be acknowledged. Abstract, tables and figures are all provisional

We considered the challenge of simulating multiple decades of estuarine circulation to study the impacts of different scenarios of hydropower operation in the Columbia River. To solve this problem, we applied the novel technology of model emulators. Model emulators are machine-learning techniques that emulate the dynamics of a complex ocean model using dynamics learned from a representative simulation.

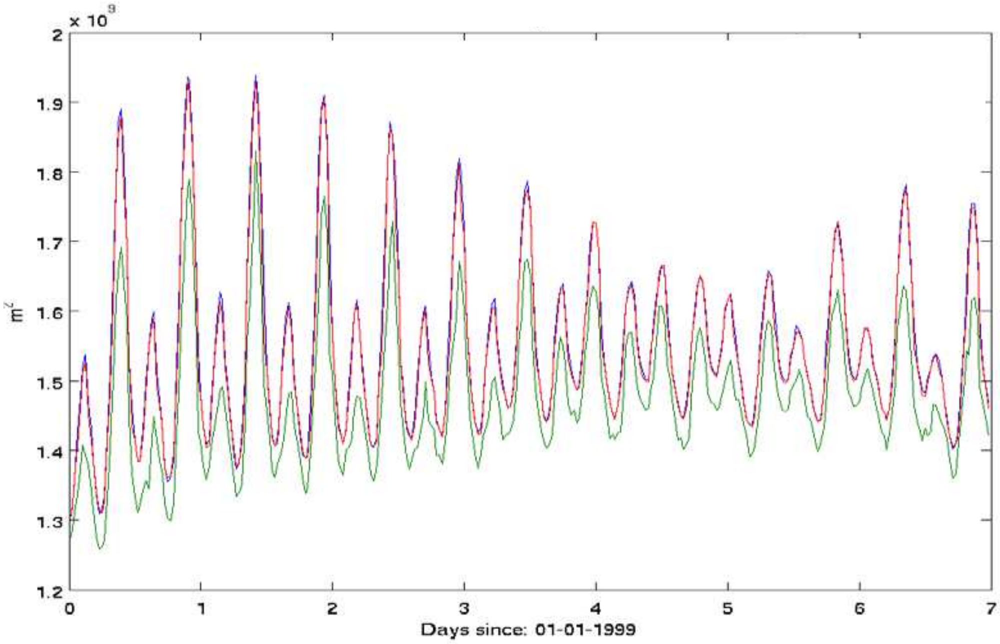
We developed and tested several extensions to the model emulator technology, including a new mixture of linear models, nested emulators, and a revised formulation of wetting and drying. Our results showed that the emulators were successful within useful error bounds. They reproduced fields of both the primary circulation variables and the physical and ecological integrative metrics derived from those fields, including salinity intrusion length, shallow-water habitat, and salmon habitat opportunity.



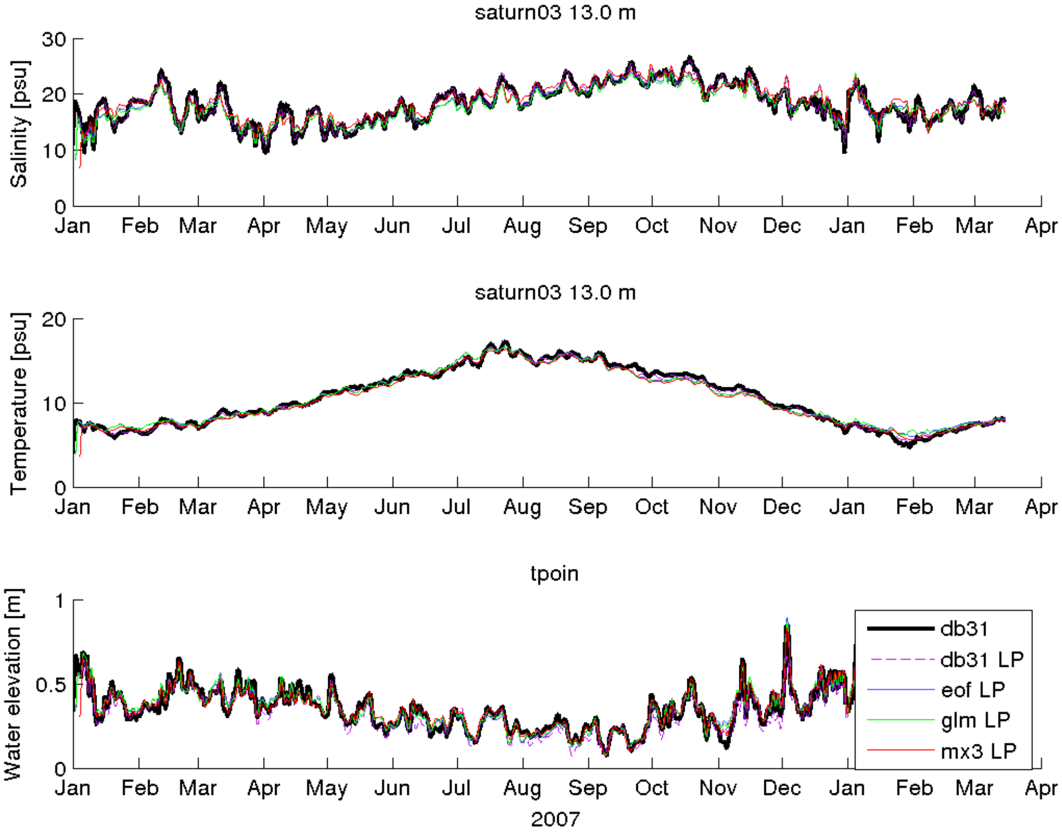
Appendix Figure A6. River discharge for the training (red rectangle) and test (blue rectangles) periods for the model emulators.



Appendix Figure A7. Illustration of the improvements in the skill of model emulators to represent wetting and drying. Both panels represent a snapshot in time; the left panel represents the skill of the original model emulator, and the right panel shows a modified emulator designed to account for wetting and drying. **Gray** represents areas described as wet by both DB31 simulations and the model emulator. **Blue** shows areas described as dry by both models. **Red** designates areas where there is disagreement between the two approaches. See the figure below for partial temporal context.



Appendix Figure A8. Areas of dry elements over a 1-week period, as described by DB31 simulations (blue dashed line), the original model emulator (red line); and a modified model emulator tailored to account for wetting and drying (green line).



Appendix Figure A9. Illustration of the ability of a range of model emulators to simulate primary circulation variables. While details of the difference among emulators matter, the key message is that several emulators capture well important scales of variability.

Factors affecting juvenile Chinook salmon growth variability in a large freshwater tidal estuary

P. A. L. Goertler, C. A. Simenstad, D. L. Bottom, S. Hinton, L. Stamatiou, and D. Teel.

Estuarine rearing habitat has been shown to foster diverse life history strategies, enhance biocomplexity within watersheds, and support growth of juvenile salmon *Oncorhynchus* spp. However, little is known about how juvenile salmon growth varies across different types of wetland habitats and what explains this variability in growth.

We evaluated changes in juvenile fish growth over a range of wetland habitats in the tidal-freshwater Columbia River estuary. We focused on use of wetland habitats by Columbia River Chinook salmon *O. tshawytscha*, a species that includes nine ESUs (evolutionarily significant units) listed under the U.S. Endangered Species Act. This study is a comprehensive examination of juvenile Chinook estuarine growth that incorporates otolith microstructure, life history variation, microsatellite genetics, GIS habitat mapping, and diet composition.

We found growth most associated with habitat and life history diversity. Juvenile Chinook salmon growth rates were higher in off-channel than in mainstem habitats. Diet composition analysis showed that back-channel sites had higher percentages of emergent prey items, and mainstem sites had higher percentages of planktonic prey items. This pattern may be due to a loss of connectivity to wetland habitats for juvenile Chinook salmon in the more deeply incised navigation channel of the lower Columbia River and estuary.

We also found that mid-summer and late summer/fall subyearlings had the highest estuarine growth rates. In general, juvenile Chinook salmon growth rates were highest later in the summer, suggesting that there may not be a bioenergetic limitation in the tidal freshwater estuary for these juveniles. In the diet composition analysis, we found a transition away from planktonic prey and an increased reliance on emergent and terrestrial prey from May to September. However, there were pulses of high-caloric prey in some diets in July, when a subset of juvenile Chinook fed on small stickleback *Gasterosteus aculeatus*.

Furthermore, seasonal temperatures at our sampling sites did not reach levels lethal for salmon, as occurs in some areas of the upper watershed. The tidal freshwater estuary may buffer high temperatures with riparian vegetation and input from cooler tributaries in the lower basin. Estimated mean growth rate of juvenile Chinook in the tidal freshwater estuary was 0.23 mm/d (range 0.11-0.43 mm/d). This growth rate was similar to those estimated previously in the brackish estuary but lower than those estimated in the plume and upstream reservoirs. Survival studies from the system elucidate a possible tradeoff between growth and survival. These findings are directly applicable to wetland habitat restoration and salmon conservation and management.

Modeling estuarine turbidity maxima events in an energetic, river-dominated estuary

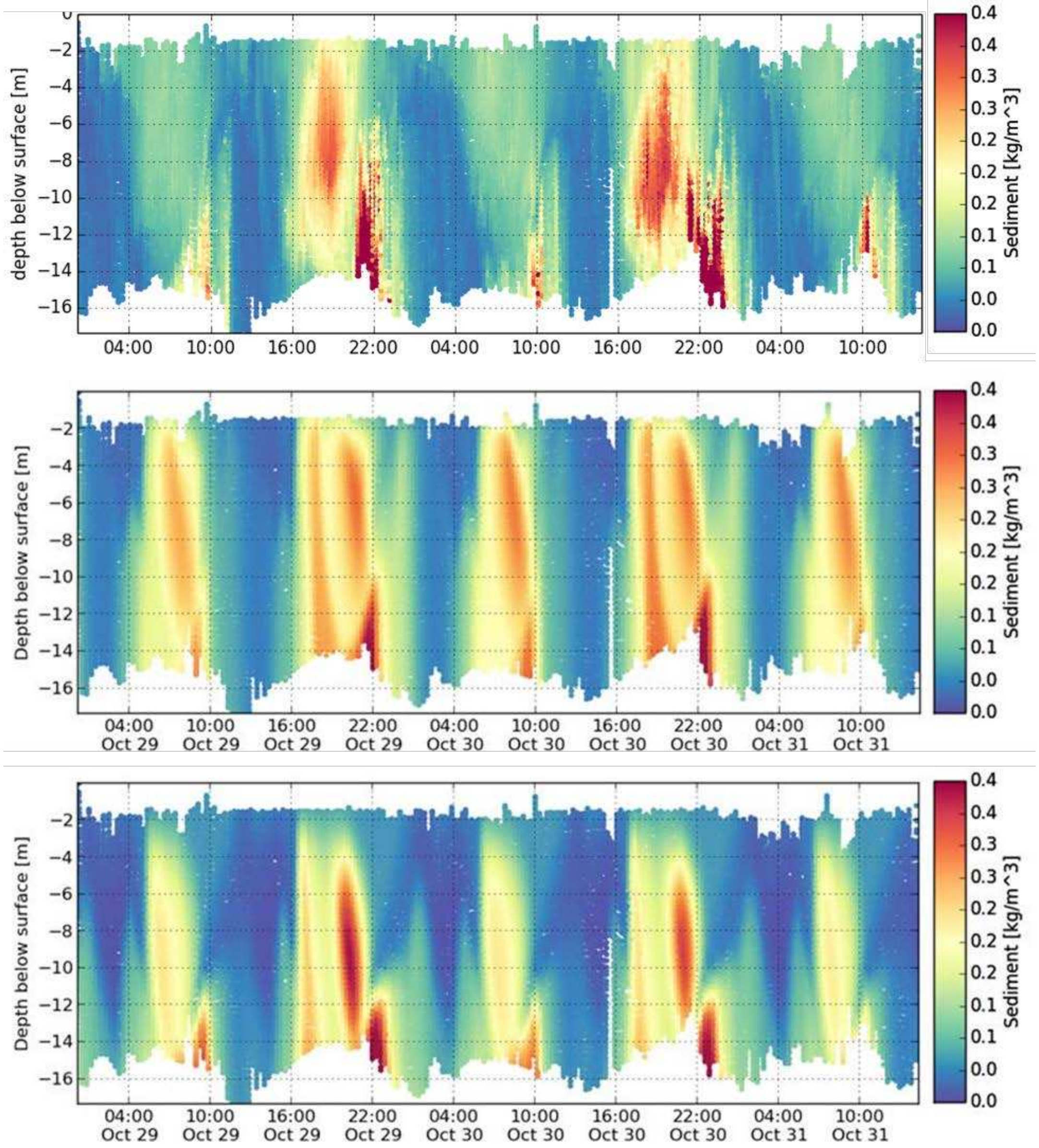
Jesse Lopez, Antonio M. Baptista, Tuomas Kärnä, Craig McNeil, Thomas Sanford

Status: In preparation (September 2014 target date) for Ocean Modeling or Limnology & Oceanography: Fluids & Environment; thematic issue on River-Dominated Estuaries as Bioreactors. Primary funding source is NSF; USACE co-funding will be acknowledged. Note: Abstract, tables and figures are provisional

We examine sediment dynamics in the Columbia River estuary, with an emphasis on the formation and characteristics of the estuarine turbidity maxima (ETM). The analysis relies on a three-dimensional numerical model that includes alternative treatments of cohesive behavior, to represent the presence of flocs in and near the ETM. Simulations are calibrated and skill assessed against time series of circulation variables and suspended particulate matter from (a) endurance stations throughout the estuary, (b) a shipborne Winded Profiler instrument stationed at two anchorages in the North Channel of the lower estuary, and (c) two autonomous underwater vehicles in the Fall of 2012.

Density fields of the model tend to be more diffusive than observations, resulting in a depressed pycnocline that dampens the penetration of high sediment concentrations into the mid-water column. Despite this, the timing, magnitude, and diurnal asymmetry of the ETM match well with observations. Simulations suggest that a single turbidity maximum forms near the mouth of the estuary at slack before flood. This ETM is advected upstream and splits into two distinct entities at the bifurcation of the North and South channels. During the subsequent flood, these dual entities are advected seaward, where they merge back into a single entity.

Local re-suspension occurs near the salt-wedge, adding to the strength of the advected ETM. Strong ebb tides provide source material from fluvial and shoal sources generating a mid-water increase in the sediment concentrations during maximal ebb currents. These materials are deposited during slack waters, re-suspended, and advected back upstream in the ensuing flood tide. Overall, model results suggest that the Columbia River ETM are advective phenomena amplified by local processes.



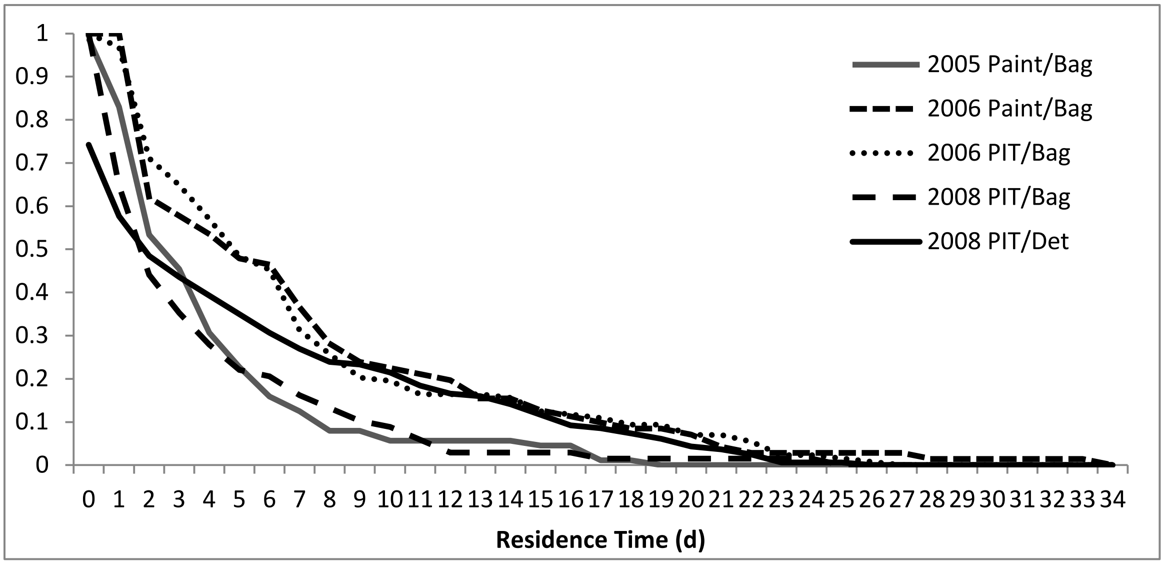
Appendix Figure A10. Progress in the development of an estuarine sediment-transport model that captures strong-gradient regions such as ETMs. Top panel shows sediment concentrations measured with a shipboard winched profiler in October 2012 in the North Channel of the Columbia River estuary. The effect of diurnal tidal asymmetry is apparent in the varying intensity of bottom-focused flood ETM and elevated mid-water column concentrations during ebb tides. Center panel: treating flocs as primary particles with constant settling velocity captures both flood ETM events and ebb mid-water column concentrations, but severely over-predicts concentrations during slack before ebb and moderately over predicts weaker ebb values. Bottom panel: Salinity-derived floc method better represents the ETM flood and mid-water column ebb concentrations and diurnal tidal variation in concentrations, but the maximal ebb concentrations are found lower in the water column than seen in observations.

Scales of juvenile Chinook salmon residency and movement in an intertidal marsh of the Columbia River estuary

McNatt, Regan, Dan Bottom, Susan Hinton, and David Teel

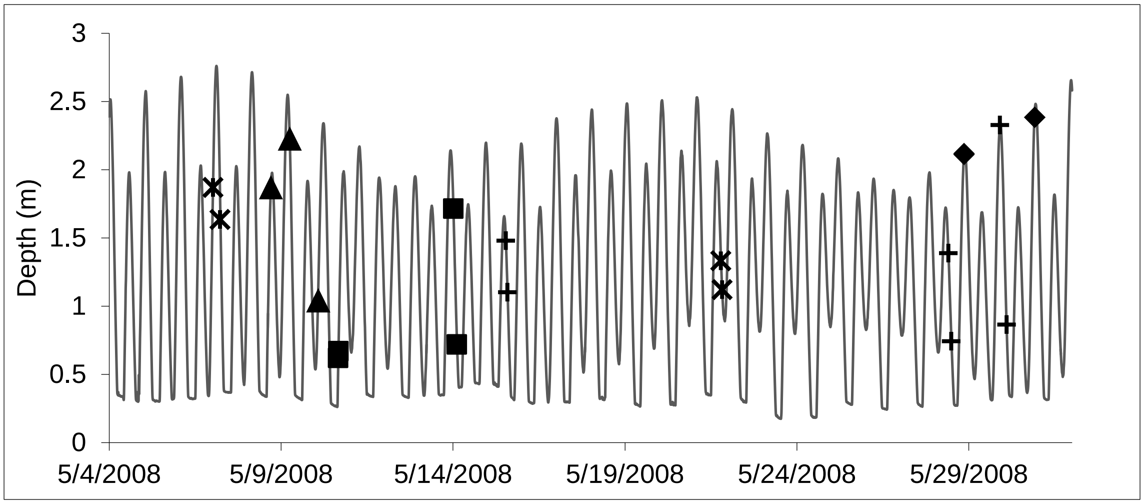
Utilization of the Columbia River estuary by salmon is garnering more attention as recovery efforts look to improve juvenile salmon survival through estuary restoration. Studies have shown that juvenile salmon are abundant in shallow-water habitats within the Columbia River estuary. However, residence time and movement data are typically presented as by-products of estuary survival studies and do not provide information regarding how juvenile salmon utilize specific estuarine habitats.

In this study we used a combination of physical marks and PIT technology to record residence time, movement and growth of juvenile Chinook salmon within an emergent marsh complex. We were able to document movement and residency within the greater marsh complex and within two small experimental channels outfitted with PIT detection arrays. There was wide variation in the length of residency within the emergent marsh complex. Some fish stayed in the area for only a few hours or a few days. Other fish remained in the area for a month.



Appendix Figure A11. Residence time decay curve. Declining cumulative percent of recaptured Chinook salmon based on year, mark type (paint or PIT tag), and method of recapture (bag seine or detection on PIT array).

We also documented varying degrees of site fidelity within the experimental channels. Some fish frequented the experimental channels often throughout their residency, and others were detected only once. Throughout 2 years of the study, instantaneous growth rate averaged 0.62 mm/d. Movement of juvenile Chinook salmon throughout the emergent-marsh complex suggested that juvenile salmon take advantage of the habitat complexity; possibly to maximize foraging opportunities. Knowledge of how juvenile salmon interact with their surroundings and move within specific habitats can help ensure that restoration sites provide adequate complexity and opportunity for juvenile salmon to express residence behavior.



Appendix Figure A12. Variation in site fidelity. Each symbol represents an individual fish expressing a different channel use. Detections are overlaid on water level. Solid triangle = short residence, solid square = intermediate residence, solid diamond = long residence, cross bars = early and late detection, and plus sign = middle and late detection.

Conclusions

- Maximum residence time was 34 d.
- Although fish tended to enter channels on flood tides and exit on ebb tides, 26% entered and 32% exited against water flow.
- Fish tended to exit channels at a lower water level than when they entered.
- Fish tended to enter the channel with greater frequency during the day and exit the channel with equal frequency during day and night, even though there were more daylight hours of outgoing tides.
- Fish that were detected on both PIT arrays had significantly longer residence times than fish detected on just one array.

Migration patterns of juvenile chum salmon *Oncorhynchus keta* in the lower Columbia River and estuary

G. C. Roegner, K. Hommel, and D. L. Bottom

Of the 11 threatened or endangered salmonid stocks in the Columbia River Basin, restoration of chum salmon (*Oncohrynchus keta*) has received the least attention to date. This is surprising considering chum historically comprised one of the largest spawning biomass of any salmonid in the region (Good et al. 2005), with wide ecological implications due for example to extensive nutrient transfer associated with spawned-out carcasses (Cederholm et al. 1999). Additionally, chum salmon is aggressively cultivated at numerous hatcheries around the north Pacific Rim for their roe, and thus has a significant unrealized economic potential in the Columbia River.

Despite this, annual escapement in the Columbia River since 1990 is likely fewer than 10,000 fish (Good et al. 2005), and the probability of extinction is over 90%. Recent interest in chum restoration may signal a change in this attitude, as both Washington and Oregon State have initiated population and habitat restoration plans. This report documents research on contemporary juvenile chum migration patterns that can aid implementing habitat restoration activities.

Several recent reviews have summarized chum salmon population status in the Columbia River Basin. Chum spawning habitat was historically distributed throughout the lower Columbia River and its tributaries to approximately (the now submerged) Ceilio Falls near river kilometer (rkm) 309. At present, spawning distributions are mainly limited to the Grays River, Washington, in the mainstem below Bonneville Dam, and above the dam near Multnomah Falls. All major spawning centers on the Oregon side of the river are thought to be extirpated. Genetic analysis suggests three distinct stocks are extant which reflect these remaining spawning areas, termed the Lower River, Cascades, and Gorge populations. Compared to historical adult returns estimated to exceed 1 million individuals per year, contemporary runs are near critical levels.

The generalized life history cycle of chum in the Columbia River estuary is relatively well understood. Adults return to spawn from late October through early December. In Grays River, the age of returning adults is primarily 3 years, with fewer 4- and 5-year-olds. Spawning locations in tributary streams are generally just above head of tide, and often in hyporheic zones, while mainstem spawning occurs in microtidal environments presently impacted by hydeopower operations. Egg hatch and emergence occurs January-February, and fry generally migrate within a few weeks to tidal freshwater reaches and thence to the estuary and ocean.

Restoration of chum salmon requires attention to each or the major life history stages of the species: spawning and egg rearing in freshwater habitats, freshwater and estuarine juvenile migration, ocean survival, and adult migration (returns). For each of these critical stages there are management options that can aid in recovery of the species. These options range from fishing limitations for adults in ocean and river habitats to preservation and restoration of critical habitat for spawning and juvenile migration. To restoration practitioners intent on aspects of juvenile migration characteristics in the Columbia River estuary, we provide a contemporary assessment of the timing, spatial distribution, size, and condition of chum salmon during the juvenile migration period. We conclude with recommendations for restoration priorities based on these migration data.

Methods

In this paper we synthesize data from several of our studies studies to characterize contemporary patterns of chum salmon life-history expression and habitat use in the lower Columbia River estuary. The primary data set is a 6-year time series (2002-2007) of beach-seine samples collected at four stations in the Columbia River estuary and two stations in the tidal freshwater zone near the head of Cathlamet Bay. Over the same period, trap-net samples were used to estimate salmon use at various tidal freshwater marsh habitat within Cathlamet Bay and in a restoration site in Grays River.

These samples were collected monthly year-round (beach seine) or monthly from February to July (trap net). Data summaries for these studies can be found in Roegner et al. (2010) and Bottom et al. (2011). Secondarily, during (months) 2010-2012, paired purse-seine and beach-seine samples were collected at sites in the estuary, which we use to compare chum salmon presence and size at shallow-water (beach seine) and main channel (purse seine) habitats. These data can be found in Roegner et al. (in press). Details of our standard beach-seine and trap-net sampling methods were reported by Roegner et al. (2012) and Bottom et al. (2011), respectively. Purse-seine methods were reported by (Weitkamp et al. 2011). We use salmon abundance (catch per unit effort, CPUE) to determine overall migration timing in the different habitats, and use size-at-date to elucidate life-history expression and growth during migration.

Longer Time-Series at Point Adams Beach Linked to Environmental Correlates

As a secondary analysis, we examine migration timing from tagging experiments conducted in 2008 and 2013 from studies focusing on the migration of chum salmon from the Grays River and Big Creek, Or, respectively. During 2008, we conducted an intensive 4-d beach-seine monitoring of chum fry marked by pen jet with fluorescent paint (details, reference) with a trap net time series of chum habitat use a tidal freshwater wetland restoration site in the Grays River watershed. Details of the restoration trap net sampling can be found in Roegner et al. (2010) and Johnson et al. (2011). The object of this synthesis is to evaluate residency versus migration timing in an important chum natal environment. And the size of migration—where does growth occur?

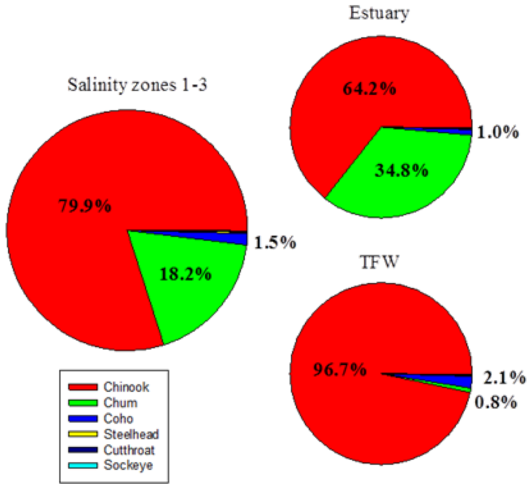
Key Findings

Landscape-scale distribution

- During 2002-2007, overall abundance at shallow water beach-seine sites varied strongly across the estuarine-tidal freshwater gradient. Chum made up ~ 35% of the salmon population in the estuary but < 1.0 % in the TFW zone.
- High densities (up to 100 ind/100 m^2) of chum were found at estuarine stations, while tidal freshwater densities were generally < 1 ind/100 m^2.

Appendix Table A1. Salmonid catches at estuary and tidal freshwater sites, 2002-2007.

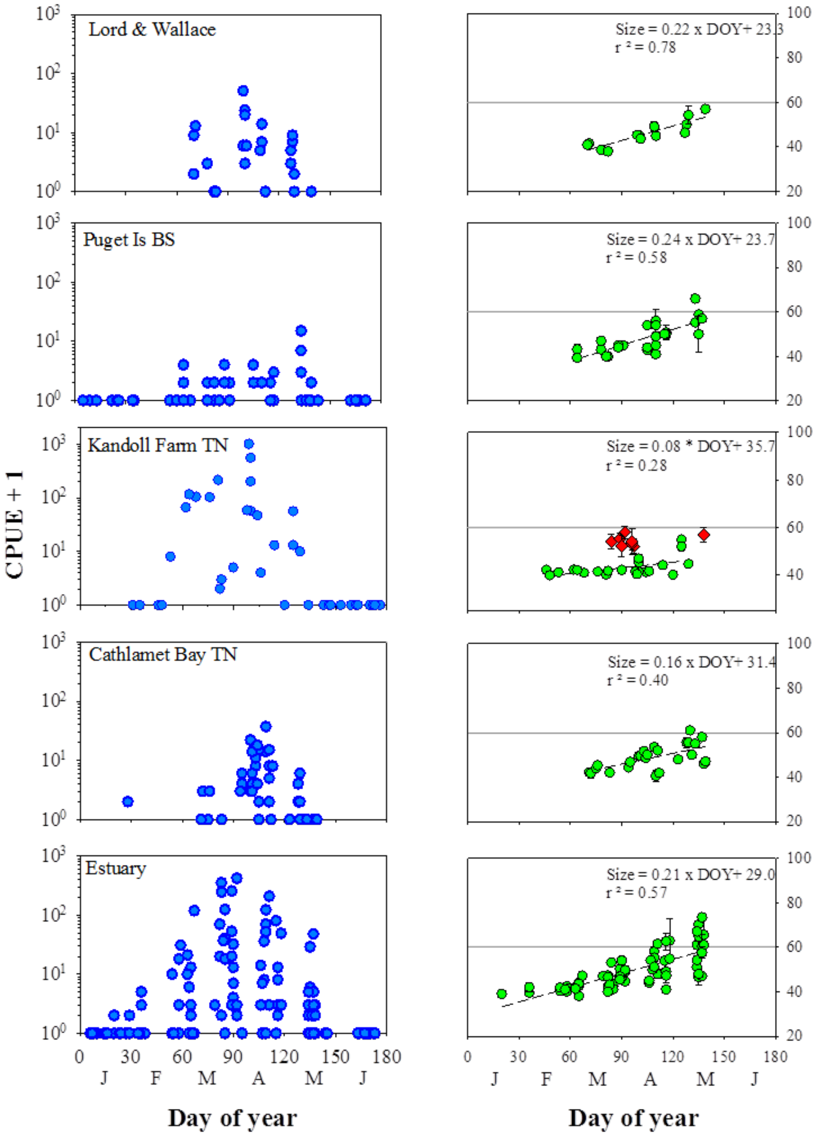
Species	Estuary sites	Tidal freshwater sites	Total
Chinook	5,445	7,614	13,059
Chum	2,920	63	2,983
Coho	85	165	250
Steelhead	16	17	33
Cutthroat	12	12	24
Sockeye	1	2	3
Total	8,479	7,873	16,352



Appendix Figure A13. Proportional abundance of chum salmon and other salmonids by salinity zone.

Migration timing

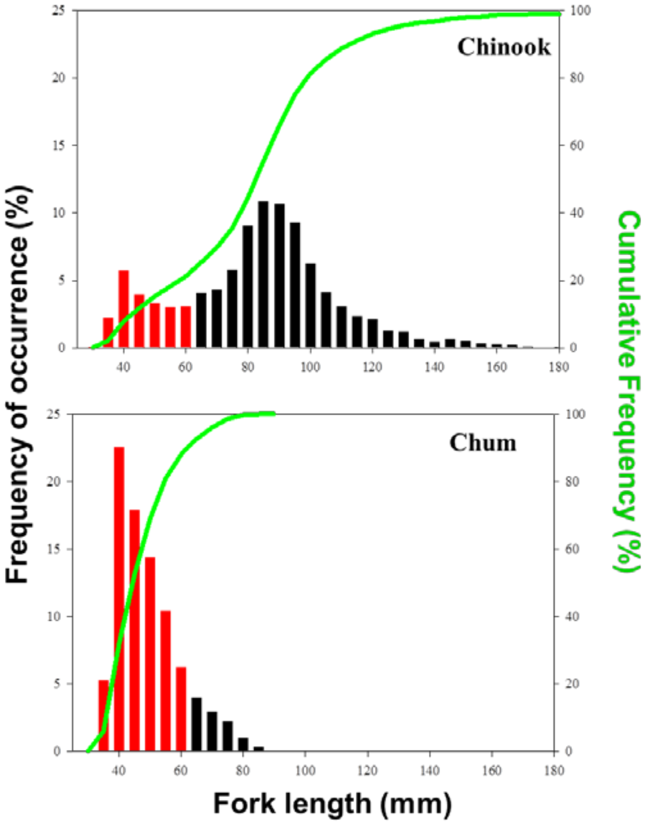
- Migration was truncated in tidal freshwater reaches.
- At mainstem beach-seine sites during 2002-2007 and at Grays River trap-net sites, juvenile chum salmon were present through the lower Columbia River estuary during a 4-month window extending from February to May. However, peaks in abundance occurred each year during April or May (Appendix Figure A14). At Cathlamet Bay trap net sites during 2002-2007, chum was present from March to May, with a peak in April.
- Migration was complete by 1 June.



Appendix Figure A14. Proportional abundance of chum salmon and other salmonids by salinity zone. Locations are arranged from upriver (top) to lower river (bottom).

Size

- In the Grays River, growth of juveniles was slight and the sizes remained around 40 mm. Larger chum (~55 mm) had been raised in the hatchery. This suggests a relatively rapid emigration to the estuary.
- Sizes and slopes of size x time regressions increased with distance toward the mouth, indicating growth during migration.
- The widest size range was observed at the estuary mouth; potential ocean entry could occur over a size range of 40 to 80 mm. Few chum were > 55 mm in tidal freshwater zones.
- Chum salmon were 85% fry (≤ 60 mm); in comparison 20% of Chinook salmon in the estuary were fry sized.



Appendix Figure A15. Size-frequency of Chinook and chum salmon.

Restoration Recommendations

1. Maintain shallow water habitat to preserve rearing areas during migration. The critical time period is February–May. Peripheral Bays such as Baker, Youngs and Cathlamet bays appear particularly important.

2. Restore spawning habitat. This is the critical factor limiting chum salmon reestablishment in the Columbia River basin. Emphasis should be on historically productive areas, including Chinook River and the Youngs Bay watershed.

Stock-specific response of Chinook salmon habitat to physical variability in a river-dominated mesotidal estuary: an *in silico* sensitivity study

Mojgan Rostaminia, António M. Baptista, Dan Bottom, Curtis Roegner, David Teel, Kurt Fresh, and Charles Simenstad

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Since 1999, twelve Evolutionarily Significant Units of Columbia River salmonids have been listed under the Endangered Species Act as either endangered or threatened. The listings reflect declining numbers of adults returning to spawn, as well as loss of stock diversity. The variability and change of salmon-supporting habitat, along the river-to-ocean continuum, plays a key role on the status and trends of specific stocks—and is thus critical to preservation and restoration efforts, and to the management and operation of key regional economic resources such as hydropower production and navigation.

Here, we address the stock-specific response of juvenile Chinook salmon habitat to the physical variability in the estuary. The estuary is river-dominated and mesotidal, and influenced by coastal upwelling and by regulated discharges of the Federal Columbia River Power System. Diverse hydro-geomorphic reaches in the estuary support salmonids in their journey to the ocean, by providing nursery habitats, food resources, and transition zones. Cutting across these reaches, the main channel of the estuary is characterized by low residence times, and serves primarily as a migration corridor.

We focus on Chinook salmon because its juveniles remain in the estuary longer than those of sockeye and steelhead, other major Columbia River species. We include in the analysis both listed and unlisted Chinook stocks, for which some understanding exists of the temporal and spatial use of the estuary: Upper Columbia River spring-run (an endangered species), Snake River spring/summer-run and Snake River fall-run (a threatened species), Spring Creek Group fall-run, West Cascade fall-run, Willamette River spring-run, and Upper Columbia River summer/fall-run.

Underlying the analysis is a skill-assessed archive of high-resolution simulations of circulation for 1999-2012, covering a river-to-shelf domain that ranges from the first dam in the Columbia River to the Pacific Northwest continental shelf. These simulations were created with an unstructured grid model, SELFE, which has been separately calibrated and skill assessed. Variables of interest for this study are the water depth and the 3D fields of velocity, salinity, and temperature. These variables are filtered through specific criteria to calculate metrics of salmon habitat opportunity.

While the concept of circulation-based salmon habitat opportunity has been used for over a decade in support of regional decisions, past studies have not been stock specific, and have relied on a straight application of individual or simply combined thresholds for favorable water depth, velocity, salinity and temperature conditions. Favorable thresholds are set to:

Water depth: $0.5 \leq D \leq 2$m Velocity: $V \leq 0.35$m/s
Temperature: $T \leq 19$oC Salinity: $S \leq 5$psu

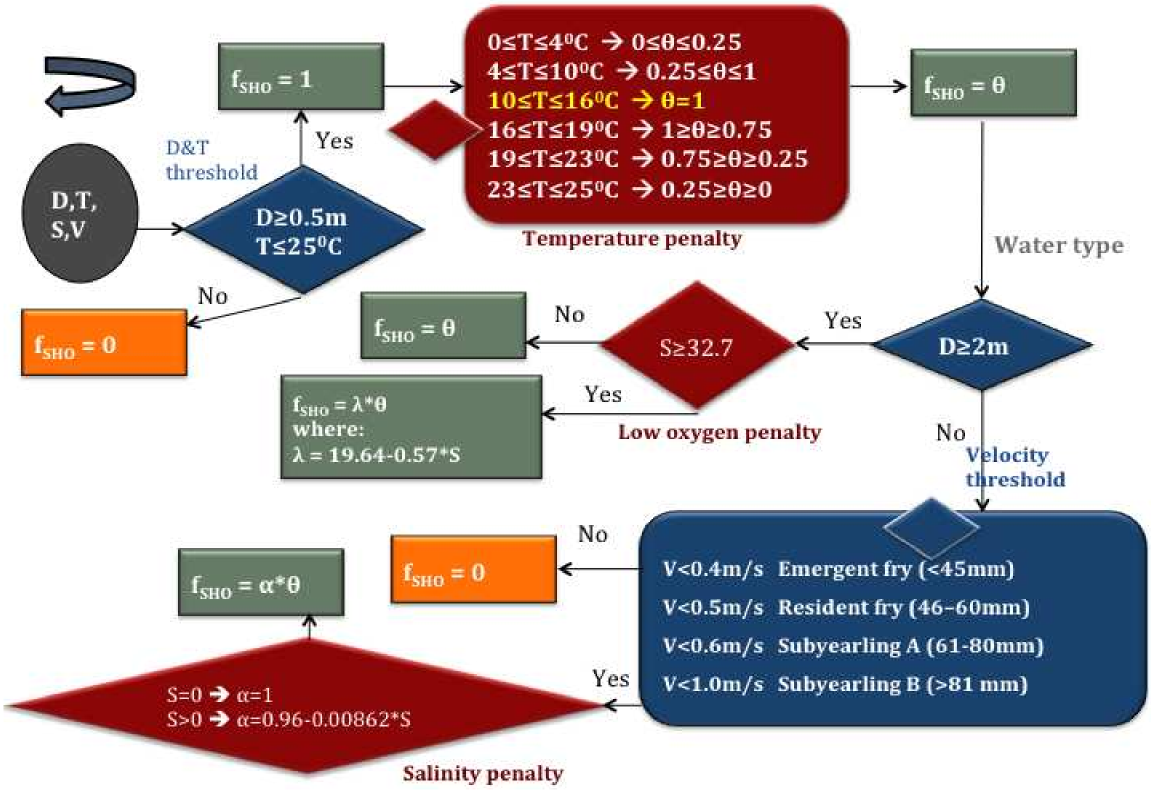
with threshold values typically interpreted as an average over the water column. Results are most often expressed in areas of favorable habitat opportunity, without recognition of the fact that salmon has awareness of the vertical structure of the estuary.

Here, we do use these historical metrics to create a description of the contemporary variability of salmon habitat, with salmon habitat opportunity computed from the most recent version of the simulation databases. However, this description serves only as a reference for a sensitivity analysis involving four other approaches, each building upon the previous towards what we expect to be a progressively more realistic representation of the use of estuarine habitat by salmon.

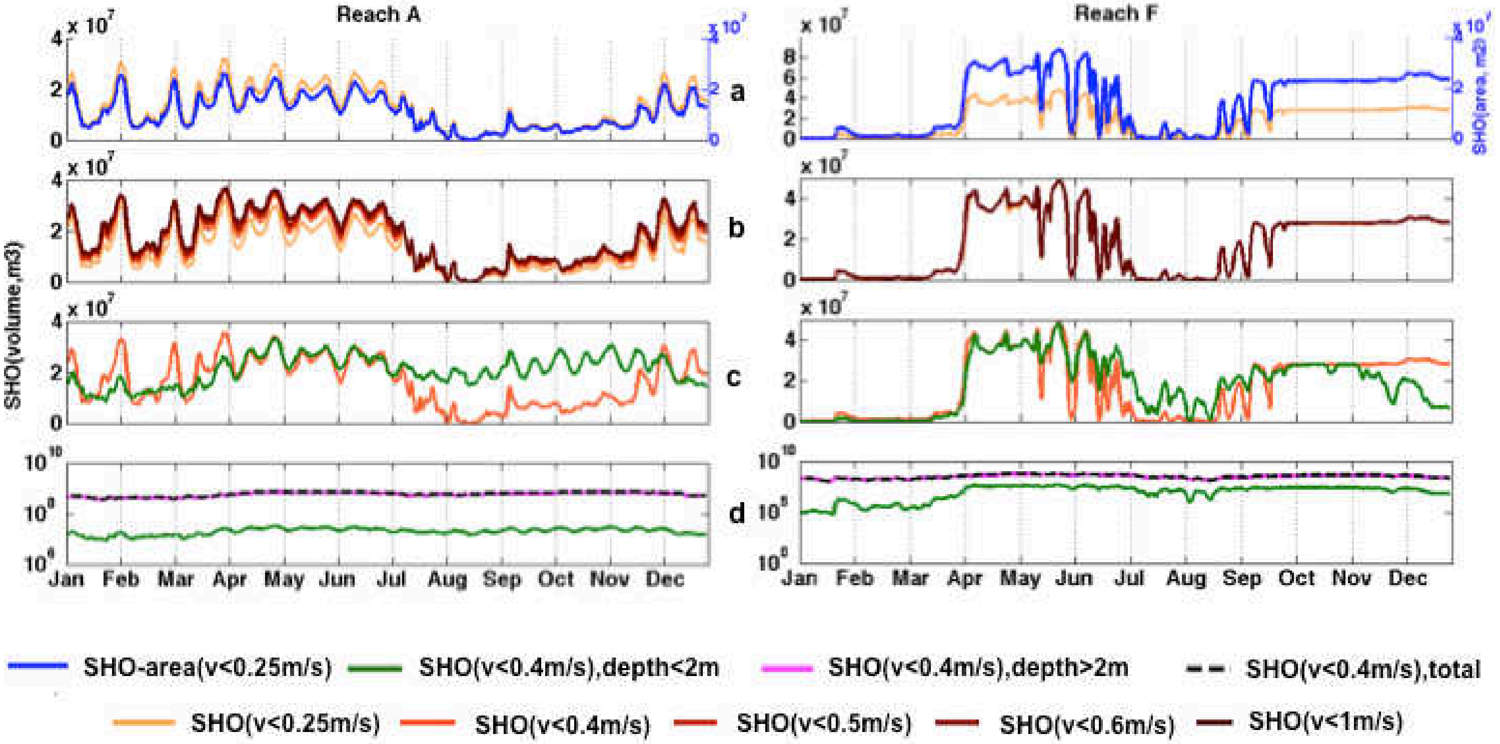
Three of these approaches allow the differentiation among life stages, but not directly among stocks. The first consists of a volumetric rather than area-based characterization of salmon habitat opportunity, obtained by applying the above criteria in an explicitly 3D manner. The second allows thresholds for favorable velocity to vary as a function of fish size; the depth, salinity and temperature criteria remain unchanged.

The third embodies a more sophisticated understanding of the use of the estuary by juvenile Chinook salmon: favorable habitat is characterized first through depth thresholds, which are then adjusted via 3D modifiers associated with bioenergetics (via temperature) and environmental (via velocity and salinity) considerations. T he fourth approach is both stock and life stage specific; it combines the third approach with specific knowledge, from fisheries data, of when different stocks occupy different reaches of the estuary.

Preliminary results show that the various alternatives offer substantively different characterizations of salmon habitat opportunity and its contemporary variability. While each approach should better reflect (relative to prior approaches) the use of the estuary by juvenile Chinook, this cannot be formally demonstrated. What our step-by-step progression allows, though, are insights into how different factors affect estimates of habitat opportunity. As a whole, the results offer a strong motivation—and set the foundation—for revisiting approaches that are currently accepted in the region as best practices to assess impacts on salmonids of past and future estuarine changes.



Appendix Figure A16. Illustration of the computation of salmon habitat opportunity (SHO), when favorable habitat is characterized first through depth thresholds, which are then adjusted via 3D modifiers associated with bioenergetics (via temperature) and environmental (via velocity and salinity) considerations.



Appendix Figure A17. Seasonal variation of SHO, calculated with different approaches, for reaches A and F. Top panel set (a): Threshold approach, using a surface versus a volumetric representation of the metric; the contrast shows anticipated qualitative consistency between the two expressions of the metric. Second from top (b): Threshold approach, using different velocity criteria; this contrast illustrates the (limited) differences of habitat opportunity across class sizes. Third panels (c): Threshold approach and new approach involving bioenergetics and environmental considerations (restricting the latter to shallow waters); differences are significant, and come primarily from the handling of temperature. Fourth panels (d): The new approach, considering shallow ("nursery") habitat, deep ("migration") habitat and the combination; this contrast suggests that combining nursery and migration habitat might be counterproductive, as the latter overwhelms the former.

Appendix B: Abstracts from submitted and published manuscripts (2010-2014)

Salmon habitat opportunity in the Columbia River estuary: modeling the physical environment to inform management decisions

Burla, M, A.M. Baptista, Y. Zhang, C. Seaton, E. Casillas, D.L. Bottom, and C. Simenstad

In review, *Estuaries and Coasts*

Long-term variability and abrupt changes in the physics of the Columbia River (CR) estuary-plume-shelf ecosystem are believed to modulate salmon survival and life histories. Flow regulation, navigational improvements, and diking and filling have profoundly modified the CR estuary over the past century, with extensive loss of wetland habitat. Using the high-resolution modeling capabilities of a multi-purpose, cross-scale coastal-margin observatory developed over the past decade for the CR, we investigated the impact of natural variability and anthropogenic change on estuarine physical habitat opportunity (PHO) for salmon. With multi-year simulations and scenario comparisons between modern and predevelopment conditions, found that only strategies aimed at re-establishing some connectivity between the river and its floodplain through modification of both flow and bathymetry can significantly restore PHO in the CR estuary. The simulations also provided insight into the role of salinity and temperature on PHO in different regions of the contemporary and predevelopment estuary.

Evaluation of size and timing estimates derived from otolith elemental ratios of Chinook salmon

Claiborne, AM and L Campbell.

Submitted

Otolith chemistry is often used to reconstruct origin and migratory history in anadromous fishes, although the accuracy and precision of back-calculated estimates are often not known. In this paper, we evaluate back-calculated size and timing estimates based on otolith ratios of Strontium:Calcium (Sr:Ca) in Chinook salmon (Oncorhynchus tshawytscha) marked with increased concentrations of Sr. Overall, back-calculated size at marking was underestimated by < 2 mm using direct and proportional back-calculations of fish length based on otolith Sr:Ca. Proportional back-calculations of fish length were underestimated when somatic growth (%/day) was less than otolith growth (%/day) and overestimated when somatic growth was greater than otolith growth. Direct back-calculations of fish length were more robust to differences between somatic and otolith growth rates after marking. However, a negative relationship between somatic growth rate and accuracy was observed such that slower and faster growing fish were over and underestimated, respectively. Overall, the number of otolith daily increments since Sr:Ca inflection underestimated the actual days since marking by a median of 1 d (± 0.57 d). However, for individuals sampled 8-79 d after marking there was no significant difference between actual and estimated days since marking. Results from this study suggest that back-calculated estimates of size and timing based on otolith Sr:Ca and daily increment formation may be suitable estimates in ecological field studies.

Parasites in subyearling Chinook salmon (*Oncorhynchus tshawytscha*) suggest increased habitat use in wetlands compared to sandy beach habitats in the Columbia River estuary

Claxton, A., K.C. Jacobson, M. Bhuthimethee, D. Teel, and D. Bottom

2013. Hydrobiologia 717:27-39

Many estuaries in the Pacific Northwest have been severely altered reducing wetlands habitat and resulting in an interest in their importance as rearing areas for juvenile salmon. To examine differences in habitat use during residency in the Columbia River estuary, we examined parasite communities acquired through food web interactions in subyearling Chinook salmon (*Oncorhynchus tshawytscha*) collected from four different habitat types in May and July of 2004 and 2005. Collections were made from two sandy bottom habitat types in the tidal freshwater and marine mixing areas of the estuary. These were compared to two wetlands types: one composed of scrub and shrub vegetation and another with emergent vegetation. Parasite assemblages differed among habitats suggesting differences in salmon feeding opportunities and rearing behaviors. In both years, the nematode, *Hysterothylacium aduncum* and the acanthocephalan, *Echinorhynchus lageniformis*, which use intermediate hosts found in the estuary, were more prevalent in lower wetlands suggesting increased feeding by salmon in these habitats. The differences in parasite assemblages among habitats suggests a variety of rearing and migration patterns through the Columbia River estuary and the increased prevalences of some parasites in the wetlands show that these habitats can be important feeding grounds for salmon.

Rearing in natural and restoring tidal wetlands enhances growth and life-history diversity of Columbia River estuary tributary coho salmon *Oncorhynchus kisutch* population

Craig, B.E., C.A. Simenstad, and D.L. Bottom

2014. Journal of Fish Biology DOI: 10.1111/jfb.12433

This study provides evidence of the importance of tributary tidal wetlands to local coho salmon *Oncorhynchus kisutch* populations and life-history diversity. Sub-yearling and, to a lesser extent, yearling *O. kisutch* life histories utilized various estuary habitats within the Grays River, a tidal freshwater tributary of the Columbia Estuary, including restoring emergent wetlands and natural forested wetlands. Migration timing data, size distributions, estuary residence and scale patterns suggest a predominance of sub-yearling migrant life histories, including several that involve extended periods of estuary rearing. Estuarine-rearing sub-yearling *O. kisutch* exhibited the greatest overall growth rates; the highest growth rates were seen in fish that utilized restoring emergent wetlands. These results contrast with studies conducted in the main-stem Columbia Estuary, which captured few *O. kisutch*, of which nearly all were hatchery-origin yearling smolts. Restoration and preservation of peripheral and tributary wetland habitats, such as those in the Grays River, could play an important role in the recovery of natural *O. kisutch* populations in the Columbia River and elsewhere.

Variability in isotopic (δ13C, δ15N, δ34S) composition of organic matter contributing to detritus-based food webs of the Columbia River estuary.

Maier, G.O, J. D. Toft, and C. A. Simenstad

2011. Northwest Science 85(1):41-54.

The use of stable isotopes has recently grown in studies of trophic structure and the recruitment and migration patterns of consumers. This type of analysis allows the flow of organic matter and trophic relationships to be outlined within complex systems. Although multiple stable isotope analysis is useful in distinguishing linkages between sources and consumers, its efficacy is contingent on the isotopic similarity within each source and the distinctiveness of producer isotope values. As part of a study investigating juvenile Chinook salmon (*Oncorhynchus tshawytscha*) food webs in the Columbia River estuary we examined the isotopic (δ13C, δ15N, and δ34S) composition of five prominent primary producers. We sought to examine statistical variability of primary producer isotope values and its effects on differentiation between sources. We found that within-group isotopic variability occurs at different scales, related to the heterogeneous landscape in which producers grow. Aquatic and wetland vascular plants displayed the greatest range in isotopic composition while benthic algae and particulate organic matter were more constrained in their isotope signatures. When examining differences between groups we found that although δ13C was the most variable isotope ratio, it was also the most useful in distinguishing sources, especially benthic producers compared to water column and emergent producers. Signatures of δ15N and δ34S were most useful in differentiating benthic algal and vascular marsh plant groups. Isotopic composition along with chlorophyll and elemental composition was also useful in distinguishing phytoplankton samples from particulate organic matter (POM) samples. The type and extent of isotopic variability revealed by this study will help inform future food web studies using isotopes to characterize trophic linkages in large estuaries such as the Columbia River estuary.

Distribution, size, and origin of juvenile Chinook salmon in shallow-water habitats of the lower Columbia River and estuary, 2002–2007

Roegner, G.C., R. McNatt, D.J. Teel, and D.L. Bottom

2012. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 4:450-472.

We monitored fish assemblages monthly at estuarine and tidal freshwater sites in the lower Columbia River and estuary from January 2002 through September 2007 in order to identify specific salmon stocks and migration stages that may benefit from habitat restoration initiatives. We report landscape-scale and seasonal variation in abundance, size, hatchery production (based on adipose fin clips), and genetic stock of origin of juvenile Chinook salmon *Oncorhynchus tshawytscha*. From fish implanted with coded wire tags (CWTs), we also determined the sites of release and inferred migration patterns. Chinook salmon were found in diverse life history stages and forms, including fry migrants, fingerlings, and (fewer) yearlings. Abundance increased in February and decreased in August, but salmon were present in all months each year. Spatial gradients in abundance and size were strong, with fewer but larger fish in brackish than in tidal freshwater zones. Overall, 30% of the Chinook salmon measured were fry (≤60 mm) that were likely naturally produced fish. These occurred at higher mean monthly proportions in tidal freshwater than in estuarine zones. In contrast, most larger fish were probably raised in hatcheries. Genetic stock assessment revealed that the majority of the Chinook salmon analyzed were from fall-run stock groups originating in the lower Columbia River, with 15% originating from other stock groups. Of these minority contributors, about 6% were identified as upper Columbia River summer–fall-run Chinook salmon while seven other stock groups accounted for the remainder, including 3% from transplants originating in southern Oregon's Rogue River. Recaptures of tagged fish revealed maximum migration times of 143 d for subyearlings and 52 d for yearlings, and both CWT and genetic data indicated that fall Chinook salmon from coastal rivers occasionally entered the estuary. These data demonstrated a widespread temporal and spatial distribution of subyearling Chinook salmon in shallow-water habitats of the lower Columbia River and estuary.

Juvenile salmonid use of reconnected tidal wetlands in Grays River, Lower Columbia River basin

Roegner, G.C., E.W. Dawley, M. Russell, A. Whiting, and D.J. Teel

2010. Transactions of the American Fisheries Society 139:1211-1232.

Degraded wetland systems with impaired hydraulic connections have resulted in diminished habitat opportunity for salmonid fishes and other native flora and fauna in the Pacific Northwest. Many of these lost habitats were once intertidal freshwater marshes and swamps. Restoration of these systems is effected in part by reestablishing tidal processes that promote connectivity, with a central goal of restoring rearing habitat for juvenile Pacific salmon *Oncorhynchus* spp. In the Grays River tidal freshwater system of Washington, we measured hydrologic changes that resulted from the removal of tide gates from diked pastureland and we determined the subsequent time series of salmonid abundance and size frequency in the restoring marshes. Dike breaching caused an immediate return of full semidiurnal tidal fluctuations to the pasturelands. Juvenile Pacific salmonids quickly expanded into this newly available habitat and used prey items that were presumably produced within the marshes. Habitat use varied by species and life history stage. Fry of chum salmon *O. keta* migrated rapidly through the system, whereas populations of Chinook salmon *O. tshawytscha* and coho salmon *O. kisutch* resided from March to at least July and were composed of fry, fingerlings, and (for coho salmon) yearlings. Based on salmon size at date and the timing of hatchery releases, we concluded that most salmon sampled in restored and reference sites were the progeny of natural spawners. However, the presence of adipose-fin-clipped Chinook salmon indicated that hatchery-raised fish originating outside the Grays River system also used the restoring wetland habitat. Because of extensive mixing of stocks through hatchery practices, genetic analyses did not provide additional insight into the origins of the Chinook salmon but did reveal that out-migrating juveniles were an admixed population composed of lower Columbia River ancestry and nonindigenous Rogue River stock. Restoration of tidal wetlands in the Columbia River estuary will improve overall ecosystem connectivity and reduce habitat fragmentation and may therefore increase survival of a variety of Pacific salmon stocks during migration.

Density and condition of subyearling Chinook salmon in the lower Columbia River and estuary in relation to water temperature and genetic stock of origin.

Roegner, G.C., and D.J. Teel

2014. Transactions of the American Fisheries Society 143:1161-1176

We examined the hypotheses that density and morphometric condition of subyearling juvenile Chinook salmon *Oncorhynchus tshawytscha* would decline during periods of high water temperatures in the lower Columbia River and estuary. The hypotheses were tested using salmon density measurements and a condition anomaly calculated from residuals of the length-weight linear regression relationship of 5536 subyearlings collected from brackish estuarine and tidal freshwater habitats. We found Chinook salmon at all temperatures encountered (4.2-23.5°C). In the tidal freshwater zone, densities were highest at optimal temperatures and lowest at suboptimal and supraoptimal temperatures, while in the estuary no differences were found among different temperature regimes. Salmon condition was lowest in winter, when temperatures were suboptimal, and highest in summer, when temperatures were supraoptimal. Pairwise comparisons between condition during optimal temperatures (spring), and those during supraoptimal or stressful temperatures (summer), showed little change in the estuary, but a large positive increase with temperature in the tidal freshwater zone. Similarly, we examined seasonal differences in the condition of fry-sized salmon between 50 and 60 mm, and again found condition to be lowest during winter and highest in summer. Finally, using genetic information, we found stock-specific differences in migration timing, and concluded that most large yearling and many subyearling fish migrated in late winter or spring, and thus were never exposed to high temperatures. Other prevalent stocks persisted in the estuary during periods of elevated temperature; however condition of these salmon stocks also tended to be higher or neutral in summer than in spring. High temperatures appear to influence migration timing as evidenced by reduced density in tidal freshwater reaches in summer. However, we found little support for the hypothesis that condition of juvenile Chinook salmon is reduced during periods of high water temperatures in the lower Columbia River and estuary.

Variation in fish assemblages between adjacent estuarine habitat types: strong evidence for fine-scale habitat use in the Columbia River estuary

Roegner, G.C., L.A. Weitkamp, and D.J. Teel

In review. Transactions of the American Fisheries Society.

Paired sampling of shallow shoreline and deeper water channel habitats in the lower Columbia estuary over three years (2010-2012) allowed us to document species-specific habitat use by the five salmonid species native to the Columbia River basin and stock-specific variation for Chinook salmon. Our results indicate a high degree of fine-scale spatial heterogeneity in fish habitat occupancy including non-salmonids. Salmon species composition in shallow water sites is composed primarily of subyearling Chinook and chum salmon and yearling Coho salmon, with fewer other salmonids present. In contrast, the fish assemblage in the channel habitat contains a higher diversity of salmon species representing all species with extant spawning populations. Fish in the channel are generally composed of larger individuals of sub- and yearling Chinook salmon and yearling Coho, Sockeye, and Steelhead. Much higher densities of fish including some salmon species are found in shallow water than in the mainstem channels, which has ramifications for feeding, growth, and competitive interactions. The proportion of hatchery fish was also higher in channel habitats than shallow habitats for all salmon. Multidimentional scaling analyses show the fish assemblages at shallow and channel habitats to be very distinct from each other although both are strongly influenced by seasonal changes. The two channel habitat stations investigated are much more similar to each other than the shallow site, despite the close proximity (100s of m) of one channel site to the shoreline site. Genetically-determined stock-specific habitat use was apparent in Chinook salmon: most upper river Chinook stocks primarily use deep channels while lower river populations use both deep and shoreline areas, although at least a few individuals of 11 Columbia River Chinook salmon ESUs were present along the shoreline where lower river stocks predominate. We conclude sampling at both habitat types is required to fully encompass the migration patterns of all salmon Evolutionarily Significant Units in the Columbia River basin

Seasonal, diel, and landscape effects on resource partitioning between juvenile Chinook salmon *Oncorhynchus tshawytscha* and threespine stickleback *Gasterosteus aculeatus* in the Columbia River Estuary

Spilseth, S.A., and C.A. Simenstad

2011. Estuaries and Coasts 34:159-171.

The objective of this study was to determine if exploitative competition between juvenile Chinook salmon *Oncorhynchus tshawytscha* and threespine stickleback *Gasterosteus aculeatus* reduces the foraging opportunity of juvenile Chinook salmon in tidal channels of the Columbia River estuary. We sampled Chinook salmon and stickleback diets monthly and over a diel cycle in spatially distinct emergent marshes of the Columbia River estuary. Diets of the two fish species did not differ among marsh systems, but both fish species exhibited diel and seasonal differences in diet composition. Diet overlap between the two fish species was greatest in March and June. Exploitative competition was unlikely based on a comparison between consumption rates and estimated invertebrate production.

Genetic identification of Chinook salmon in the Columbia River estuary: stock-specific distributions of juveniles in shallow tidal freshwater habitats.

Teel, D.J, D.L. Bottom, S.A. Hinton, D.R. Kuligowski, G.T. McCabe, R. McNatt, G.C. Roegner, L.A. Stamatiou, and C.A. Simenstad

2014. North American Journal of Fisheries Management 34(3): 621-641.

Extensive efforts are underway to restore and conserve near-shore shallow water habitats in the Columbia River estuary with the intent of increasing the estuary's capacity to provide food, refuge, and other crucial ecosystem functions for juvenile salmon. Juvenile Chinook salmon, including those from the five Evolutionarily Significant Units listed as threatened or endangered under the U.S. Endangered Species Act, are particularly expected to benefit from the habitat improvements. However, information on the temporal and spatial estuarine distributions of juveniles from specific populations or stocks is lacking and impedes restoration planning for at-risk salmon. We conducted a series of surveys to sample juvenile Chinook salmon occupying shallow sandy beach habitats in six hydrogeomorphic reaches across the tidal freshwater portion of the estuary and also at one long-term reference site near the estuary mouth. Sites were sampled bi-monthly over 26 months during 2010-2012 to capture seasonal patterns of stock-specific habitat use. Genetic stock identification analyses were conducted on the samples using microsatellite DNA loci and genotypic data representing spawning populations from throughout the Columbia River Basin. We identified three tidal freshwater areas having differing patterns of genetic stock composition. Lower tidal freshwater reaches were dominated by fall run juveniles from West Cascade tributaries (>70%), upper reaches had a large proportion of fish from the Upper Columbia River summer/fall stock (>60%), and middle reaches were characterized by greater stock diversity with no single stock contributing more than 30% in each reach. Stock-specific juvenile habitat use differed by season, life history type, and between natural and hatchery produced fish. Data from this study provide improved descriptions of the near-shore tuary habitat use of several Columbia River genetic stocks of Chinook salmon that can assist managers in the design and selection of estuary restoration projects.