

# Estuarine Habitat and Juvenile Salmon

## Current and Historical Linkages in the Lower Columbia River and Estuary, 2002-2004



G. Curtis Roegner, Antonio Baptista,<sup>1</sup> Daniel L. Bottom, Jennifer Burke,<sup>2</sup> Lance Campbell,<sup>3</sup> Crystal Elliot,<sup>4</sup> Susan Hinton, David Jay,<sup>1</sup> Mary-Austill Lott,<sup>2</sup> Trica Lundrigan, Regan McNatt, Paul Moran, Charles A. Simenstad,<sup>2</sup> David Teel, Eric Volk,<sup>5</sup> Jen Zamon, and Edmundo Casillas

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Fish Ecology Division, Northwest Fisheries Science Center  
U.S. National Marine Fisheries Service  
National Oceanic and Atmospheric Administration  
2725 Montlake Boulevard East  
Seattle, Washington 98112

*to*

U.S. Army Corps of Engineers  
Portland District  
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Portland, Oregon 97208  
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1 OGI School of Science & Engineering, Oregon Health and Science University, Beaverton, OR

2 School of Aquatic and Fishery Science, University of Washington, Seattle, WA

3 Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR

4 Center for Urban Horticulture, College of Forest Resources, University of Washington, Seattle, WA

5 Washington Department of Fish and Wildlife, Olympia, WA



## PREFACE

Diversity and abundance of salmonid populations in the Columbia River Basin have declined through the past 150 years in association with environmental alterations to salmon habitat, especially degradation and loss of spawning and rearing areas, alteration of river flows, and impediments to juvenile and adult migration. Direct alterations of the estuary such as fill, diking, and dredging resulted in loss of large areas of tidal swamps and marshes. Changes in the timing and magnitude of river flow by dam construction affected water depth and velocity, sedimentation rates, and salinity intrusion. Mitigation practices, including hatchery supplementation of stocks and corrective measures to recover from the many anthropogenic impacts, have been attempted throughout the 20th century, but have been insufficient to maintain fish stocks at high abundance. The present mitigation focus is on restoration of critical rearing habitat previously lost through anthropogenic alterations of the lower Columbia River and estuary.

Juvenile salmonids originating from upland freshwater spawning grounds in the Columbia River Basin migrate to the ocean through a complex environment of tidal freshwater and estuarine (saline) habitats. In the lower Columbia River and estuary, our understanding of the spatiotemporal use of these habitats by stocks of juvenile salmon is incomplete and requires elucidation to better plan habitat restoration projects.

In our research of the lower Columbia River and estuary, we adopted the broad definition of *estuary*, which encompasses the entire complex of ecosystem gradients, ranging from fluvial to nearshore-ocean ecosystems (Fairbridge 1980; Day et al. 1989; McLusky and Elliott 2004). This definition is based on tidal variation, rather than on salinity and geomorphology, as controlling hydrological, sedimentological, geochemical, and ecological gradients. We further characterize the estuary as a continuum of tidal freshwater, oligohaline, euryhaline, and near-ocean plume ecosystems. This definition follows the *Columbia River Estuary Ecosystem Classification System* being adopted by the Lower Columbia River Estuary Partnership for monitoring and restoration planning in this region ([www.lcrep.org](http://www.lcrep.org)).

The ultimate goal of this research is to define habitat protection and restoration priorities for the lower Columbia River and estuary. These priorities will be based on the relationships between estuarine habitat conditions and juvenile salmonid life history diversity, abundance, and performance, as well as the potential responses of salmonids to past and future habitat change. Toward these ends, we conducted research projects during 2002-2004 with the following objectives:

- 1) Commence long-term monitoring to track landscape-scale trends in salmon abundance, population structures, and life histories.
- 2) Measure salmonid use of and performance within selected wetland habitats
- 3) Characterize historic changes in tides, river flow, and sediment input have affected habitat availability for juvenile salmon

This document synthesizes the third year of the program, and encompasses monitoring, empirical studies to define contemporary salmon-habitat associations and life-histories, historic analyses of physical habitat changes, and modeling tools to assess the response of juvenile salmon to these or other potential changes. Results to date further our knowledge of information needed to establish criteria for restoring habitat in the Columbia River estuary.

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## **OBJECTIVE 1: Compare Landscape-Scale Trends in Juvenile Salmonid Abundance and Life History**

### **Executive Summary**

Our first research objective was twofold: First, to categorize temporal and spatial variation in fish community structure using a landscape-scale monitoring program at characteristic shallow-water environments. Salmonid abundance and population size structure were emphasized, and reported in section 1.1. Second, to collect samples of juvenile salmon to investigate aspects of salmonid habitat use, including genetic analyses to determine stock-of-origin, chemical analysis of otoliths and scales to investigate estuarine residence and growth, and stomach analysis to evaluate trends in feeding. These analyses are detailed in sections 1.2-1.5. Section 1.6 details variation of hydrography and fish community structure over tidal time scales. Together these components provided a baseline time series of fish habitat use in an understudied region of the juvenile salmon migration corridor in the Columbia River.

Fish community structure varied widely on the spatial and temporal scales measured. At the landscape scale, salinity tolerance was a primary factor determining species abundance. Diversity in tidal freshwater habitats was much lower than that of estuarine sites. Threespine stickleback were the community dominant at tidal freshwater sites on all dates sampled, and comprised over 99% of the total abundance in emergent marsh environments. At the landscape scale, they comprised 25, 68, and 86% of the total fish population at lower estuary, middle estuary, and tidal freshwater sites, respectively. Reproductive activity was important for temporal variation in fish community structure. Introduced species (killifish and American shad) made up high proportions of species in tidal freshwater environments. Variations in fish community structure may have important effects on salmon performance in estuary habitats due to predatory (prey-switching) and competitive (diet overlap) interactions. This avenue will be investigated more fully as this synthesis develops.

Juvenile salmon were abundant in shallow-water habitats of the estuary. The landscape-scale time series revealed that juvenile Chinook salmon were present year-round, with peaks in abundance from March to July. During the peak migration period, salmon made up a high proportion of the total catch. CPUE was generally greater in tidal freshwater habitats than in the estuary. In the wetland habitats of Cathlamet Bay, abundance peaked in May and was minimal after June or July, and salmon abundance was dwarfed by that of stickleback. Chum salmon were concentrated at estuarine stations

during February through May. We encountered fewer steelhead or yearling Chinook in these wetland habitats, as these life history types tend to migrate swiftly through the system in main channel environments.

Time series of mean size suggests growth during residency in the estuary. At most shallow-water beach-seine and wetland habitats, Chinook salmon mean size tended to increase with time. However, during a given time period, salmon at tidal freshwater habitats were 20-50 cm smaller than those caught further downstream in the estuary. For estuarine fish, overall size-frequency histograms showed a relatively binomial distribution, centered near the overall mean size of 80 mm. Sizes of fish captured at tidal freshwater sites were negatively skewed, with most individuals over 80 mm. Most fish captured at wetland sites in Cathlamet Bay were less than 90 mm. Salmon fry (< 60 mm) were present at all habitats. These data supported the concept that small Chinook salmon utilizing tidal freshwater habitats grew as they migrated downstream to estuarine habitats.

Juvenile Chinook were found feeding during estuarine residency. Fifty-eight percent of fish captured in shallow habitats of the mainstem had stomachs over 50% full of prey. These salmon were consuming primarily terrestrial insects, which are typically produced in wetlands (such as Cathlamet Bay), and *Corophium* amphipods, which are found in freshwater and estuarine sediments. In all wetland habitats of Cathlamet Bay, salmon fed primarily on chironomid insects in preference to other available prey types (Section 2.2). Salmon diets changed with habitat and size (age). Salmon in the estuary had more diverse diets that included fish and crab larvae. In wetland habitats, diversity of prey items increased with size of fish.

To date, the preponderance of salmon genetically identified by evolutionarily significant unit (ESU) were found to have originated from the Lower Columbia River fall-run Chinook ESU. This was expected, since this ESU typifies the "ocean-type" Chinook life history strategy. However, 15% of the samples analyzed to date were from the Interior Columbia River Fall and Spring Chinook and Upper Willamette River Chinook ESUs. Many of these ESU are listed as endangered or threatened.

From our data, it was not possible to distinguish wild versus hatchery-produced fish, other than those with external markings or internal tags. However, few hatchery Chinook salmon in the basin are marked, and only a small proportion of individuals captured at estuary habitats had external marks. Only 2.9% of fish captured in off-channel habitats were marked, and only half of these had coded-wire or PIT tags that would allow their origin to be determined.



Based on the chemical microstructure of salmon otoliths analyzed to date, residency in estuarine environments ranged from 0 to 88 d. Sizes at estuary entry ranged from 26 to 104 mm, which emphasized the variability in life history strategies found in the Columbia River estuary. Data from the tidal time series study showed that, at the estuarine sites, a range of salmon sizes were captured in salinities from 2 to 31 psu. Time series of mean salmon size in off-channel and wetland habitats also supported residency of Chinook salmon in the system ranging from weeks to months. From the landscape-scale sampling, we found juvenile Chinook salmon present in the estuary year-round. This contrasted with findings for chum salmon, all of which appeared to move to the ocean during 1-2 months in spring.

## **1.1 Community Structure and Hydrography**

### **Introduction**

Estuarine ecosystems constitute important habitats of juvenile Pacific salmon and represent an integral component of the continuum of habitats that salmon occupy during migration to the sea. Unfortunately, the majority of historic emergent and forested wetlands of the lower Columbia River and estuary have been lost to diking and filling (Thomas 1983; Sherwood et al. 1990). Additionally, the hydrosystem has substantially altered the timing, magnitude, and duration of hydrological conditions that salmon populations were adapted to. Hatchery practices favored “desirable” salmon stocks.

As a consequence, temporal and spatial patterns of rearing by juvenile Chinook salmon have been simplified compared with those of a century ago. These life history changes are likely the result of the variety of human disturbances both upstream and within the estuary (ISG 2000; Bottom et al. 2001). The reduced diversity of salmon life histories, including those dependent upon estuarine habitats, has likely diminished the resilience and productivity of salmon in the Columbia River Basin. The long history of wetland loss in the estuary coupled with change in flow patterns suggests that restoration of these habitats may benefit recovery of depressed salmon stocks, and concerted efforts are presently underway to mitigate the effects of degraded and destroyed salmon rearing habitat (Diefenderfer et al. 2005).

There is, however, a general lack of information concerning what habitat attributes are needed to sustain diverse life histories of juvenile salmon in the Columbia River estuary. This is particularly true for tidal freshwater and oligohaline transition zones. To date, no empirical studies of tidal wetland habitats have been conducted in the estuary to assess their ecological functions or to establish their significance as rearing

habitat for juvenile salmonids. Most biological surveys in the estuary have been conducted over short time intervals (a few years or less), involving a limited range of habitat types and site-specific locations.

A variety of environmental studies have evaluated the effects of dredging and other development activities in the Columbia River estuary. Many of these target sensitive benthic invertebrate assemblages but, with a few exceptions, provide little or no information about the linkages between invertebrate prey and fish predators or about the effects of anthropogenic changes on salmonid habitats and salmon growth or survival. Furthermore, fish surveys primarily have targeted mainstem and distributary channel margins, which are heavily used by larger yearling “stream-type” salmon migrants, including hatchery fish, which tend to migrate rapidly through the estuary to the ocean. Most of these surveys have ignored shallow wetlands, forested swamps, sloughs, and other backwaters that may be among the principal habitats for small subyearling “ocean-type” salmon that often rear in estuaries for extended periods (Reimers 1973).

Long-term monitoring and evaluation is needed to 1) ensure that there are no adverse effects of planned anthropogenic modification of the Columbia River (either upstream or downstream from the dams) on estuarine-rearing salmonids in critical shallow-water habitats, and 2) develop criteria and a process for selecting, designing, and evaluating restoration projects based on their potential benefits to salmon rearing habitats and life history diversity.

From other areas in the Pacific Northwest, we know that shallow, low-velocity estuarine habitats are particularly productive rearing areas for a variety of Pacific salmon species and life history types (e.g., Levy and Northcote 1982; Levy et al. 1979). Life history diversity within and among salmon species is reflected in varying times and sizes of entry to the estuary, periods of estuarine residence, habitat and microhabitat distribution, diet, and growth rates. Many studies have shown that salmonid movements and habitat use within estuaries are size-related. Small Chinook and chum salmon usually occupy shallow, nearshore habitats including salt marshes, tidal creeks, and intertidal flats (Levy and Northcote 1982; Myers and Horton 1982; Simenstad et al. 1982; Levings et al. 1986).

As subyearling salmon grow to fingerling and smolt stages, their distribution typically shifts toward deeper habitats farther from the shoreline (Healey 1982, 1991; Myers and Horton 1982). In river-dominated systems like the Fraser and Columbia River estuaries, emergent and forested wetlands and their networks of shallow, dendritic channels and backwater sloughs offer refugia for small juvenile salmon to avoid the strong current velocities of main river channels. Juvenile salmon “performance”

(products of habitat opportunity and capacity) is determined by physical and biological conditions and ecological interactions within these particular habitats. Local differences in prey availability, water temperature, and habitat complexity, for example, ultimately determine salmonid feeding success, growth rates, and survival during estuarine residency.

Of particular concern for Columbia River salmon are the extensive tidal freshwater and oligohaline wetlands that encompass a critical staging area and transition zone, particularly for small subyearling salmon when they first encounter and must acclimate to salt water. Cathlamet Bay is an example of this transition area. The off-channel habitat complex within these transition zones constitutes biologically sensitive areas where small changes in salinity distribution could have substantial effects on the salmon rearing capacity of the estuary. Historical degradation of habitat and hydrology has likely contributed to loss of productivity in salmonid populations.

## Methods

**Study Area**—The landscape-scale sampling area was comprised of seven beach-seine sites that have been sampled monthly since December 2001 (Figure 1). For this analysis, we consolidated sampling sites into three spatial zones based on salinity variation. The high-salinity zone included Clatsop Spit and West Sand Island (CS and WSI), two lower estuary sites near the mouth of the Columbia River. Middle estuary sites were located near the seasonally fluctuating boundary of the salt/freshwater interface, and included Point Ellice and Point Adams Beach (PE and PAB). Tidal freshwater sites were Lower Elochoman Slough, East Tenasillahe Island, and Upper Clifton Channel (LES, ETI, and UCC), located at the upriver end of Cathlamet Bay. Samples were generally collected within 2 h of low tide.

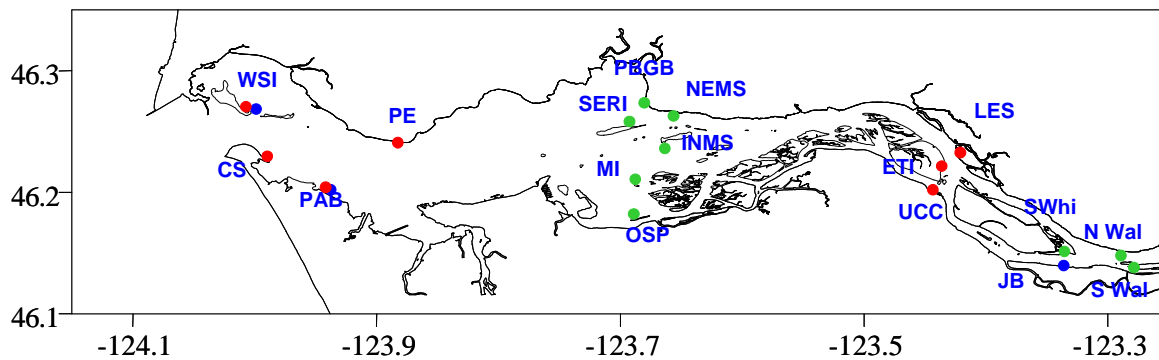


Figure 1. Location of beach seine and sampling sites 2002-2004. Red dots show the seven sample sites for the landscape-scale sampling study (shaded rows in table below). Blue dots show sample sites for the tidal time series study (Section 1.6). Green dots are sites used for the CIPI study (Kagley et al. 2005).

Key			
CS	Clatsop Spit	OSP	Off Settlers Point
ETI	East Tenasillahe Island	PAB	Point Adams Beach
INMS	Interior Miller Sands	PBGB	Pigeon Bluff, Grays Bay
JB	Jones Beach	PE	Point Ellice
LES	Lower Elochoman Slough	SERI	Southeast Rice Island
INMS	Inside North Miller Sands	SWAL	South Wallace Island
MI	McGregor Island	UCC	Upper Clifton Channel
NEMS	North East Miller Sands	WSI	West Sand Island
NWAL	North Wallace Island		

**Species Composition**—Fish were sampled with a tapered 3 × 50-m variable-mesh (19.0-, 12.7-, and 9.5-mm) beach seine with knotless web in the bunt to reduce descaling. During deployment, one end of the seine was anchored on the beach while the other was towed by a skiff to enclose ~3500 m<sup>2</sup> of surface area. If the initial beach seine contained less than 10 salmon, a second seine was conducted at an adjacent location. We sorted catch on site. For non-salmonid species, we measured fork length (FL; nearest 1.0 mm) for a representative sample (30 individuals) of each species, after which fish were released. All other non-salmonids were counted and released.

For salmonids, during 2002-2003, we sacrificed a maximum of 10 individuals of each species and size class for genetic, otolith, scale, and stomach samples (analyses described in sections below). For an additional 20 individuals of each salmonid species and size class, we measured FL (nearest 1.0 mm) and weight (nearest 0.1 g) prior to release. Fin clips and scales from these individuals were retained for genetic and age/growth analyses. In 2004 and beyond, we retained up to 30 salmon individuals for laboratory study, measured and released up to 70 additional individuals, and counted and released the remainder.

**Community Structure**—We examined fish community structure and made expanded analyses for salmonids. Spatial and temporal variability in fish community structure was consolidated by grouping percent abundance data first into landscape zones (described above) and then into four-month seasonal periods determined by river flow and temperature. The winter season (October-January) occurs around the fall transition to downwelling conditions in the Northeast Pacific Ocean. This season is characterized by declining water temperatures and high rainfall. Spring conditions (February-June) encompass the spring transition to ocean upwelling conditions, increasing river temperatures, and high river flow. The summer period (July to September) occurs during the ocean upwelling period, which coincides with high river temperature and low river flow. We computed proportional species composition for each zone by season and year. For Chinook and chum salmon, we plotted time series of catch per unit effort (CPUE) for each seine haul to display seasonal and interannual variation, and computed time series of mean size by landscape zone. We determined overall size-frequency distributions to assess habitat use by size (age) of fish, and computed length/weight regressions to ascertain deviations from standard allometry.

**Hydrography**—Before each beach seine, we profiled the water column with a Sea Bird 19 plus CTD<sup>†</sup> equipped with a Turner Designs SCUFA optical backscatterance sensor and a Wet Labs Wet Star fluorometer. Four casts were made perpendicular to

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<sup>†</sup> Use of trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

shore in a transect extending from the beach-seine site (2-5 m depth) out to the channel 250-300 m from shore. Here we report on general patterns of vertical and horizontal gradients of salinity and temperature during representative seasonal periods.

## Results

**Species Composition**—Overall, we identified over 143,000 individual fishes from 42 species (Table 1). Eighteen species accounted for greater than 0.01% of total abundance. Threespine stickleback *Gasterosteus aculeatus* comprised 71.0% of the total catch, and were an order of magnitude more abundant than all other individuals combined. The next most abundant fishes were shiner perch *Cymatogaster aggregata*, followed by surf smelt *Hypomesus pretiosus*, and then Chinook salmon *Oncorhynchus tshawytscha*, with all others comprising less than 2% of the total. Note that two exotic species, American shad *Alosa sapidissima* and banded killifish *Fundulus diaphanous*, were among the top 18 most abundant species.

Patterns of species composition were similar between sites within zones, but varied significantly among zones (Table 2; Figure 2). Threespine stickleback was numerically dominant in the tidal freshwater zone during all sample periods. The middle estuarine zone had large numbers of stickleback during winter, but proportions of shiner perch increased during spring and summer. Diversity was highest at the estuary mouth, where stickleback comprised the lowest overall fraction of the populations, and surf smelt was numerically dominant during spring and summer. Chinook salmon was a measurable proportion of total abundance during all sample periods. Resident, seasonal, and episodic species distributions followed five general spatial patterns with some overlap (Table 2): lower estuarine (3 species); estuarine (6 species); freshwater (3); euryhaline species (2); and anadromous (4). Salinity and thermal tolerances likely determined these patterns. Diversity and species richness were generally higher in the estuary than in the tidal freshwater zone.

Table 1. Total and percent abundance of fishes captured by beach seine (sorted by overall abundance 2002-2004).

Common Name	2002		2003		2004		2002-2004	
	N	%	N	%	N	%	N	%
Threespine stickleback	38,698	70.16	26,679	68.97	35,811	73.58	101,188	71.00
Shiner perch	4,863	8.82	4,031	10.42	2,090	4.29	10,984	7.71
Surf smelt	3,206	5.81	2,355	6.09	4,737	9.73	10,298	7.23
Chinook salmon	2,601	4.72	2,091	5.41	2,141	4.40	6,833	4.79
Starry flounder	1,116	2.02	1,037	2.68	644	1.32	2,797	1.96
American shad	502	0.91	756	1.95	804	1.65	2,062	1.45
Chum salmon	593	1.08	284	0.73	789	1.62	1,666	1.17
Pacific staghorn sculpin	256	0.46	357	0.92	436	0.90	1,049	0.74
Peamouth	546	0.99	318	0.82	168	0.35	1,032	0.72
Pacific herring	625	1.13	198	0.51	1	<0.01	824	0.58
Prickly sculpin	669	1.21	47	0.12	85	0.17	801	0.56
English sole	250	0.45	195	0.50	322	0.66	767	0.54
Pacific sardine	418	0.76	54	0.14	13	0.03	485	0.34
Sand sole	214	0.39	72	0.19	161	0.33	447	0.31
Banded killifish	9	0.02	23	0.06	182	0.37	214	0.15
Coho salmon	169	0.31	11	0.03	23	0.05	203	0.14
Pacific sand lance	150	0.27	1	<0.01	20	0.04	171	0.12
Pacific sanddab	12	0.02			129	0.27	141	0.10
Northern anchovy	9	0.02	108	0.28	7	0.01	124	0.09
Walleye surfperch	86	0.16					86	0.06
Northern pikeminnow	26	0.05	16	0.04	19	0.04	61	0.04
Largescale sucker	36	0.07	5	0.01	13	0.03	54	0.04
Topsmelt	2	<0.01	11	0.03	36	0.07	49	0.03
Pacific Tomcod	34	0.06	3	0.01	2	<0.01	39	0.03
Rainbow trout (steelhead)	9	0.02	9	0.02	5	0.01	23	0.02
Cutthroat trout	4	0.01			16	0.03	20	0.01
Saddleback gunnel	8	0.01	11	0.03			19	0.01
Largemouth bass	4	0.01			5	0.01	9	0.01
Longfin smelt	9	0.02					9	0.01
Black crappie	4	0.01	3	0.01			7	<0.01
Speckled sanddab	3	0.01	4	0.01			7	<0.01
Eulachon	5	0.01	1	<0.01			6	<0.01
Snake prickleback	6	0.01					6	<0.01
Whitebait smelt	3	0.01			2	<0.01	5	<0.01
Yellow perch			1	<0.01	4	0.01	5	<0.01
Bay pipefish	2	0.00			2	<0.01	4	<0.01
Common carp	4	0.01					4	<0.01
Redtail surfperch	3	0.01					3	<0.01
Sand roller	3	0.01					3	<0.01
Sockeye salmon			2	0.01			2	<0.01
River lamprey			1	<0.01			1	<0.01
Smallmouth bass					1	<0.01	1	<0.01
<b>Total</b>	<b>55,157</b>	<b>100.00</b>	<b>38,684</b>	<b>100.00</b>	<b>48,668</b>	<b>100.00</b>	<b>142,509</b>	<b>100.00</b>

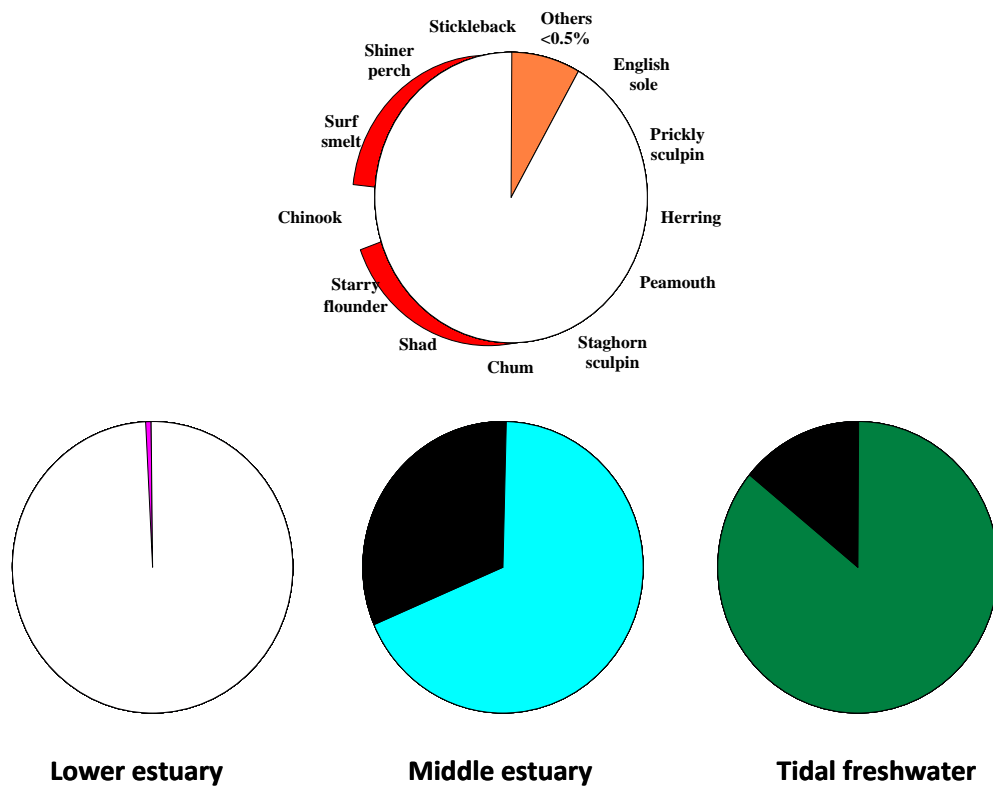


Figure 2. Top, color key to species. Bottom, overall proportional abundance of fishes sampled at landscape scale zones during 2002-2004.

**Community Structure**—We sampled 6,833 Chinook, and caught similar numbers during 2002 through 2004. Based on size-frequency histograms, subyearling fish dominated the catch. Trends of Chinook salmon abundance varied among river sections and years (Figure 3). Chinook salmon was found at tidal freshwater sites every month of the year. Overall, abundance increased in February (2003) or April (2002 and 2004), peaked during May-June, and decreased after August (2002) or July (2003 and 2004). In the estuary, Chinook salmon was abundant May through August. There was a tendency for CPUE to decrease from up- to down river sites.

In contrast, abundances of coho *Oncorhynchus kisutch* and chum salmon *O. keta* were restricted both spatially and temporally. We sampled only 203 coho salmon, and 93 of these were from a single beach seine during May 2002 at LES. We sampled 1,666 chum salmon, of which 97% were from estuarine stations. Chum salmon was present from February to May, after which abundances dropped off markedly. Peak abundances occurred in April (2002), March (2003) and March-April (2004).



Table 2. CPUE of the 18 most abundant fish species captured in beach-seine samples by habitat zone, site, and year.

		Lower estuary						Middle estuary						Tidal freshwater								
		Clatsop Spit			West Sand Isl.			Pt Adams Beach			Point Ellice			E Tenasillahe Isl			L. Elochoman Slough			U. Clifton Channel		
Type	Species	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004
1	Pacific sand lance		1		150		20															
1	Pacific sardine	5		5	413	43	6		3	2		8										
1	Sand sole	127	22	36	80	46	94	6	1	6	1	3	25									
2	English sole	11	6	3	24	19	212	43	96	99	172	74	8									
2	Pacific herring	219	7		331	168		73	4	1	2	19										
2	Pacific sanddab				11		100			25	1		4									
2	Pac staghorn sculpin	17	10	3	22	48	46	92	38	36	124	259	349		1					1	1	2
2	Shiner perch	3	23	42	1	93	3	4060	2028	992	791	1887	1053							8		
2	Surf smelt	725	819	549	2,083	833	2586	305	629	1249	93	74	353									
3	Banded killifish					1	7			2		2	23		13		3	4	10	6	3	140
3	Peamouth											1		6	7	8	95	94	83	445	216	77
3	Prickly sculpin		1		1			1			2	1		35			191	2		440	42	85
4	Starry flounder	14	25	30	30	31	22	184	302	52	435	489	317	61	26	54	46	65	42	346	99	127
4	Threespine stickleback	466	1335	2198	59	61	110	4369	7679	17706	3429	750	3348	2641	2374	1617	13305	10906	4827	14429	3574	6005
5	American shad	1		2	13		8	78	10	41	29	1	14	101	35	101	80	517	189	200	193	449
5	Chinook salmon	399	96	100	111	71	134	348	419	158	190	183	250	391	182	285	608	641	281	554	499	933
5	Chum salmon		41	21	136	166	111	4	39	277	431	19	375	2	6	2	20	10	2	2	3	1
5	Coho salmon	12	2	1			2	20		8	2		2	40		7	93	8	3		1	

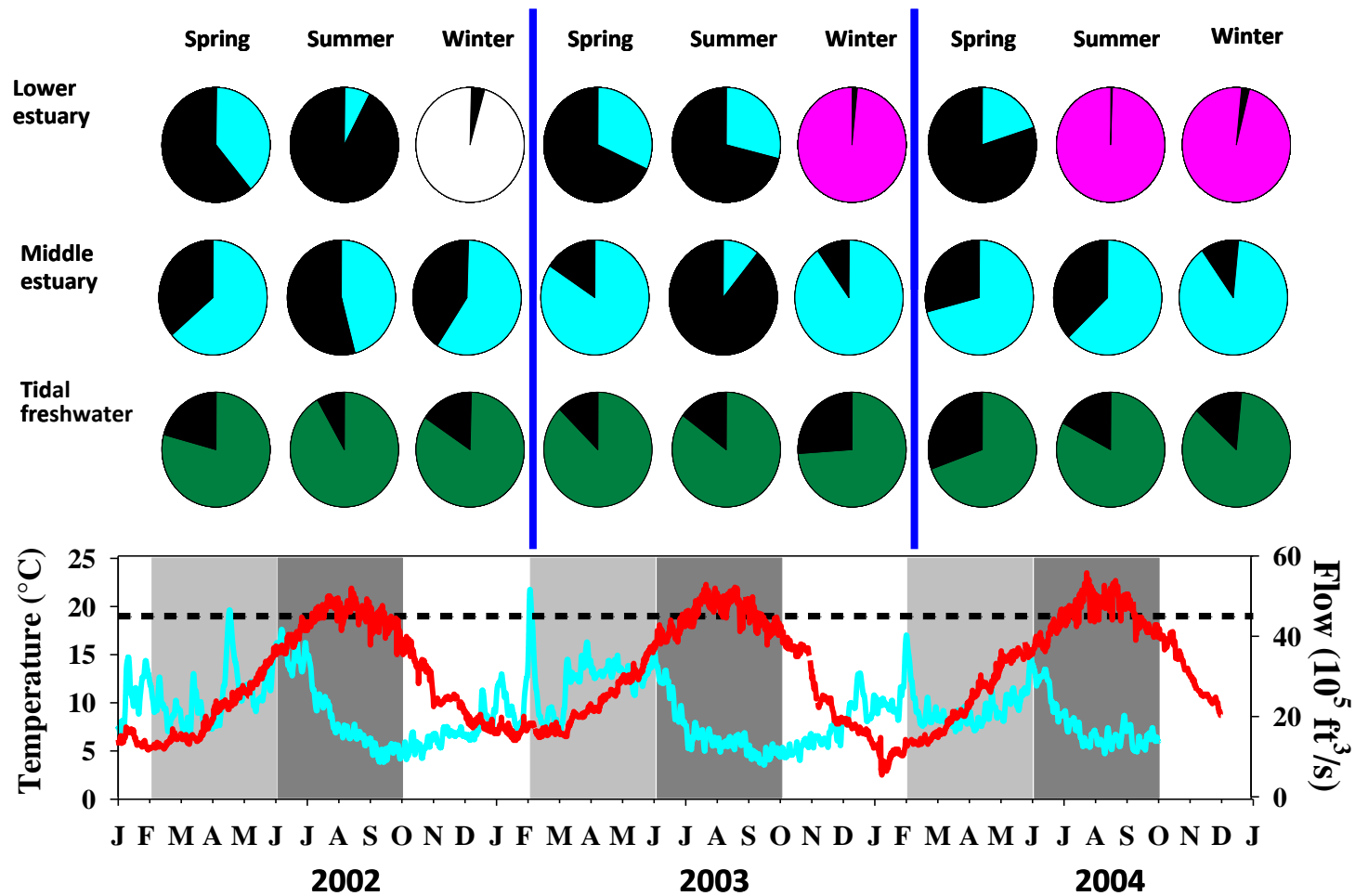


Figure 3. Seasonal species composition for each landscape zone 2002-2004 (Pie charts) compared with time series of temperature (red line) and river discharge (blue line). Dashed line indicates 19°C isotherm. Pie chart color patterns described in Figure 2.

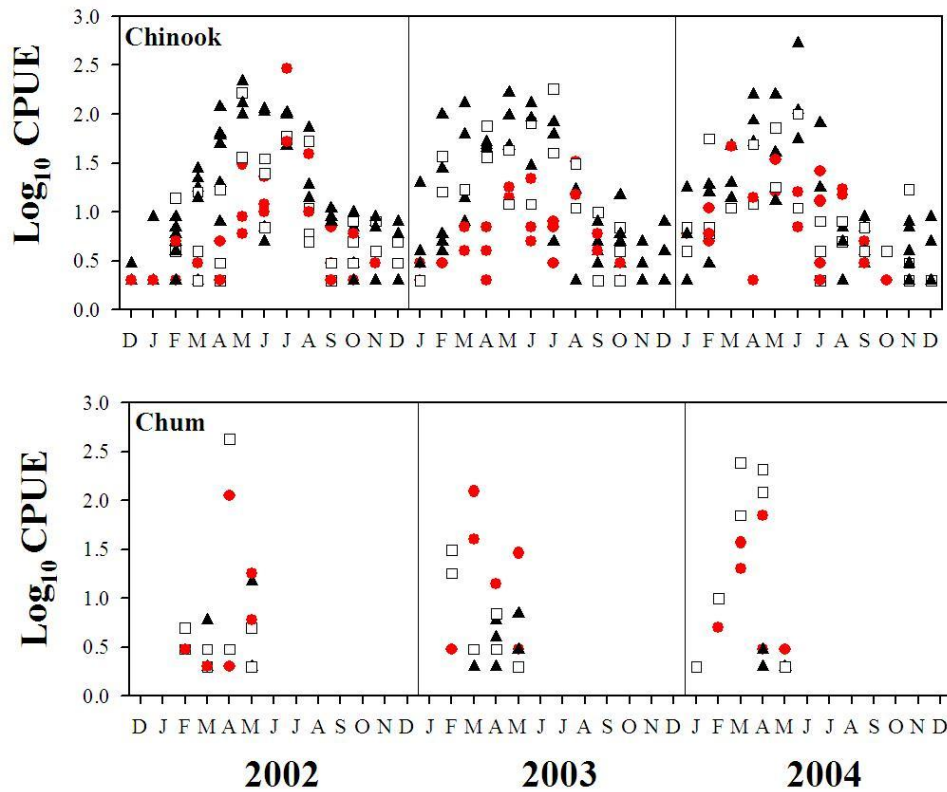


Figure 4. Time series of Chinook (top) and chum salmon (bottom) abundance 2002-2004 for each landscape zone. Red circles show lower estuary sites; white squares show middle estuary sites, and black triangles show tidal freshwater sites.

Mean size of Chinook generally increased with time, with the exception of increases in mean size and variance due to the presence of yearling fish in January through May samples (Figure 5). Mean size and size-frequency distributions varied between estuarine and freshwater sites. After March, Chinook captured in the estuary were 20-50 mm larger than fish caught in the freshwater zone at a given date. Mean growth in freshwater habitats appeared to lag that of estuarine caught fish by 1 to 2 months. Overall size-frequency distributions of Chinook spanned similar ranges across the landscape scale, although we caught few fish over 150 mm at the estuary mouth (Figure 6). However, most upriver fish were less than 80 mm. In contrast, the bulk of fish sampled from estuary stations were between 60 and 100 mm. Fry less than 60 mm were found at all sites. Overall mean size ( $\pm \text{SD}$ ) of Chinook was  $79.9 \pm 29.0$  mm. Log weight-log length regressions were highly correlated at all sites (Table 3).

Chum salmon ranged from 35 to 80 mm, and they also tended to increase in size with time (Figure 5). The largest chum were generally found in May, immediately before abundance decreased. Size-frequency histograms were nearly identical between the two estuarine zones, each showing a peak abundance at 40 mm (Figure 6). Fewer chum were caught upriver; there were peaks at 30-35 mm and at 55 mm. The overall mean size ( $\pm$ SD) of chum was  $51.1 \pm 10.0$  mm. Log weight-log length regressions for chum were more weakly correlated than those for Chinook (Table 3).

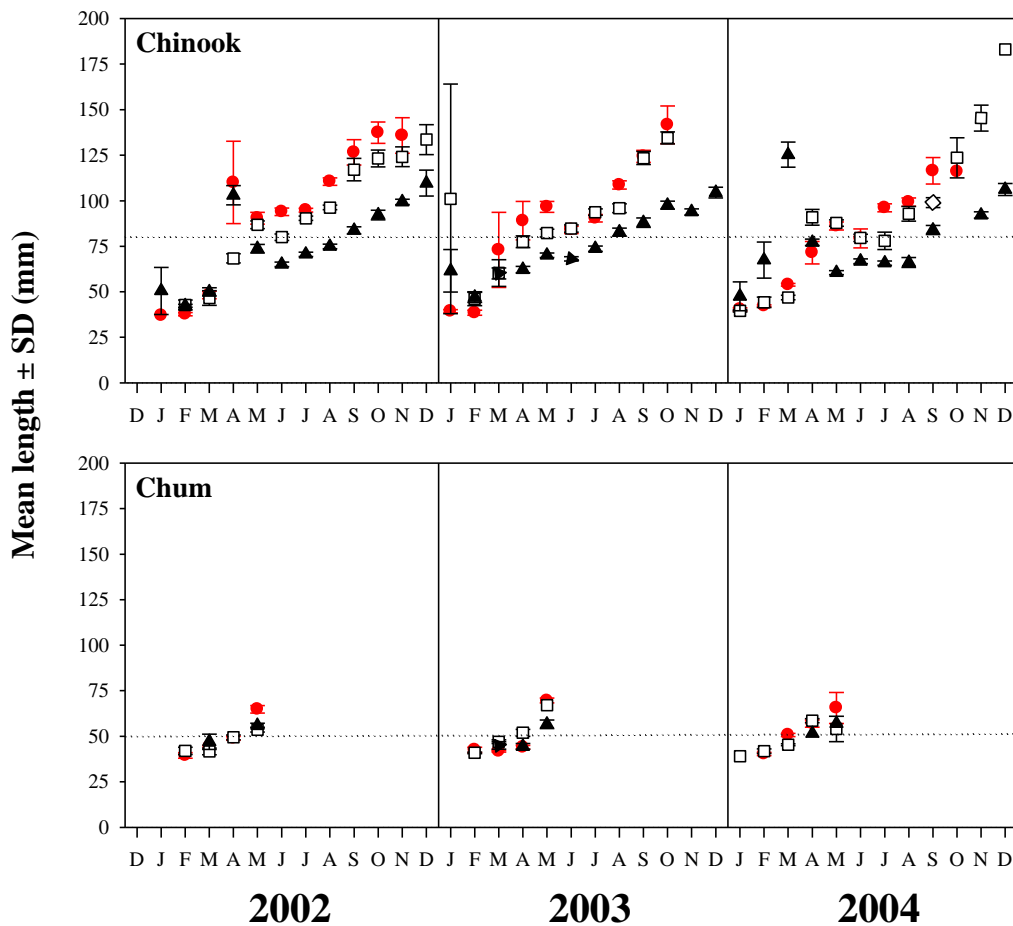


Figure 5. Time series of Chinook (top) and chum salmon (bottom) mean size 2002-2004 for each landscape scale zone. Circles, lower estuary; squares, middle estuary; triangles, tidal freshwater zone. Dotted lines show overall mean size of Chinook and chum, respectively.

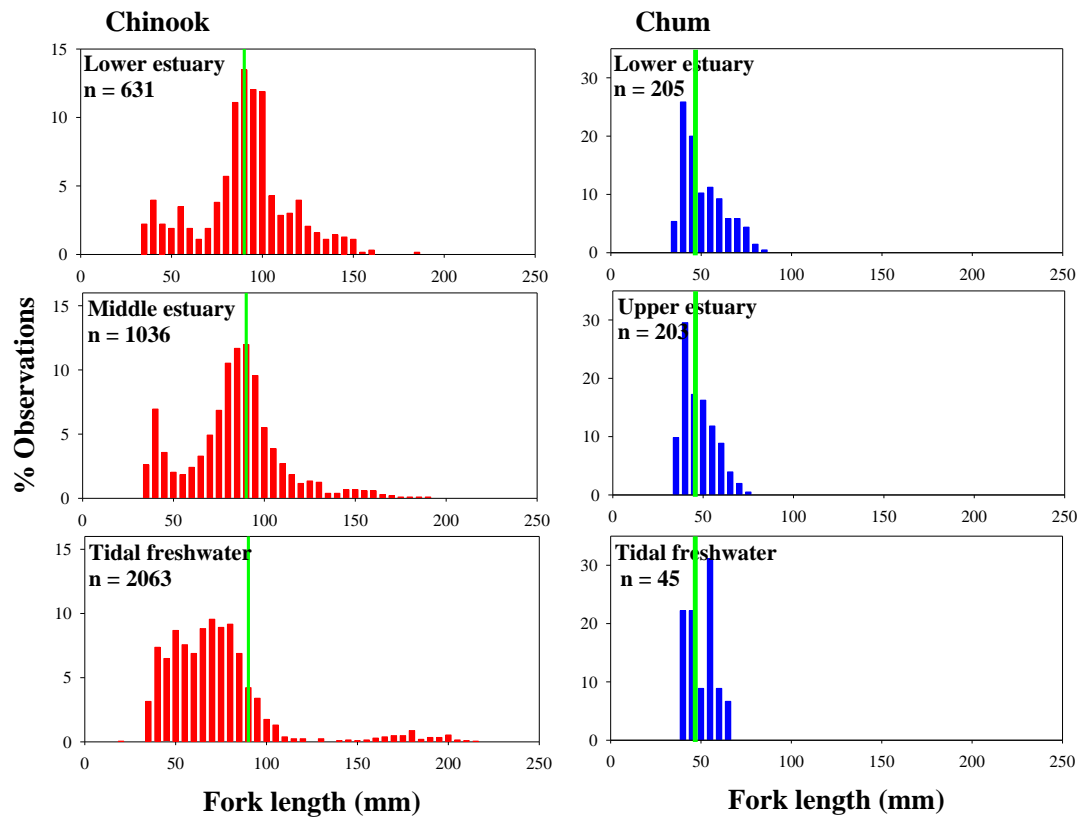


Figure 6. Composite length-frequency histograms for Chinook (left) and chum salmon (right) compiled for each landscape zone. Green lines denote overall mean lengths.

Table 3. Regression equations for log length (mm) - log weight (g) allometric relationship.

Species	Zone	Regression equation	$r^2$
Chinook	Lower estuary	$L = 3.23W - 5.45$	0.98
	Middle estuary	$L = 3.16W - 5.29$	0.96
	Tidal Freshwater	$L = 3.12W - 5.22$	0.96
Chum	Lower estuary	$L = 3.44W - 5.90$	0.91
	Middle estuary	$L = 3.29W - 5.64$	0.80
	Tidal Freshwater	$L = 3.37W - 5.78$	0.86

Statistics on marked and tagged salmonids are shown in Table 4. These numbers for PIT- and coded-wire tags are conservative since the detector was not always available. Note the mean size of marked Chinook (presumably hatchery-reared fish) is almost twice the overall average size (79 mm). Archived coded-wire tags have not yet been processed.

Table 4. Numbers of marked Chinook and coho salmon 2002-2004. AD, adipose fin clip; PC, pelvic fin clip; CWT, coded wire tag; AD+CWT, adipose fin clip and coded wire tag; PIT, passive integrated transponder tag; % Total computed from total abundance, FL fork length; SD, standard deviation.

Species	AD	PC	CWT	AD +CWT	PIT	Total	Total (%)	Mean FL (mm)	SD (mm)
Chinook	111	28	10	51	1	201	2.9	141.6	42.2
Coho	68	0	1	8	0	77	37.9	141.7	24.3

**Hydrography**—We have made over 1,000 nearshore CTD casts to date, and detailed analysis is presently underway. Here we describe general findings. During low-tide sampling periods, horizontal and vertical gradients of salinity and temperature varied strongly among sites and sample periods, and could be pronounced. Within a site, water masses were nearly isothermal, with both horizontal and vertical temperature gradients generally less than 3°C. However, seasonal temperature variation was large (6-22°C), and because we sampled near low tide, was mostly a function of river water temperature (Section 2.3). Temperatures exceeded 20°C from June or July through September each year.

Salinity patterns varied widely, depending on seasonal factors and location. Mixing of river and ocean water resulted in highly stratified conditions at the estuarine stations: intense vertical salinity gradients, at times exceeding 1 psu/m, were observed at nearshore sites. At the surface, strong convergence zones resulted in horizontal gradients sometimes exceeding 4 psu over the 250-m transect. Salt was never detected at the three upriver sites. Chlorophyll concentration exhibited marked seasonal fluctuation related to annual phytoplankton production, with maximum concentrations (>25 mg/m<sup>3</sup>) found in river water during the spring bloom in April and May. However, vertical distributions of chlorophyll had surface minima and generally increased with depth. Turbidity patterns were quite variable, with strong vertical, horizontal, and between-site gradients apparent but without consistent pattern.

## Discussion

Overall fish community structure exhibited consistent seasonal patterns during 2002-2004 with some interesting interannual variation (Figure 2, Table 2). On the landscape scale, community structure between estuarine and tidal freshwater sites was segregated by salinity. Overall patterns at tidal freshwater sites included numerical dominance by sticklebacks during all seasons and years. Chinook generally made up a high proportion on the remaining catch, and was sampled year-round. The estuary sites exhibited a more temporally variable community structure. Upper estuary sites exhibited dominance by stickleback in spring and winter, while shiner perch had greatly increased abundance during summer months. Chinook salmon abundance was highest in spring and summer; chum salmon was abundant in spring. Lower estuary sites were most diverse and temporally variable. Surf smelt generally dominated the numerical abundance in spring and summer, while sticklebacks were mercifully few except during winter. Chinook salmon abundance was highest in spring and summer; chum salmon had proportionally higher abundance than Chinook during spring 2002 and 2003.

We found consistent differences between the mean size of Chinook salmon collected at estuarine and tidal freshwater sites during the same month (Figure 5). Upriver fish were 20-50 mm smaller than the corresponding estuarine fish. While we likely were sampling fish originating from different locations, this size difference suggested extended rearing in the lower Columbia system, rather than rapid migration down river. A pattern of rapid migration would tend to homogenize the size-frequency and monthly mean size patterns. At a growth rate of 0.75 mm/d (Section 1.4), residency in the system of about one month is implied.

Physical gradients measured at the landscape scale were both intense and variable. There was a strong seasonal component associated with variation in river flow. In the lower estuary, vertical salinity gradients were notably strong, and salmon usually were in water of measurable salinity. At upper estuarine stations, water was often relatively fresh during sampling, and no salt was detected at the upriver sites. Seasonal temperature maxima likely affecting salmon abundance and performance were also measured.

Future work will entail a more detailed analysis of salmonid abundance in relation to physical gradients. We will also consider ecological interactions of salmonids with other fish, including coincidence of salmon and similarly sized baitfish during migration as a possible predator swamping effect, and trophic competition between salmon and other dominant fish species.

## **1.2 Genetic Analysis of Migration and Stock-Specific Habitat Use**

### **Introduction**

Genetic samples collected from Chinook salmon caught in beach-seine (Section 1.1) and trap-net hauls (Section 2.1) are being analyzed to characterize the stock-specific spatial and temporal distribution of juvenile salmon in the Columbia River estuary. These data will be correlated with a wide range of biotic and abiotic factors in collaboration with other research groups. This information is expected to help mitigate human impacts and facilitate conservation and recovery efforts.

### **Methods**

Assignment of individual fish to population-of-origin was used to evaluate the distribution of Chinook salmon juveniles through time and space. From a variety of sources, approximately 5,000 individual Chinook salmon were genotyped for simple-sequence repeats (microsatellites) to create a basin-wide data set representing all known genetic lineages in the Columbia River. This includes over 70 Chinook populations. Eight microsatellite markers were used initially, and eight more were added for populations in the Lower Columbia River Chinook evolutionarily significant unit (ESU). This "baseline" data set provided reference populations or "reporting groups" to which individual fish were assigned a stock-of-origin based on their multilocus genotype.

Individual assignments were made using the algorithm of Rannala and Mountain (1997). Several methods were used to evaluate bias and precision in individual fish assignment. First, jackknife resampling was used to sequentially leave out one individual fish from the baseline, recalculate allele frequencies, and assign that "unknown" individual to its putative population of origin. Those estimated assignments were then compared to known origins of the fish to estimate average assignment accuracy and precision. A second approach to power analysis was to use genetic data from tagged fish of known origin to estimate the origin of fish tagged at hatcheries in various ESUs. This later approach provided completely independent estimates of baseline utility.

Once the power of the baseline data set of reference populations was ascertained, individual assignments to stock of origin were conducted for a series of mixtures of unknown of juveniles. Mixtures were chosen to compare the frequency distribution of various ESUs among habitat types, salinities, and along different migration pathways. Samples were also examined from different time periods (May and July). Sampling methods for analyses of mixed juveniles included beach seines and trap-net sets for nearshore and tidal channel sites (this study), and purse-seine sets for mid-channel sites.



## Results

Descriptive population genetic analyses were broadly concordant with earlier allozyme studies (protein electrophoresis). Multivariate analysis revealed clear geographic structuring, and reporting groups were constructed based on the level of that structuring. The principal genetic division in the Columbia River basin was found between inland populations, dominated by a yearling smolt life history, and coastal populations, which produced mostly subyearling smolts. This geographic breakdown of life history was not absolute because some coastal populations produce yearling migrants and some inland populations produce subyearlings (e.g., terms such as stream-type and ocean-type "lineage" have been confusing).

Jackknife estimates of accuracy of individual assignment ranged between 87 and 96% among higher-level reporting groups (Figure 7; Table 5). Similarly, individual test assignments of known-origin coded wire tagged fish ranged between 80 and 100%.

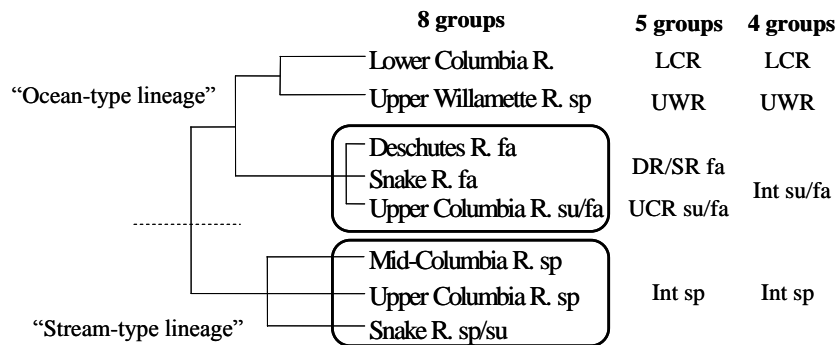


Figure 7. Condensed dendrogram based on  $F_{ST}$  distance representing all of the populations in the baseline and including various higher-level reporting groups. Different numbers of groups represent various higher-level reporting groups.

Table 5. Accuracy of individual Chinook salmon assignment to higher level reporting groups estimated with jackknife resampling.

		<i>Lower Columbia R.</i>	<i>Upper Willamette R.</i>	<i>Interior Spring</i>	<i>Interior Fall</i>	<i>N</i>
Lower Columbia R.	N	409	21	8	33	471
	%	86.84	4.46	1.70	7.01	
Upper Willamette R.	N	17	259	1	7	284
	%	5.99	91.20	0.35	2.46	
Interior Spring	N	22	9	1,665	35	1,731
	%	1.27	0.52	96.19	2.02	
Interior Fall	N	18	12	5	420	455
	%	3.96	2.64	1.10	92.31	

Not unexpectedly, most juvenile Chinook salmon from shallow water beach-seine and trap-net sites originated from the lower Columbia River ESU (Figure 8). Spatial and temporal differences were small and non-significant for beach-seine and trap-net samples. One exception may be the 2002 Point Ellice sample, which had an especially high proportion of lower Columbia River fish ( $P = 0.02$ ). There seemed to be some segregation of ESUs by habitat, with relatively more LCR fall-run fish found in scrub-shrub habitat relative to forested habitat (Figure 9).

Purse-seine samples from the mid-channel sites produced a very different pattern of ESU distribution than that of the shallow water sites ( $P < 0.00001$ ; Figure 8). Again not unexpectedly, many more interior spring-run fish were observed in mid-channel mixtures. The purse-seine samples also exhibited highly significant differences in the distribution of ESUs between May and July samplings ( $P < 0.00001$ ) (Figure 10.).

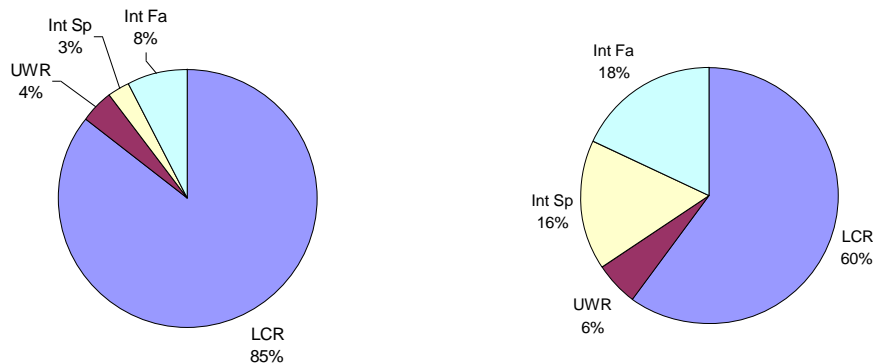


Figure 8. Percentage of the four high-level reporting groups in off-channel (left) versus mid-channel habitats (right).

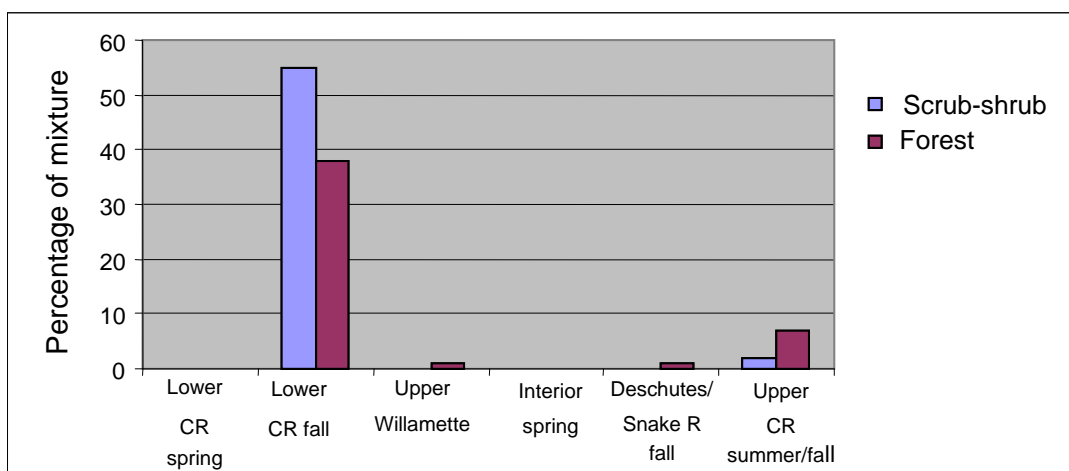


Figure 9. Frequency distribution of ESUs between habitat types at Karlson Island showed more Lower Columbia River (LCR) fish and less diversity in scrub-shrub habitat than in forest ( $P = 0.02$ ).

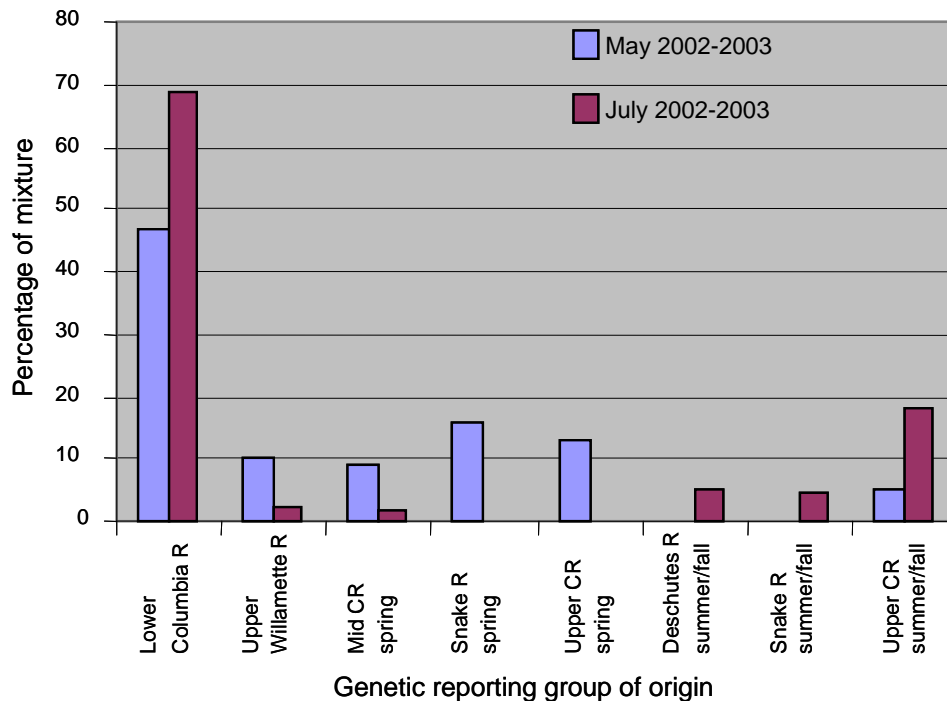


Figure 10. Highly significant temporal shift in the frequency distribution of ESUs taken in mid-channel purse seines ( $P < 0.00001$ ); yearling migrants come as a pulse in spring that tails off by July.

## Conclusion

Genetic baseline data collected to date have clarified the population genetic structure of Columbia River Chinook salmon. These data also provide substantial resolution of individual population-of-origin, especially at higher level reporting groups (e.g., combining genetically very similar Snake, Deschutes and upper Columbia River fall- and summer-run fish).

More unknown mixtures have been analyzed recently, and we have conducted additional power analyses and comparison of assignment algorithms. We have also begun to assemble all our existing data for final analysis and reporting. Analysis and reporting of existing data are our highest priorities and primary tasks now, with two papers currently in progress. The first paper describes spatial and temporal results comparing habitat associations and migratory timing and pathways in the Columbia estuary. A second paper reports on Willamette River mixture analysis.

More markers and better geographic representation will undoubtedly increase the power of inferences regarding potentially different distributions (or trophic interactions, body burdens, migration timing, etc.) of individuals from populations within the lower Columbia River ESU. More work remains to be done in building baseline data and in power analysis; nevertheless, we have demonstrated the utility of this new tool and look forward to significant progress in analyses, particularly those related to differential habitat use and body burdens of toxins, our proximate goals.

### **1.3 Scale and Otolith Analyses of Life History Characteristics and Habitat Associations**

#### **Introduction**

We used otolith chemical and structural analyses to determine the timing, residence, and growth of individual Chinook salmon in habitats of the lower Columbia River. Analyses of age-specific strontium-to-calcium ratios in otoliths has been used to establish migratory history or environmental associations in individuals of diadromous species such as striped bass (Secor and Piccoli 1996), eel (Tzeng and Tsai 1994), shad (Limburg 1995), sockeye salmon (Rieman et al. 1994), and Arctic charr (Radtke et al. 1996). Where salinity gradients are sharp, it appears that migrations across them are often reflected by changes in strontium/calcium (Sr/Ca) ratios in juvenile fish otoliths. Studies on a wide array of Pacific salmon species and populations support the connection between associations with seawater and freshwater and Sr/Ca ratios in otoliths (Volk et al. 2000).

#### **Methods**

A brief description of how the data are acquired will show the utility of these analyses. Once the otolith has been sectioned to reveal the entire life history of the individual, from initial otolith formation in the embryo to death, a chemical analysis transect is performed across the otolith. This results in a detailed profile of strontium abundance in the otolith (Figure 11). Sr/Ca ratios typically rise in proportion to contact with salinity, and these values are used as an indicator of when fish encounter estuary habitat. In Figure 11, the spike in strontium abundance demarks estuary entry for this individual, following a long period of low strontium count rates corresponding to freshwater residence (FW). The initial peak represents elevated strontium count in the otolith core during the embryo and alevin stage resulting from maternal anadromy (Volk et al. 2000).

Once the point of estuary entry is identified on the otolith, the close relationship between fish size and otolith size (typically  $r^2 > 0.90$ ) can be used to estimate the size at which fish entered the estuary. Additionally, we can locate the estuary entry point on the otolith section and count daily otolith increments to gain an estimate of the length of estuary residence time prior to capture. Finally, since we have an estimate of size at estuary entry and a known size at capture, and a measure of the time period between, we can estimate growth rates during estuary residence. Also, assuming most fish emerge from the gravel at approximately the same size, we are able to obtain a relative measure of residence time in fresh water habitats. These data components represent a fairly complete description of life history for every individual of interest and allow us to paint a detailed picture of relationships between estuary habitat and juvenile Chinook life history.

Chinook salmon were collected from beach-seine samples, and the otoliths were removed in the laboratory. As of this writing, samples from estuarine stations Clatsop Spit, Pt. Adams Beach, and Point Ellice, and the tidal freshwater site East Tenasillahe Island have been processed (Figure 1).

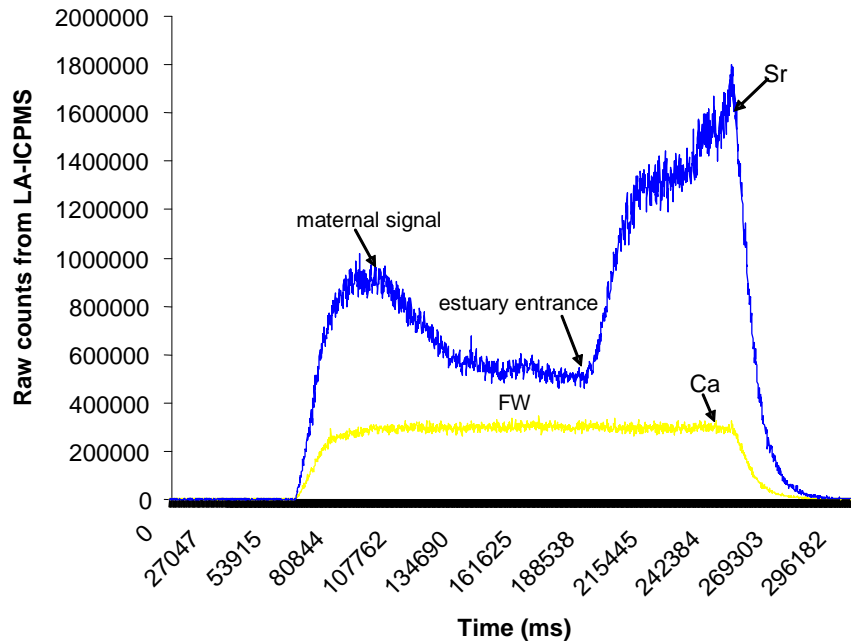


Figure 11. Plot of strontium abundance across an otolith transect from a juvenile Chinook salmon captured in the Columbia River Estuary. Note maternal effect, freshwater, and estuarine residence times. LA-ICPMS, laser ablation-inductively coupled plasma mass spectrometer; FW, freshwater residence.

**Otolith Preparation**—Dissected otoliths were cast sulcus (medial) side down into solid blocks of polyester resin. Mounted otoliths were ground on a rotating lap wheel using 500-grit, then 1200-grit silicon carbide paper until a polished hemi-section was created that exposed the surface of the otolith from core to edge. This surface was glued to a glass slide. After most of the resin block was removed with a diamond saw, the lateral otolith surface was again ground and polished by the same method until a thin section (nominal thickness = 100  $\mu\text{m}$ ) was created that included exposed primordial core elements evident with reflected light. Sections were fine polished with 1  $\mu\text{m}$  alumina slurry.

**Otolith Analysis**—All sectioned specimens were analyzed at the Keck Laboratory for Plasma Mass Spectrometry at Oregon State University. The laser ablation system consists of a New Wave DUV 193 nm ArF laser coupled to a Thermal Elemental PQ Excell quadrupole inductively coupled plasma mass spectrometer (ICP-MS). The sample chamber has a continuous flow of helium gas that carries the ablated material to the mass spectrometer. Analytical transects were initiated from a point near the otolith core and ended at a point beyond the margin of the otolith along a dorsal-posterior radius. There was some variation in the precise axis analyzed due to difficulties aligning the cross hairs with the laser or obvious cracks or pits in the otoliths. Each otolith analysis was paired with an analytical transect on a polished sample of NIST 612 glass standard, a sintered silica glass standard with ~35 to ~80 ppm of some commonly analyzed trace elements.

**Strontium Profiles**—Time-resolved data were examined visually following each analysis and two regions were selected. The first was prior to the onset of ablation (background), and the second after ablation began. Integrated counts per second and standard deviations were calculated for all elements in both regions, and inflection points or peaks in elemental raw counts were determined from plots of the data. For strontium, we focused on the inflection point where count rates began increasing after their nadir, which we hypothesized indicated the fish's entry to waters with measurable salinity (see results). A z-test was used on running averages of 10 count rate values in the region to determine when count rates were significantly increasing. The position of peak values was determined by eye, and we used the mean of ten surrounding count rates for quantitative determinations.

Once the location of any of these points of interest (POI) was recognized on raw count plots, we noted the time in the analytical transect where they occurred and determined their position on the otolith using the following equation,

$$\text{Distance from edge } (\mu\text{m}) = ((\text{Time Margin (msec)} - \text{Time POI}) / 1000) \times 5 \mu\text{m}.$$

To account for variations in the start of the laser transect with respect to an otolith core element, we determined the distance of a POI from the otolith core by applying a distance correction factor to the transect measures. A series of radial measures on each otolith section allowed us to compare the distance to a common feature along the laser scar, such as the otolith edge, with direct measurement from the otolith core. This difference was used to correct calculated distances to any POI along the laser transect to represent actual distances from the otolith core to the POI.

**Measures and Counts**—We viewed each sectioned otolith with light microscopy to conduct radial measures and increment counts using image analysis software. All otoliths were measured along a standard dorsal-posterior radius starting at the posterior most core element and ending at the otolith edge. The length of the laser scar was also measured from its beginning to the edge of the otolith. Since it was rarely possible to position the start of the laser transect precisely over the preferred core element, this measure gave us a means to correct the position so that the chemical transect data could be accurately placed on the actual otolith radius. Along the same radius, we attempted to enumerate otolith increments.

Back-calculations of fish size at any POI, such as estuary entry, were based on the established otolith-fish length relationship for Chinook salmon in the Columbia River. Estuary residence time was determined by assuming a mean otolith increment width and dividing this into the otolith radial distance after the strontium increase. Estuary growth rates were determined by subtracting estimated estuary entry length from capture length and dividing by estimated residence time in the estuary. Growth rates were only calculated for fish resident in the estuary longer than ten days.

## Results

Estuarine residence time varied widely among fish, ranging between 0 and 88 days (Table 6). Fish with residence times < 10 d were found at all stations. A few juvenile Chinook salmon at the tidal freshwater sites also had slight to moderate increases in Sr (Figure 12), even though increased salinity was never detected there during our CTD sampling that occurred at low tide.

Table 6. Estimates of estuarine residence time for Chinook salmon sampled from four sites during 2002 and 2003. Values are range, N, and mean for both years sampled.

Site	Zone	Residence time (d)		
		May	June	July
E Tenasillahe Isl	Freshwater	0-50 (12) mean = 17		0-31 (6) mean = 5
Pt Adams Beach	Middle estuary	22-44 (14) mean = 33	8-88 (7) mean = 52	4-55 (8) mean = 26
Pt Ellice	Middle estuary	0-59 (14) mean = 21		0-79 (12) mean = 32
Clatsop Spit	Lower estuary	0-50 (9) mean = 28		3-45 (6) mean = 12

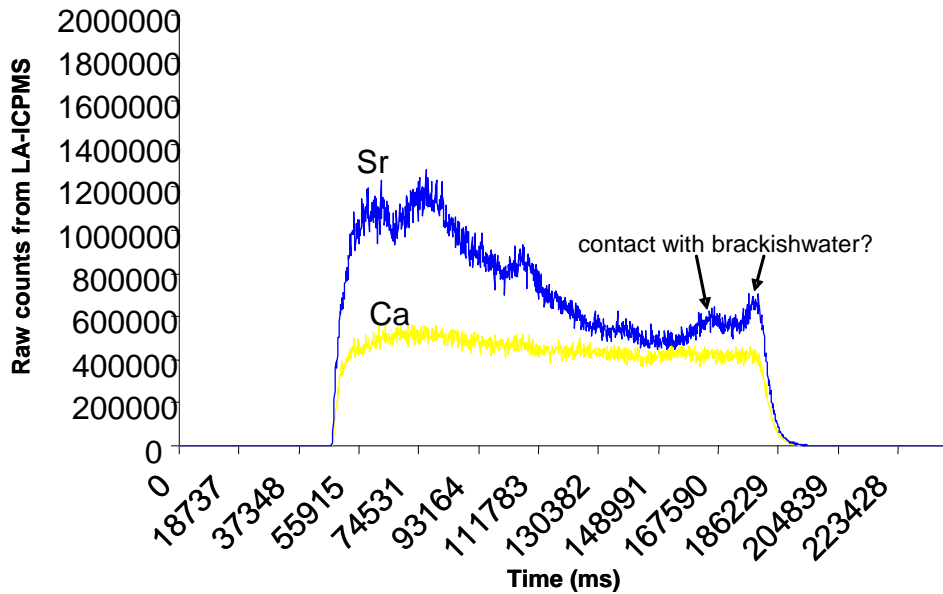


Figure 12. Example of Sr abundance across a juvenile Chinook salmon otolith. Sample collected at a tidal fresh site with a slight Sr rise on the otolith edge. LA-ICPMS, laser ablation-inductively coupled plasma mass spectrometer.

One unexpected analytical difficulty has been reliably enumerating otolith daily increments for a large proportion of specimens. Thus, the measure of elapsed time in otoliths needed for growth rate and residence time calculations cannot be accurately estimated. Until we can resolve this issue, we have made estimates based upon a mean otolith increment width of 3  $\mu\text{m}$  representing 1 day. Using this value, we found the estimated sizes at estuary entry also varied widely (Table 7). Sizes of Chinook at estuarine entry tended to increase from May through July (except at E Tenasillahe Isl). Overall, fry migrants (< 50 mm) represented about 10% of our sample while more than two-thirds of fish contacted measurable salinity at sizes between 50 and 90 mm.

Table 7. Estimates of size (mm) at estuarine entry for Chinook salmon sampled from four sites during 2002 and 2003. Values are range, N, and mean for both years sampled.

Site	Zone	Size at entry (mm)		
		May	June	July
E Tenasillahe Isl	Freshwater	26-86 (12) mean = 66		51-81 (6) mean = 64
Pt Adams Beach	Middle estuary	77-84 (2) mean = 81	51-73 (7) mean = 56	77-107 (8) mean = 93
Point Ellice	Middle estuary	55-92 (14) mean = 67		41-104 (12) mean = 81
Clatsop Spit	Lower estuary	26-86 (9) mean = 67		54-90 (6) mean = 82



Calculated estuary growth rates on a sample of fish resident greater than 10 d ranged up to slightly more than 1 mm/d. Mean values among all sites were between 0.45 and 0.86 mm/d (Table 8). For fish captured at middle estuarine sites Point Adams Beach and Point Ellis, mean growth rates were lower in July than May; however, the opposite was true for fish captured at Clatsop Spit.

Table 8. Estimates of growth rates during estuarine residency (mm/d) for Chinook salmon sampled from four sites during 2002 and 2003. Values are range and N for both years sampled.

Site	Zone	Growth (mm/d)		
		May	June	July
E Tenasillahe Isl	Freshwater	0.50-0.80 (4)		0.56 (1)
Pt. Adams Beach	Middle estuary	0.56-0.67 (2)	0.33-1.02 (5)	0.06-0.96 (4)
Pt. Ellis	Middle estuary	0.39-0.92 (7)		0.36-1.05 (6)
Clatsop Spit	Lower estuary	0.26-1.06 (5)		0.81-0.90 (2)

## Discussion

Results to date show that strontium profiles in juvenile Chinook salmon otoliths from the Columbia River Estuary are very similar to those observed for migrating juvenile Chinook in other river systems (Volk et al., in prep), and suggest that they are useful in determining when fish encounter brackish water. The strontium concentration time series allows estimation of estuarine residence to time of capture, size at estuary entry, and growth rates during estuarine residence.

We found a fairly large variation in the time Chinook salmon spent in the estuary before capture. Of the samples completed to date, 40-60% had estuarine residence times less than 10 d, including the site at the mouth of the estuary. Conversely, all sites examined had individuals that had been in estuarine water at least one month, and residence times of up to three months were found. The finding of slight-to-moderate Sr increases (Figure 12) in Chinook captured in tidal freshwater sites was surprising. This finding suggests that some juvenile Chinook salmon caught at tidal freshwater sites had come into contact with the marine-influenced estuarine zone and returned to the tidal freshwater habitat. This variation is likely due in part to the complex hydrography of the Columbia River estuary, where the distribution of estuarine water varies greatly on vertical, horizontal, and temporal scales (Section 1.6).

The dynamic circulation patterns caused by tidal action and river flow clearly affect variation in where and when migrating salmonids contact salt water. Another important factor is individual behavioral variation associated with smolting and/or different life history strategies of the salmon we sampled, both of which would increase variance in estuary entry estimates. For instance, the appearance of fish at the mouth of the river may be due to rapid movement through the migration corridor, or it could be due to delayed encounter with saline habitats and longer rearing in tidal freshwater habitats.

Fish may volitionally remain in freshwater or estuarine water masses depending on genetically determined life history traits. The range of residence times we observed in the Columbia River estuary (0-88 d), was roughly similar to the range observed in the Salmon River estuary (0-113 d; Volk et al., in prep). The picture of estuarine residence should clarify as we progress with additional samples and synthesis with other aspects of this study.

Using the estimated otolith increment width, we found that fish contacted salt water at sizes ranging from fry to fingerling. Calculated mean growth rates among all sites (0.45-0.86 mm/d) were very similar to those calculated in the Salmon River by otoliths (0.35-0.75) or by mark and recapture studies (0.4-1.0 mm/d; Bottom et al., unpub. data) as well as those from five Vancouver Island estuaries and the Fraser River (0.22-0.61 mm/day; Levy and Northcote 1982; Healy 1991).

## **1.4 Correspondence Between Scale and Otolith Analyses**

### **Introduction**

The growth patterns of circuli (rings) of salmon scales are thought to reflect estuary entrance based on growth difference between freshwater and brackish water habitats, resulting in an “estuarine check.” To test this hypothesis, we are examining the chemical signatures of salmon scales to look for influences of marine water and the correspondence to scale structural features. This will enable calculation of growth in estuarine environments. In addition, we are comparing paired otolith and scale samples to bridge the gap between two similar methods of estimating growth and life history. If scale attributes that reflect estuary entry and residence can be validated with otoliths, it may be possible to look retrospectively at archived scale samples from the Columbia River to draw inferences about historical Chinook life history diversity.

### **Methods**

Fish samples were collected from beach-seine and trap-net sampling. Scales were removed from above the lateral line between the insertion of the anal fin and the last dorsal fin ray, and were placed between a folded piece of clear acetate and labeled. Scales were then examined in the laboratory under 10× magnification with a Micron 780 microfiche for the presence or absence of a scale check. Criteria for distinguishing scale checks (narrowly spaced circuli adjacent to wider spaced circuli) follows Rich (1925), Reimers (1975) and Bilton (1975). Scale samples were labeled, removed from the acetate under a Leica dissecting scope, and transferred to a microscope slide that had been prepared with 3M mounting tape. Between 4 and 10 scales per sample were mounted on both the distal (circuli side) and proximal (smooth side) facing up. However, after trials, we preferably analyzed scales proximal side up.

All chemical analyses occurred at the Keck Laboratory for Plasma Mass Spectrometry at Oregon State University using the ICP-MS apparatus described above. A transect for ablation was drawn from the nucleus to just beyond the scale edge, approximately 20 degrees off the midline, preferably to the dorsal edge. Each scale transect was coupled with a transect along a polished NIST (610 or 612) glass standard with known concentrations of trace elements. Raw counts of Sr and Calcium (Ca) were extremely variable and were transformed to a Sr/Ca ratio. The Sr/Ca ratio was then plotted, and points of interest were recorded.

Length measurements were taken from the nucleus of the scale along the ablation scar, measuring distances from 1) the nucleus to hypothesized estuary check, 2) from nucleus to scale edge, and 3) between circuli. All measurements were taken with a Leica microscope under 10× magnification while using Image Pro software to digitize and measure specimens at the WDFW Otolith Laboratory. Transformations of scale length to fish fork length were made with the Lee-Fraser method (Ricker 1971):

$$L_t = [S_t/S(L-C)]+C$$

where  $L_t$  = fork length (mm) of fish at time  $t$ ,  $L$  = fork length (mm) of fish at capture,  $S_t$  = scale radius (microns) at time  $t$ ,  $S$  = total scale radius (microns) and  $C$  = length (mm) of fish when the scale radius is equal to zero.

## Results

To date approximately 110 paired otolith and scale samples have been prepared and analyzed. Twenty-two individual scale samples were determined to have elevated Sr/Ca ratios from the initial values along the laser ablation transect (e.g. Figure 12). In all 22 cases the corresponding otoliths for those samples were also found to have elevated Sr, indicating contact with marine water (Figure 11). However otoliths that had evidence of estuary entrance (chemical signal) did not always show increased Sr/Ca ratios on their corresponding scale samples.

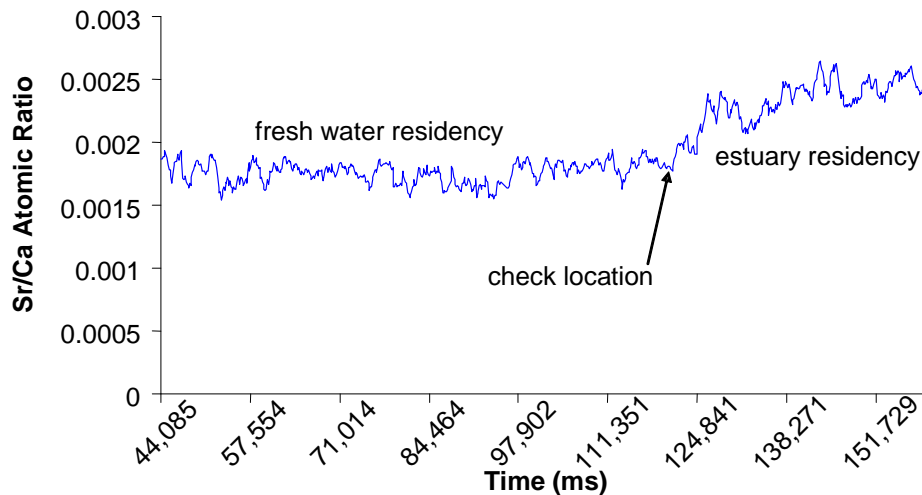


Figure 13. Example of a transect across a juvenile Chinook salmon scale where elevated values indicate the incorporation of higher Sr levels located in the saline portion of the estuary.

Visual scale checks, denoted by narrowing circuli followed by wider circuli, were tested for a correspondence with the location of Sr/Ca increases in the scale samples. Back-calculated fish size at the scale chemical check was highly correlated to that of the scale visual check ( $r^2 = 0.74$ , Figure 14). However, back-calculated fish size at estuary entrance on the otolith and scale did not correlate well ( $r^2 = 0.14$ , Figure 15).

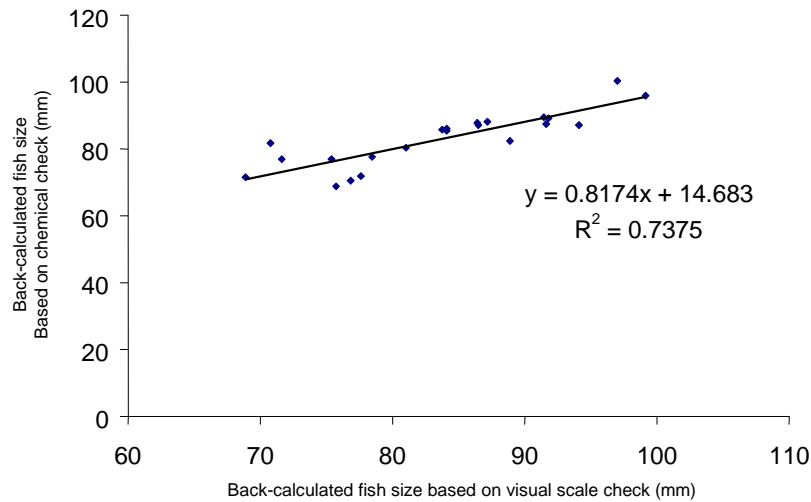


Figure 14. Relationship between back-calculated fish sizes from visual and chemical signals on juvenile Chinook salmon scales.

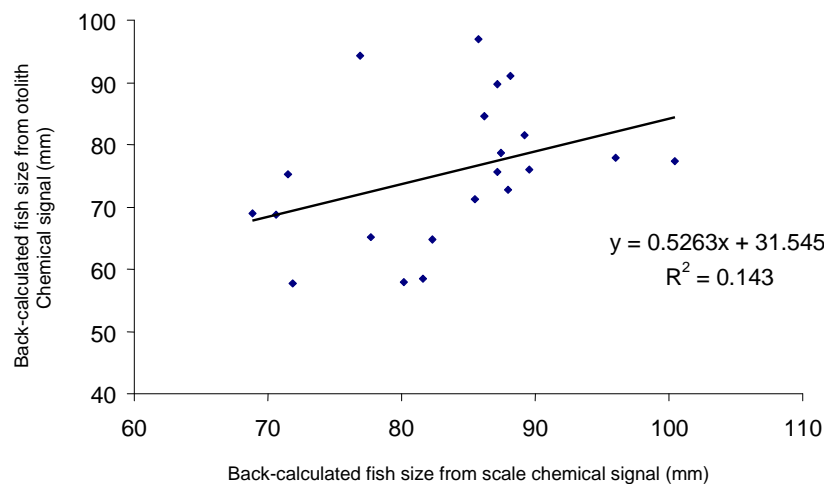


Figure 15. Relationship between back-calculated fish sizes of juvenile Chinook salmon using Sr/Ca signals on otoliths and scales.

## Discussion

All scale samples that had a clear Sr/Ca rise also showed elevated Sr on their respective otoliths. However, a significant rise in Sr on the otolith was not always indicative of a marked Sr/Ca rise in the scale. There are several possible reasons for the discrepancy between uptake of Sr in scales vs. otoliths. First, salmonid otoliths form while the embryo develops (Kalish 1990; Volk et al. 2000; Zimmerman 2002), while scales form some time after hatching and emergence. In the Columbia River estuary, we found scales on juvenile Chinook salmon ranging from 35 to 40 mm. Fish entering the estuary before scale formation would not record a visual check or Sr/Ca rise due to estuary entrance. We may be able to quantify the Sr/Ca ratio to predict whether or not scale formation first occurred while in the estuary.

Another possibility is a time lag between exposure to Sr and uptake in the scale. Several experiments have pointed out an apparent lag time between treatment effects (temperature, feeding level) and their subsequent detection on the scale (Bilton 1975; Boyce 1985). In examining daily growth increments on otolith specimens that exhibited Sr increases, we found that elevated Sr levels on fish with less than 2 weeks of exposure to saline water were not detectable on the scale. Finally, there seems to be some threshold of Sr that needs to be attained before it is incorporated into the scale. We observed otoliths that showed a rise in Sr over an extended period of time, but the overall Sr level had not increased to the level of the maternal Sr signal (blue box Figure 16). After counting otolith increments for these samples, we determined that the fish had been in the estuary longer than the observed lag time of scale formation. We hypothesize that the relatively low Sr concentrations in water might explain the lack of Sr incorporated into the scale.

Several researchers have proposed that observed scale checks could be caused by entrance into brackish water, and have used this method of pattern recognition to determine the proportions of Chinook salmon exhibiting an estuarine-resident life history (Rich 1920; Reimers 1973; Schluchter and Licatowich 1977). However no physical evidence has been reported up to this point to link the presence of these “estuary checks” to actual estuary entrance. We believe that we have linked the established method of detecting estuary entrance and residency time in otoliths to scales. Furthermore, we have shown an apparent relationship between the rise in Sr/Ca ratio to that of the physical location of the scale check (Figures 14 and 15). This method provides a measure of validation for the reported estuary check that can occur on juvenile Chinook salmon scales in the Columbia River estuary during our sampling period. In addition these data support past studies using estuary scale checks to denote estuary entrance and estuarine life history type.

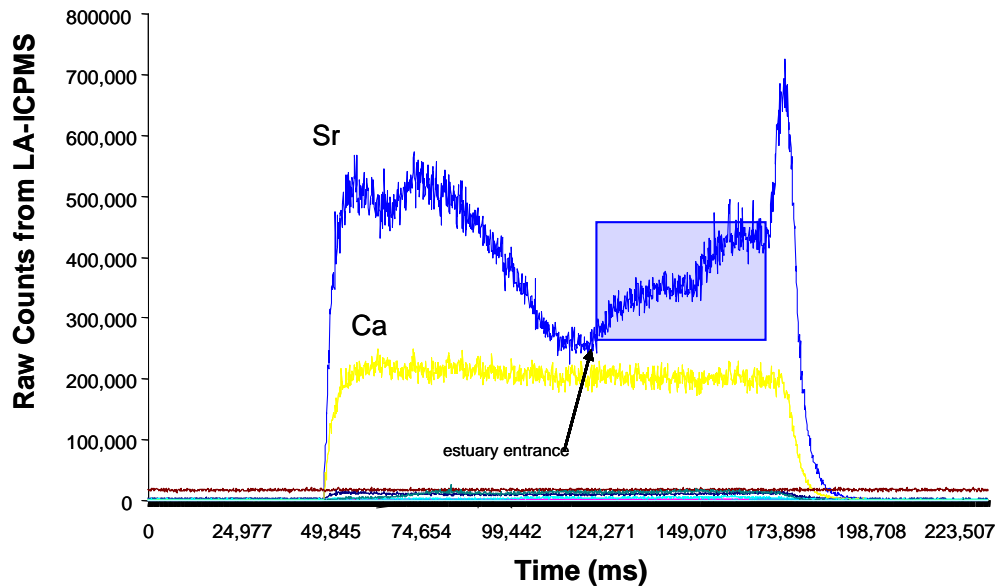


Figure 16. Otolith microchemistry profile for a juvenile Chinook salmon captured at the Point Adams middle estuary site. Light blue rectangle represents the period of gradual Sr uptake not detected in the fish's scales. LA-ICPMS: laser ablation-inductively coupled plasma mass spectrometer.

## 1.5 Trophic Relationships of Species and Life History Types to Selected Habitats

### Introduction

In 2002, we began monitoring spatial and temporal variation in juvenile Chinook salmon diet associated with landscape-scale sampling. These data will be used to determine the seasonal and spatial variation in salmon diet among seven estuary sites (tidal freshwater sites at Lower Elochoman Slough, Upper Clifton Channel, and East Tenasillahe Island; middle estuary sites at Point Adams Beach and Point Ellice; and lower estuary sites at West Sand Island and Clatsop Spit).

## Methods

Juvenile Chinook salmon between 42 and 143 mm FL were collected during beach-seine operations. Fish were euthanized immediately after collection, frozen at the laboratory, and later dissected to remove the stomach. The stomach and its contents were preserved in 10% buffered formalin. Data processing included

- 1) Ranking stomach fullness by volume between 0 and 100%
- 2) Measuring the mass of stomach contents
- 3) Sorting prey items found in the stomach by taxonomic category and habitat associations (e.g. terrestrial insects, benthic invertebrates, plankton, fish)
- 4) Measuring the numerical and gravimetric contributions of each category of prey item to the diet

To determine which prey items were most important in the diet of salmon, an Index of Relative Importance (IRI) was calculated for each prey type (see Section 2.2 for detailed description of this index).

## Results

**Stomach Fullness**—Processing and analysis of stomachs is not complete, and results presented here are preliminary. Below is a general summary of results from stomachs analyzed to date from all seven landscape-scale sampling sites in May 2002 (n = 33), July 2002 (n = 35), May 2003 (n = 30), and July 2003 (n = 35). Very few stomachs were effectively empty: less than 10% were 0-5% full, and over half (57%) were more than half full (Table 9).

Table 9. Percent stomach fullness.

<b>Stomach fullness rank (% volume)</b>	<b>Percent of total analyzed (%)</b>
0-5	7
6-25	17
26-50	18
51-75	16
76-100	41



**Numerical Composition of Prey**—During May and July, juvenile Chinook salmon fed primarily on terrestrial insects (flies, beetles) and benthic organisms (gammarid amphipods, other crustaceans, and polychaete worms). Overall, salmon diet was numerically dominated by dipteran flies (gnats and midges) and benthic, tube-dwelling amphipods of the genus *Corophium* (estuarine crustaceans; Figure 17). Cladocerans (water fleas) were sometimes found in the diet of fish captured in the tidal freshwater sites (Lower Elochoman Slough, Upper Clifton Channel, East Tenasillahe Island) and one middle estuary site (Point Ellice). Parasitic nematodes were occasionally found in salmon stomachs. These have been sent to a parasitology laboratory for further identification.

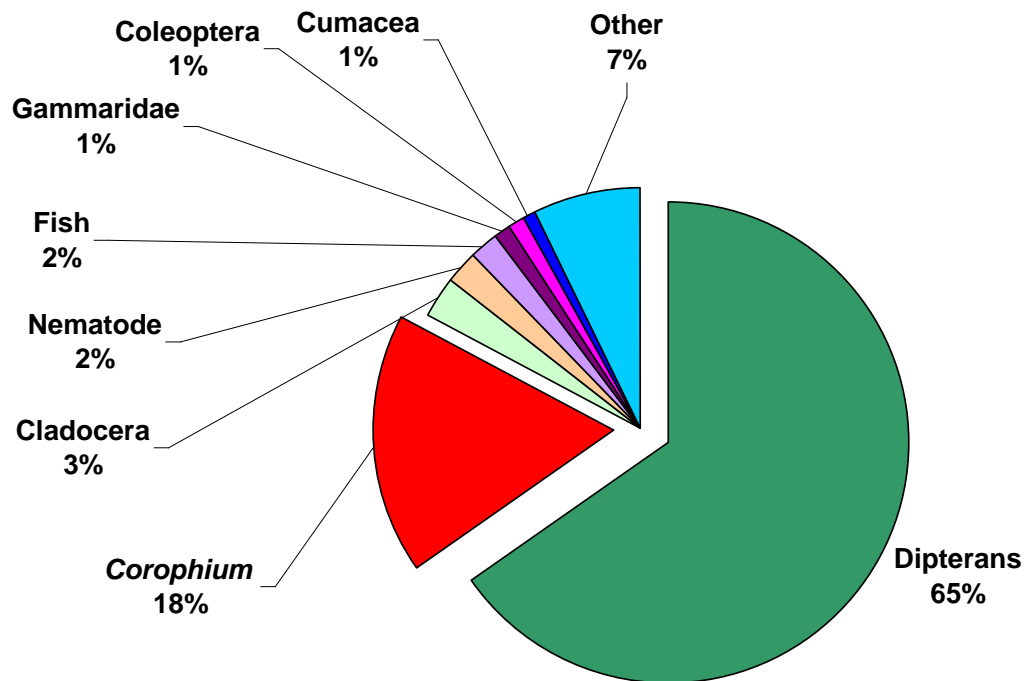


Figure 17. Chinook diet by percent numerical composition (all samples combined).

Gravimetric composition of prey. Percent diet by biomass was dominated by tube-dwelling amphipods of the genus *Corophium* and dipteran flies (gnats and midges; Figure 18). Although fish, beetles, and megalopae of *Cancer magister* (Dungeness crab) were seen infrequently in the diet, these prey categories accounted for a significant amount of prey biomass because their body mass is several orders of magnitude greater than that of the numerically dominant flies or amphipods.

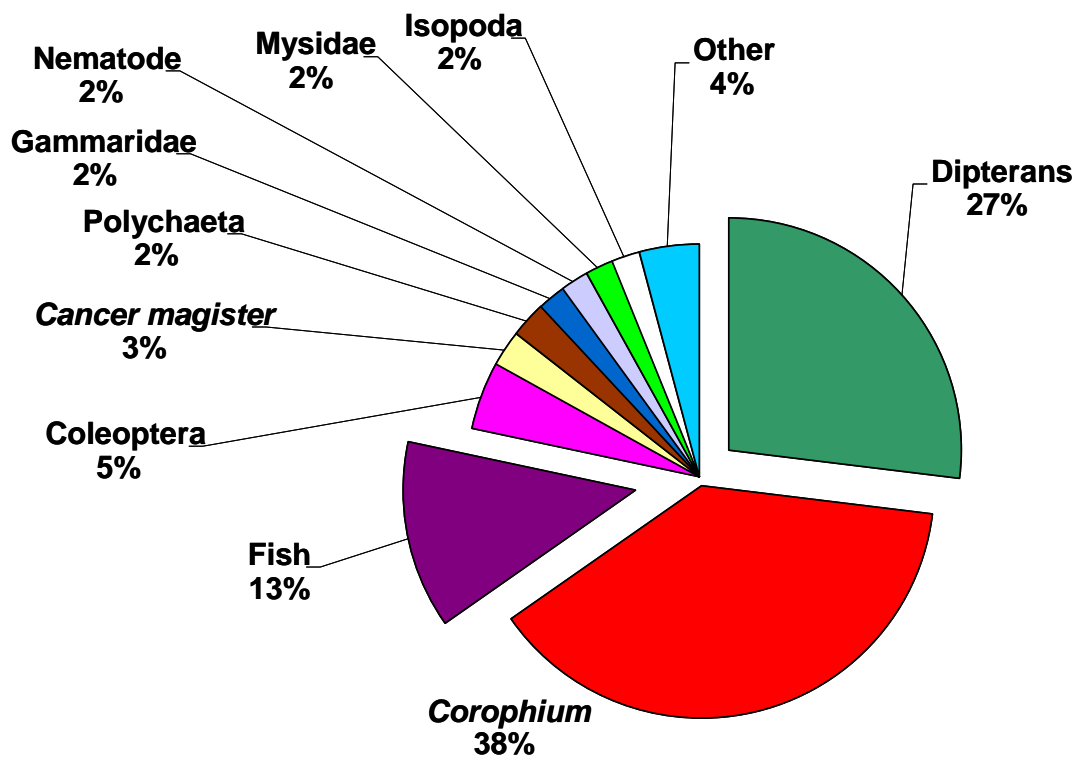


Figure 18. Chinook diet by gravimetric composition (all samples combined).

**Relative Importance of Prey Types**—Examination of the Index of Relative Importance indicated that dipterans and *Corophium* amphipods were the two most important of all prey types found in Chinook diet (Figure 19). These prey types accounted for 94% of all contributions to total IRI. *Corophium salmonis* was more important than *Corophium spinicorne* (17.4 vs. 4.1% total IRI).

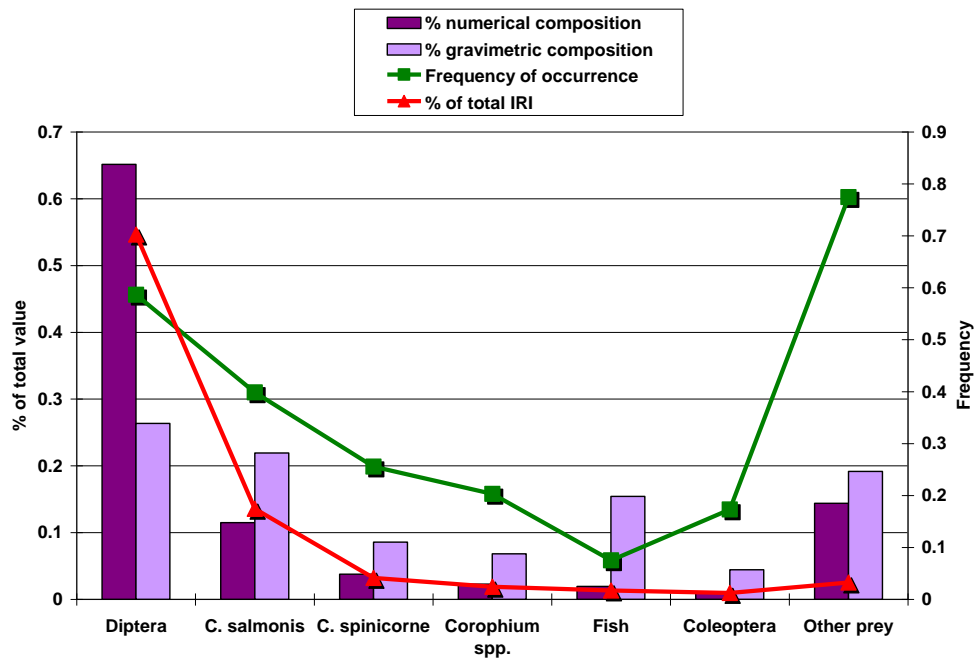


Figure 19. Indices of relative importance of different prey types found in Chinook diet (all samples combined).

Dominant prey types by sampling site and month. Dipterans were found in the diets of Chinook throughout the estuary during July (Figure 20). No measurable biomass of dipterans was found in stomachs sampled during May. *Corophium* amphipods were also found in the diet of fish captured throughout the estuary, and amphipods made up a larger proportion of diet mass in July than in May (Figures 21 and 22). *C. spinicorne* was primarily found in diets of fish captured from the middle and lower estuary, whereas *C. salmonis* was primarily found in diets of fish captured from tidal freshwater and middle estuary sampling sites.

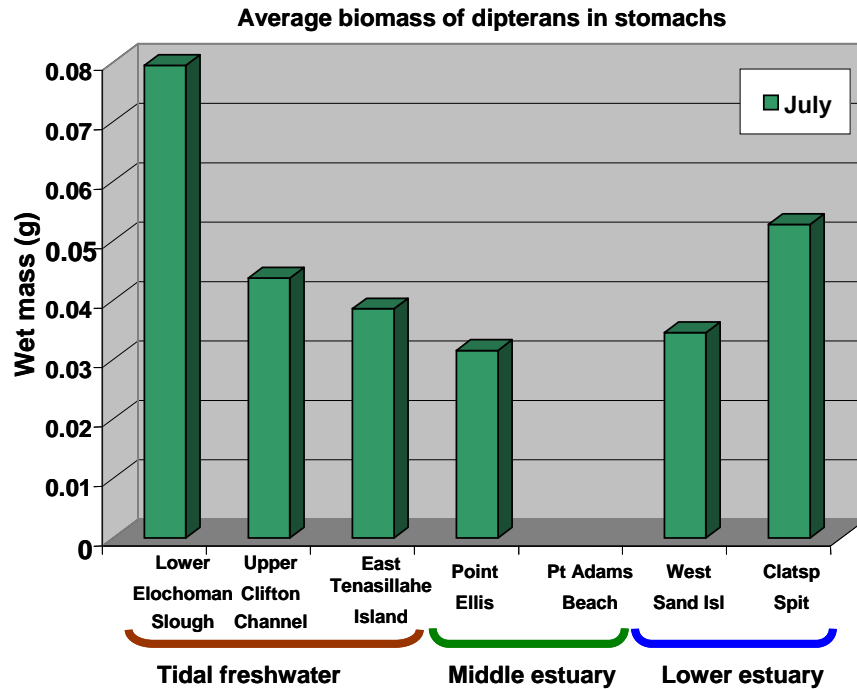


Figure 20. Biomass of dipterans in Chinook stomachs collected in July by sampling site (2002 and 2003 combined).

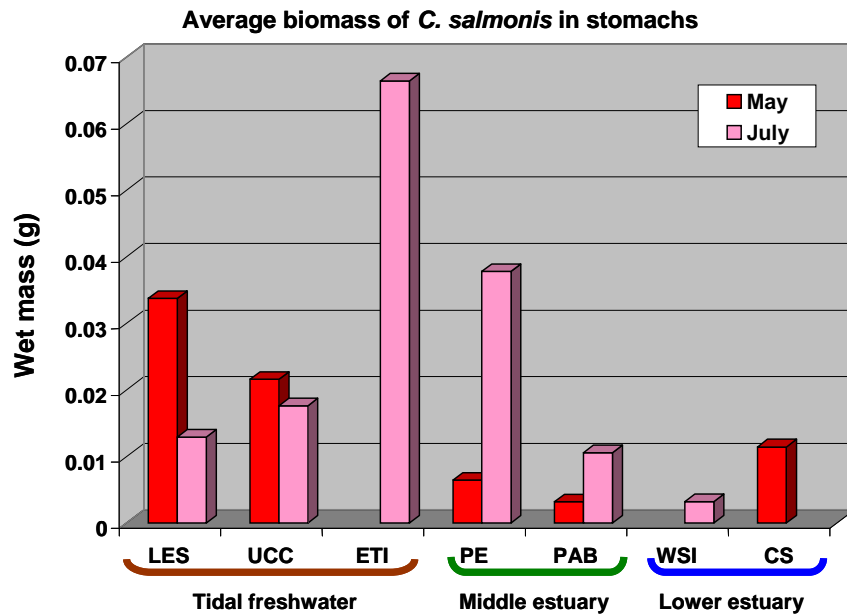


Figure 21. Biomass of *Corophium salmonis* in Chinook stomachs collected in May and July by sampling site (2002 and 2003 combined). Abbreviations correspond to sites shown in figure 20.

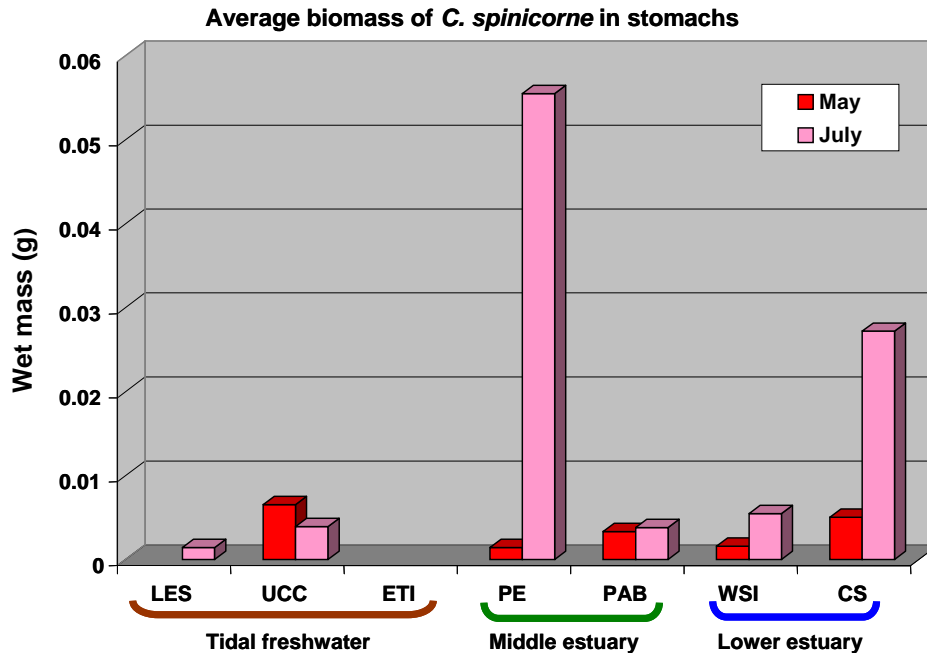


Figure 22. Biomass of *Corophium spinicorne* in Chinook stomachs collected in May and July by sampling site (2002 and 2003 combined). Abbreviations: LES, Lower Elochoman Slough; UCC, Upper Clifton Channel; ETI, East Tenasillahe Island; PE, Pt Ellice, PAB, Pt Adams Beach; WSI, West Sand Island; CS Clatsop Spit.

## Discussion

The high proportion of juvenile Chinook found with stomachs more than half full and the low proportion of empty or near-empty stomachs is an indication that these fish are actively feeding throughout the seven estuary sample sites.

The prevalence of gnats and midges in the diets of fish captured outside of tidal freshwater marshes indicates that terrestrial insect production provided an important food source for juvenile Chinook, even when those Chinook are not found within marsh habitat. There are three explanations for the presence of terrestrial insects in salmon diet away from marsh habitat: 1) salmon recently visited marsh habitat, 2) salmon are continually moving into and out of freshwater marsh habitat, or 3) insects are being exported from marshes to other estuary habitats by wind or water flow. These explanations are not mutually exclusive. Until the movements of subyearling Chinook relative to insect production within the estuary are better understood, it is not possible to determine which of these mechanisms are operating. In any case, freshwater marshes are providing important food items for subyearling Chinook.

*Corophium* species were also important in subyearling diet. These prey are benthic tube-dwellers that require fresh- or brackish-water habitat with shallow, fine sediments (mud or sand) and benthic detritus. Salmon therefore must also be using benthic production from shallow sand and mud flats, as well as marsh production. The preference of *C. spinicorne* for higher salinities likely explains that this species was more common than *C. salmonis* in the diets of fish captured in the middle and lower estuary, where salinities are higher.

The occasional presence of marine prey types (e.g. fish larvae, Dungeness crab megalopae) in Chinook diet from the lower estuary indicates that some fish are making the transition to marine diets while still in the estuary. The lower estuary therefore provides a third and distinct source of food for juvenile salmon.

## **1.6 Tidal-Scale Time Series of Juvenile Salmon Abundance**

### **Introduction**

In the lower Columbia River, tidal fluctuations cause daily variation in hydrographic parameters such as salinity and temperature. Subyearling salmon from lower Columbia River stock tend to exhibit extended rearing in estuarine and tidal freshwater habitats, but it is unclear whether salmon abundance is affected by these varying physical conditions. For example, high temperatures are known to have deleterious effects on juvenile salmon, and fish entering the estuary (i.e. contact with salt) may have to undergo stressful physiological adaptations. The objective of these experiments is to compare salmonid abundance relative to hydrological parameters (water level, stage of tide, salinity, and temperature) at shallow estuarine and tidal freshwater environments. These data are compared to our landscape scale measurements that are made primarily around the low tide period.

### **Methods**

Physical parameters and fish species composition were measured at three shallow-water sites over three periods in 2004. Two of these sites, West Sand Island and Pt. Adams Beach, were estuarine stations sampled during landscape-scale monitoring. The third site at Jones Beach was in the tidal freshwater zone and was selected because an extensive beach-seine database exists for the site (Dawley et al. 1986).

Collections were made during 24-26 May, 22-26 June, and 4-6 August 2004 using the standard beach-seine protocol described in Section 1.1. Sites were occupied on consecutive days (except in August) for 10 to 12 h, and beach seines were made at approximately hourly intervals from around high water to low water or vice versa. Abundances were expressed as catch per unit effort (CPUE). We additionally collected fin clips of up to 30 Chinook salmon to ascertain ESU affiliation, and scanned all salmonids for tags and marks.

Hydrologic conditions were assessed with both moored (time series) and profile (transect) measurements. We deployed a moored anchor station at the 3-4 m depth, which held CTD instruments (YSI model 9261 with fluorometer) at the surface (0.5 m) and bottom positions. Data were recorded at 5-min intervals. Additionally, before each seine, we made vertical CTD profiles (Sea Bird 19 plus with Wet Star fluorometer and Turner Designs SCUFA OBS) at stations 10, 40, 140, 240 m from shore, as described in Section 1.1. Since the seine net fished the upper 3 m of the water column, surface temperatures and salinities were probably most related to fish abundance. Water level and tidal phase predictions were acquired from Harbor Master Tidal® software. Predicted water level values were found to compare well to actual values ( $r^2 = 0.92$ ) at the Astoria NOAA station.

Principal Components Analysis (PCA) was used to partition variance in the biological and physical variables. For salmonids, we also computed mean size per sample interval and utilized ANOVA ( $\alpha = 0.05$ ), to evaluate size differences within stations. ANOVA was also utilized to test for differences in mean size between sites.

## Results

During fish sampling, water column salinity ranged from 0 to 31 psu and temperature ranged from 9 to 24°C (Figure 23). Hydrography varied widely with stage of tide at the estuarine stations but exhibited little variation at Jones Beach. At the estuary stations during most sample dates, the water column was strongly stratified during flood tides, when surface-to-bottom salinity gradients exceeded 20 psu at high water. Salinity and stratification minima occurred near predicted low tide, but salinities were over 2 psu in the estuary during all sampling periods. Ocean water (>31 psu) intruded to West Sand Island, but water at Point Adams Beach remained brackish, with surface salinities relatively low (<10 psu) even at maximum flood. Mean salinity values increased seasonally. Temperature profiles were nearly isothermal at low tide but stratified during salinity intrusion. At the tidal freshwater site, temperatures varied little in relation to tidal fluctuations, and no thermal stratification was evident. Temperatures increased seasonally at all stations, averaging about 14, 18, and 21°C during May, June and August, respectively.

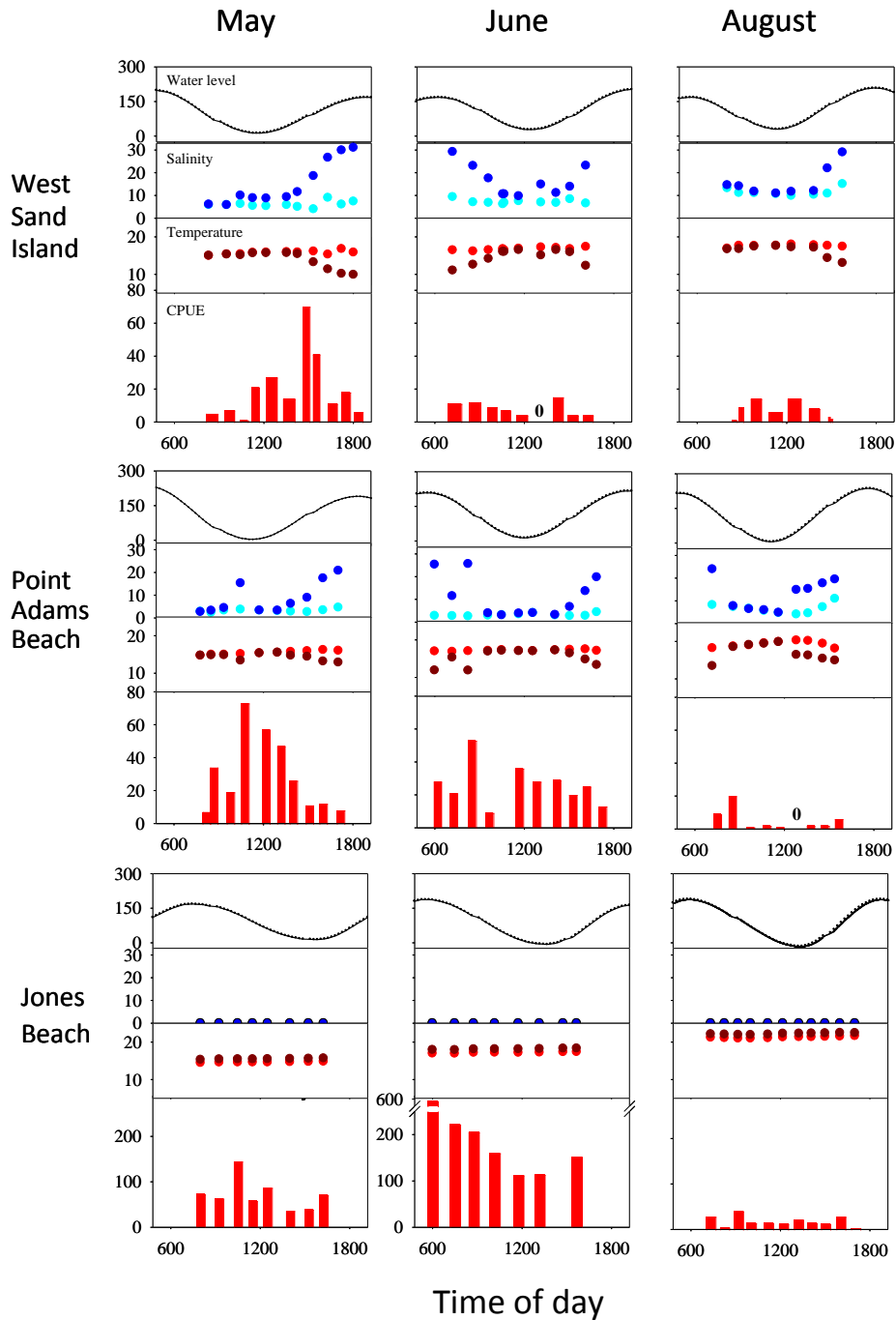


Figure 23. Hydrography and Chinook abundance during the Tidal Time Series study. Water level, m; salinity, psu (surface, cyan; bottom, blue); temperature (°C, surface, red; bottom, brown); CPUE, Chinook salmon abundance.



We captured a total of 19,124 individuals of 23 species (Figure 24; Table 10). Fish species composition and abundance patterns followed general trends observed in landscape-scale sampling (Section 1.1), and were markedly different between estuarine and tidal freshwater sites. The number of species ( $S$ ) and Shannon-Wiener species diversity index ( $H'$ ) were greater in the estuary than in the tidal freshwater areas. Again, threespine stickleback accounted for the majority of individuals captured. However, the overall proportion of stickleback was about 10% less than that found during landscape-scale sampling.

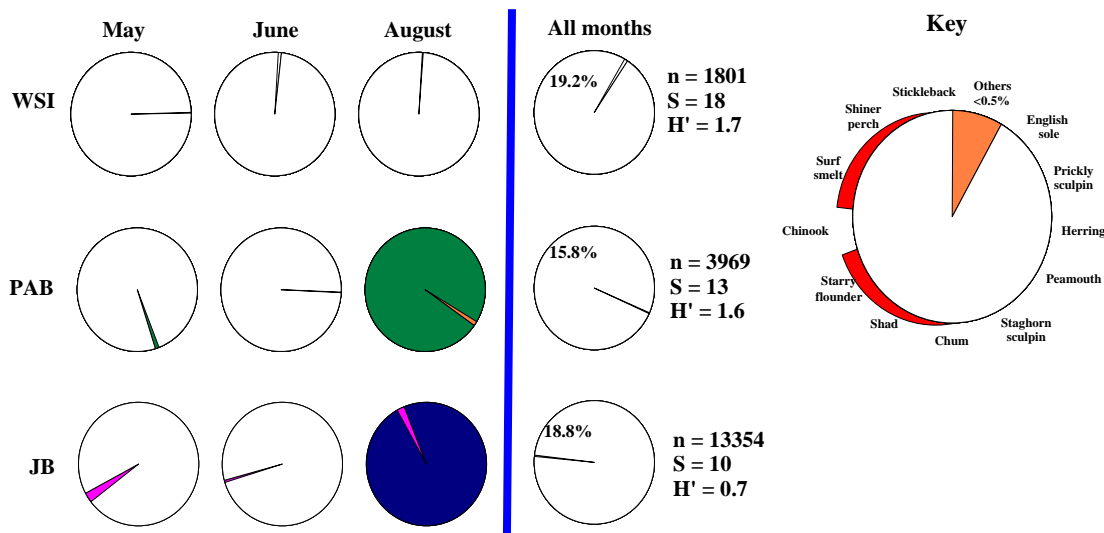


Figure 24. Proportional abundance of fishes captured during tidal time series sampling. N, number of individuals, S, number of species,  $H'$ , diversity. WSI, West Sand Island; PAB, Point Adams Beach; JB, Jones Beach.

Chinook salmon presence was high (Figure 20), with Chinook captured in every seine haul but two. Chinook was present at all tidal phases and through the entire range of salinity and temperature measured. All salmon captured in the estuary were found in waters less than 2 psu. Chinook abundance was greatest in the tidal freshwater region and lowest at West Sand Island, but overall Chinook salmon made up a relatively high percentage of the total catch (15.8-19.2%). Neglecting sticklebacks, Chinook salmon comprised 46.7% of the total catch. Chinook abundance at estuarine stations was relatively high in May and June but decreased by August. Chum salmon was abundant only during May at Jones Beach. Statistics on marked fish are shown in Table 11.

Table 10. Overall species CPUE and percent abundance for fishes sampled during the Tidal Times Series experiment.

Species	West Sand Isl		Pt Adams Beach		Jones Beach		Total	
	N	%	N	%	N	%	N	%
Threespine stickleback	139	7.72	1,261	31.77	10,268	76.89	<b>11,668</b>	61.01
Chinook salmon	346	19.21	627	15.80	2,506	18.77	<b>3,479</b>	18.19
Surf smelt	876	48.64	575	14.49			<b>1,451</b>	7.59
Shiner perch	50	2.78	1,183	29.81			<b>1,233</b>	6.45
American shad	5	0.28	2	0.05	374	2.80	<b>381</b>	1.99
Pacific staghorn sculpin	74	4.11	231	5.82			<b>305</b>	1.59
English sole	105	5.83	36	0.91			<b>141</b>	0.74
Peamouth					98	0.73	<b>98</b>	0.51
Starry flounder	40	2.22	36	0.91	9	0.07	<b>85</b>	0.44
Chum salmon	2	0.11	9	0.23	49	0.37	<b>60</b>	0.31
Banded killifish	11	0.61	4	0.10	43	0.32	<b>58</b>	0.30
Pacific sand lance	53	2.94					<b>53</b>	0.28
Pacific sardine	51	2.83					<b>51</b>	0.27
Sand sole	27	1.50					<b>27</b>	0.14
Pacific sand dab	16	0.89					<b>16</b>	0.08
Pacific herring	3	0.17	3	0.08			<b>6</b>	0.03
Smallmouth bass					3	0.02	<b>3</b>	0.02
Largemouth bass	1	0.06	1	0.03			<b>2</b>	0.01
Mountain whitefish					2	0.01	<b>2</b>	0.01
Northern pikeminnow					2	0.01	<b>2</b>	0.01
Largescale sucker	1	0.06					<b>1</b>	<0.01
Longfin smelt			1	0.03			<b>1</b>	<0.01
Northern anchovy	1	0.06					<b>1</b>	<0.01
<b>Total</b>	<b>1,801</b>		<b>3,969</b>		<b>13,354</b>		<b>19,124</b>	

Table 11. Numbers of marked Chinook captured on each date sampled during the Tidal Time Series study. AD, adipose fin clip; PC, pelvic fin clip; CWT, coded wire tag; AD+CWT, adipose fin clip and coded wire tag; PIT, passive integrated transponder tag; FL fork length; SD, standard deviation.

Station	Month	AD	PC	CWT	AD+CWT	PIT	Total	Mean FL	SD
Jones Beach	May	0	0	0	0	0	0	-	-
	June	3	0	17	11	1	32	82.5	6.7
	August	0	0	0	0	0	0	-	-
Pt Adams Beach	May	1	1	7	2	0	11	79.2	14.7
	June	3	0	0	4	0	6	86.5	4.3
	August	0	0	0	0	0	0	-	-
West Sand Isl	May	0	0	0	11	0	11	90.1	14.1
	June	1	0	0	0	0	0	-	-
	August	0	0	0	0	0	0	-	-

Mean Chinook salmon size varied by sample, station, and date (Figure 25; Table 12). We found significant size differences between Chinook sampled over time during six of nine sample series (exceptions were West Sand Island in June and August, and at Jones Beach in August). There were significant differences in overall mean size of Chinook caught at estuarine vs. tidal freshwater sites in all months (Figure 26; Table 13). As in the landscape-scale sampling, Chinook salmon were significantly larger at estuarine sites vs. tidal freshwater sites at the same date (Figure 5).

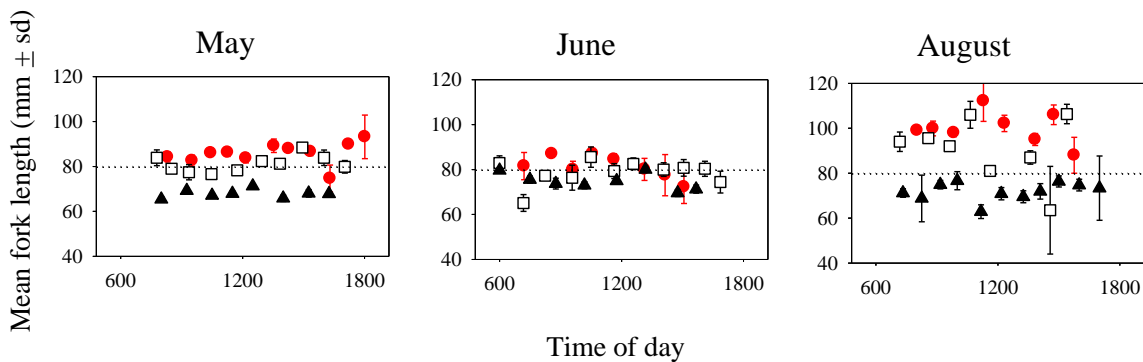


Figure 25. Time series of Chinook salmon mean size for each station and month. Circles, lower estuary; squares, upper estuary; triangles, tidal freshwater zone. Dotted lines show overall mean size of Chinook computed from landscape scale data.

Table 12. ANOVA results for mean size between sample by station and month

Station	Month	df	<i>F</i>	<i>P</i>
West Sand Island	May	10	2.557	0.006
	June	8	0.643	0.738
	Aug	7	1.606	0.156
Pt Adams Beach	May	9	2.418	0.012
	June	10	2.322	0.012
	Aug	7	3.701	0.004
Jones Beach	May	7	3.323	0.002
	June	7	5.165	<0.001
	Aug	10	1.574	0.118

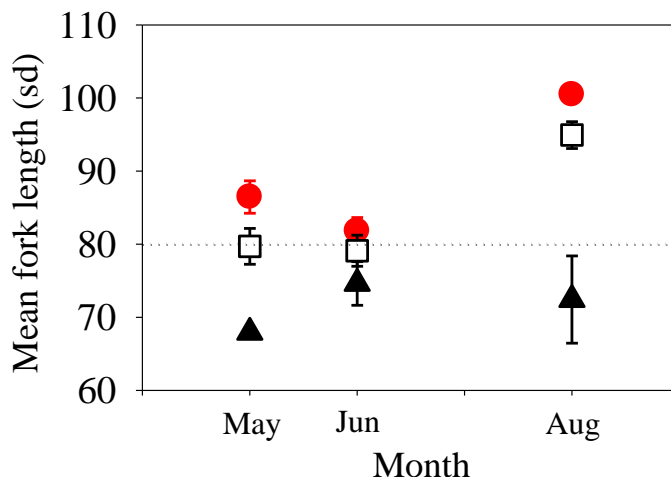


Figure 26. Comparison of overall mean size of Chinook salmon sampled during the Tidal Time Series study. Circles, lower estuary; squares, upper estuary; triangles, tidal freshwater zone. Dotted line shows overall mean size of Chinook computed from landscape scale data.

Table 13. ANOVA results for mean size between stations by month.

Month	df	<i>F</i>	<i>P</i>
May	2	318.01	<0.001
June	2	12.57	<0.001
Aug	2	135.80	<0.001

Size-frequency plots constructed for each site and date show differences in the overall population structure of Chinook salmon (Figure 23). Salmon at West Sand Island were concentrated in a relatively narrow size range around 70-100 mm, with some outside this range. At Pt Adams Beach, fish sampled during May and June had a wider size range (50-90 mm) and included both fry and fingerlings, while in August, only fish over 70 mm were found. At Jones Beach, fish of 40-70 mm were found at all dates, in contrast to the larger fish sampled in August at West Sand Island and Pt Adams Beach. These data indicate segregation of salmon by sizes during the migration period.

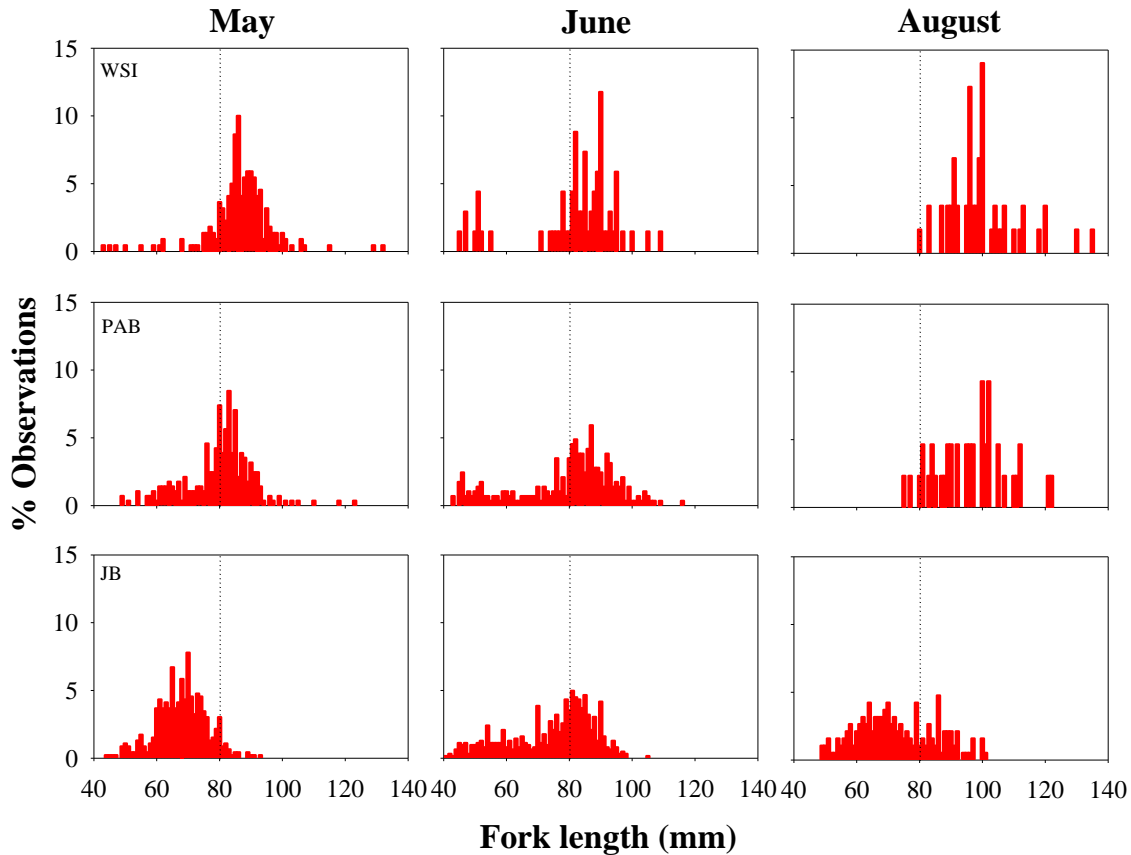


Figure 27. Length frequency histograms of Chinook salmon sampled during the each site and date of the Tidal Time Series study. Dotted line shows overall mean size of Chinook computed from landscape scale data.

PCA analyses were run with physical and log CPUE values to examine for associations in the biophysical data set (Table 14). We ran analyses with 1) all stations, 2) both estuarine stations, and 3) the tidal freshwater station only. To evaluate the contribution of individual variables to each factor, the critical factor-loading correlations were set at 0.6, and only factors that explained more than 10% of the total variance were considered. The following discussion concentrates on salmonids.

Using all data, the first two principal components together explained 48.5% of the data. Chinook and chum salmon were positively correlated together and negatively correlated with surface temperature and month. Neither water level nor tidal phase explained significant variation.

Table 14. Factor-variable correlations (factor loadings) for factors explaining more than 10% of the variance. Factor loadings over 0.60 are shaded.

Variable	All Stations		Estuarine stations			Freshwater station		
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Station	-0.8986	0.1660	0.3120	-0.8404	-0.2559			
Month	-0.2331	-0.8893	-0.8407	-0.2881	-0.1938	-0.9864	0.0183	0.0329
Tidal phase	0.3678	-0.0796	0.2242	0.1418	-0.4298	-0.3621	-0.6576	-0.1587
Tidal height	0.2152	0.0003	-0.0334	0.2647	-0.8545	0.1372	0.7162	-0.3252
<b>Surface</b>								
Temp	-0.4358	-0.8113	-0.6890	-0.4751	-0.2720	-0.9921	0.0114	0.0092
Salin	0.8129	-0.3818	-0.6707	0.4776	-0.1347			
Chl	0.0009	0.5154	0.0021	0.2321	0.0081	0.9579	-0.1706	-0.0266
<b>Bottom</b>								
Temp	-0.7865	-0.4777	-0.4374	-0.5827	0.5692	-0.9917	0.0172	0.0156
Salin	0.8284	-0.1522	-0.1359	0.5674	-0.7238			
Chl	0.6739	0.2740	0.4071	0.0583	-0.4216	0.9401	-0.1491	-0.0412
Chinook	-0.4799	0.6240	0.6140	-0.0374	0.0993	0.6634	0.4738	0.1524
Chum	-0.1416	0.6221	0.5736	0.0176	0.1474	0.6942	-0.4963	0.0972
Dungeness	0.5133	0.4020	0.7321	0.3395	0.0746			
Stickleback	-0.7970	0.1949	0.4588	-0.7745	-0.0661	-0.1273	0.7445	0.4928
Shiner Perch	0.2863	-0.2902	-0.1601	-0.7546	-0.4310			
Surf Smelt	0.5581	-0.2071	-0.2761	0.2423	0.0039			
English Sole	0.5334	0.1250	0.2453	0.4732	0.1932			
Sand Sole	0.3019	-0.2864	-0.4915	0.3873	0.3800			
<b>Starry</b>								
Flounder	0.3054	-0.4478	-0.4827	-0.1357	-0.1279			
Staghorn	0.5411	0.1521	0.5523	-0.2489	-0.2368	-0.3385	-0.0578	0.6228
Shad	-0.6404	0.1268				0.0338	0.4626	-0.6304
Peamouth	-0.4937	-0.3724				-0.6717	-0.1537	-0.3494
<b>Variance (%)</b>	<b>30.05</b>	<b>17.27</b>	<b>22.74</b>	<b>19.25</b>	<b>13.08</b>	<b>49.20</b>	<b>17.41</b>	<b>10.13</b>

PCA performed with only the estuarine stations resulted in a partition of three factors that explained 55.1% of the variance. Chinook salmon abundance was negatively correlated with surface salinity, surface temperature, and month. Water level and bottom salinity explained significant variation in Factor 3.

At the tidal freshwater site, three factors explained 76.7% of the variance. Chinook and chum salmon were negatively correlated with surface and bottom temperature and peamouth abundance, and positively correlated with each other and surface and bottom chlorophyll. Tidal phase and amplitude contributed significantly to the variance of Factor 2.

## **Discussion**

These intensive time series beach-seine sampling and coupled physical measurements clearly indicated strong spatiotemporal differences in water-column habitat and fish populations. The analysis to date focuses on Chinook salmon. Importantly, we found salmon in all hydrological conditions that were sampled. However, overall higher abundance was found at the tidal freshwater site than the estuarine sites. Negative associations were consistently found with surface temperature and month, which likely reflects the overall decrease in abundance in August compared to May and June samples. In the estuary, Chinook abundance had negative associations with surface temperature and salinity, however, all water samples at West Sand Island and Pt Adams Beach were actually estuarine (i.e., measurable salt was present). The correlation with surface conditions suggests fish are residing within the surface layers.

## **OBJECTIVE 2: Evaluate Salmonid use of Emergent and Forested Wetlands in Relation to Habitat Features**

### **Executive Summary**

The Columbia River estuary includes a continuum of habitats interspaced along a seasonally varying gradient of salinity and temperature ranging from tidal freshwater to oceanic. Forcing of physical variability comes from both ocean and river end members. Contemporary measurements of hydrography, from beach-seine, trap-net, and tidal time series studies, and the CORIE network reveal the dynamic nature of physical conditions in the estuary. These factors affect salmon opportunity and performance. At wetland trap-net sites, high water temperature appeared to differentially limit salmon habitat opportunity, and in tidal freshwater habitats, decreased mean size during August 2004 may be attributed to excessive temperature. On the tidal time scale, salmon at main channel sites were found at all stages of the tide and at the full range of salinities encountered (0-15 at the surface, and 0-32 at the bottom). However abundance of both Chinook and chum salmon were negatively associated with surface salinity and surface temperature. Overall CPUE appeared related to seasonal temperature changes.

Vegetation assemblage structure in woody, scrub-shrub and forested wetlands at Welch Island demonstrated considerable variability between two tidal channel/slough sites. The Welch Island-South site was more complex and floristically diverse, where herbaceous emergent assemblages grew on low terraces at the base of steep-sided banks and on higher flat areas adjacent to the tidal channel. Vegetation at the Welch Island-North site consisted primarily of a scrub-shrub assemblage and less complex herbaceous understory growing along a steep-banked tidal channel.



## **2.1 Sampling Fish at Emergent and Forested Wetland Sites**

### **Introduction**

Tidal wetlands that provide important rearing habitats for ocean-type juvenile salmon in other Pacific coast estuaries have not been systematically sampled in the Columbia River (Bottom et al. 2005). In 2002 we initiated fish and prey resource surveys for a variety of wetland types in the estuary. These included emergent marsh, scrub-shrub, and forested habitats located in the island complex that stretches from Cathlamet Bay to Tenasillahe Island (approx. rkm 40–56; Figure 24). The objective of these surveys is twofold:

- 1) Determine whether salmonid use (determined by measures of abundance, seasonality, and residency) and performance (measured by foraging success and growth) vary among wetland types; and
- 2) Evaluate whether size-specific patterns of habitat use by juvenile Chinook salmon support the hypothesis that subyearling (ocean-type) life history expression may be linked to rearing opportunity in tidal wetlands.

### **Methods**

During 2002-2004, we sampled juvenile salmonids and other fish species in four areas of the tidal freshwater zone of the lower estuary within and immediately above Cathlamet Bay (Figure 28). Two of the sampling areas are intertidal emergent marshes, one on Russian Island (RI) and the other on Seal Island (SI). Two replicate tidal channels (north and south) were sampled in each of these areas. A third sampling area, Karlson Island, includes two types of wetland habitat, a forested and a scrub-shrub wetland channel. The forested channel (KIF) has large woody debris and mature conifers along the banks, whereas the scrub-shrub site (KIS) has lesser amounts of small woody debris and is lined with deciduous bushes and shrubs. The final sampling area at Welch Island, approximately 10 km upstream from Karlson Island, consists of two scrub-shrub channels (north and south).

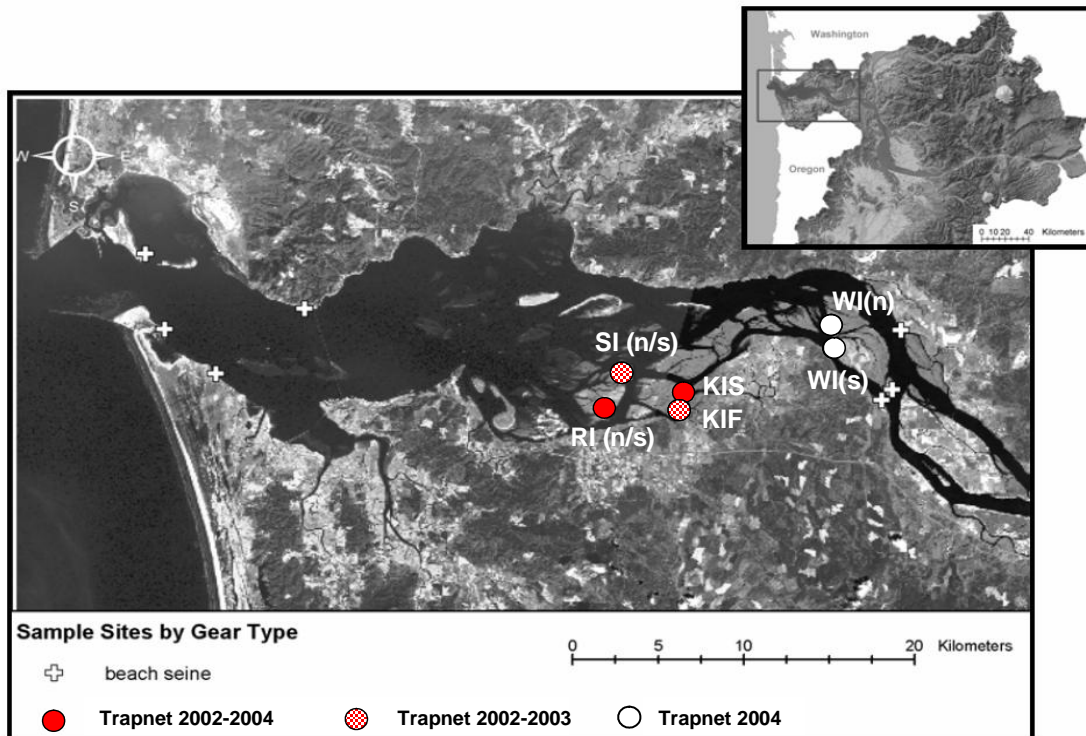


Figure 28. Trap-net locations and years of sampling in the lower Columbia River estuary: Sites include Russian Island north and south channels (RI(n/s), Seal Island north and south channels (SI(n/s), Karlson Island Forested (KIF), Karlson Island Shrub (KIS), Welch Island North (WI(n)), and Welch Island South (WI(s)) channels. The locations of beach seining sites are shown for comparison.

We surveyed fish species abundance and composition at each channel site with a trap net adapted from the design of Gray et al. (2002). Each trap net consisted of two wing nets connected to a tunnel that leads to a live box (0.60-cm mesh). The tunnel and live box were placed in the channel thalweg at high slack tide, and the two wing nets were set to opposite channel banks. As the tide receded, the wing nets directed all downstream migrants up stream of the trap into the live box.

Monthly trap-net sampling began in March or April each survey year to coincide with the approximate period of earliest salmon arrivals to the marsh. One exception was the Karlson Island shrub site where sampling was delayed until April (2002 and 2004) or May (2003) because high spring water levels prevented the channel from fully draining at low tide. Annual sampling was discontinued at all sites after July or August because few salmon entered shallow wetlands in late summer.

To expand the number of habitat types and locations, we discontinued sampling at the Karlson Island forested and Seal Island emergent sites in 2004 and added two new shrub channels at Welch Island. Years sampled at each wetland channel are shown in Figure 28. Trap net samples were treated as described for beach-seine samples in Section 1.1.

## Results

**Community Structure**—During 2002-2004, among all three sample areas and for the various sampling years combined, we captured 17 fish species (Tables 15 and 16). At all sites, threespine stickleback was by far the dominant species throughout each survey season. Sticklebacks accounted for 99% of the Russian and Seal Island total catch, and 90-93% of the catches at forested/scrub-shrub channels at Karlson Island and Welch Island (Tables 15 and 16; Figure 29). Excluding stickleback, other species captured in the emergent marshes at Russian and Seal Islands were Chinook salmon, banded killifish *Fundulus diaphanus*, and peamouth *Myoxocheilus caurinus* (Figure 30). American shad *Alosa sapidissima*, prickly sculpin *Cottus asper* (and another unidentified sculpin), and Chinook salmon were among other common species at the forested/scrub-shrub sites.

Table 15. Annual fish species composition for emergent marsh sites at Russian and Seal Island, 2002-2004. Catch totals are the sum of replicate samples (north and south channels) at each location over six monthly sampling periods, March-August of each survey year. Sampling at Seal Island was discontinued after 2003.

Species	Emergent marsh									
	Russian Island					Seal Island				
	2002	2003	2004	N	%	2002	2003	N	%	
Threespine stickleback	149,190	110,299	119,083	378,572	99.53	107,900	54,017	161,917	99.35	
Chinook salmon	269	378	105	752	0.20	319	362	681	0.42	
Banded killifish	21	50	478	549	0.14	136	125	261	0.16	
Peamouth	13	332	3	348	0.09	9	65	74	0.05	
Chum salmon	52	32	27	111	0.03	15	23	38	0.02	
American shad	13	5	2	20	0.01	0	3	3	0.00	
Coho salmon	0	6	0	6	0.00	3	0	3	0.00	
Black crappie	0	1	0	1	0.00					
Common carp	2	0	0	2	0.00	2	0	2	0.00	
Starry flounder	1	0	0	1	0.00					
Prickly sculpin	0	1	0	1	0.00	1	1	2	0.00	
Pacific staghorn sculpin	0	3	0	3	0.00					
Pacific lamprey?	1	0	0	1	0.00					
Largemouth bass						0	1	1	0.00	
Coastal cutthroat trout						1	0	1	0.00	
Sockeye salmon									0.00	
Total	149,562	111,107	119,698	380,367	100	108,386	54,597	162,983	100	

Table 16. Annual fish species composition for a forested marsh site at Karlson Island and for shrub marsh sites at Karlson and Welch Island. Totals for both forested and shrub marshes at Karlson Island are the sum of all trap net catches at a single channel site sampled during five monthly surveys, April–August, 2002 and 2003 and during four monthly surveys, April–July in 2004. Totals for Welch Island are the sum of all catches for a pair of replicate channels (north and south) during five monthly surveys, April–August 2004.

Species	Forested				Scrub-shrub						
	Karlson Island				Karlson Island				Welch Island		
	2002 <sup>a</sup>	2003 <sup>a</sup>	total	%	2002 <sup>a</sup>	2003 <sup>a</sup>	2004 <sup>b</sup>	total	%	2004 <sup>a</sup>	%
Threespine stickleback	7,132	959	8,091	93.18	6,961	5,228	3,007	15,196	90.92	6,985	93.20
American shad	7	352	359	4.13	83	438	0	521	3.12		
Prickly sculpin	13	12	25	0.29	172	197	53	422	2.52	105	1.40
Chinook salmon	60	56	116	1.34	111	43	31	185	1.11	210	2.80
Peamouth	33	20	53	0.61	96	45	6	147	0.88	8	0.11
Largescale sucker	1	2	3	0.03	52	65	2	119	0.71	2	0.03
Unidentified sculpin sp.	14	4	18	0.21	20	34	1	55	0.33	64	0.85
Banded killifish	3	0	3	0.03	3	4	13	20	0.12	21	0.28
Unidentified sp.					0	0	17	17	0.10	75	1.00
Starry flounder	1	0	1	0.01	8	1	1	10	0.06		
Coho salmon	3	5	8	0.09	6	3	0	9	0.05	3	0.04
Chum salmon	3	0	3	0.03	2	1	2	5	0.03	22	0.29
Largemouth bass	0	3	3	0.03	1	2	0	3	0.02		
Black crappie					2	0	0	2	0.01		
Sockeye salmon					0	0	1	1	0.01		
Common carp					1	0	0	1	0.01		
Pacific lamprey					0	0	1	1	0.01		
Total	7,270	1,413	8,683		7,518	6,061	3,135	16,714		7,495	

<sup>a</sup> April–August sampling

<sup>b</sup> April–July sampling

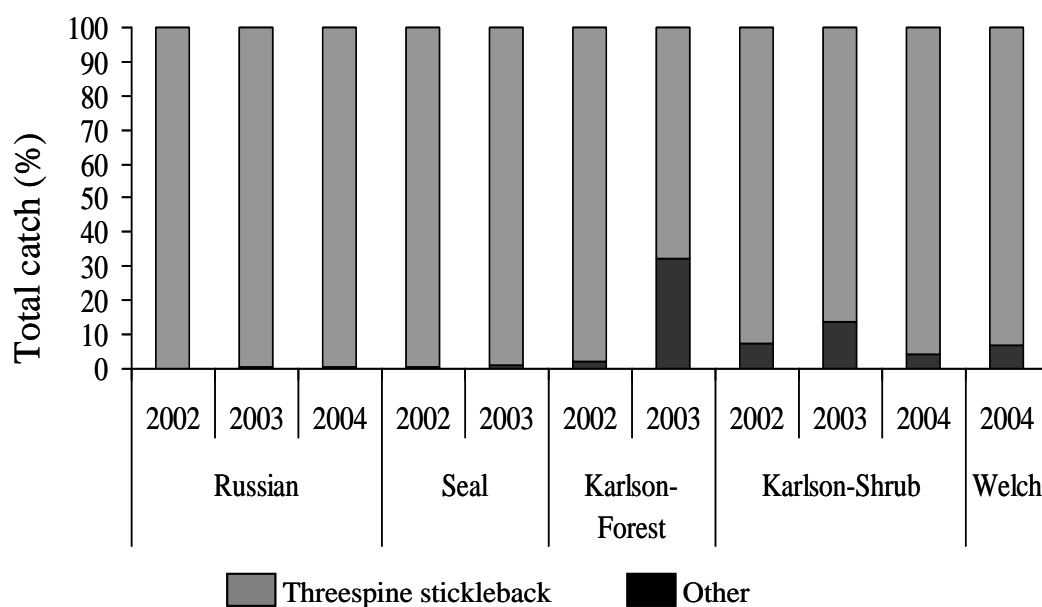


Figure 29. Percent composition of threespine stickleback and all other fish species in each marsh sampling site for each year of sampling.

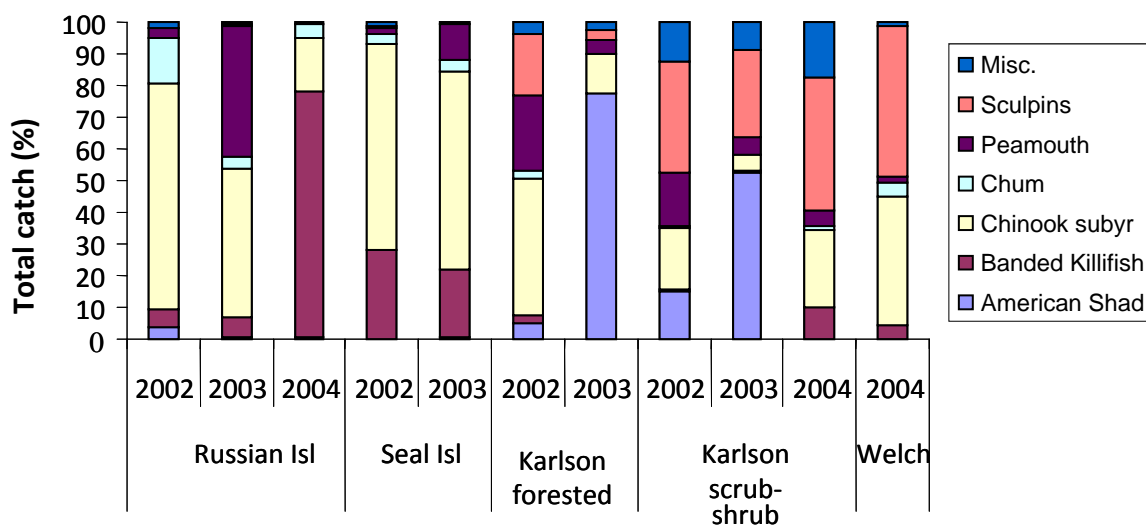


Figure 30. Percent of most abundant fish species in each marsh survey site for each sample year, excluding threespine stickleback.

**Salmon Abundance and Size**—Results to date indicate that juvenile salmon rear in all types of shallow wetland habitats of the Columbia River during spring and summer. Chum, and to a lesser extent coho salmon, appeared in all areas briefly during spring (March-May), but Chinook salmon was generally the most abundant salmonid throughout the trap-net season. Chinook salmon abundance peaked in April or May in most years (Figure 31). Abundance at the emergent marsh sites reached their highest levels in May 2003, but quickly declined to low levels by June.

Salmon abundance was relatively low at the Karlson Island forested and scrub-shrub sites during all 3 years (Figure 31). We found evidence of slightly greater use of the Welch Island scrub-shrub site by juvenile Chinook in 2004. However, because we did not begin sampling at Welch Island until April, we do not know whether abundances at this upriver site may have peaked even earlier in the spring.

Mean lengths of juvenile Chinook salmon generally ranged between 40 and 90 mm at all wetland sites (Figure 32). Except for the scrub-shrub wetlands in 2004, where sizes remained uniformly small (<60 mm), mean lengths of Chinook salmon increased in wetland habitats through spring and summer.

Length frequencies for all years combined reveal a bimodal size distribution of subyearling Chinook salmon at the emergent marsh sites April through June, consisting of a group of fry, primarily 40 to 55 mm, and larger fingerlings, primarily 75 to 85 mm (Figure 32). Although fingerlings also entered scrub-shrub and forested sites later in May, the larger size class was a relatively minor component of these wetlands. Recently emerged fry continued to appear in all marsh types until June, but few individuals larger than 90 mm entered wetland sampling sites during any month. By July, when salmon abundance had declined substantially, individuals in the emergent marshes consisted of a single fingerling group.

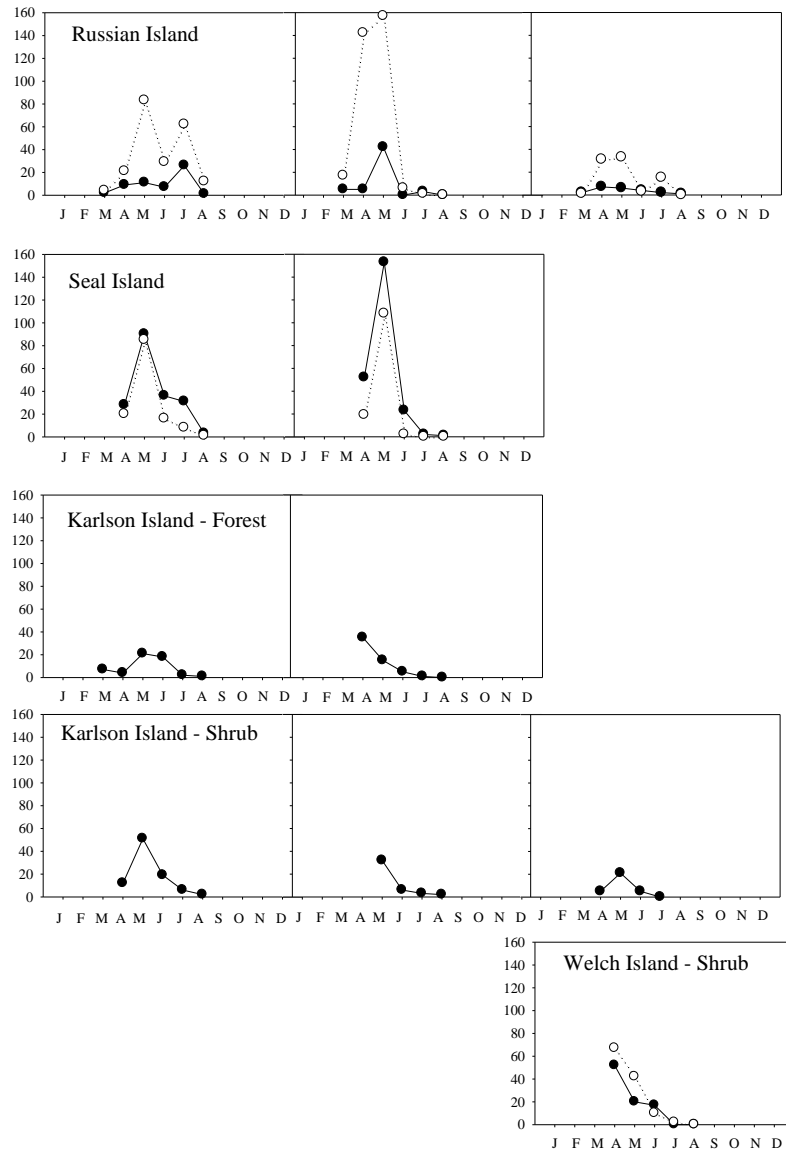


Figure 31. Monthly abundance of juvenile Chinook salmon for each trap-net site in 2002–2004. Stations with replicate sampling sites show separate plots for north (filled circle) and south (open circle) channels. Abundances cannot be compared among sites because the results have not been normalized by amount of channel area above each trap net.



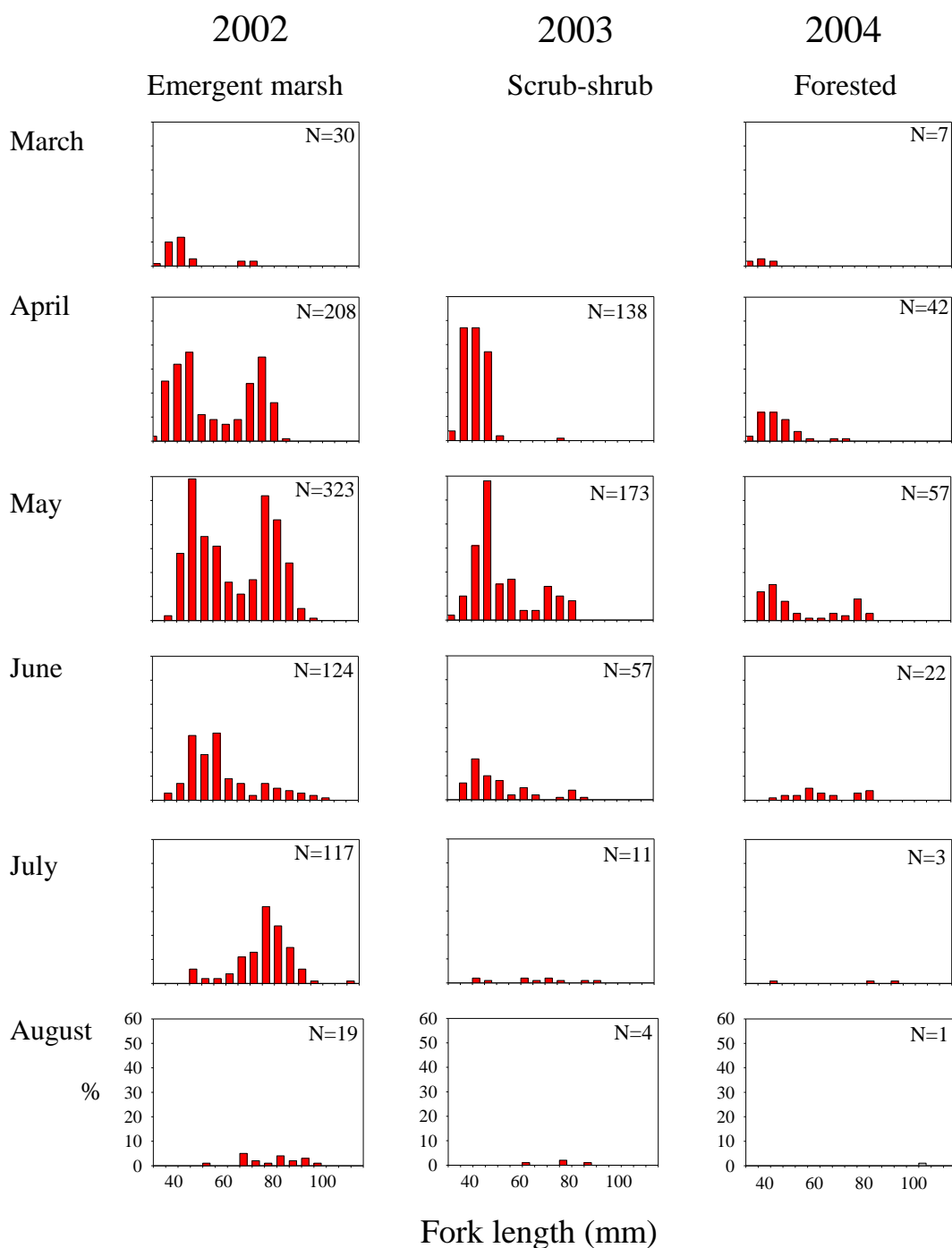


Figure 32. Length frequencies of juvenile Chinook salmon for each of three habitat classes sampled in 2002-2004. Emergent marsh habitat combines fish from replicate channels sampled at Russian Island (2002-2004) and at Seal Island (2002-2003). Scrub-shrub habitat included individuals from the Karlson Island shrub channel (2002-2004) and replicate channels at Welch Island (2004 only). Forested habitat consists of salmon from a single forested channel at Karlson Island (2002-2003).

**Water Temperature**—Water temperatures varied between years, particularly at the emergent marsh sites. At Russian Island, daily minimum water temperatures in spring-summer were generally higher in 2003 than in 2002 and 2004 (Figure 33). For example, in June 2003, minimum water temperatures approached 18°C. Daily minimum temperatures at the Karlson scrub-shrub wetland were generally higher and less variable than the minimum values at the emergent Russian Island emergent marsh. Daily mean temperatures at Russian Island were higher and more variable than those at the Karlson Island scrub-shrub wetland (Figure 34).

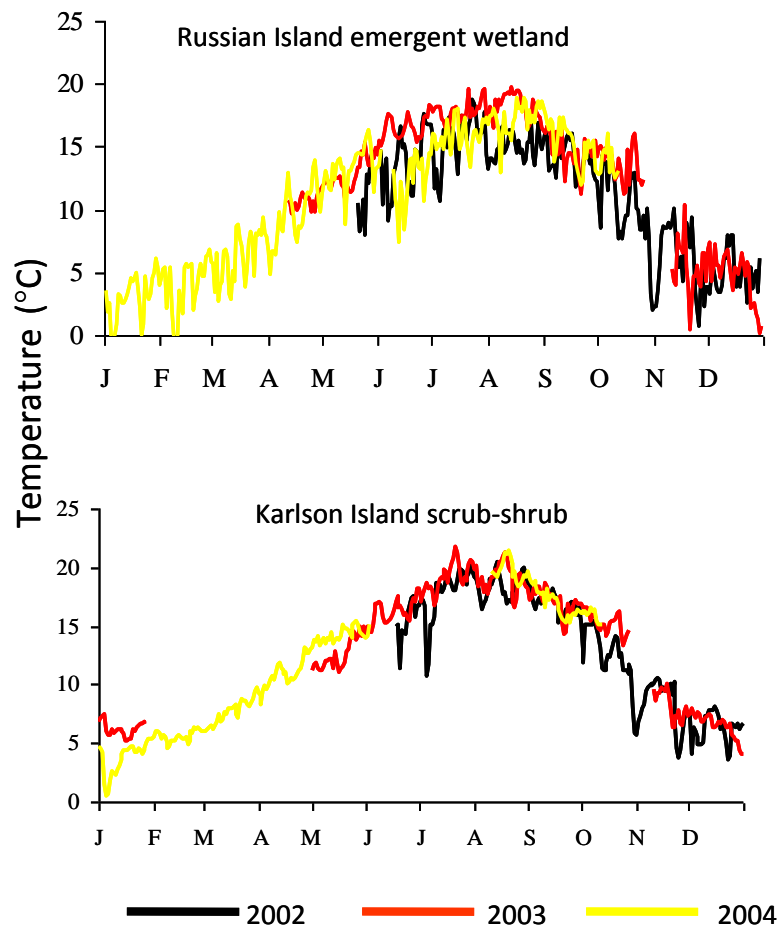


Figure 33. Daily minimum water temperatures at Russian Island emergent and Karlson Island scrub-shrub sites, 2002-2004

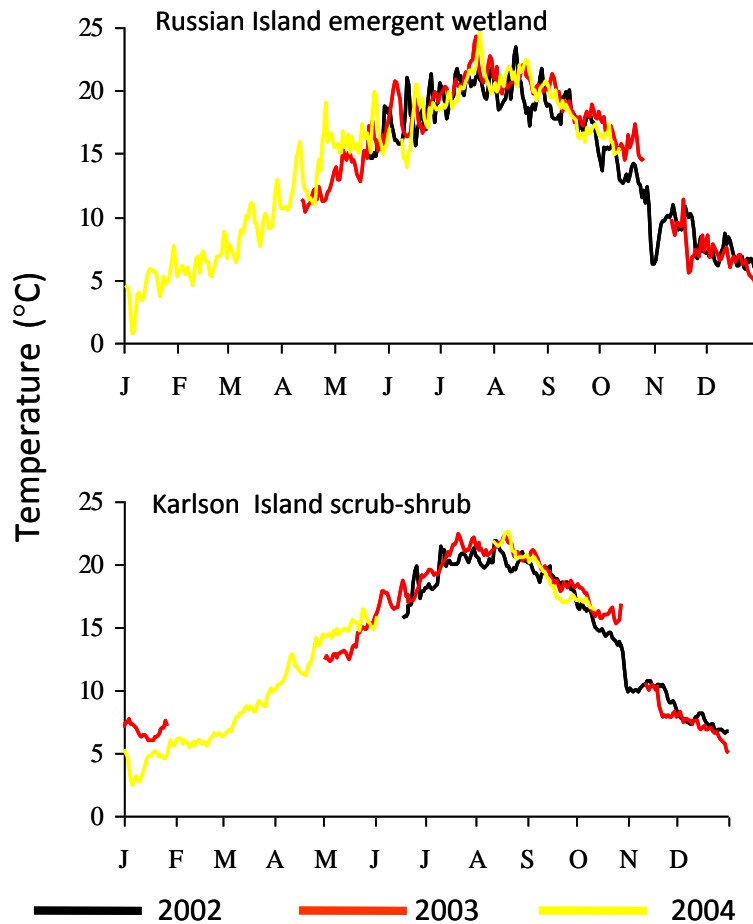


Figure 34. Daily average water temperatures at Russian Island emergent and Karlson Island scrub-shrub sites, 2002-2004.

Short-term fluctuations in temperature exhibited strong diel, tidal, and seasonal patterns with greater variation at the Russian Island emergent marsh channel than at the Karlson Island forested wetland channel (Figure 35). The emergent marsh habitat tended to exhibit colder extreme temperatures during winter and warmer extremes during late winter to spring. Both mean temperatures and variability increased throughout the spring and summer rearing period for juvenile Chinook salmon, and may have been a factor in the decline in salmon abundance at marsh sites by mid summer (Figure 35). Temperature extremes began approaching 20°C by mid-March in the emergent marsh channel, but did not exceed 20°C in the forested wetland channel until late April. Differences between the two habitats appeared to be greatest (often >10°C warmer in emergent marsh) during the increasing spring tides between February and May. At the emergent marsh channels at Russian and Seal Island, peak abundances of juvenile Chinook salmon occurred during moderate temperatures between 11 and 13°C. Very few salmon were captured at temperatures above 19°C.

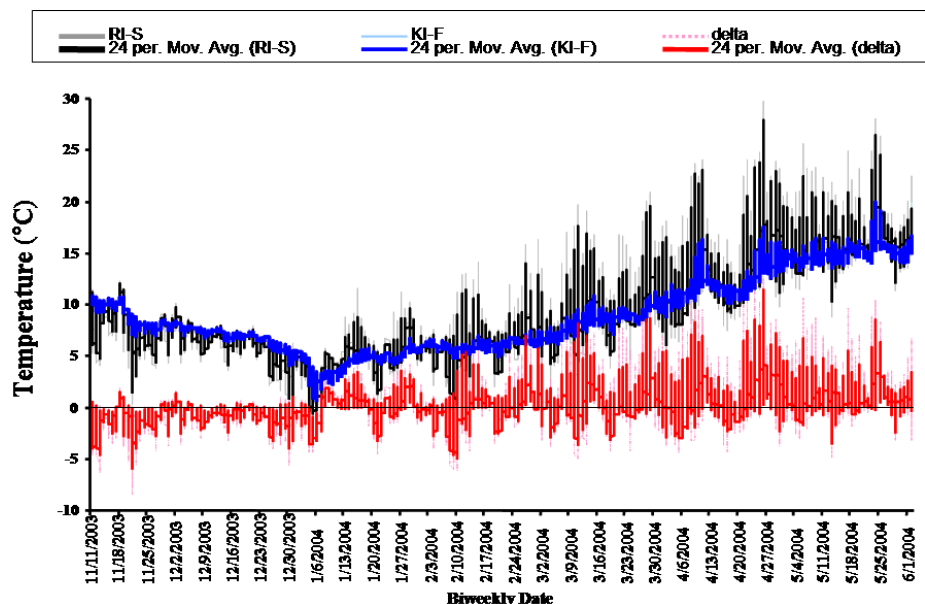


Figure 35. Short-term temperature variability for Russian Island emergent marsh and Karlson Island forested wetland channels 5 November 2003 to 2 June 2004. Temperature readings shown are for Russian Island emergent marsh (black line) and Karlson Island forested (blue line) channels. The red line below shows temperature difference (delta) between the two channels for each observation period.

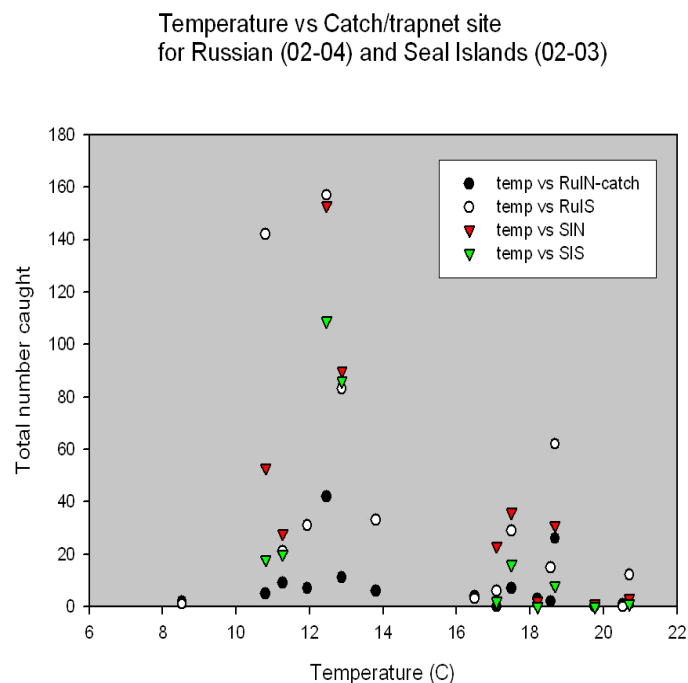


Figure 36. Scatterplot of juvenile Chinook salmon catch versus water temperatures during trap-net surveys at four emergent marsh channels: Russian Island north (RuIN), Russian Island south (RuIS), Seal Island north (SIN), and Seal Island south (SIS).

## Discussion

Results of trap-net sampling indicate that subyearling salmonids, particularly ocean-type Chinook salmon, consistently use wetland habitats of all types in the lower Columbia River. Note that species composition and relative abundances have not yet been standardized to the channel areas and volumes of the respective habitats, which hampers direct comparisons between sites. Channel measurements from existing aerial imagery are particularly problematic for the forested and scrub-shrub sites because the channel network is largely obscured in available aerial imagery by the forest and shrub canopy, and ground surveys are impeded by dense vegetation and wood debris. We are hopeful that LIDAR data (light detection and ranging, a remote sensing system used to collect topographic data), available from November 2004, can be used to complete channel measurements for the forested and scrub-shrub sites, allowing all trap-net catches to be normalized by total channel area sampled.

Species richness and diversity were relatively low within wetland sites. Densities of threespine stickleback were extremely high, particularly at emergent marsh sites. The most obvious differences in species structure among wetland types were 1) greater dominance of threespine stickleback in emergent marsh sites, 2) greater abundance of exotic banded killifish in emergent marsh sites, and 3) greater contribution of juvenile American shad and sculpin species in forested and scrub-shrub sites. Although catches of juvenile Chinook salmon were low at Karlson Island, additional sampling is needed to evaluate whether this pattern is generally characteristic of forested and scrub-shrub wetlands.

Results to date are consistent with the hypothesis that shallow-water habitats are used primarily by subyearling (ocean-type) salmon. In contrast to catches at the beach-seine sites, we found relatively few individuals larger than 90 mm in emergent marsh channels. However, other seine surveys within the island complex indicate that somewhat larger subyearling and yearling fish may enter the larger channels, which were not sampled by trap net. Broader-scale surveys are planned at Russian Island to assess whether the distribution of juvenile salmonids from the outer shore of the island complex to the innermost channel network is size-related.

Because few hatchery Chinook salmon in the basin are marked, and only a small proportion of individuals captured in the marshes have external marks, it was not possible to distinguish the proportions of hatchery and wild individuals in our catch. We cannot discern, for example, whether hatchery releases may be a factor in the observed bimodal size distribution of Chinook salmon (Figure 32). We are hopeful that genetic and otolith data may provide clues about the upriver sources of Chinook salmon in wetland habitats.

Dense vegetative canopy over the forested and scrub-shrub channels dampened temperature extremes relative to tidal channels of the more exposed emergent marshes. It is possible that daily mean temperatures could have been artificially inflated by periods of channel dewatering at low tide (therefore, exposing temperature sensors). However, this would not account for the temperature differences between sites, because all channel types were dewatered for some periods. Dense vegetative cover, which may moderate nighttime air temperatures, may also account for the higher minimum daily temperatures seen at forested/scrub-shrub sites compared to emergent marsh sites. Dampening of extreme high and low temperatures was most evident in the comparison of short-term variation between the Karlson forested and Russian Island emergent marsh sites (Figure 35). Such variations in temperature regime could significantly influence the bioenergetic requirements and growth potential of juvenile salmon occupying different marsh types during spring and summer (see Section 2.2).

Although the movement of salmon out of marsh habitats during summer months is likely influenced by temperature, size-related migration also could be a factor. Fish size increased throughout the period of wetland rearing, and maximum size ranges for fish in shallow wetland habitats coincided with the period of warmest water temperatures. A slight decline in the rate of size increase of salmon captured at estuary beach seining sites typically occurred between May and July, about the same time fish abundance in wetlands began to decline (Figure 4). It is possible that the movement of small subyearlings from shallow wetlands and other areas into near-channel habitats could be reflected in the size distribution of individuals captured during the landscape-scale beach-seine surveys.

## 2.2 Availability of Invertebrate Prey and Food Habits

### Introduction

The objective of this section is to evaluate the importance of shallow-water wetland habitats to juvenile (predominantly ocean-type) Chinook salmon in the lower Columbia River and estuary through examination of 1) salmon prey abundance and composition, and 2) diet composition, selectivity and relative consumption rate.<sup>2</sup> We examined food resources and feeding in three wetland types: emergent marsh, scrub-shrub and forested wetlands. The presence of shallow wetlands in the overall estuarine landscape has been drastically altered (Section 3.2), and this study will help us to determine the function of these wetlands in terms of their ability to support juvenile salmonids migrating through the estuary. We are also evaluating the size of the salmon that are utilizing these habitats and the differences in diet that may occur in differing salmon size classes. The information gained from this study, in conjunction with the results from collaborative studies and recognition of the present landscape organization of estuarine habitats in the Columbia River, will allow us to design efficient and effective restoration and recovery plans.

### Methods

**Sampling Design**—Our methodology has been consistent throughout the 3 years of study, with only sampling sites changing among years. Coincident with the sampling of shallow-water wetland habitat (Section 2.1), we sampled sites at the same three islands in Cathlamet Bay region: Russian, Seal, and Karlson Islands. Welch Island was added in 2004, but fish diet and prey resource samples are not sufficiently processed at this point to be included in this report. We use the following convention for identifying the six specific channels: RuI-N (Russian Island north), RuI-S (Russian Island south), SI-N (Seal Island north), SI-S (Seal Island south), KI-F (Karlson Island forested), KI-Sh (Karlson Island scrub-shrub).

The western portion of Cathlamet Bay, and particularly the navigational channel, is positioned in the upper extent of salinity intrusion, while Russian, Seal and Karlson Islands are predominately tidal freshwater habitats. Russian and Seal islands are emergent marshes, experiencing frequent tidal inundation. Two dendritic channels were sampled at each island (Section 2.1). In accordance with the three different vegetation assemblages represented at these islands; this resulted in four replicates of emergent

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<sup>2</sup> Results presented herein are in part synopsisized from Mary Austil Lott's M.S. research thesis that encompassed the initial two years of research (Lott 2004). A manuscript is currently being prepared for submission to a peer-reviewed scientific journal.

marsh habitat and only one replicate each of forested and scrub-shrub habitat. Sampling occurred over three consecutive days each month, sampling one island per day. All of the channels dewater on low tide, and sampling was conducted during spring tides.

**Prey Abundance and Composition**—Two types of invertebrate samples were collected from each site 1) insect fallout trap and 2) benthic core samples. Both types were needed to evaluate the abundance and composition of salmon prey resources potentially available to and selected by juvenile ocean-type salmon. We did not sample water column zooplankton because our pilot studies and all prior data suggest that small juvenile ocean-type salmon found in these habitats consume few zooplankters.

***Terrestrial Invertebrates.*** Insect fallout traps collect terrestrial insects and other invertebrates associated with the wetland vegetation that might fall on the water surface in tidal channels. Five insect fallout traps were haphazardly placed along each study channel within 100 m of the mouth of the channel, during each month of the sampling seasons. An insect fallout trap consists of a plastic bin ( $51.7 \times 35.8 \times 14$  cm) filled about halfway with soapy water. The bin rests on a stand of PVC pipe placed in the ground and secured with three bamboo stakes and a PVC pipe. The trap is allowed to float vertically with the tides. This sampling technique has been successful in capturing flying adult insects found as prey items in salmon diet (e.g., Gray et al. 2002). In 2002, all traps were deployed from 24 to 48 h. In 2003, traps were set on the first day of sampling and collected after 48 h. Samples were sieved through a 0.106-mm sieve, placed in a jar with 70% isopropanol, and returned to the lab for processing. A dissecting microscope was then used to identify and count insects in each trap. Insects were identified to taxonomic level (class, order, family) depending on abundance and importance of prey in salmon diet.

***Benthic Invertebrates.*** At each insect fallout trap site, we also acquired a 0.0024-m<sup>2</sup> sediment core sample from unconsolidated, unvegetated sediments in the adjacent channel at low tide. Core sampling coincided with trap-net fish sampling at each site. Each sample was placed in a jar and fixed with a buffered 7-10% formalin solution. In the lab, the sample was concentrated on a 0.5-mm sieve. The macrofaunal sample was then placed in a 70% isopropanol solution and stained with rose Bengal. All organisms in each sample were identified to taxonomic level (class, order, family) depending on abundance and importance of prey in salmon diet.

***Descriptive Statistics.*** Descriptive analyses of abundance and composition of invertebrates from the fallout traps were conducted using pivot tables (Microsoft Excel). Densities were standardized to area and reported as average density of invertebrates per m<sup>2</sup>. The Shannon-Weiner diversity index ( $H'$ ), which takes into account both species



richness and relative abundance, was used to quantitatively describe species diversity,

$$H' = \sum [-P_i \cdot (\ln P_i)]$$

where  $P_i$  = the proportion of species in the community (number of individuals in a species/number of individuals in the community, Zar 1999). The higher the value ( $H'$ ), the greater the diversity found in the traps.

We also calculated an evenness index ( $J'$ ), a measure of the distribution in density of different taxa. The evenness index is a positive value ranging from 0 to 1, and takes into account the number of categories ( $k$ ),

$$J' = H'/H'_{\max}$$

where  $H'_{\max} = \ln k$  (Zar 1999).

A nonparametric statistical test, Kruskal-Wallis comparison of means, was used to test differences in fallout trap composition among the six channels. Nonparametric analyses were used due to the non-normal distribution of data. This test was followed with a nonparametric multiple range test, the Student-Newman-Keuls (SNK) multiple comparison of means, to specify the differences among sites (Zar 1999).

Descriptive analyses of invertebrate abundance and composition from sediment cores were conducted using pivot tables (Microsoft Excel). Densities were standardized to area and reported as average density of invertebrates per  $m^2$ . The Kruskal-Wallis nonparametric comparison of means was used to test differences in specific benthic invertebrates that are important prey items for juvenile Chinook salmon (i.e., Chironomidae larva and *Corophium* spp.). This test was followed with a nonparametric multiple range test, the Student-Newman-Keuls (SNK) multiple comparison of means, to specify differences among sites (Zar 1999). Due to low sample sizes of fish at some sites and time constraints, not all benthic core samples were processed in April and June 2003. Sites included were those where a sample of more than 5 salmon were caught. We set  $\alpha = 0.05$  for all these statistical tests.

The Index of Relative Importance (IRI) was used to describe the diets of juvenile salmon within each site (Pinkas et al. 1971). The IRI is a metric that has been used in many diet studies to assess the relative importance of different prey items (Simenstad et al. 1991; Gray et al. 2002). IRI of different prey taxa are calculated taking into account the numerical composition (NC), gravimetric composition (GC), and frequency of occurrence (FO) of all prey items found in the diet (Pinkas et al. 1971; Bowen 1983),

$$\text{IRI} = \text{FO} \times [\text{NC} + \text{GC}].$$

Results are expressed as the percent of total IRI for all prey taxa. Percent numerical composition of prey is calculated as the number of items of a given taxon as a percentage of the total number of prey items counted in the sample of stomachs. Gravimetric composition is calculated as the weight of items in a given taxon as a percentage of the total weight of all items in the sample of stomachs. Frequency of occurrence of prey items was calculated as the proportion of the total sample of stomachs that contain one or more of a prey taxon. Statistical summaries of the relative importance of prey, frequency of occurrence, numerical composition and gravimetric composition are presented.

Relative consumption rate was measured using an Index of Feeding Intensity (% IFI) which was expressed as a percentage of the total weight of the stomach contents divided by the total weight of the fish (Bottom and Jones 1990; Gray et al. 2002),

$$\text{IFI} = (\text{total weight of prey} / \text{total weight of predator}) \times 100.$$

Statistical summaries of %IFI values are presented as graphs that also contain the qualitative ranking of fullness (1 – 6) that was given to each dissected stomach.

**Diet Composition and Intensity**—All fish for diet analysis were captured during the trap-net sampling described in Section 2.1. Sacrificed fish were initially stored on ice in the field and immediately frozen as soon as possible. In the lab, fish were partially thawed, and stomachs were removed from the abdominal cavity and preserved in a 10% buffered formalin solution until processing. Stomach contents of the juvenile salmon retained from each channel were analyzed to determine diet composition and relative consumption rates. Fullness was ranked by stomach fullness index (FI), using a qualitative rank scale ranging from 1 (empty) to 6 (distended).

For analysis, stomach contents were removed and organisms identified to class, family, or order (depending on the physical state of the organism). Contents were blotted dry, counted, and weighed in prey taxa groups. Total weight of the stomach content was obtained by adding the total weight of prey taxa groups to weight of the unidentified material. Total weights were obtained after the blotting process to avoid damage to the insects prior to identification. A qualitative ranking scale from 1 (nothing could be identified) to 6 (100% identification) was also applied to stomach contents to assess the state of digestion that had occurred. After identification, enumeration, and weighing, prey items were stored in 70% isopropanol.

**Feeding Selectivity**—Feeding selectivity by juvenile Chinook salmon was measured using Jacob's modified electivity index, which is a modification of Ivlev's electivity index (Jacobs 1974),

$$D_i = [(r_i - P_i)/(r_i + P_i - 2 r_i P_i)]$$

where  $D$  is electivity of prey type  $i$ ,  $r_i$  is the proportion of the numerical prey density in the diet and  $P_i$  is the proportion of the prey item in the environment. The modified electivity index is independent of the relative abundance of prey items in the environment, and is used when relative abundance of prey items differs. The value obtained is very similar to Ivlev's index, but it is unaffected by changes of food composition in the environment (Jacobs 1974).

Diet overlap with the sampled prey resource was calculated using a modified Percent Similarity Index (PSI; Hurlbert 1978),

$$PSI = \sum \text{minimum } (P_{xi}, P_{yi})$$

where  $p_{xi}$  = percentage of prey  $i$  in predator  $x$  and  $p_{yi}$  = percentage of prey  $i$  in the sampled prey resources  $y$ .

## Results

Two approaches were taken to the 2002-2003 dataset: (1) a time series analysis of prey availability and juvenile Chinook diets using data from Russian Island South 2002 March-August, and (2) a spatial (habitat) analyses from 2003 that allowed us to compare the habitat capacity of three distinct shallow-water wetland habitat types in terms of subyearling Chinook diet and prey resources available.

**Prey Abundance and Composition**—Results from the 2002 temporal analysis of terrestrial invertebrates showed an increase in both abundance and diversity of insects as the months progressed (Figure 37). Thirty-five taxa were represented in the traps from 13 orders of Insecta and Arachnida. Trends in the Shannon-Weiner diversity index ( $H'$ ) indicated low diversity of prey taxa in March ( $H' = 0.19$ ), but a steady increase was seen until diversity peaked in June ( $H' = 1.31$ ). A slight decrease in diversity was seen in July ( $H' = 1.25$ ) followed by a further decrease in August ( $H' = 0.99$ ).

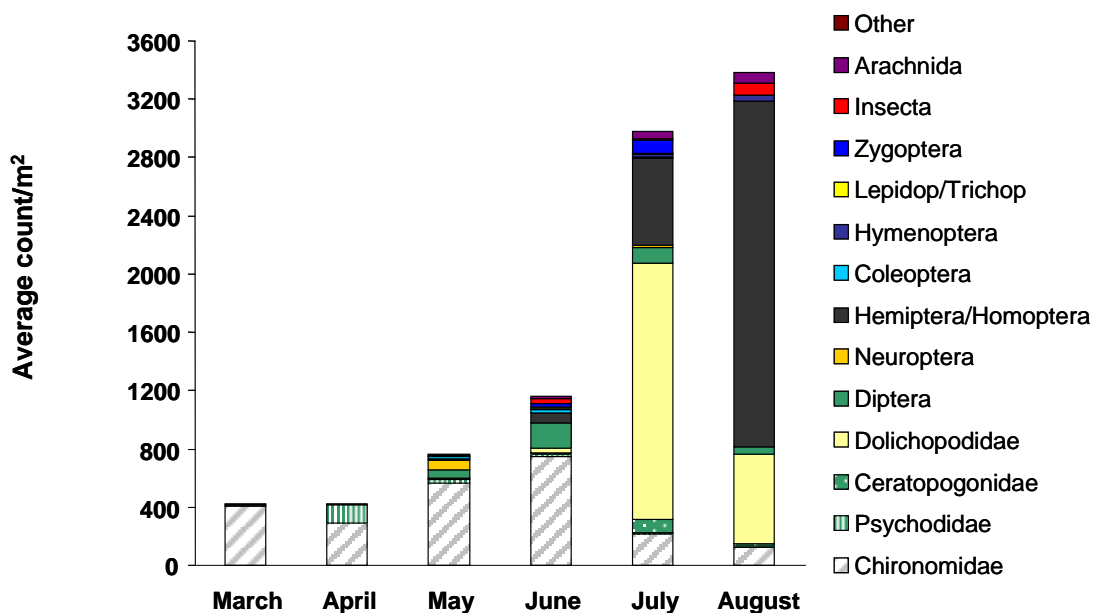


Figure 37. Abundance and composition of fallout trap invertebrates at Russian Island South, 2002.

March and April showed the lowest diversity values over the 6-month period. Results of the evenness index followed the same pattern, but with less noticeable change in value over the six month period. Based on the Kruskal-Wallis comparison of means, the average total abundance of insects per trap were significantly different ( $P < 0.001$ ) across the six-month sampling period. Significant differences were also observed for densities of chironomids, hemipterans, homopterans, and dolichopodids.

In the 2003 spatial habitat analyses, 43 taxa from 16 orders of Insecta and Arachnida were documented during the April, May, and June fallout traps from the six channels. Shannon-Weiner diversity was consistent and high over the 3 months at both Karlson Island sites ( $H' = 1.35-1.53$ ), but the diversity of insects in the four emergent marsh channels (north and south channels of Russian and Seal Island) steadily increased over the three month period. In April, the diversity of insects in the emergent marshes was noticeably lower than the Karlson Island wetland sites, but by June the insect diversity among all sites was similar (Figure 38 and 39, respectively).

While the emergent marshes had an overall greater density of insects available as compared to the forested and scrub-shrub sites in April and May, the June abundance levels were not significantly different among the sites. The forested and scrub-shrub sites did, however, contain lower abundances of chironomid larva and emerging adults in April, May, and June.

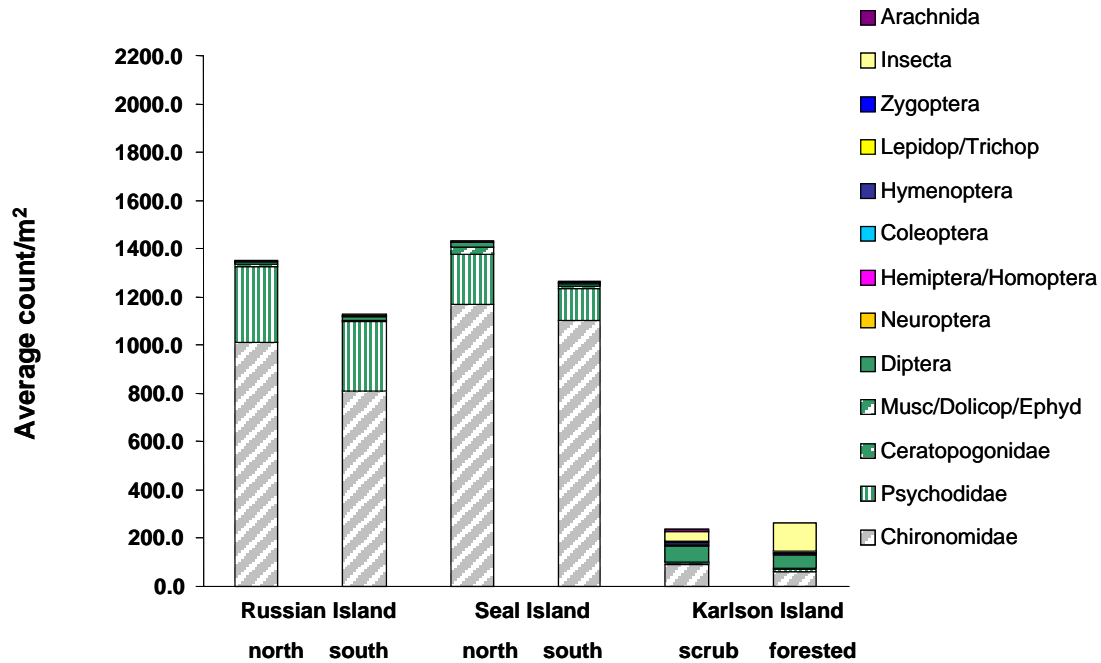


Figure 38. Abundance and composition of fallout trap invertebrates, April 2003.

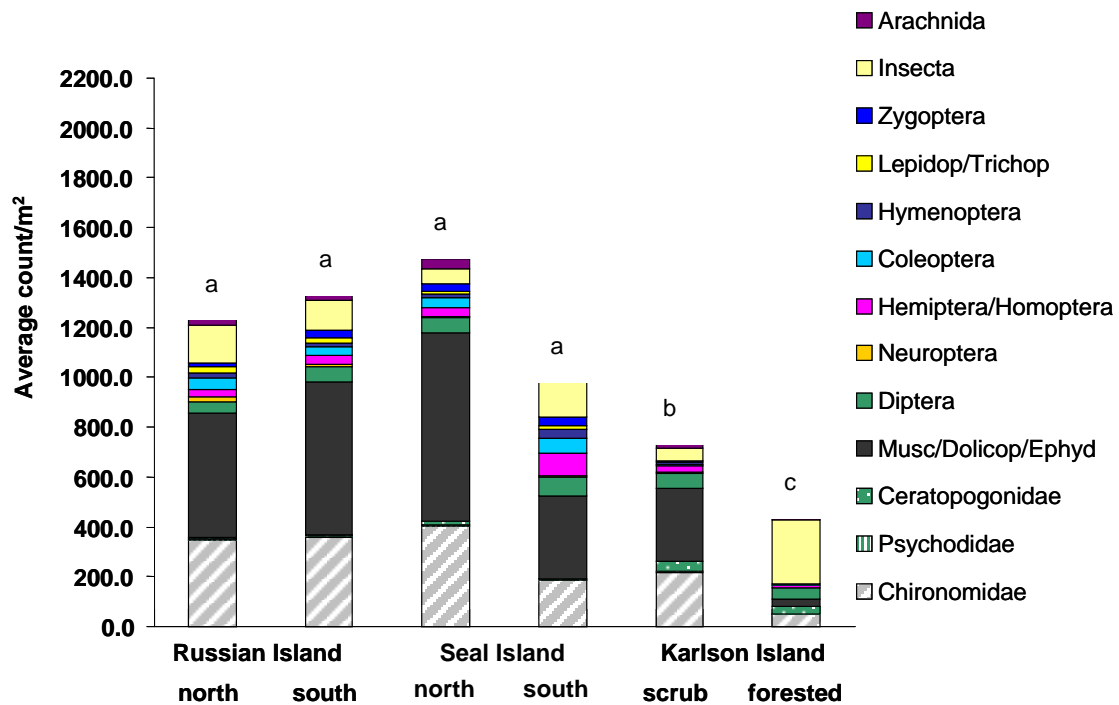


Figure 39. Abundance and composition of fallout trap invertebrates, June 2003.

The increase in abundance and diversity of insects in the emergent marshes corresponded directly with the growth of marsh vegetation. Kruskal-Wallis comparison of means indicated a significant difference in total density of fallout trap invertebrates ( $P < 0.001$  to  $0.018$ ) among the six channels during all three months. The SNK multiple comparison of means indicated that total density and chironomid density in May and June 2003 were significantly different only between the Karlson Island forested and scrub-shrub sites in total density and chironomid density.

*Benthic Invertebrates.* Twenty-two invertebrate taxa were represented among the benthos samples over the 6-month temporal series from March to August 2002. Oligochaetes and nematodes comprised the majority of benthic core density in all months. The only salmon prey item found in any abundance in the cores was chironomid larva, which occurred in samples from all 6 months (Figure 40). Amphipods constituted a negligible proportion of total density in the March cores. The Kruskal-Wallis comparison of means indicated total density ( $P = 0.019$ ) and chironomid larva density ( $P = 0.015$ ) were significantly different across the six months. Chironomid larvae were also the only important salmon prey item that appeared regularly in the core samples across the 2003 spatial series. The Kruskal-Wallis comparison of means indicated that differences in total density and chironomid larva density were significant among all included sites in April to June 2003.

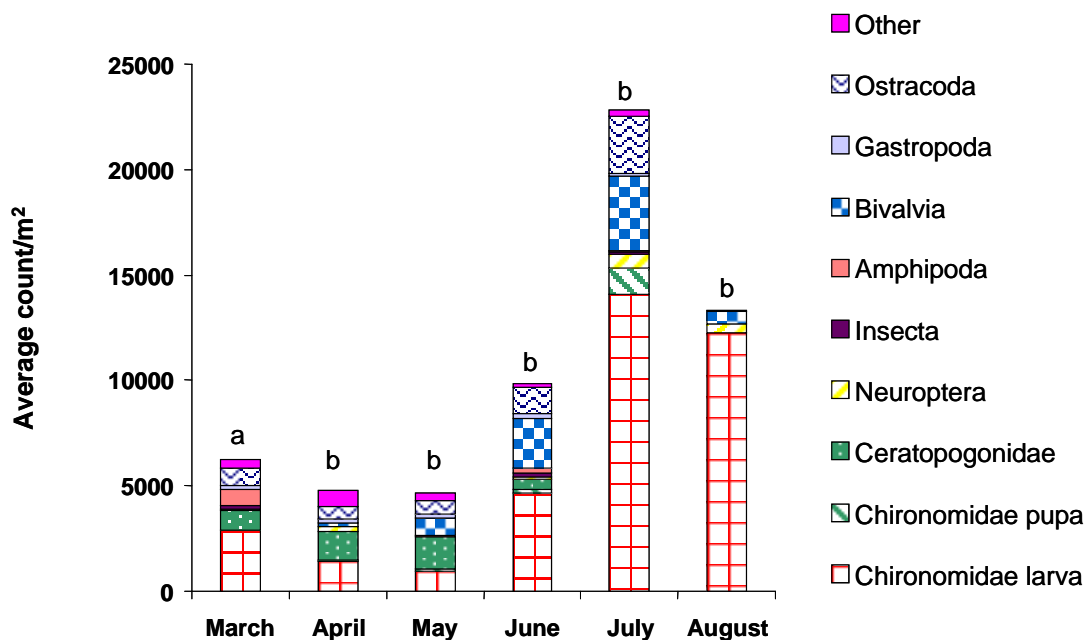


Figure 40. Benthic invertebrate abundance and composition (without oligochaetes and nematodes) at Russian Island South, 2002. Small letters above the bars indicate statistical groupings for total abundance (oligochaetes and nematodes included).

**Diet Composition and Intensity**—Marsh insects, including emerging adult chironomids, other dipterans, and neuropteran adults, dominated diet compositions of juvenile Chinook at Russian Island south through the April-July 2002 time series. Mean length of processed Chinook from Russian Island South 2002 was 74.3 mm FL (fork length). Emerging chironomids comprised 73.4% of total IRI% for Russian Island South 2002 (Figure 41). Although marsh insects dominated diets of all size classes of fish, amphipods (the majority of which were *Corophium* spp.) also appeared to be an important prey item in March, April, May, and August. Amphipod contribution to the total IRI% ranged from 54.5% in March to 1.9% in July.

Based on IRI, diet composition shifted over the six-month period (Figure 42). Amphipods represented a large component of diets in March and April, while chironomids dominated the diets in May through July. Hemipteran and homopteran insects dominated the August diets, and amphipods and emerging/adult chironomids were also represented to a lesser degree. The highest IFI value of 0.73% occurred in May and the lowest IFI value of 0.21% occurred in August. A downward shift in IFI occurred between the months of May and August.

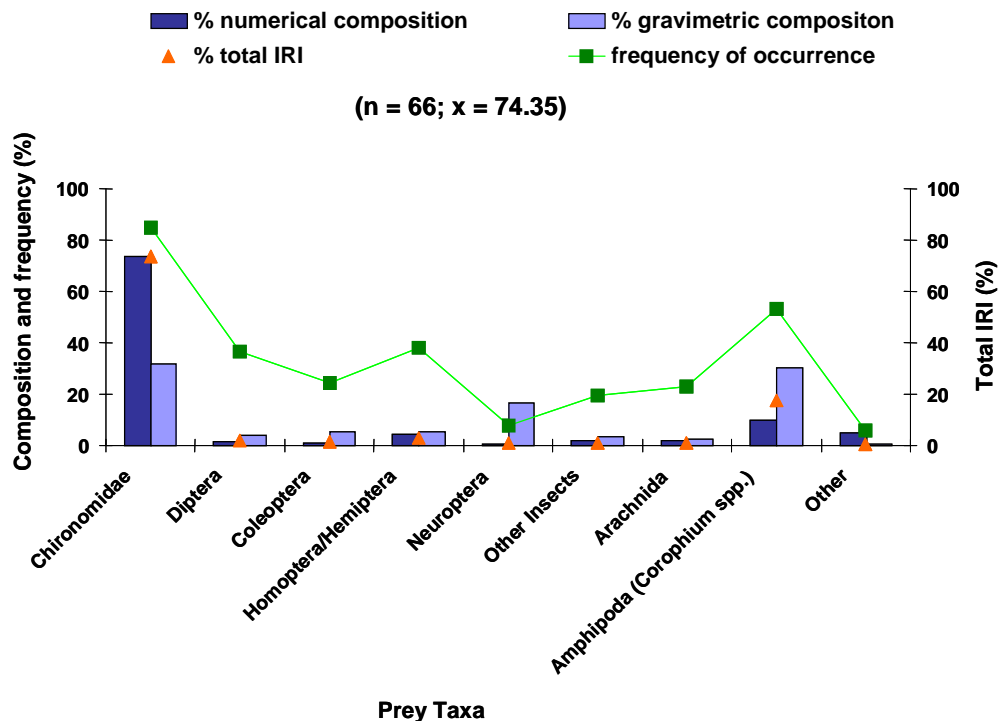


Figure 41. Diet compositions for juvenile Chinook from Russian Island South 2002, as percent numeric abundance, percent gravimetric abundance, percent frequency of occurrence and percent total Index of Relative Importance.

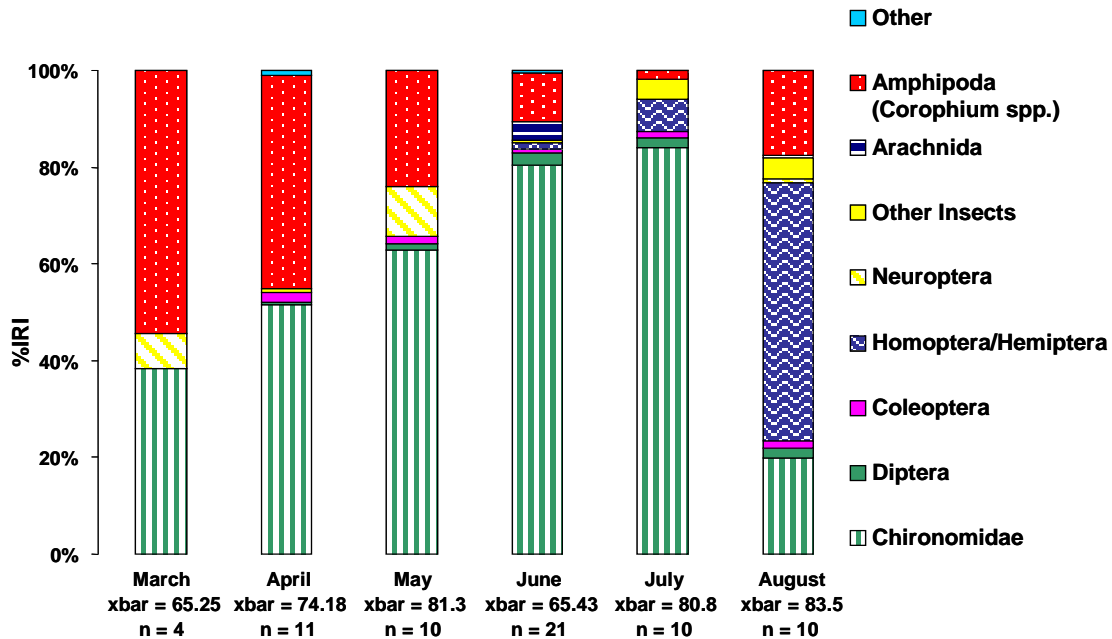


Figure 42. Diet compositions for juvenile Chinook from Russian Island South 2002, as percent total Index of Relative Importance (IRI), March to August.

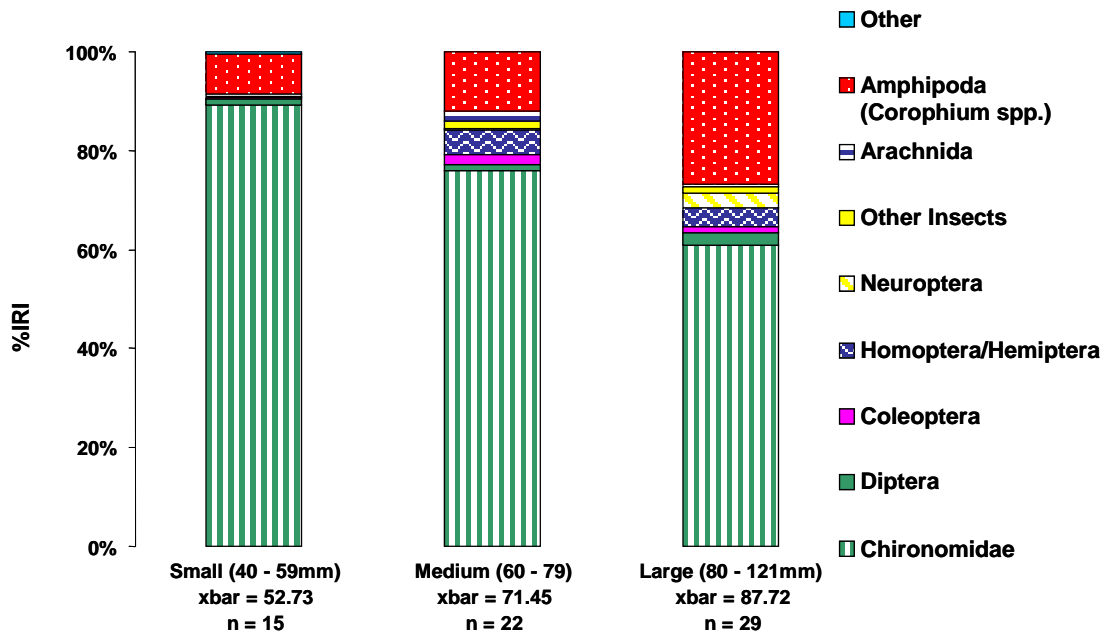


Figure 43. Diet compositions for juvenile Chinook from Russian Island South 2002, as percent total Index of Relative Importance (IRI), based on three distinct size class groupings.



Marsh insects, including chironomids and other dipteran insects, also dominated the diets of juvenile Chinook in 2003. Emerging chironomids were the predominant prey item for juvenile Chinook of all sizes and sampling locations and accounted for 85.3% of the total IRI for all 2003 fish. The mean length of the processed Chinook was 62.6 mm FL; over half of the Chinook were fry < 60 mm FL.

Diet composition among the emergent marsh and Karlson Island scrub-shrub sites was not materially different (Figure 44). Diets of fish from the Karlson Island forested channel contained a greater component of larger insects and spiders than those from the emergent marsh and scrub-shrub sites, but chironomids still dominated all diets. In order to compare the three habitat types, the four emergent marsh channels were combined, and then compared to the forested and scrub-shrub sites (Figure 45). Chironomids dominated the diets of all habitat types, with IRIs ranging from 76% in Karlson Island forested to 90% in the emergent marsh sites. However, there were noticeable differences among fish size classes (Figure 46). The majority of Chinook salmon found in all the channels were from the smallest size class (40-59 mm FL). The diet of these small Chinook was consistently dominated by emerging chironomids and terrestrial insects across all sites and months, while the diet of medium (60-79 mm FL) and large (80 to 106 mm FL) Chinook was more diverse and included neuropteran insects and some benthic prey (namely, amphipods and chironomid larva).

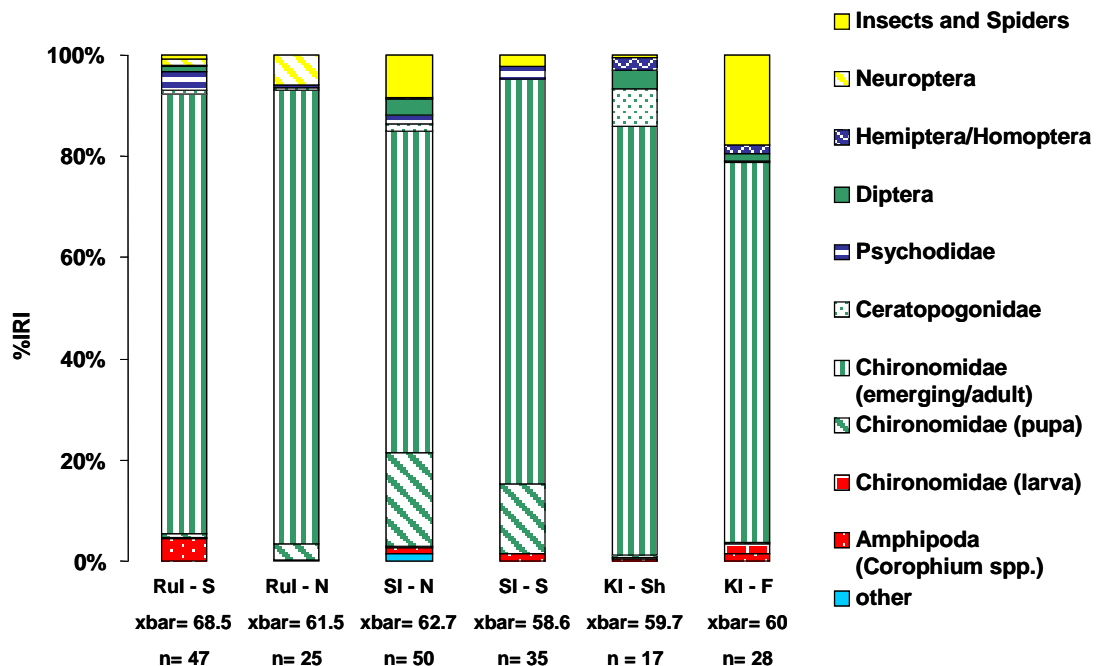


Figure 44. Diet composition of juvenile Chinook salmon across sites, April to June 2003, as percent total Index of Relative Importance (IRI). Rul-S/N, Russian Island south and north; SI-S/N, Seal Island south/north; KI-Sh/F, Karlson Island scrub-shrub/forested.

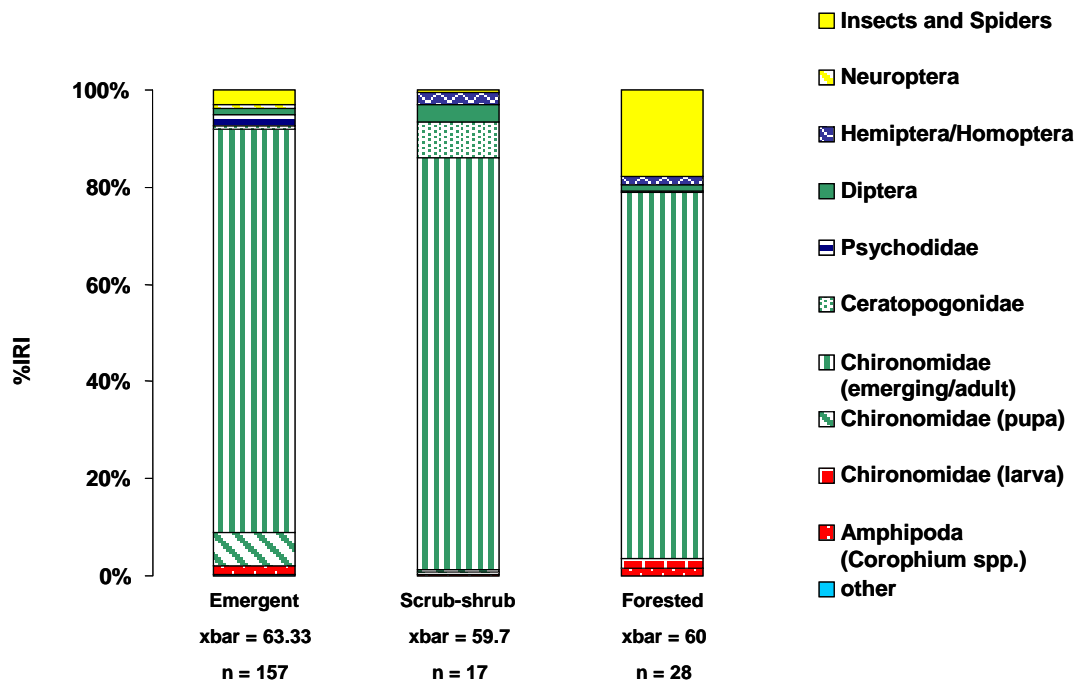


Figure 45. Diet composition of juvenile Chinook salmon from three wetland types, April to June 2003, as percent total Index of Relative Importance (IRI). The emergent bar includes all four of the emergent marsh channels included in study.

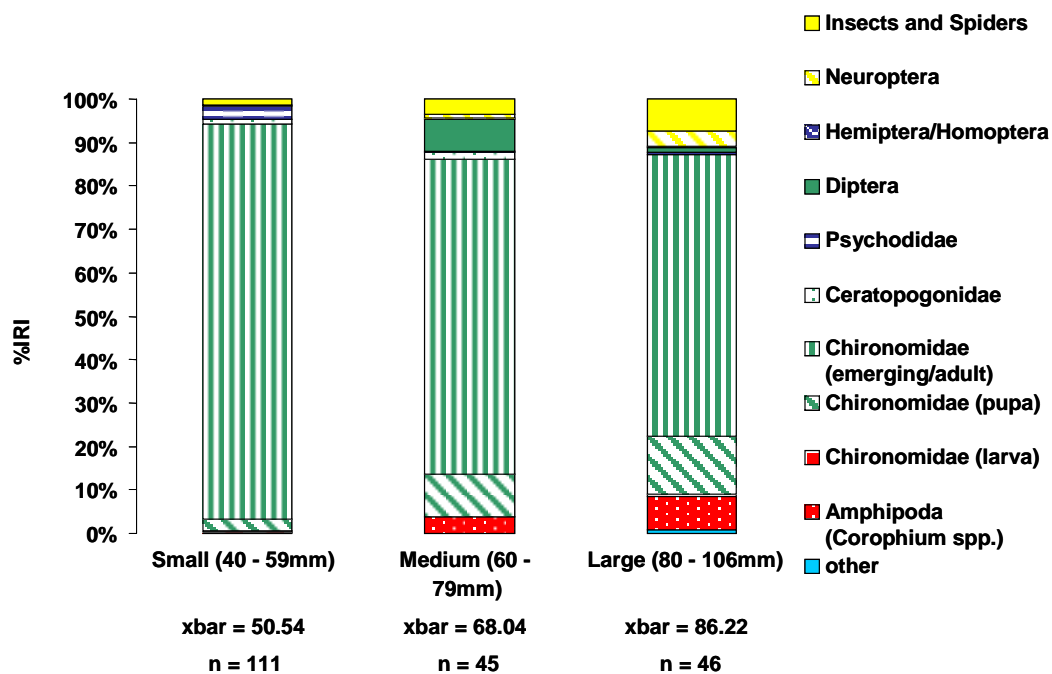


Figure 46. Diet composition of juvenile Chinook salmon, April to June 2003, as percent total Index of Relative Importance (IRI) for all sites and size classes.

Feeding intensity (IFI) of Chinook (excluding the Karlson Island scrub site, where no fish were caught in April and no weights taken in May) suggested higher consumption rates for fish in emergent marsh habitats than in the forested wetland channel (Figure 47). Chinook captured in emergent marshes may be eating more than their counterparts at the forested site over a comparable time period occupying the channel habitats. The most sufficient sample size of Chinook from both wetland types occurred in the small size class, where average IFI was 0.91% for fish from emergent marsh compared to 0.56% for fish from the forested channel. An expected decrease in IFI values was also evident with increasing size class.

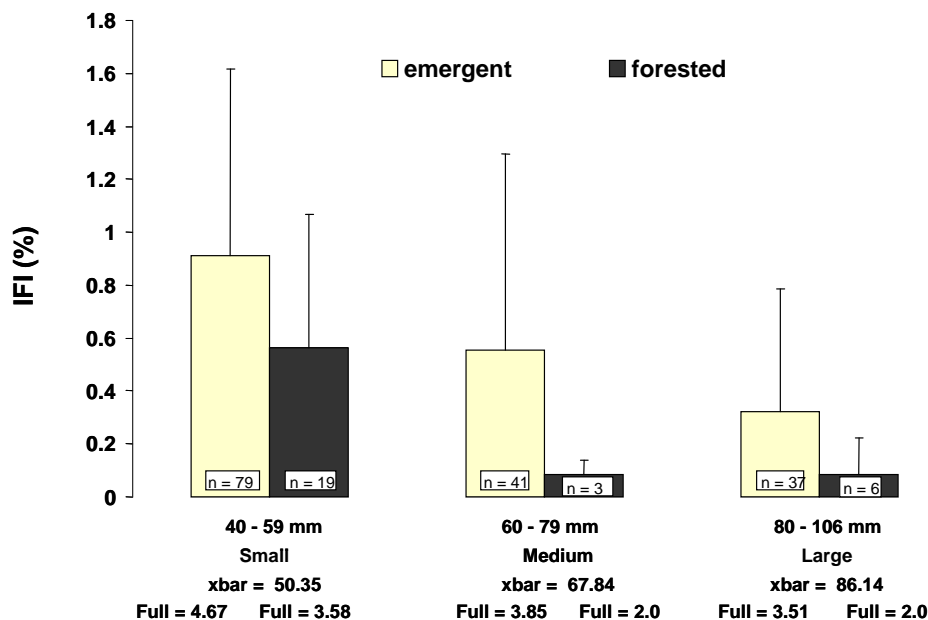


Figure 47. Index of Feeding Intensity as indicator of relative consumption rate of juvenile Chinook salmon within emergent marshes and forested wetlands, April to June 2003.

**Feeding Selectivity**—Based on the Jacob’s electivity index, juvenile ocean-type Chinook appeared to select against most dipteran insects, with the exception of chironomids, which the fish actively selected from the environment (Figure 48). Selection of amphipods, hemipteran, homopteran and neuropteran insects occurred predominately in larger fish (Figure 49). Overlap between Chinook diet and invertebrates sampled in the fallout trap was considerably higher (PSI = 36.3%) than overlap between Chinook diet and benthic invertebrates (PSI = 2.5%). Medium and large Chinook in forested and scrub-shrub wetlands also showed selectivity for hemipteran and homopteran insects, with values ranging from 0.38 to 0.91. High selectivity was also

seen for amphipods, especially in the emergent marsh sites, with values ranging from 0.18 to 0.87 (Figure 50). Results of the 2003 diet analysis also indicated a distinctive overlap between juvenile Chinook diet and fallout trap composition, with overlap high between Chinook diet and fallout-trap invertebrates (PSI = 68.57%) and considerably lower between Chinook diet and benthic invertebrates (PSI = 2.29%).

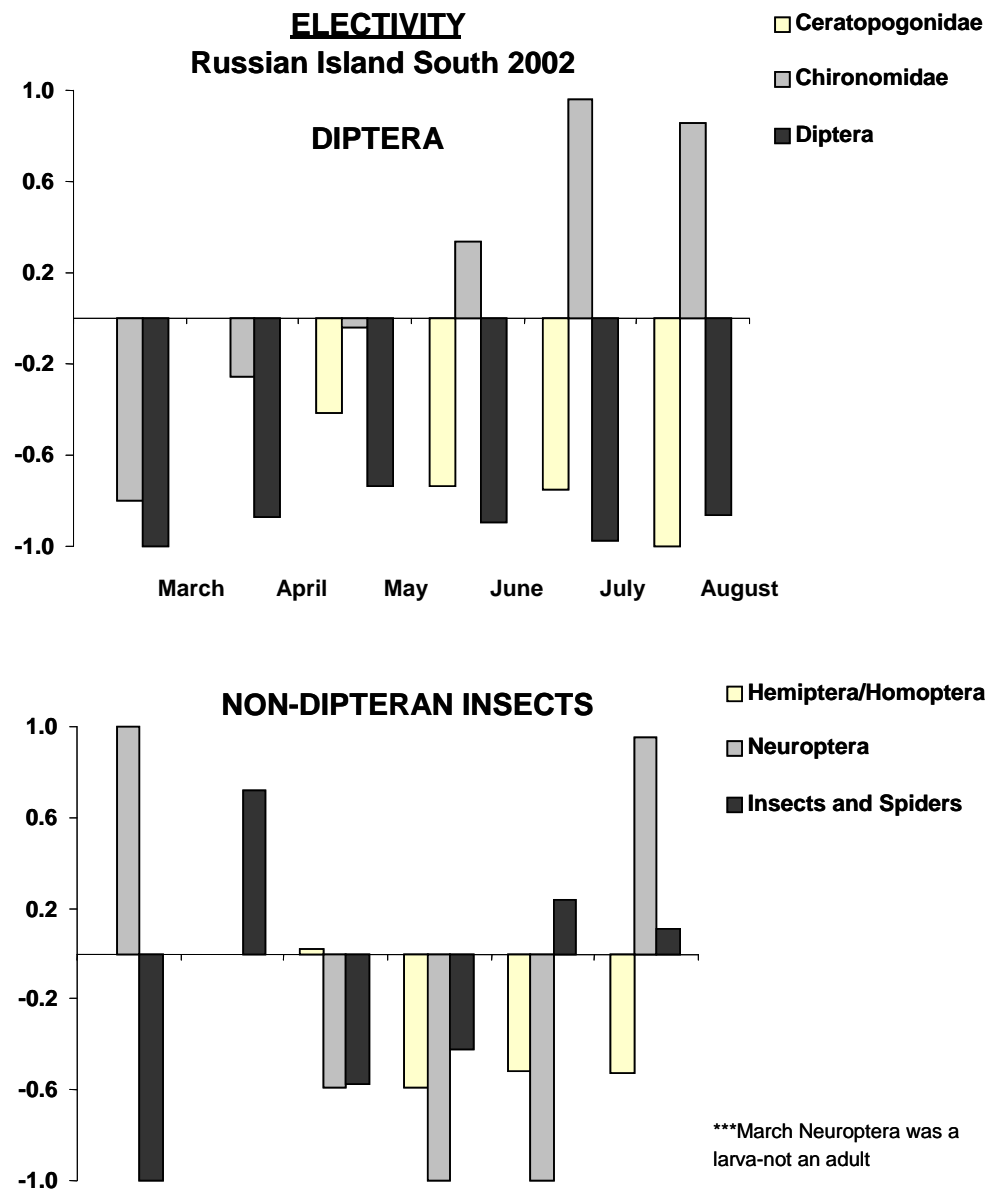


Figure 48. Electivity Index for Chinook salmon diets (n = 66) from Russian Island South 2002. Index ranges from 1 to -1 (from selective feeding to avoidance of prey, respectively).

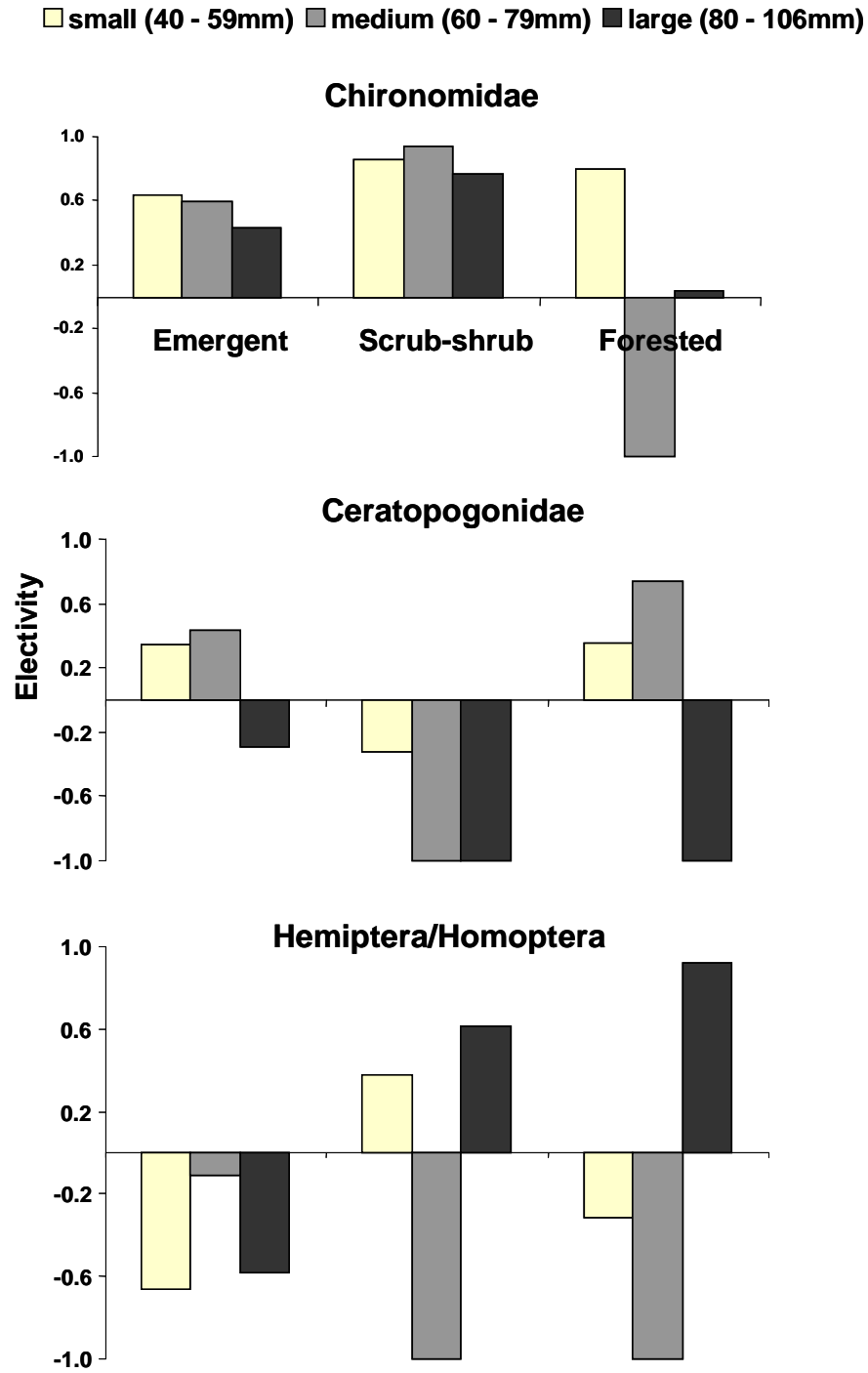


Figure 49. Electivity Index for Chinook salmon diets, April to June 2003, for three wetland types and three size classes. Index ranges from 1 to -1 (selective feeding to avoidance of prey, respectively).

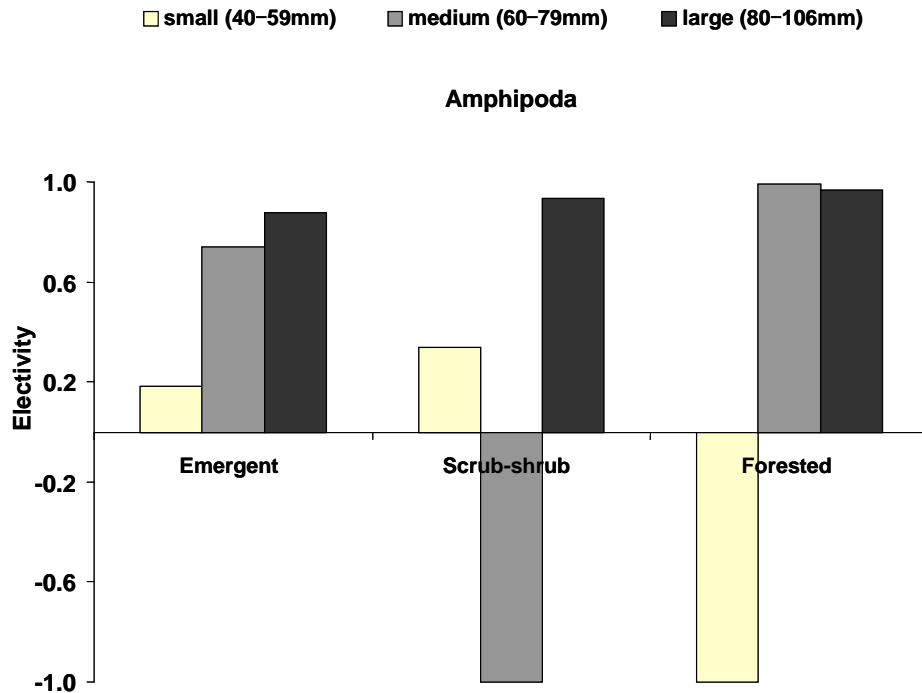


Figure 50. Electivity Index for Chinook salmon diets, April to June 2003, from three wetland types and three size classes. Index ranges from 1 to -1 (selective feeding to avoidance of prey, respectively).

## Conclusions

These results indicated that greater densities of terrestrial insects occurred in the emergent marsh sites as compared to the forested and scrub-shrub sites. Chironomids dominated the insect fallout traps from March to May-June. By July, herbaceous vegetation was in full bloom, abundance of insects in the emergent marsh sites significantly increased, and traps were dominated by numerous dipteran and hemipteran/homopteran insects. Density of insects in all months was greater in emergent marshes than in forested wetland.

Overall, Chinook diet was dominated by chironomids. However, Chinook diet in forested wetland channels contained a higher proportion of larger insects, which are commonly associated with woody vegetation. Consumption rate, as defined by feeding intensity, was higher in Chinook from the emergent marsh sites compared to Chinook from the forested wetland site. Chinook appeared to be actively selecting for chironomids and *Corophium* spp.

A shift in diet was seen in the three size classes of juvenile Chinook included in this study. Diets of smaller fish (40-59 mm FL) were consistently dominated by chironomids, with higher diversity in the diets of larger Chinook. Amphipods and larger insects appeared with greater frequency in the diets of medium (60-79 mm FL) and large (80-106 mm FL) Chinook. Based on IRI, diet compositions among all wetland types were almost monotypically dominated.

These results support the interpretation that different shallow-water tidal wetland habitats are likely linked but provide somewhat different support of *opportunity* and *capacity* for juvenile Chinook and possibly chum salmon. Forested and scrub-shrub wetlands, being typically at the upper end of the environmental gradient that the fish are transiting in their migration and rearing in the estuary, appear to provide lower prey availability (expressed also in FI) than emergent tidal marshes. However, water temperature fluctuations and extremes were considerably less and occurred later in these woody vegetation habitats than in the marshes. The tidal marshes appear to provide higher capacity, which may be significant because they occur at the cusp of the transition to oligohaline waters and the requirement for physiological adaptation. However, fish appeared to be forced out of tidal marsh channels earlier due to increasing water temperatures (Section 2.1).

The dense cover of forested and scrub-shrub channels likely moderated water temperature at these sites, in contrast to the shallow and more open emergent marsh channels of the lower estuary. Thus, even though forested and scrub-shrub sites may have provided fewer feeding opportunities than emergent marsh sites, they may also provide thermal refugia, where fish can lower their metabolism for energy conservation, and therefore require less energy input for growth (Brett and Glass 1973). The main channels of forested wetlands lacked the complex dendritic networks and considerable edge habitat of emergent marshes; however, the greater length and depth of these channels, and abundant sources of wood debris, would allow retention of large pools of water during most low tides. Thus, juvenile salmon would not be frequently forced out into the main channel with outgoing tides but could occupy protected channel habitat throughout a tidal cycle. Testing the actual mechanisms behind these observed patterns will be pursued through subsequent research using bioenergetic models. These models are 'driven' by data that describe fish opportunity (e.g., occurrence, density and size; diet composition; temperature) and new (consumption rate) capacity and performance.

## 2.3 Monitor Physical Attributes in the Estuary

### Introduction

The objective of this component of the project was long-term monitoring of physical properties in Cathlamet Bay (in particular salinity, temperature, and water levels). This monitoring is required to understand seasonal and interannual physical variability relative to natural and anthropogenic forcings, to provide context to understand salmon habitat opportunity and its variability, and to validate long-term simulation databases of estuarine circulation and associated physical habitat opportunity. While monitoring activities are funded through this project, data analysis and modeling activities are primarily funded by a companion project, sponsored by the Bonneville Power Administration.

### Methods

Instrumented stations are deployed in the Cathlamet Bay region, and complement the existing network of real-time physical monitoring stations in the lower Columbia River and estuary (Figure 51). As synthesized in Table 17, most Cathlamet Bay stations have salinity (via conductivity) and temperature sensors, and several have depth sensors (via pressure).

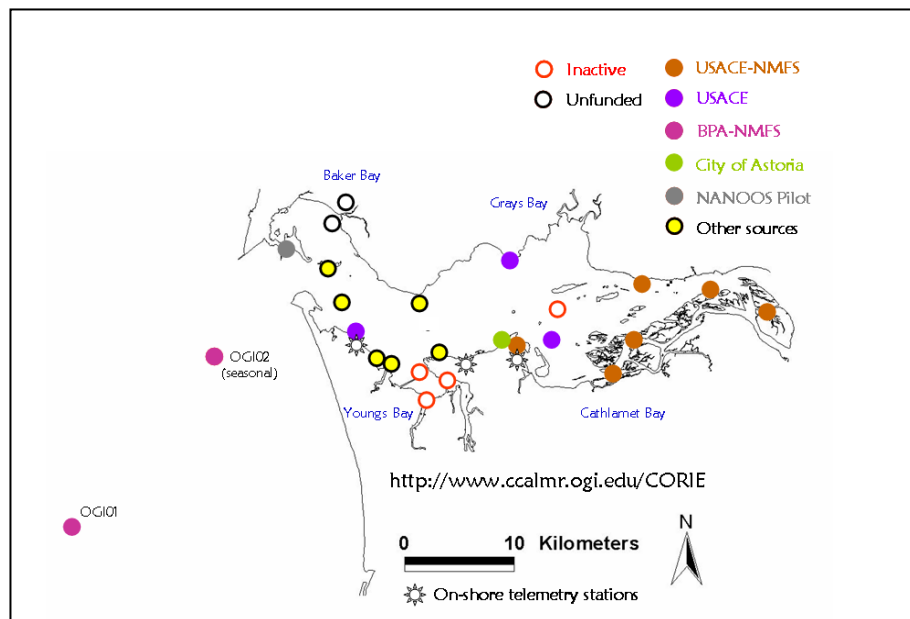


Figure 51. Stations comprising the CORIE Network, with reference to their primary funding source. Stations supported by this project are marked USACE-NMFS, and concentrate on the Cathlamet Bay region.



Data from these core sensors are typically collected at 1-minute intervals. Data is available at [www.ccalmr.orgi.edu](http://www.ccalmr.orgi.edu) both in real-time (graphical displays of essentially unverified data) and in archival form (verified data, statistics, and graphical displays). Data quality control procedures adopted to verify the data are described at [www.ccalmr.orgi.edu/CORIE/data/publicarch/methods\\_quality.html](http://www.ccalmr.orgi.edu/CORIE/data/publicarch/methods_quality.html)

Table 17. CORIE stations supported by this project. CTD, conductivity, temperature, depth.

Station	Instrumentation	Telemetry	Starting date
Mott Basin	CTD	Radio	2000
Cathlamet Bay North Channel 3	CT	Radio	2000
Svensen Island	CTD	Radio	2001
Marsh Island	CTD	Radio	2001
	Atmospheric station	Radio	2002/Experimental
	Turbidity	Radio	Experimental
Elliot Point	CTD	Radio	2001
Tenasilahe Island	TD	Radio	2003

Additionally, the Marsh Island station has a turbidity sensor and an atmospheric station. Water turbidity and solar radiation are still experimental measurements. Other atmospheric data are routinely collected at 0.5 Hz, and then locally processed to describe at 10-minute intervals wind speed and direction, peak gust, air temperature, and relative humidity.

## Results

Long-term time-series of monitored variables at the six Cathlamet Bay stations are the primary result of this project, and are available at [www.ccalmr.orgi.edu/CORIE/network](http://www.ccalmr.orgi.edu/CORIE/network). The time-series revealed useful trends and patterns. As an example, we focus on water temperatures.

All stations exhibited strong seasonal variation of temperature, with summer temperatures (in particular from mid-July to early September) commonly exceeding the 19°C suggested by Bottom et al. (2005) as the threshold for favorable temperature for juvenile salmon. However, there were large differences in hydrology due to variation in oceanic influence. In the lower estuary, stations exemplified by Tansy Pt. (Figure 52) showed significant ocean influence in temperature and salinity records.

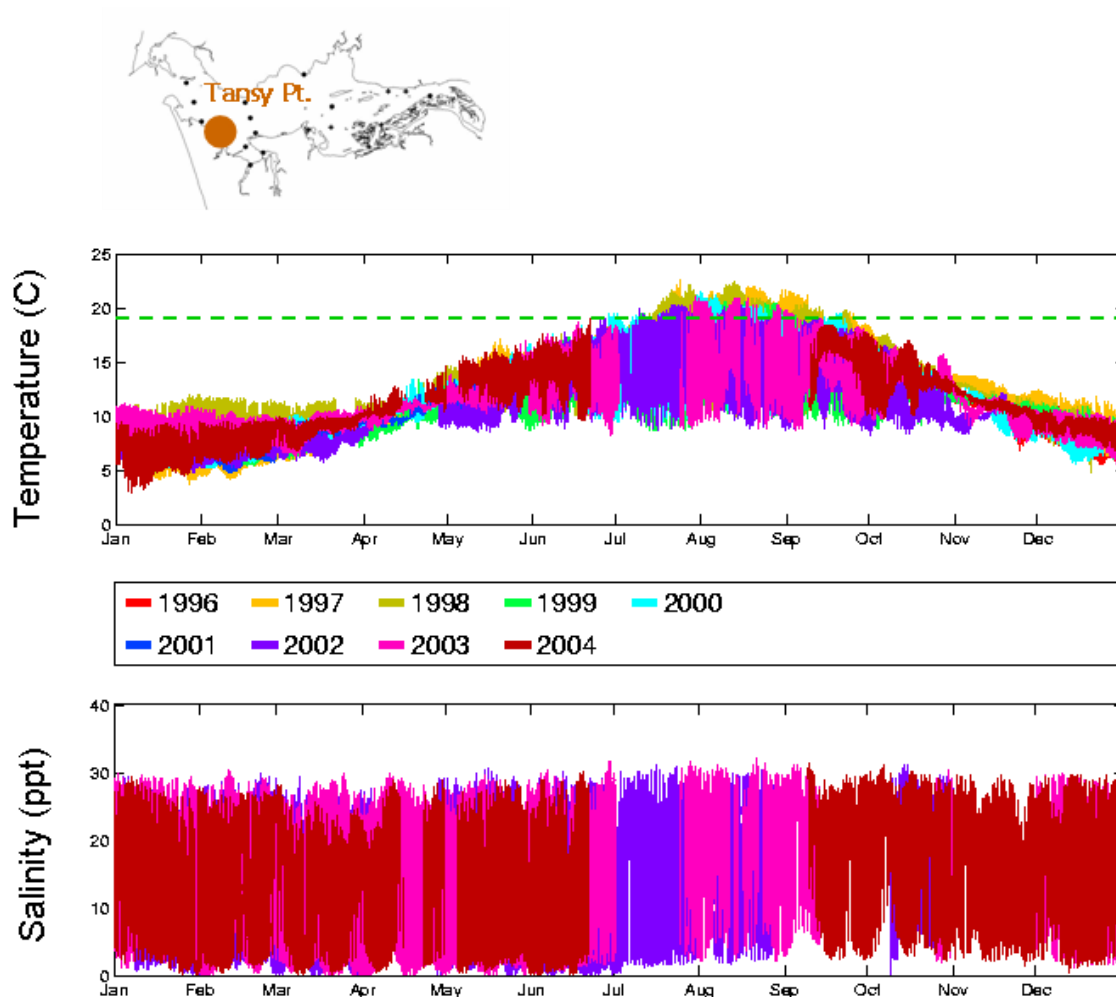


Figure 52. Time series of temperature (top) and salinity (bottom) from the Tansy Pt. estuarine station.

Because they are warmer in winter and cooler in summer than river waters, ocean waters have a moderating effect on temperature. There is also wide variation in salinity (seasonally ranging from essentially fresh to oceanic). Because ocean influence is tidally driven, there are substantial daily fluctuations in these physical parameters, except during the two transition periods per year where ocean and river temperatures are similar. In contrast, stations in the Cathlamet Bay region, exemplified by Elliot Pt. (Figure 53), experienced only occasional (if any) ocean influence. Daily fluctuations of temperature were much smaller than in the lower estuary, and salinity intrusion was consistently episodic. Stations upstream from Elliot Pt. are classified as tidal freshwater habitat (no salt penetration).

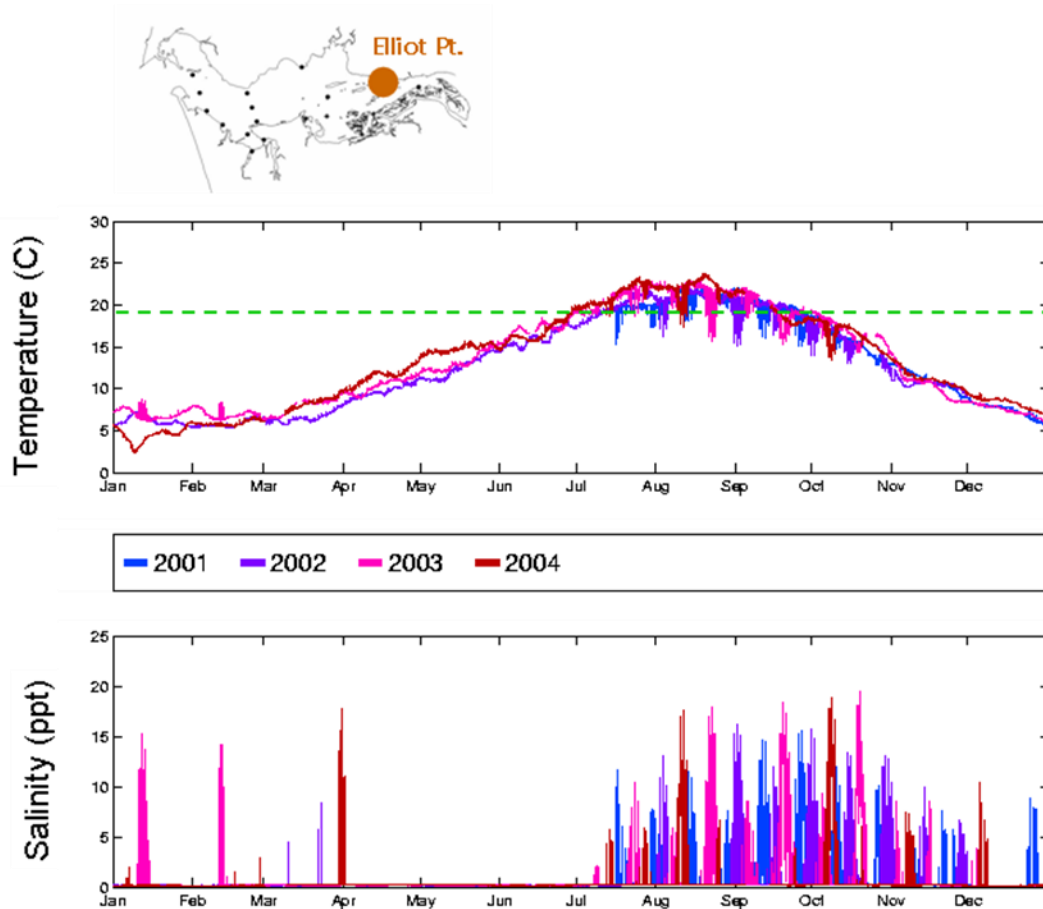


Figure 53. Time series of temperature (top) and salinity (bottom) from the Elliot Pt. estuarine station.

An analysis of temperature variation for stations in the Cathlamet Bay area shows that the influence of ocean temperatures was marginal in Cathlamet Bay (Figures 54-55). Temperatures had weak or no fluctuations with the tidal cycle, implying that the ocean had little moderating effect on the high summer temperature. Further, comparison with the temperature time series from Beaver Army terminal suggested that upstream river temperatures largely control daily median temperatures in Cathlamet Bay (Figure 56). Beaver Army daily median temperatures were strongly correlated with those of Cathlamet Bay stations (1997 to 2004), reinforcing the notion that ocean influences are small and restricted to selected stations (Elliot Pt., Mott Basin, Cathlamet Bay North Channel 3, and Grays Pt.). The correlation was broken by ocean influences, most visible at Mott Basin, Cathlamet Bay North Channel 3, and Grays Pt. Weak correlations at the Russian Island station likely reflected the effect of wetting and drying of sensors. Note that changes in the correlation between Beaver Army and Cathlamet Bay temperatures have the potential to serve as detection of increased ocean influences in the estuary, for instance as the possible impact of channel deepening or hydropower management.

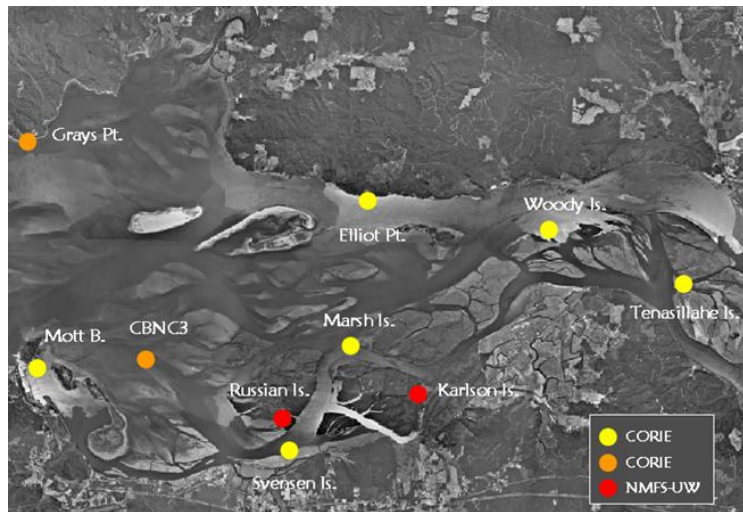


Figure 54. Cathlamet Stations used for the analysis in Figures 52 and 53. Yellow circles mark the CORIE stations supported by this project. Red circles mark stations maintained through this project by NMFS-UW.

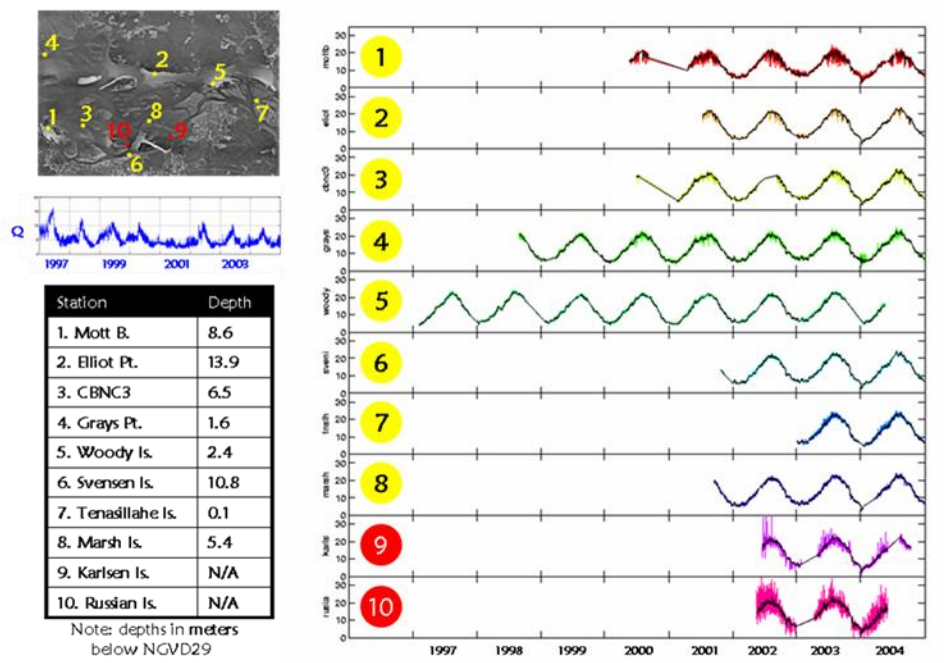


Figure 55. Time series of temperatures (black lines are median daily temperatures) for the Cathlamet Bay stations (1997-2004) shown in map.

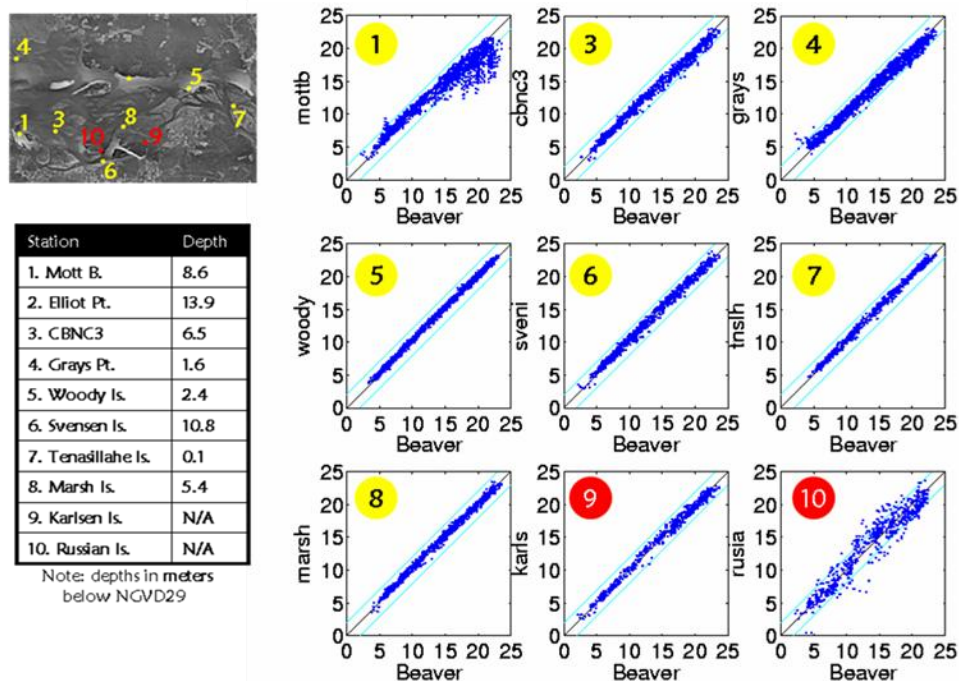


Figure 56. Relation of temperature at stations in the Cathlamet Bay region to upstream temperatures at Beaver Terminal. Deviation from linearity indicates ocean influence on temperature (e.g. mottb) or periods of aerial exposure (e.g. rusia).

The time-series data are also playing a major role in the development of circulation models for the estuary, and in particular, in the development of sound strategies for the simulation of salinity penetration. An example is provided in Figure 57, where two simulation databases are contrasted against salinity observations at Cathlamet Bay North Channel 3 (CBNC3).

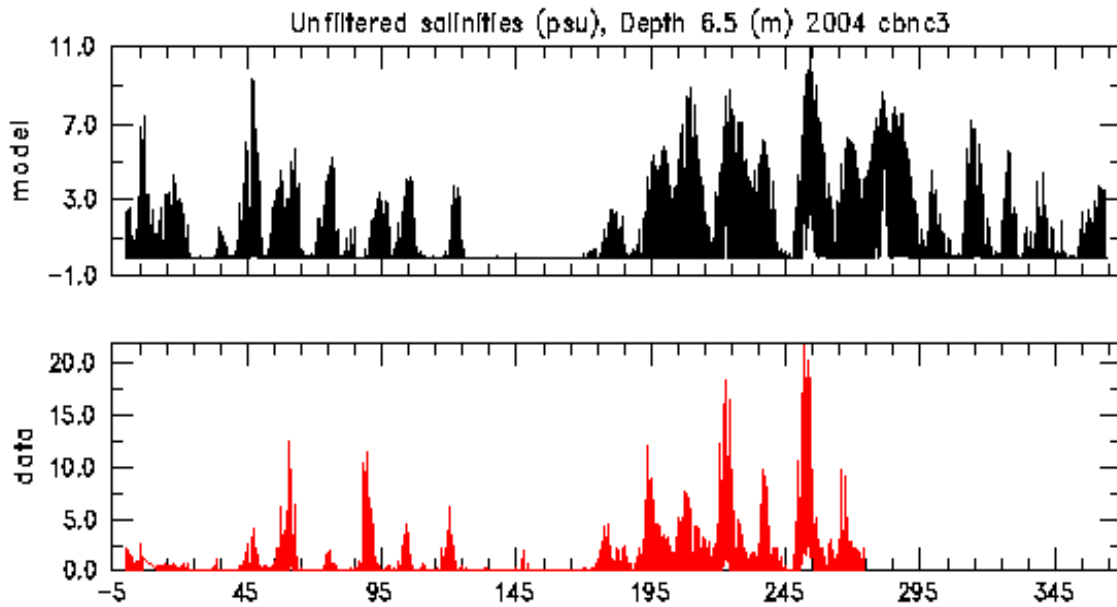


Figure 57. Comparison of modeled (top) vs. instrument (bottom) salinity time series (day of year) for 2004 at Cathlamet Bay North Channel 3. Long-term comparisons such as this permit characterization of simulation errors and have been instrumental in improving the ability of successive simulation databases to describe salt penetration in the estuary.

## Conclusions

Monitoring of physical properties in Cathlamet Bay is proceeding according to plan, and the time series at several of the stations have now reached the length that renders them useful for analysis of patterns and trends, as well as for validation of long-term simulation databases. Perhaps of particular importance is the finding that there is a strong correlation between median daily temperatures in Cathlamet Bay and upriver temperatures at Beaver Army terminal. This information is useful to reconstruct the history of temperatures in Cathlamet Bay (because Beaver Army temperatures have a much longer record of observations), and can lead to the creation of an effective index for the potential impact of channel deepening on ocean intrusion in the estuary. The creation of this index is a goal for the next year of the project.

## **2.4 Classification of Vegetation Assemblage Structure at Each Wetland Site**

### **Introduction**

To understand the biotic structure potentially influencing the juvenile salmon response to different shallow-water habitats, we conducted systematic surveys of the emergent and woody vegetation surrounding our fish sampling sites. Sampling was concentrated around the insect fallout traps described in Section 2.2. We also characterized the geomorphic structure (marsh and swamp platform elevations and channel profiles) and temperature conditions. Studies in 2004 included surveys at the recently added Welsh Island sites.

### **Methods**

Sampling techniques and plot sizes differed among emergent, scrub-shrub, and forested wetland sites on Russian Island, Seal Island, and Karlson Island to accommodate differences in physiognomic diversity. Each sampling site or plot was characterized in terms of assemblage type and then sampled in the method designated for that type (described below). Vegetation assemblages were assessed using species frequency (presence/absence) and relative abundance, following Elliot (2004).

For emergent marsh assemblages, we used a 1-m<sup>2</sup> quadrat to sample herbaceous species. To capture elevation-based heterogeneity in species composition at emergent marsh sites, we assessed assemblages along a transect perpendicular to the channel edge at three different locations: low marsh shelf, high marsh matrix, and high marsh depression (Figure 58). At scrub-shrub sites, vegetation assemblages were described within an estimated 5-m radius half-circle plot centered around each insect fallout-trap (Figure 59). In forested sites, we estimated a 20-m radius half-circle plots around the fallout traps. At all sites, vegetation species were designated to be dominant (DD), codominant (D), present (X), or trace (T) within the sampling area.

All fallout trap sites at Welsh Island-North were characterized as the scrub-shrub assemblage type, and only the 5-m half-circle radius with the fallout trap point as the center was used to sample vegetation. None of the sites were emergent marsh (quadrat sampling) or forested types (20-m radius plot) at Welsh Island-North. However, the Welsh Island-South sites were different from those sampled previously in the Columbia River estuary because they contained both emergent and herbaceous communities within a scrub-shrub component. Thus, we “over-sampled” and used both the 5-m radius

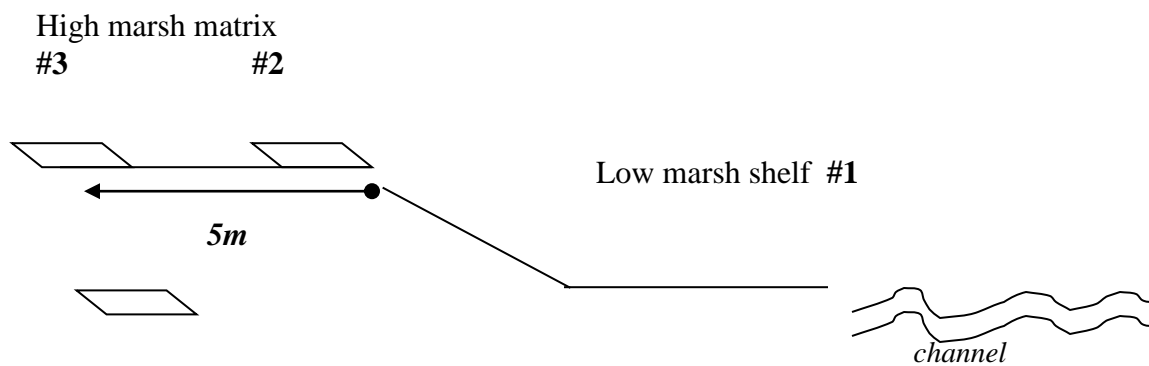


Figure 58. Profile view of 1 m<sup>2</sup> sampling along at high and low marsh in emergent marsh sites.

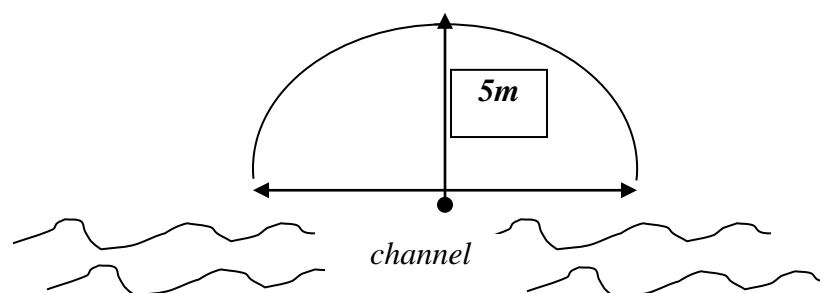


Figure 59. Plan view of 5-m half-circle radius sampling scheme for scrub-scrub sites, centered around insect fallout trap (at center).

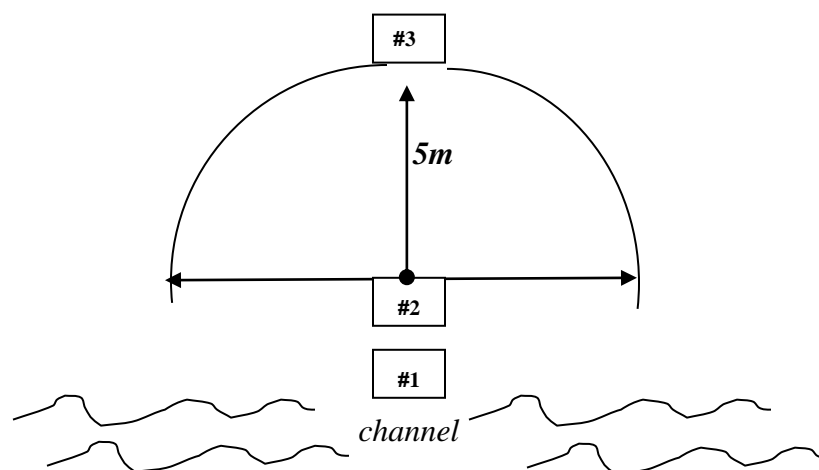


Figure 60. Plan view of 5-m half-circle radius sampling scheme for mixed scrub-scrub and 1 m<sup>2</sup> herbaceous sites at Welsh Island-South, centered around insect



fallout trap (center).

sample plot for scrub-shrub assemblages and the three 1-m<sup>2</sup> quadrats plots for herbaceous assemblages as well (Figure 60). Three 1-m<sup>2</sup> quadrats were centered on a transect oriented perpendicular to the channel: quadrat 1 in the low marsh, quadrat 2 placed next to the fallout trap on the channel side, and quadrat 3, 5 m from the fallout trap. At Welsh Island-South, there were no high marsh depressions. The third sample along the transect served as a replicate of the high marsh matrix. In some instances, other herbaceous species within the 5-m half-circle plot were noted (in field notes) in order to capture prevalent species that fell outside of the quadrats. Care was taken not to sample “trampled” areas. Relative dominance was noted for the most abundant species and ‘trace’ species only.

## Results

Vegetation communities at the sampling sites, along the channel in the high marsh area of these islands were dominated by herbaceous wetland plants. The dominant species is *Carex lyngbeii* (Lyngby’s sedge), with *Myosotis laxa* (small-flowered forget-me-not), *Oenanthe sarmentosa* (Pacific water-parsley), *Aster* spp. (wetland asters), *Lotus corniculatus* (birds foot trefoil), and *Juncus oxymersis* (pointed rush) also being abundant. Depressions in the high marsh are dominated by *Callitriche* spp. (water-starwort), *Polygonum hydropiperoides* (water pepper), *Sagittaria latifolia* (wappato), and *Carex lyngbeii* (Lyngby’s sedge). Vegetation communities in the low marsh areas were dominated by *Polygonum hydropiperoides*. Vegetation at the Karlson Island forested site was structurally diverse, with canopy, shrub, and herbaceous layers. The canopy was dominated by *Picea sitchensis* (sitka spruce); the shrub layer dominated by *Cornus sericea* (red-osier dogwood), *Rubus spectabilis* (salmonberry), *Lonicera involucrata* (twinberry), and *Physocarpus capitatus* (Pacific ninebark); and the herbaceous layer was dominated by *Carex obnupta* (slough sedge), *Rubus ursinus* (trailing blackberry), and *Impatiens noli-tangere* (common touch-me-not). The Karlson Island scrub-shrub site was dominated by a dense, shrub layer of *Salix sitchensis* (sitka willow). The herbaceous layer was dominated by *Carex obnupta*, *Lystichitum americanum* (skunk cabbage), *noli-tangere* (common touch-me-not), *Poa trivialis* (rough bluegrass), and *Typha latifolia* (cattail).

**Welsh Island–South**—The Welsh Island-South site was more structurally and floristically diverse than the Welsh Island-North site. Herbaceous emergent assemblages grew on low terraces at the base of steep-sided banks and on higher flat areas (high marsh matrix) adjacent to the edges of the tidal channel. Woody scrub-shrub species and emergent species were intermixed in the high flat areas within 5 m (the sampling distance) of the channels. The scrub-shrub species generally became denser with increasing distance from the channel. Consequently, sampling techniques for both emergent (quadrats) and scrub-shrub (5-m radius landward of the fallout trap) vegetation

were employed at this site. A single tree (*Fraxinus latifolia*) with 45-cm diameter at breast height was found 20 m from the fallout trap at the station furthest upstream. Trees were otherwise not present within 20 m of the fallout traps and channel, and therefore no canopy layers were reported.

The emergent marsh assemblage in the lower half of this sampling area (closer to the river) was dominated by *Iris pseudacorus*, *Phalaris arundinacea*, and *Sagittaria latifolia*. *Lythrum salicaria* was dominant in the middle portion of the site. In the upper portion, *Iris pseudacorus* and *Impatiens noli-tangere* were dominant. Although they dominated certain sections of the site, *Iris pseudacorus*, *Impatiens noli-tangere*, and *Phalaris arundinacea* were also found in lesser quantities throughout the site. *Bidens cernua*, *Carex obnupta*, *Equisetum fluviatile*, and *Rubus ursinus* were common but not dominant throughout the site. Less common species present in the lower portion of the site were *Alisma plantago-aquatica*, *Athyrium filix-femina*, *Eleocharis palustris*, *Galium trifidum*, *Glyceria grandis*, *Hypericum anagalloides*, *Juncus effusus*, *Lathyrus palustris*, *Lotus corniculatus*, *Lysichiton americanus*, *Mentha arvensis*, *Myosotis laxa*, *Platanthera dilata*, *Polygonum hydropiperoides*, *Potentilla pacifica*, and *Veratrum viride*. Less common species present in the middle to upper portion of the site were *Epipactis gigantea*, *Galium aparine*, *Heracleum lanatum*, *Lathyrus palustris*, *Lotus corniculatus*, *Lysichiton americanus*, *Polygonum hydropiperoides*, *Rumex crispus*, *Veronica americana*, and *Vicia gigantea*.

The scrub-shrub layer was dominated by *Salix lasiandra* near the mouth of the tidal channel and codominated by *Salix sitchensis* and *Cornus sericea* along most of the remainder of the channel. *Physocarpus capitatus* replaced *Cornus sericea* as a codominant at one sampling station in the upper portion of the site but was not present at other sampling sites.

**Welsh Island–North**—The Welsh Island–North site was less structurally and floristically diverse than the Welsh Island–South site. Vegetation consisted primarily of a scrub-shrub assemblage growing along the mostly steep-banked tidal channel. The scrub-shrub layer was dominated by *Cornus sericea*, with *Salix sitchensis* always present and, near the upper end of the site, codominant with *Cornus sericea*. Other scrub-shrub species present in the lower part of the site (closer to the river) were *Lonicera involucrata* and *Malus fusca*. *Salix lasiandra* was present in the middle portion of the site, and *Crataegus douglasii* was present in the upper part of the site. Because fallout traps 2 and 3 were located just 2.5 m apart, the corresponding 5-m sampling radii overlapped at this site.

The herbaceous understory was dominated by *Lysichiton americanus* and *Carex obnupta*. Both were present throughout most of the site, with *Lysichiton americanus*

being dominant in the lower portions (closer to the river channel), *Carex obnupta* being dominant in the middle, and both being codominant in the upper parts. Other common but non-dominant species found throughout most of the site (at least four of five sampling stations) were *Athyrium filix-femina*, *Equisetum fluviatile*, and *Impatiens noli-tangere*. Less common species found in the low to middle portions of the site were *Galium trifidum*, *Heracleum lanatum*, *Juncus effusus*, *Phalaris arundinacea*, POGL, RONU, *Rubus ursinus*, *Rumex crispus*, and *Vicia gigantea*. Less common species found in the middle to upper portions of the site were *Galium aparine*, *Heracleum lanatum*, *Iris pseudacorus*, *Phalaris arundinacea*, RONU, *Polygonum hydropiperoides*, and *Vicia gigantea*.

A distinct emergent assemblage not rooted among the woody species was found at the lowest sampling station (closest to the river channel), where the banks sloped gradually rather than dropping steeply to the channel bed and where the channel was wide enough for some light penetration between scrub-shrub canopies on either bank. The crescent-shaped, 2-m wide and 4-m long emergent assemblage grew under the overhanging woody vegetation and was still considered an understory. Species present here were *Alisma plantago-aquatica*, *Callitriche* sp., EPCI, *Galium trifidum*, *Lysichiton americanus*, *Phalaris arundinacea*, *Rumex crispus*, *Sagittaria latifolia*, and *Sium suave*.

## Conclusions

Vegetation assemblage structure at Welsh Island North and South study sites demonstrated some of the potential variability encountered in tidal channel/slough sites in woody, scrub-shrub and forested wetlands in the estuary. The south site was the more complex and floristically diverse of the two sites. Herbaceous emergent assemblages grew on low terraces at the base of steep-sided banks and on higher flat areas adjacent to the tidal channel. After intermixing with emergent assemblages on the higher flat (within 5-m of channel), woody scrub-shrub assemblages generally became denser with increasing distance from the channel. Emergent marsh assemblages were dominated by *Iris pseudacorus*, *Phalaris arundinacea*, and *Sagittaria latifolia* close to the river channel, *Lythrum salicaria* in the middle portion of the channel, and *I. pseudacorus* and *Impatiens noli-tangere* in the upper reaches of the channel, at greatest distance from the river channel. Scrub-shrub assemblages were dominated by *Salix lasiandra* near the mouth of the tidal channel and codominated by *Salix sitchensis* and *Cornus sericea* along the rest of the channel. In contrast to the south site, vegetation at the north site consisted primarily of a scrub-shrub assemblage growing along a steep-banked tidal channel. *C. sericea* and *S. sitchensis* codominated the scrub-shrub assemblages through most of the site, coincident with a herbaceous emergent understory dominated by *L. americanus* and *C. obnupta*.



### **OBJECTIVE 3: Characterize Historical Change in Tides, Flow, and Sediment Input and Change in Habitat Availability**

#### **Executive Summary**

There is little doubt that historical changes in river flow and the destruction of tidal wetlands has harmed the resilience of Pacific salmon in the Columbia River Estuary. To date, diking and alterations of historical flow patterns caused by the hydrosystem have changed the character of hydrodynamics. We estimated a decrease of 62% in the shallow-water habitat area available to migrating juvenile salmon over the reach from Skamokawa, WA to Beaver Army Terminal, OR.

Flow regulation has also caused a vertical displacement to lower elevations of the remaining shallow-water habitat, in addition to changing its character: tides during summer are stronger than they have been historically. Analysis of historic topographic and hydrographic surveys revealed large decreases in salmon habitat throughout the system during the last century. This has led to a decreased opportunity for salmon life history types dependent on these habitats. Identification of the relative importance of these habitats will guide restoration priorities. Because of the redundancy of the flood control system, both flow restoration and dike breaching may be needed to achieve substantial habitat restoration.

The reservoir system has also increased summer river water temperatures by 1-2°C between 1938 and 2004, and changed the response of temperatures to air temperature forcing. Temperatures continued to increase even after Hanford heat inputs largely ceased. A small improvement in temperature conditions has occurred since about 1998, possibly due to management of the reservoir system to reduce summer temperatures. Finally, tidal ranges are increasing in the Columbia at a rate of 0.7-1 ft century<sup>-1</sup> for two reasons: 1) there has been a long-term increase in tidal amplitudes along most of the West Coast, and 2) dredging and channelization have reduced the frictional energy loss of the tidal wave propagating upriver. These changes work together with flow regulation to alter the character of shallow-water habitat availability by increasing the incidence of shallow-water habitat drying during spring and summer.

### **3.1 Effects of Variation in Tides, Flows, and Sediment Input on Salmonid Habitat Availability**

#### **Introduction**

River flow controls juvenile salmonid habitat availability directly by altering river stage and indirectly by influencing tidal range. There is also a daily power peaking cycle at the dams that propagates downstream to the vicinity of Beaver Army Terminal, changes the character of the tide above Beaver, and affects the timing of high and low waters. These processes are relevant to salmonids for several reasons. First, it is important that chum salmon redds immediately below Bonneville Dam remain underwater during certain key periods, and water elevations in this portion of the river are a function of both dam operation and oceanic tidal influence. Second, tidal range affects salmonid habitat location and availability during the juvenile migration through the lower river and estuary. Changes in coastal tides and alterations of seasonality and strength of the annual river flow cycle (especially changes in volume and timing of the spring freshet) mean that the annual cycle of tidal range has changed since construction of the hydropower system. The net result is that juvenile salmonid habitat has been displaced in time and space. Habitat availability reaches a maximum earlier in the season than historically, and habitat is available only at lower elevations (and decreased in extent) by the reduction in river stage in spring. Its character has changed because of the displacement, because tidal range during spring has increased, and because the new habitat is at elevations more strongly affected by tides.

Attempts to restore salmon habitat in the Columbia River tidal-fluvial regime require that the interaction of basic physical processes (e.g., river flow, tides, and sediment input) with habitat be defined. It is also important to define and model the trajectory of physical change over the last century, and determine how this has influenced salmonids, salmonid habitat, and the tidal-fluvial ecosystem as a whole. We used new measurements, available data, new data analysis methods, and models to determine:

- 1) how changes in river flow, salinity and temperature, and tidal and sediment-transport regimes affect habitat availability
- 2) how these changes are related to climate and human alterations.

For this objective, we analyzed contemporary and historical data to understand ongoing physical processes in the system and changes therein. Four major research topics, outlined below, are being investigated.

### 3.1.A Interaction among Tides, River Flow, and Shallow-Water Habitat

**Methods**—Innovative use of existing tidal analysis methods and development of new methods have been particularly important to the following research goals:

- 1) understand how tides and river flow interact
- 2) deal with challenges presented by the historic data set
- 3) separate local anthropogenic effects on tides from those related to changes in coastal tides
- 4) model changes in shallow-water habitat
- 5) hindcast river flow
- 6) understand along-coast changes in river flow (in conjunction with other work)

Tidal analyses have been carried out using two methods:

- 1) *Wavelet tidal analysis* (Jay and Flinchem 1997, 1999; Flinchem and Jay 2000; Kukulka and Jay 2003a): this approach uses a wavelet filter bank tuned to the frequencies of the tidal species (e.g., diurnal and semidiurnal) to optimally extract information concerning the modulation of tides by river flow.
- 2) *Modified harmonic analysis* (Flinchem and Jay 2000): this approach uses a least-squares approach to extract tidal information from a time series. Departures from traditional harmonic analysis include imposition of a smoothing window to focus the analysis on a shorter time period and a particular selection of overtides. This is particularly useful for hindcasts of river flow from tides.

In conjunction with other funded research, we improved the method of extracting tidal characteristics from short, noisy tidal records with possible gaps. The improvement is accomplished by changing the traditional least-squares minimization of harmonic analysis to a more flexible minimization that varies with the strength of noise in the record (Bube and Langan, 1997). This approach has been widely used in solid-earth geophysics, but not previously for tidal analysis. This technical innovation will help us greatly in analyzing noisy tidal height and salinity records.

We developed a method to hindcast flow from observed tides in both the Columbia River Plume and San Francisco Bay (Jay and Kukulka 2003; Jay et al. 2004, 2005). Hindcasts for both systems are valuable because:

- 1) We are experiencing ongoing difficulties with availability of pre-1900 tide data for the Columbia from NOS/NOAA, and there is considerable similarity in climate fluctuations and events in the two systems before 1900.
- 2) Salmonid survival in the ocean is related to climate all along the coast. Thus, having pre-1900 flow data from both the Columbia and San Francisco Bay (the latter previously available only back to 1930) provide a good view of climate phenomena all along the coast.



Finally, we developed simple models of the tides in the Columbia River plume, their response to river flow, and their effect on shallow-water habitat availability (Kukulka and Jay 2003a,b). A test reach from Skamokawa, WA, to Beaver Army Terminal, OR, was used to analyze historic change in the availability of shallow-water habitat. These are ready to be extended to a larger domain, once the LIDAR (light detection and ranging) topography data become available.

**Results**—We improved the method for analysis/modeling of river tides devised by Jay and Flinchem (1997) and Flinchem and Jay (2000). We then analyzed the 1980-2001 Columbia River tidal height data set (about 50 station-years) to establish the response of tidal properties to river flow from the estuary to Bonneville Dam (Kukulka and Jay 2003a; Kukulka 2002; Figure 61). This approach provided a simple but accurate way to model tides in the system, and a precise definition of the response of tides to river flow throughout the system.

We modeled the response of river stage, tidal range and other tidal properties to flow throughout the lower-river and estimated (using a depth criterion) the shallow-water habitat area (SWHA) available every day for the 1974-1998 period in the reach between Skamokawa and Beaver Army Terminal. Four SWHA scenarios were considered: a) virgin flow, no dikes, b) virgin flow with dikes, c) observed flow, no dikes, and d) observed flow with dikes (Kukulka and Jay 2003b). We found that dikes have been the greatest cause of total SWHA loss during the habitat season (62%). However, controls on habitat inundation were redundant in that the sum of diking effects (52% loss in isolation) and changes in flow regime (29% in isolation) was greater than the total loss. Because of this redundancy, both dike removal and modification of the flow regime would likely be needed to provide a major increase in habitat in the tidal-fluvial regime (Table 18, Figure 62).

In conjunction with research funded by the National Science Foundation (NSF), we have found that the tidal range is increasing at the rate of about 0.7 to 0.8 ft century<sup>-1</sup> at Astoria, and faster than that at Wauna (Figure 63). The semidiurnal tide is increasing more rapidly than the diurnal tide, so the system is becoming more semidiurnal. This ongoing, rapid increase in tidal range has important implications for navigation (larger tides mean a shallower channel at low water), salmonid habitat (different in location, timing and characteristics), sediment transport (higher and more variable bed stress), and the river-estuary ecosystem as a whole (all aspects of the ecosystem are affected by tides). Increasing tidal range appears to have two causes: a) channelization of the river and estuary, which reduces friction and funnels the tide, and b) changes in tides on the continental shelf outside the estuary. Because part of this increase is related to processes in the coastal ocean, it is widespread along the coast, though the rate of increase in Oregon is more rapid than in California or Washington (Figure 65).

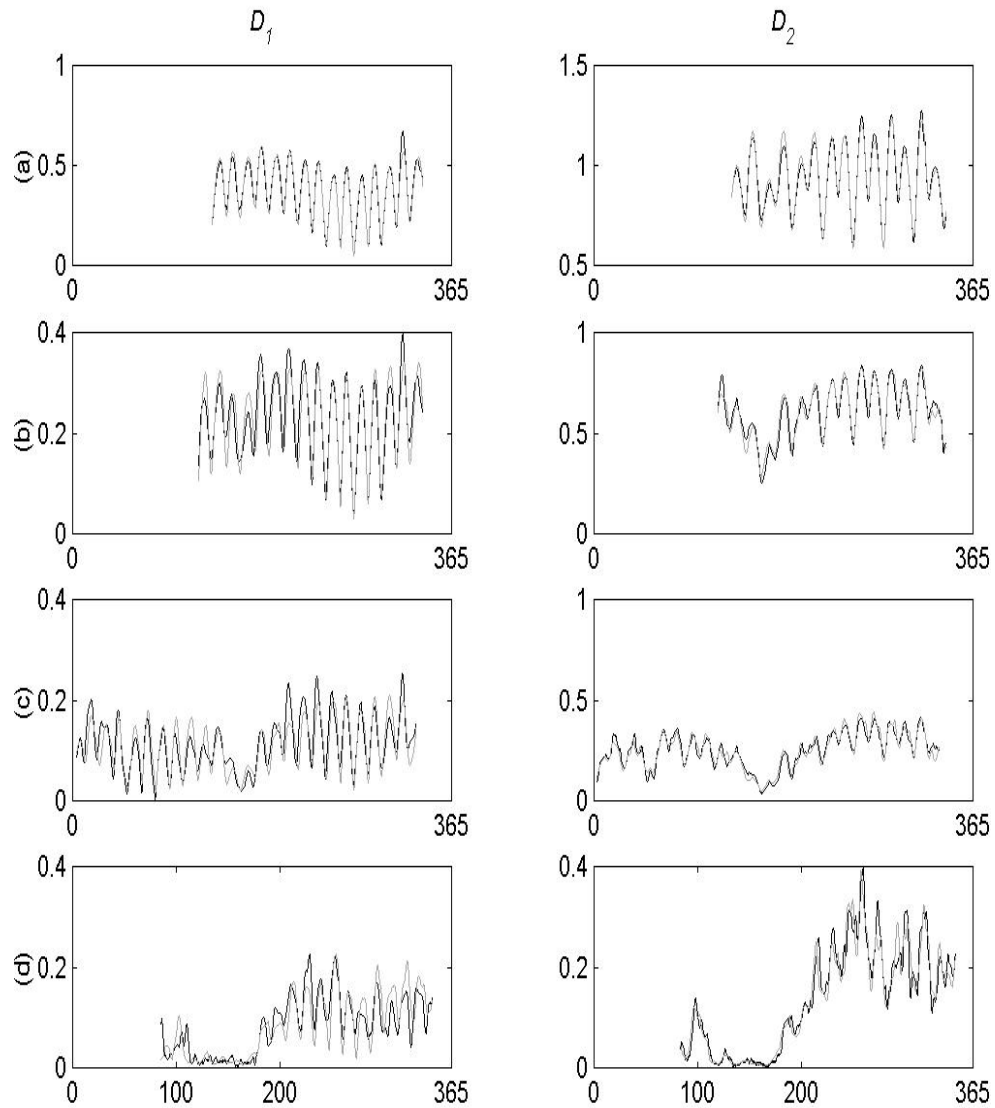


Figure 61. Observed (black) and modeled (gray) tidal amplitudes (m) for  $D_1$  (diurnal) and  $D_2$  (semidiurnal) tidal species at (top to bottom) Altoona, WA, Beaver Army Terminal, OR, and Columbia City, OR, in 1981, (a), (b), and (c) respectively, and Vancouver, WA, in 1997 (d). Note the strong seasonal variations in tidal amplitude caused by variations in river flow. This is most prominent in the very high-flow year of 1997, when tides were almost absent at Vancouver during the spring. Time in days is on the x-axis starting at 1 January.

Table 18. Summary of average shallow-water habitat area (SWHA) by scenario and season.

Scenario	Average SWHA ( $10^7 \text{ m}^2$ )	
	Freshet season (May-July)	Non-freshet season (rest of year)
a) Virgin flow, no dikes	4.5	3.0
b) Virgin flow with dikes	2.2	1.6
c) Observed flow, no dikes	3.2	2.9
d) Observed flow with dikes	1.7	1.6

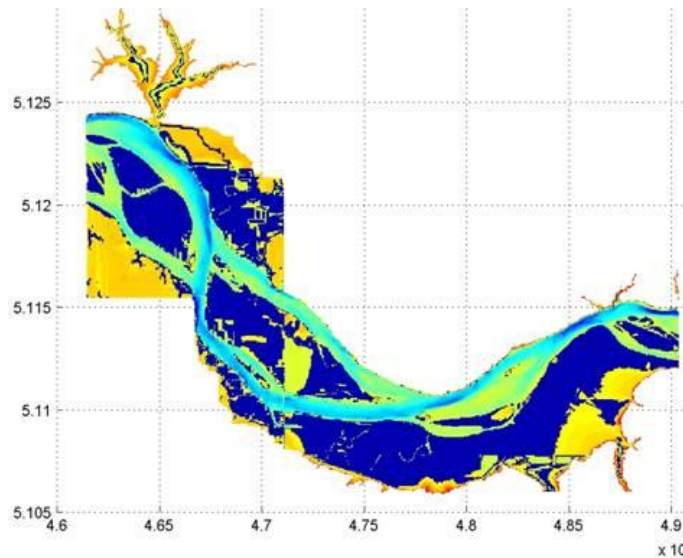


Figure 62. Modeled SWHA for the June 1974 freshet for four scenarios: virgin flow without dikes (top left), virgin flow with dikes (bottom left), regulated flow without dikes (top right), and regulated flow with dikes (bottom right). Immersed SWHA is in dark blue, deeper waters are in lighter shades (depending on depth), and dry land is in yellow. June 1974 was the largest spring freshet since 1956.

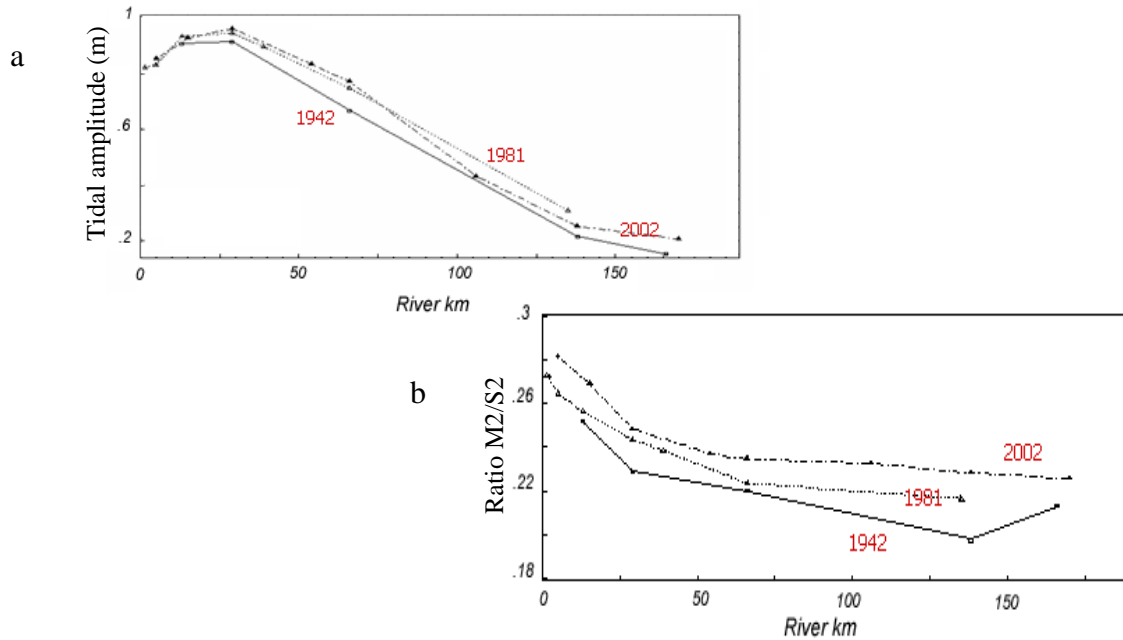


Figure 63. At left (a) principal semidiurnal ( $M_2$ ) tidal constituent amplitude (in m) at selected locations in the Columbia river and estuary in 1941-1942, 1981-1987 and 1997-2002 (distance is measured from the end of the jetties). At right, (b) the unitless ratio of two semidiurnal constituent amplitudes, ( $M_2/S_2$ ) as a function of position along the estuary and river. Left panel (a) shows that tidal amplitudes are increasing rapidly, at least in the lower 75 km of the system. Note that the total increase in range is more than twice the increase in  $M_2$  amplitude. Right panel indicates that friction is decreasing, a feature particularly indicated by the increase in ( $S_2/M_2$ ) ratio over time.

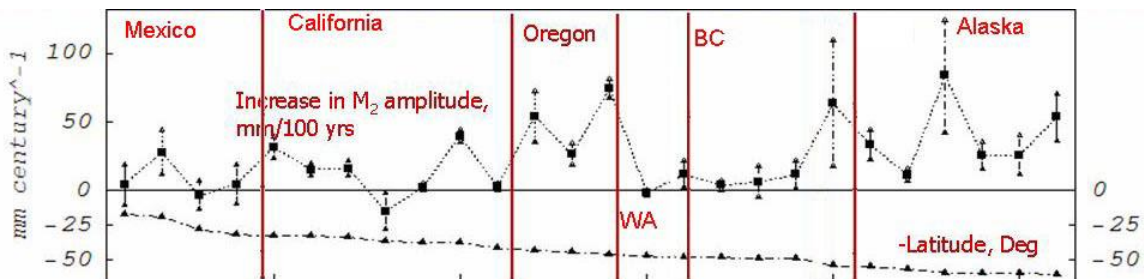


Figure 64. Dotted squares show rate of increase of the principal semidiurnal constituent amplitude ( $M_2$ ) in  $\text{mm century}^{-1}$  at all Pacific Coast locations between  $16$  and  $61^\circ\text{N}$  with long tidal records. Dashed triangles below show the negative of the latitude of these stations. In most cases, rate of increase in tidal range will be more than twice the increase in amplitude, because other constituents are increasing as well. Note that the Oregon coast is experiencing a particularly rapid increase in range. More than 17 million hourly tidal observations 1854-2004 were analyzed to construct this figure.

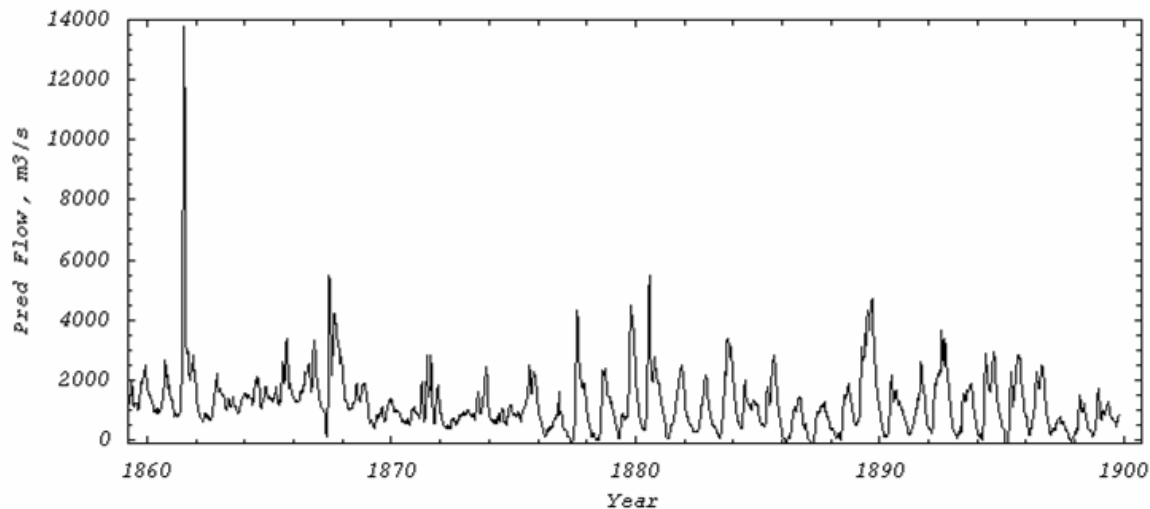


Figure 65. Hindcast San Francisco Bay inflow for 1859-1900. Note the very large flood of winter 1862, which was almost twice as large as any subsequent event. The largest known flow in the Willamette also occurred in this winter. Very high flows in 1880-1881 corresponded to those in the Columbia River plume, as did the low flow of 1877. Summer flows were elevated from 1859 to 1876. It is not known if this occurred in the Columbia River.

In conjunction with the BPA-funded estuary project, we are analyzing a spatially extensive data set (1940-1943), collected when only one mainstem dam was operating in the middle Columbia River (Bonneville). This 1940-1943 data represents the best available description of pre-dam tidal behavior, and is the most complete tidal data set ever compiled for the river. Examination of these data suggests that during this period, power-peaking was limited in scope and timing, and there was little regulation of mean flow. Comparing the 1940-1943 data with contemporary observations will help us define the current tidal regime and determine the effects of both power peaking and flow regulation. The spatially distributed data also assist in diagnosing the extent and causes of increased tidal amplitude in the system. Preliminary results using this approach suggest that the tidal range in the tidal fluvial part of the system has become somewhat less sensitive to river flow, consistent with a reduction in bed friction. Power peaking noticeably affects tidal elevations throughout the system from Bonneville Dam to at least Beaver Army Terminal, OR, which is 145 km seaward.

Finally, we defined a method to hindcast river flow in the lower river from tidal data (Jay and Kukulka 2003). This method is being used to improve knowledge of river flow and climate fluctuations during low flows in both the San Francisco Bay and Columbia estuary/plume systems. However, the along-coast similarity did not extend to all winters before 1900. The highest known spring flow in the Columbia River occurred in 1894, an only slightly above average flow year in San Francisco Bay. Finally, summer flows were very high in San Francisco Bay from about 1859-1876, coincident with a strong negative period of the Pacific Decadal Oscillation (PDO) index. This may

correspond to a period of glacial melt at the end of the “little ice age,” or may simply reflect high summer precipitation.

The only years before the onset of daily flow measurements (at The Dalles in 1878) for which hourly data were available in digital form for the Columbia River are 1870 and 1871. The tidal regime had changed more over time in the Columbia River estuary/plume than was the case for San Francisco Bay. A preliminary 1870-1871 hindcast of flow at Beaver Army Terminal (Figure 66) shows hindcast 1870 and 1871 spring freshets of 22,000 and 22,800  $\text{m}^3\text{s}^{-1}$  (~15-d averages). This compared favorably with values of 20,000 and 22,500  $\text{m}^3\text{s}^{-1}$  estimated from USGS records derived from flooding of the Oregon Steam Navigation Company tracks in Cascade Locks. (USGS values have been reduced to account for ~15-d averaging comparable to the model estimates). The degree of reduction of the freshet peak caused by averaging was determined by averaging daily data from freshet periods during 1878-1899.

While the freshet peak was on June 5 both years, freshet flows  $>20,000 \text{ m}^3\text{s}^{-1}$  continued well into July in both years; unfortunately the USGS records did not provide freshet dates for 1870-1871. However, available USGS data for 1878 forward also indicate high flows enduring into July in many years before 1900. Figure 66 also suggests that flows of 5,000 to 10,000  $\text{m}^3\text{s}^{-1}$  occurred throughout summer until September, especially in 1870. Additional high-low tidal data, yet to be digitized, exist for many years from 1853 to 1868. Further analysis will indicate how reliable such hindcasts are for the Columbia.



Figure 66. Hindcast of flows at Beaver Army Terminal in the Lower Columbia River, 1870-1871. Summer flows are quite high in both years, though these were followed in 1870 by a very dry fall.

### 3.1.B Temperature and Salinity Intrusion and Shallow-Water Habitat

**Methods**—We used available temperature, salinity, flow, tide, and bathymetric data to understand water property changes related to altered river flow, climate, and bathymetry. The primary focus was on temperatures at Bonneville Dam and locations downstream. Changes in temperature may affect habitat utilization by juvenile salmonids and migration of both juveniles and adults. Salinity records were analyzed in conjunction with river flow, temperature, and tidal data, because salinity intrusion length also affects habitat and is a function of river flow, tides, and depth. This analysis is important for restoration of shallow-water habitat because large tidal freshwater areas previously available to juvenile salmonids in spring are no longer available. This loss of tidal freshwater habitat has occurred because greatly decreased spring flows and deeper channel depths have increased salinity intrusion into the system.

Temperature data from Bonneville Dam and downstream locations were assembled, quality checked, and averaged by month. Rainfall data for Oregon, Washington, and Idaho were compiled from state climatology offices. Regression and correlation analyses were used to determine the relationship of Bonneville Dam temperature fluctuations to river flow and atmospheric temperatures.

**Results**—This subtask used temperature, salinity, flow, tide, and bathymetric data to understand changes related to human and climate impacts on water properties and habitat. The primary focus so far has been on temperature records from Bonneville Dam and downstream stations. Changes in temperature affect the ability of juvenile salmonids to use shallow-water habitat and the migration of both juveniles and adults.

The Bonneville Dam scroll-case temperature record (1938-present) has been analyzed to understand the influence of climate and increased water residence time. We found that the river was considerably warmer during 1977 to ~1999 than during even the 1956-1974 period, when Hanford heat emissions warmed the river (Figure 67). While average temperatures (and the number of days exceeding key temperatures) have decreased somewhat since 1999, these values are still higher than before 1956 (Figure 68). The number of months in which river temperatures are higher than those in the estuary has increased. In 1941-1942, the only month when water temperatures at Bonneville Dam were greater than lower river temperatures was August. This condition can now occur in any month from June to September.

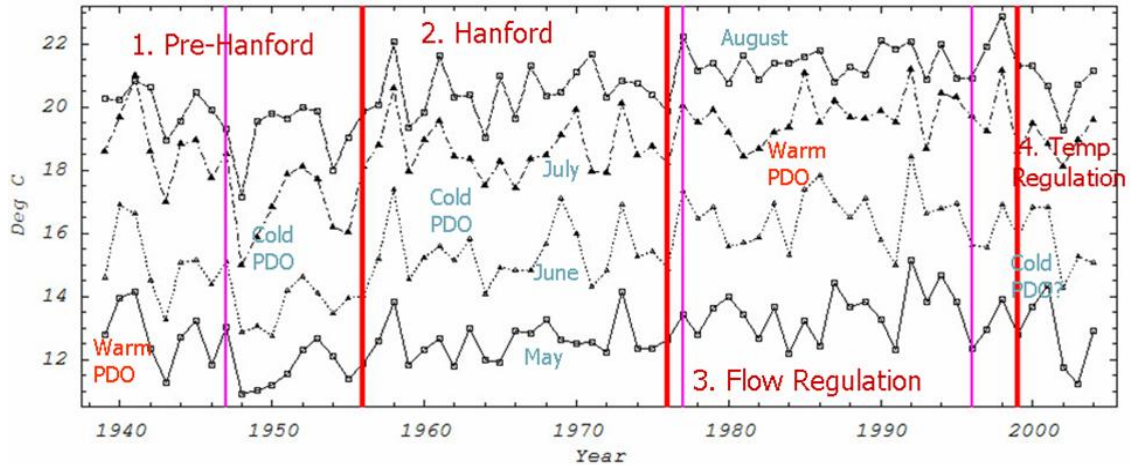


Figure 67. Monthly averaged Bonneville scroll-case temperatures for (bottom to top) May, June, July and August by year, 1938-2004. While scroll-case temperature reflects conditions in only one part of the Bonneville cross-section, it is a consistent measure over time. Vertical red lines indicate approximate boundaries between the four management regimes named in red. The four purple lines indicate PDO periods; e.g., cold PDO conditions prevailed from ~1947 to 1975 and after 1997, while warm PDO conditions prevailed before 1947 and from ~1976-1996. The highest temperatures prevailed from ca. 1977-1996, after cessation of most Hanford heat input.

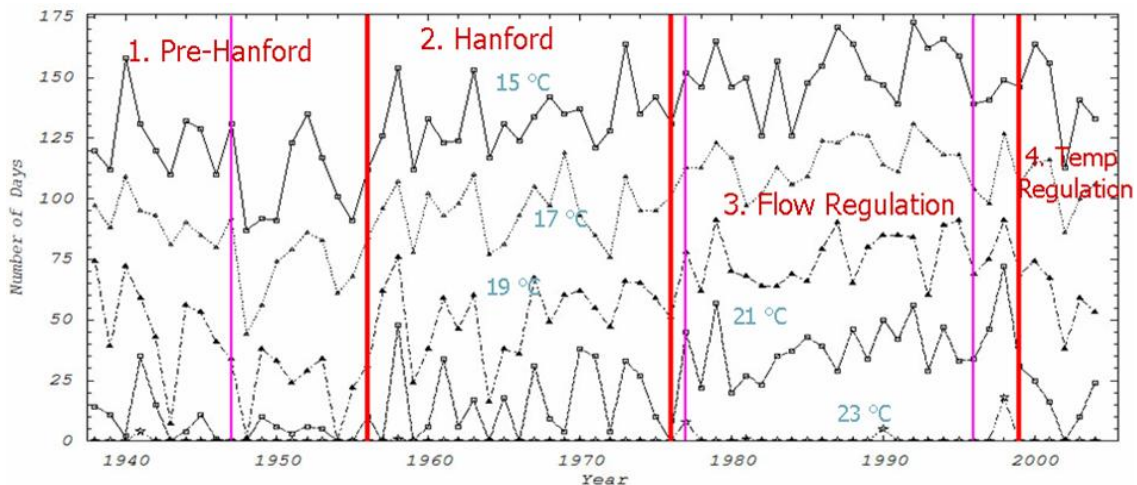


Figure 68. Number of days per year for which daily average scroll-case temperature at Bonneville Dam exceeded certain key levels, as a function of year. While scroll-case temperature reflects conditions in only one part of the Bonneville cross-section, it is a consistent measure over time. Vertical red lines indicate approximate boundaries between four management regimes indicated in red. The four purple lines indicate PDO periods (e.g., cold PDO conditions prevailed from ~1947 to 1975 and after 1997, while warm PDO conditions prevailed before 1947 and from ~1976 to 1996). The highest temperatures prevailed from ca. 1977-1996, after cessation of most Hanford heat input.



High lagged correlations between Bonneville water temperature and prior air temperature in certain seasons now extend many months further into the past than was the case before 1970 (Figure 69). The plot is based on 144 least-squares regression analysis for all combinations of 1 to 12 months averaging for the two forcing parameters. Vertical contours indicate independence of water temperature fluctuations from air temperature averaging time or domination of water temperature fluctuations by flow. Horizontal lines indicate the converse. Before 1956, only the flow for the current month exerted strong influence on water temperature, though flows the previous winter were somewhat correlated. Temperatures during the previous winter were also of some importance, in combination with winter flows.

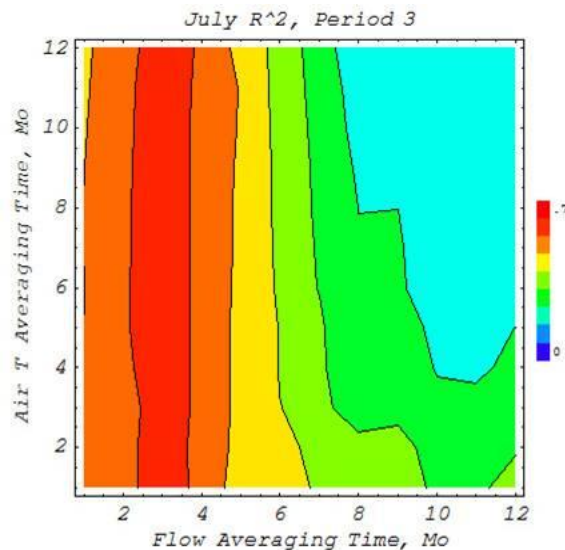


Figure 69. Contour plot of Bonneville monthly averaged June water temperature  $R^2$  explained jointly by air temperature and river flow as a function of months of flow averaging (x-axis) and air temperature averaging (y-axis). At left: the pre-Hanford period (1938-1956); at right: the flow regulation period (1977-1998).

During the 1977-1998 period, flows over the past 4 months exerted a strong influence on flow regardless of air temperature averaging time, suggesting the strong influence of increased water residence time. Winter flows decreased in importance, regardless of temperature averaging. This fact, and the warmer temperatures at Bonneville, both reflected the influence of increased water residence time in reservoirs.

The specific influence of climate was difficult to discern in most years, but appeared to be smaller than that of reservoirs. An exception was the influence of ocean conditions at the onset of warm El Niño conditions in August-September 1997, when the influence of oceanic conditions penetrated throughout the estuary.

We also revisited U.S. Coast and Geodetic Survey temperature records for the Astoria tide gauge during 1854-1980 (now located at Tongue Point, but located in downtown Astoria before 1900). These data were originally analyzed by Simenstad et al. (1992); see Figure 70. Temperatures before ~1870 were very cold, with the coldest individual months in the winter of 1861-1862, which produced record flows in the Willamette River and San Francisco Bay. Newspaper reports suggest that there was about a meter of snow on the ground in the Willamette Valley before the great flood of early December 1861, which was caused by a warm rain on the snow. Very cold temperatures followed this event. A large snow pack developed despite loss of the entire early season snow pack in the December flood, causing the Columbia spring freshet of 1862 to be one of the largest on record. While precipitation in California and Oregon was high all during the winter of 1861-1862, the largest flow event was in late January in San Francisco Bay. However, the coldest winters overall occurred in Astoria later in the 1860s.

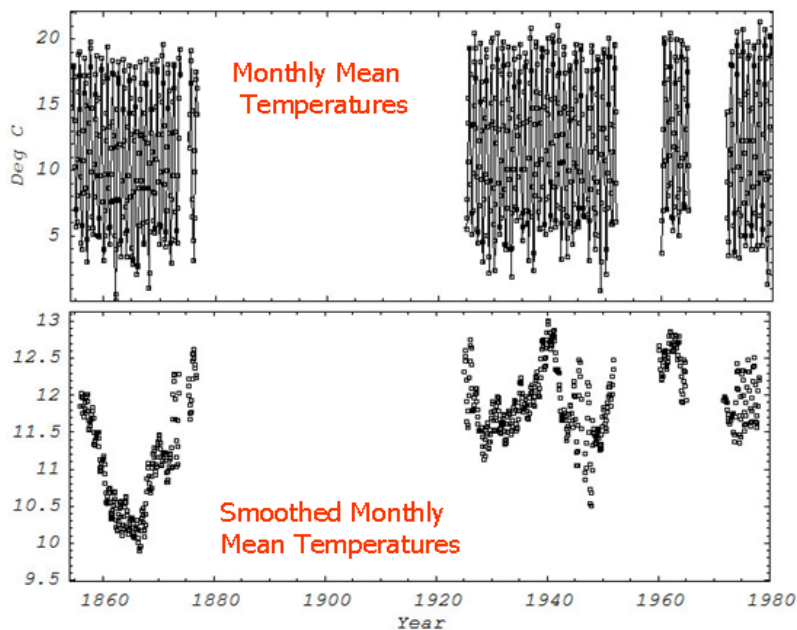


Figure 70. Monthly averages of once-daily temperature data collected at the Astoria tide gauge (at Tongue Pt after 1925, but in downtown Astoria before 1900). Because of salinity intrusion, temperatures below 0°C were sometimes measured. Temperatures during the 1860s were very cold, >2°C below those for 1960-80. However, the 1945-50 period was also very cold.

### 3.1.C Historical Changes in Flow and Sediment Input to the Estuary

**Methods**—Habitat is constructed from sediment, in this system predominantly from mixed sand and silt, the mixture depending on habitat location and exposure to bed stress. A major issue facing the system is the loss of sediment supply caused by reservoir construction and reduction of high flows. This has caused the sand budget to be out of balance because less material is being supplied than is being exported by dredged material disposal (at sea and on land) and export from the estuary to shelf (during high flows). Fine sediments (silt and clay) are also important for their role in water quality (in terms of both toxic content and effect on oxygen levels in the water column and in the bed), as a detrital food source supporting the estuarine food web, for maintenance of the estuarine turbidity maximum, and for their contribution to habitat construction.

This part of the research uses data collected by the USGS, Environment Canada, and the U.S. Army Corps of Engineers to understand changes in: 1) seasonality and amount of river flow, 2) the supply of fine and coarse material to the estuary, and 3) long-term changes in flow and sediment transport. Also, in coordination with other funded research, we have examined how particle characteristics evolve as the particles move from the river to the estuary and then to the ocean.

Time series analysis activities have been carried out with the following objectives completed during 2002-2004:

- 1) Compiled historical flow data from The Dalles and for western sub-basin tributaries. This included estimating missing flow data for the Willamette River at Albany during 1878-1893 (the actual record was only 40% complete). Albany hindcasts used multi-lag correlations between flows and precipitation found using the available flow and precipitation data before 1900.
- 2) Routed Willamette River flows from Albany and Salem to Portland using the formulation of Orem (1968).
- 3) Routed flows to Beaver Army Terminal from The Dalles, the Willamette at Portland, and other west-side tributaries using the formulation of Orem (1968).
- 4) Estimated virgin flows for The Dalles, the Willamette at Portland, and Beaver Army Terminal from 1878-present. The methodology and irrigation corrections for these calculations are those of the Bureau of Reclamation (USBR 1999).
- 5) Used USGS flow and sediment transport data to develop rating curves for the Columbia at Vancouver and the Willamette at Portland for sand, fines, and total sediment load.

**Results**—This subtask defines historic and contemporary processes from flow, sediment transport, and climate time series data. Work to date has mostly consisted of laborious compilations of observed and virgin flows and derivation of sediment transport rating curves. One element of hindcasting sediment supply to the estuary is to determine the historic flow at Beaver Army Terminal, which has been monitored only since 1991. We implemented a routing algorithm from Orem (1968) to estimate a daily flow at Beaver Army Terminal for 1878-2004. We also extended knowledge of spring freshet timing and volume backward to before the beginning of the daily record at The Dalles using historic records and tide data. These results have been published in part (Jay and Naik 2002). Naik and Jay (2005) also laid the basis for climate-change analyses for sediment by defining Columbia River virgin flow at The Dalles from 1878. Changes in volume and timing of sand transport and total sediment load at Vancouver, WA, have been partitioned between climate change, flow regulation, and flow diversion (Figures 71a and 71b). Rating curves for transport of sand and fines have been derived for both Vancouver, WA, and the Willamette River at Portland, OR.

A presentation at a meeting of the American Geophysical Union (MacGregor et al. 2003) examined historic changes in sediment transport rating curves; this represents a collaboration with the U.S. Geological Survey (USGS). This work suggests that the rating curves of several mid-Columbia tributaries have changed, possibly in response to major floods (1964 and 1996), logging, or other factors. Also, the mainstem rating curves may have changed after ca. 1975 because of completion of the four Snake River dams, but insufficient data are available post-1975 to demonstrate this.

We have derived the necessary corrections to flow for tributaries seaward of Bonneville for estimation of adjusted and virgin flow at Beaver Army Terminal through 2004, along with revisions for The Dalles virgin flow for 1990-2004. Virgin flow estimates are now available for the Columbia River at The Dalles and Beaver, and for the Willamette River at Portland. Virgin flows before 1900 were larger than those after 1900 in both systems.

Flow record for the Willamette River at Albany is only about 40% complete for 1878-1887 and missing for 1888-1892. Because the record for The Dalles begins in 1878, we have completed record for the Willamette at Albany for 1878-1892, so that a complete record for Beaver for 1878-present could be derived. This was carried out using the existing data to derive a correlation between river flow at Albany and precipitation at Corvallis (Portland before 1881) and hindcast the missing values (Figure 72).

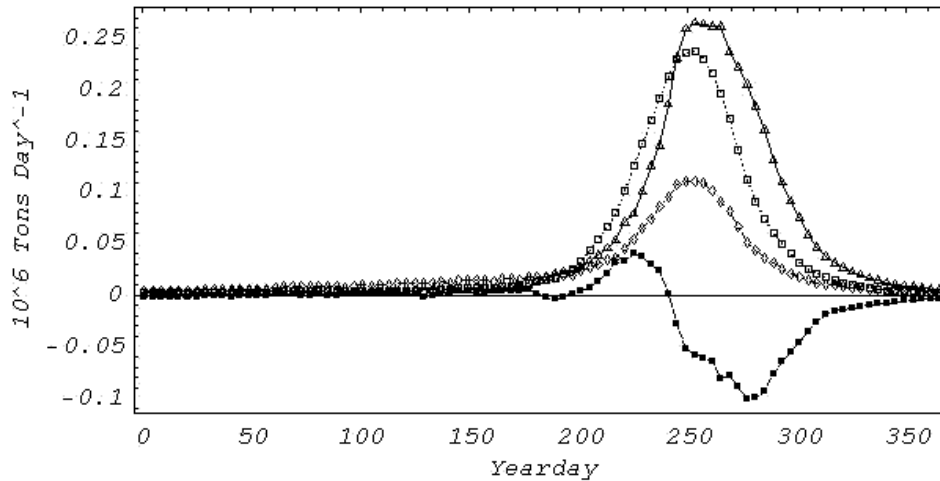


Figure 71a. Changes in Columbia River total sediment load at Vancouver caused by climate change: average 1879-1899 ( $\Delta$ ) and 1971-1999 virgin ( $\square$ ) flow total loads, average total load associated with the 1971-1999 observed flows ( $\diamond$ ), and the 1879-1899 to 1971-1999 effect of climate change ( $\times$ ). Sediment load in May has actually increased, because of the earlier onset of the freshet. Day 1 is October 1.

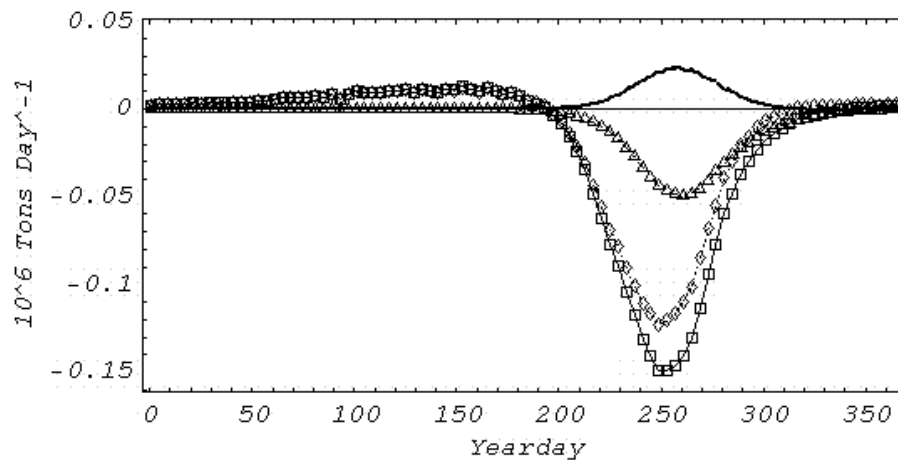


Figure 71b. Human factors changing Columbia River total sediment load associated with the observed flow for 1971-1999 relative to those for 1879-1899: total reduction from 1879-1899 levels ( $\square$ ), reduction due to flow regulation ( $\diamond$ ), reduction due to irrigation ( $\Delta$ ), and joint effect of irrigation and regulation ( $\sim$ ). Clearly, flow regulation accounts for most of the lost transport. Winter transports have increased slightly due to diversion of flow into the winter season. Comparison to Figure 12a shows that total load losses associated with flow regulation are almost twice those caused by reduction of flow associated with climate change. Additional losses (not included here) have been caused by sediment trapped behind the Snake River dams and changes in land use. Day 1 is 1 October.

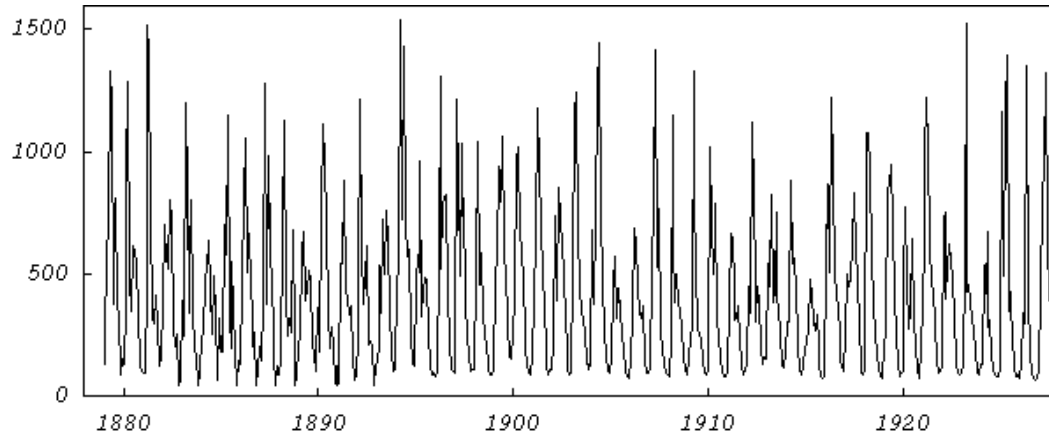


Figure 72. Monthly average Willamette River flow at Albany in  $\text{m}^3\text{s}^{-1}$  for 1878-1927, based on daily values. Daily Albany flows were observed from 1895 to 1927. Before 1887, about 40% of daily values were available, while no flow data were available 1887-1892. Three months of data were missing in 1893-94. Missing daily values were hindcast from precipitation at Corvallis (Portland before 1881).

We have compiled a preliminary list of maximum 1-d flows at Beaver Army Terminal, including known major freshets before 1900, estimates of the effect of lower river tributaries, and precipitation over the water areas of the system. As expected, most of the largest freshets in the system occur in winter, though these are very brief compared to spring freshets. Winter freshets contribute large amounts of fine sediment and iron, the latter originating primarily from the Willamette River basin.

### 3.1.D Properties of Fine and Coarse Sediment Input

**Methods**—Sediment monitoring at Beaver has been carried out with a Sequoia Instruments Laser In-Situ Scattering Transmissometer or LISST-100. This optical instrument determines optical concentrations of particles in 32 size bins ranging from 10 to 1500  $\mu\text{m}$ . These data are then calibrated (converted to mass concentration) using bottle samples that are filtered, dried, ashed and weighed, a procedure that also provides organic content. Vessel surveys have included profile measurements of temperature and salinity using an Ocean Sensors 200 CTD, and optical particle concentration obtained either with the LISST-100 or a smaller LISST-25. The latter measures optical concentrations of particles in two size bins; 7.0 to 62.5  $\mu\text{m}$  and 62.5 to 500  $\mu\text{m}$ .

**Results**—This task uses state-of-the-art optical methods to determine seasonal patterns in particle-size distribution, particle properties, and concentration of sediment transported into the estuary. Field testing was carried out in the Columbia River (at Beaver Army Terminal) and in coordination with USGS in the Grand Canyon (to test the instrument in an environment with unaggregated large particles). Contrary to expectations, aggregates were present in both environments, but those in the Grand Canyon were much more dense and compact. Micro-flocs (equivalent diameter <50  $\mu\text{m}$ ) were the dominant sort of floc at Beaver. These are combined in the estuary with other material to make the much larger flocs found there.

An exploratory field survey was carried out in June 2002 to investigate the cross-sectional distributions of flow, bed, and water-column (suspended) sediment at Beaver Army Terminal, as well as tidal variations in water column properties. The LISST-FLOC was deployed at Beaver from January to June 2004 and again from December 2004 to March 2005 (Figure 73). Appropriate calibration data were collected, and analysis of the results is ongoing. We concluded that we should mount the LISST in a horizontal (not vertical) position lower in the water column, despite greater logistical difficulties. An appropriate mount has been constructed and will be installed shortly.

Suspended particulate matter is an important component of habitat, not just in the river, but also in the estuary and plume. Therefore, in June and July 2004, sampling was extended from Beaver Army Terminal to the Columbia River estuary and plume (with NSF support), to understand how particles are transformed as they move seaward. Examination of LISST and other data suggested that most particulates originating in the river settled rapidly to the seabed in or near the estuary. Most particles seen in the plume were biogenic. Particles were, however, concentrated in and beneath plume fronts (Horner-Devine et al. 2004). Further plume and estuarine surveys were carried out in June and August 2005; data are currently being analyzed.

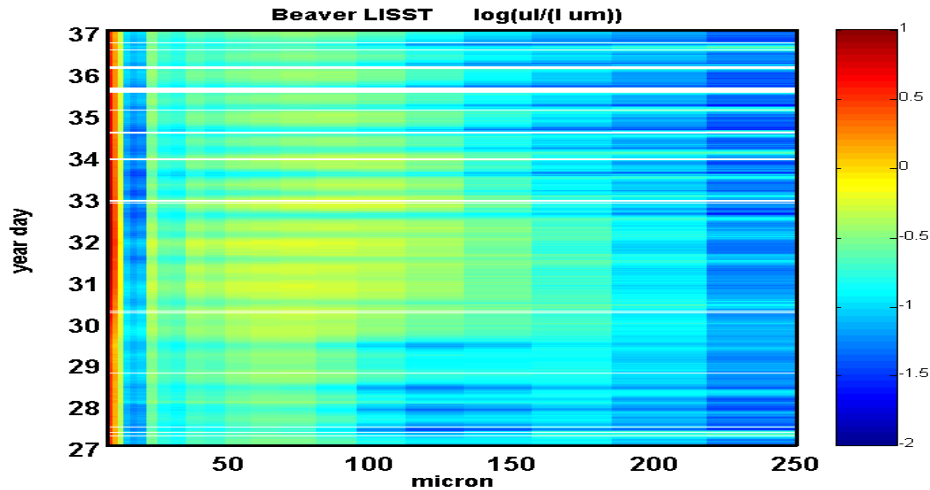


Figure 73. Volume concentration of suspended particulate during the one modest flow event (ca. 1 February 2004) that has occurred during our observation period. The largest increase in concentration occurred in the  $\sim 10\text{-}150\ \mu\text{m}$  size classes, and inorganic content also simultaneously increased. Thus, this modest flow event increased concentrations of mostly inorganic silt and fine sand. The dark band between  $\sim 12$  and  $20\ \mu\text{m}$  is an instrumental artifact.

We have examined the LISST data with a view toward determining a quantitative relationship between volume and mass concentration. We found that the relationship was seasonally variable: material collected in spring was less dense and higher in organics than material collected in winter (Chisholm and Jay 2004). This was expected because of the larger amount of phytoplankton in spring. We need, therefore, to incorporate a chlorophyll measurement into the monitoring. Because we have not had a major sediment supply event during the 18-month period of observations, we cannot fully complete calibrations.

## Discussion and Recommendations

This task defines the physical aspects of the human and climate-induced changes that have occurred in Columbia River estuary salmon habitat, and determines the reasons for these changes. This work is essential to definition of restoration strategies and for managing the system.

Surface elevation, as determined by river flow and tides, is an essential part of habitat in the river and estuary. Alteration of the surface elevation changes the location, character, and accessibility of habitat. Reduced river surface levels during spring, caused by reduced river flow, constrain restoration strategies. If dikes were removed in some areas, they would no longer flood in spring, as they did before flow regulation and diking. Diked areas to be restored must, therefore, be carefully chosen.



Surface elevation and tidal properties can be accurately modeled throughout the river using a simple approach based on tidal theory. Input parameters are ocean tidal forcing and river flow. Using this approach, we have modeled shallow-water habitat area (SWHA) under four different flow and diking scenarios for every day during 1974-1998. We found that 62% of the habitat area available during spring in the natural system (no dikes, natural flows) has been lost due to diking and flow regulation/diversion. Because engineering controls on flooding are redundant, restoration of SWHA may require both removal of selected dikes and restoration of a more natural flow cycle.

Furthermore, the tidal regime of the Columbia River and the adjacent coastal ocean are undergoing substantial changes. Specifically, tidal range is increasing at a rate of  $\sim 0.7$  ft century<sup>-1</sup> at Astoria and more rapidly than this at Wauna. Semidiurnal tides are increasing more rapidly than diurnal tides, so the tide is becoming more semidiurnal. Thus, the surface elevation of shallow water habitats is changing more rapidly than was the case historically, and these habitats are more likely to dry twice per day (instead of only once per day) than previously. These changes are due to: a) channelization of the estuary, which decreases bed friction and funnels the tide, and b) changes in tides on the continental shelf off Oregon. In fact, tidal ranges are increasing throughout most of the Eastern Pacific Ocean north of the Mexican border, and the rate of increase is especially high along the Oregon and Alaska coasts. The effects of increasing tidal range in the Columbia River are especially prominent during low-flow periods when water depths are lowest. This may also affect clearances available for ship traffic. The effects of power-peaking at Bonneville are evident throughout the system from Bonneville Dam downstream at least to Beaver Army Terminal. Power peaking greatly increases the frequency of wetting and drying in habitats between Vancouver and Bonneville Dam.

Columbia River estuary water temperatures have increased since the 1870s by about 2°C, though the 1860s were very cold, and not necessarily typical of the 19<sup>th</sup> Century as a whole. Temperatures during the 1990s may have been as much as 3°C warmer than those prior to 1900. The period from 1945 to 1950 was also very cold, but not as cold as 1860-1870. Lower Columbia River and estuary water temperatures decreased after ca. 1999, possibly due to application of temperature Total Maximum Daily Loads. In 1941-1942, the only month when Bonneville Dam water temperatures were greater than lower river temperatures was August. This condition can now occur in any month from June to September. Reservoir storage increases temperature and the influence of air temperatures on water temperatures at Bonneville and in the estuary. Generally warmer air temperatures have also likely affected historical river temperatures, though their influence appears to be less than that after reservoir construction. While climate effects are generally difficult to define, the influence of ocean conditions (e.g., the onset of warm ocean temperatures in August-September 1997) can penetrate throughout the estuary.

In coordination with other projects, we have contributed to understanding Pacific Northwest hydrologic change and climate processes over the last 150 years. We have hindcast virgin and adjusted flows for 1878-present for the Columbia River at The Dalles and Beaver Army Terminal and for the Willamette River at Portland. Virgin flows before 1900 were larger than those after 1900 in both systems. The mainstem spring freshet is now several weeks earlier than it was before 1900. Sediment rating curves have been developed for the Columbia River at Vancouver and the Willamette River at Portland. Changes in sediment transport at Vancouver have been partitioned between climate change, flow regulation, irrigation withdrawal, and combined irrigation and regulation effects. Flow regulation has had the largest impact by far, being almost twice as important as the next largest factor, climate change. Peak sediment transport now occurs earlier in the year than previously because the peak of the freshet occurs several weeks earlier.

To better understand the current regime throughout the California Current region, we have hindcast inflows to San Francisco Bay back to 1859, extending the flow record for that system back from 1930. These calculations are based on a novel method that uses the distortion of the predicted tide to measure river flow. Comparison of these results with Columbia River flows suggests substantial along-coast similarities, e.g., major floods in the winter of 1861-1862, and high flows in 1880-1881, winter freshets in 1881 and 1890 and low-flows in 1877 in association with a strong El Niño. There were also differences: for example, flows during 1894 were the highest known for the Columbia River estuary/plume, but were only slightly above average in San Francisco Bay. Years that exhibit substantial along-coast hydrologic similarity may have especially strong effects on juvenile salmonid survival (positive or negative) because large-scale hydrologic effects suggest perturbation of the entire California Current.

The winter of 1861-1862 was one of the most severe in the last 150 years along the entire West Coast. Record flows occurred in the Willamette in early December. The highest flows into San Francisco Bay occurred in late January, during a very cold period in Oregon and Washington. The San Francisco Bay inflow of late January 1862 ( $\sim 14,000 \text{ m}^3 \text{ s}^{-1}$ ) was almost twice that recorded at any other time since 1859. Astoria tidal data for 1861-1862 are under analysis to determine Columbia flows for this period.

The highest 1-d flows in the lower Columbia River may occur during brief winter freshets, but spring freshets are of much longer duration and contribute more water and sediment to the system. It is possible, however, that winter floods like that of 1964 provide more fine sediment than even the largest spring freshets. Because much of the flow in such events comes from the Willamette River, these events contribute large amounts of iron to the coastal ocean. Iron is an essential micronutrient that supports

coastal productivity and, therefore, salmon. Iron and silicate from the Columbia River appear to play an important role in fertilizing the NE Pacific Ocean, a role that may have been altered by the reservoir system.

Optical monitoring of suspended sediments at Beaver Army Terminal has led to following conclusions: Fine sediments are largely transported through the lower river in the form of micro-flocs (<50- $\mu\text{m}$  equivalent diameter). These flocs are further aggregated and processed in the estuarine turbidity maximum to form the much larger flocs seen there. Suspended sediments are lower in density and higher in organic matter during the spring freshet, reflecting the influence of phytoplankton and detritus derived from phytoplankton. No major freshet event has occurred during the 2-year monitoring event, so we do not know how particle properties change during major transport events.

## 3.2 Habitat Change Analyses

### Introduction

We are generating historic habitat maps for the estuary from topographic surveys (T-sheets) conducted in the late 1800s at a scale of 1:10,000. These maps provide the historic template for habitat analysis by allowing us to document changes in the geographic distribution, amounts, and classes of estuarine and floodplain habitat available to juvenile salmonids in the CRE. Beginning in FY 2002, we initiated the conversion of historical topographic survey maps (T-sheets) into a Geographic Information System (GIS) for the Columbia River estuary extending from the river mouth (rkm 0) to Rooster Rock (rkm 206) (Figure 74). Previous historical ecosystem reconstruction efforts, e.g. Allen 1999, Graves et al. 1995, and Thomas 1983, lacked the spatial resolution, integrity, spatial accuracy, extent, and historical context in comparison to our ecosystem reconstruction from the T-sheets. Our objective is to provide the most robust and comprehensive ecosystem reconstruction available and using the latest technology.

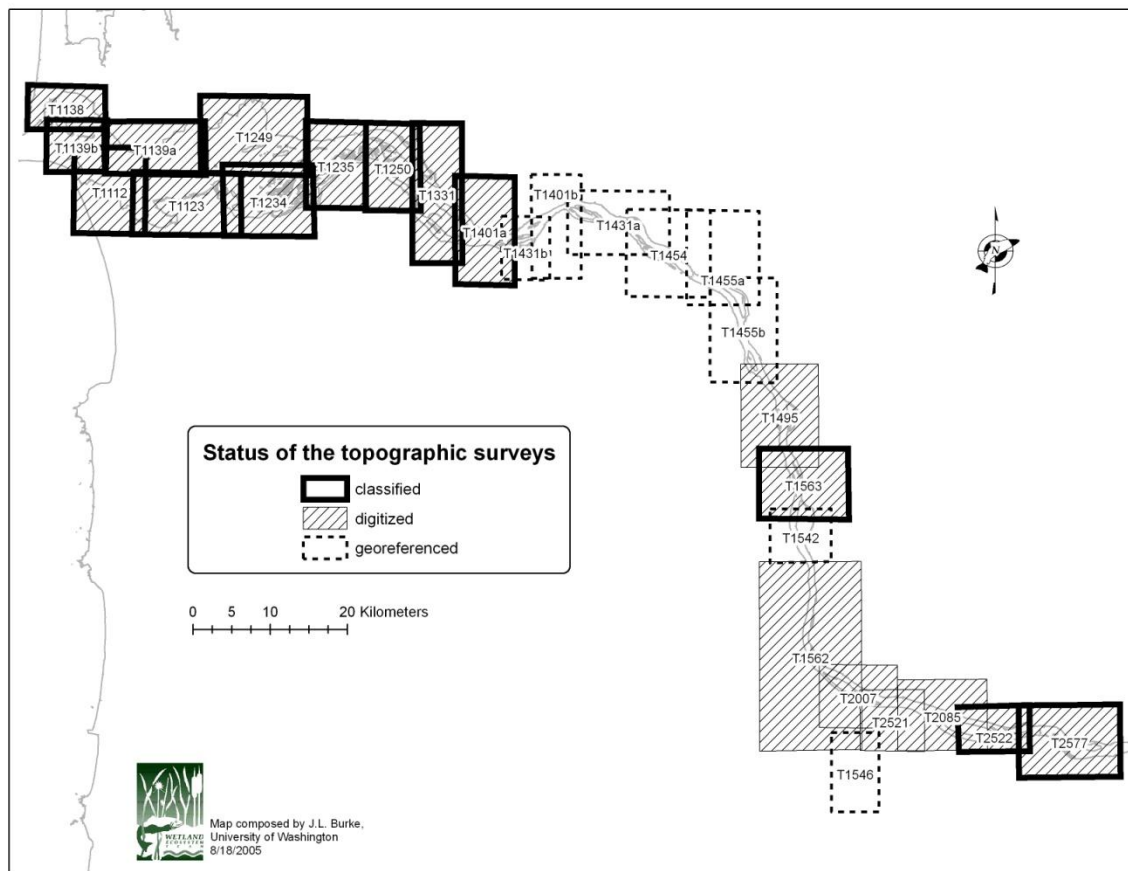


Figure 74. Status of the habitat reconstruction from topographic surveys (T-sheets).

Historical cover classes and their configurations and boundaries are critical to establishing a baseline of estuarine conditions and opportunities prior to extensive European development and alteration. These baseline conditions will provide a template for models designed to evaluate historic changes in river flow and juvenile salmon habitat opportunities (Section 2.3) and habitat conditions (Section 3.3, FY 2005). In addition, all GIS datasets and results generated from this project will be freely available as a research and monitoring tool for resource managers and estuarine investigators.

## **Methods**

Topographic surveys were conducted by the U.S. Coast and Geodetic Survey beginning in 1868 at the river mouth and ending in 1901 at Rooster Rock (rkm 206). The effort generated 27 planimetric maps (features and distances measured with a planimeter) of the estuary delineating both shallow hydrographic (mudflats and emergent marshes, floodplain) and upland features. From FY 2002 to 2004, the complete set of 27 survey maps including the habitat features and boundaries were converted to digital format and referenced to a real-world coordinate system. During FY 2004, we focused the final stages of the reconstruction effort on the lower estuary from the river mouth (rkm 0) to the upstream side of Puget Island (rkm 75), primarily to refine the base dataset for the hindcast scenarios in the CORIE simulation database.

An extensive literature review of the available datasets for the Columbia River estuary, methods concerning historical habitat reconstruction using T-sheets, and similar projects in estuaries worldwide was presented in Roegner et al. (2004). Based on the findings from the literature review, we developed the following six defensible GIS protocols:

- Protocol 1: Georeference T-sheets to real world coordinates
- Protocol 2: Generate an error accuracy assessment of the georeferencing effort
- Protocol 3: Digitize map features
- Protocol 4: Classify habitat features
- Protocol 5: Edge-match all T-sheets into one seamless dataset
- Protocol 6: Generate an error and certainty grid

All datasets, protocols, and analyses were performed in ERDAS Imagine version 8.7 and Environmental Systems Research Institute (ESRI) ArcInfo Desktop Suite, version 9.1, including the ArcGIS Spatial Analyst Extension. Specific GIS protocols and details concerning the processing of the datasets are available in metadata format accompanying the GIS datasets, and thus will not be detailed in this report.

## Results

We completed habitat reconstruction in FY 2004 (FY 2003 tasks were delayed due to budget constraints until FY 2004) using all six protocols for 11 of the 27 T-sheets. Furthermore, eight additional T-sheets were digitized as part of the continued effort in FY 2005 to complete all protocols for the entire dataset in the estuary (Figure 75). The following is a summary of the results and progress on the habitat reconstruction. Continued effort to complete the habitat reconstruction for the estuary and the habitat change analyses will proceed in FY 2005.

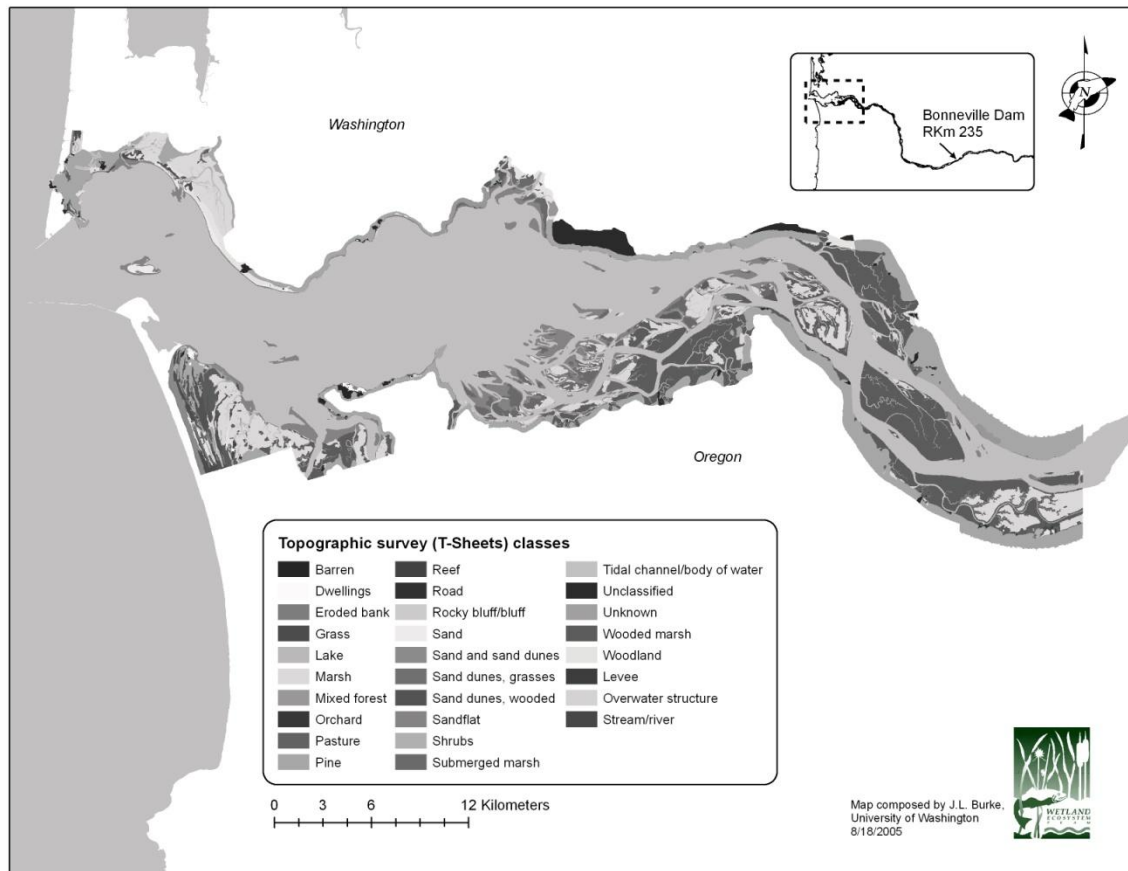


Figure 75. Reconstruction of historical habitats of the Columbia River estuary from the river mouth to the upstream end of Puget Island (rkm 75).

**Protocols 1 and 2:** Georeference T-sheets to real-world coordinates and generate an error accuracy assessment of the georeferencing effort. By the end of FY 2002, all 27 T-sheets were georeferenced with satisfactory spatial accuracy as indicated by the total root mean square (RMS) and error accuracy assessment values. The RMS, which is automatically generated as an output statistic by ERDAS Imagine for the georeferencing of each T-sheet ranged from 0.0002 to 0.0023 inches (less than 0.004 maintains a high level of accuracy). Results of the on-the-ground horizontal accuracy of the T-sheets, as determined from the mean error accuracy assessment using local benchmarks in each T-sheet, ranged from 0.25 to 7.0 m with an average of 3.0 m in longitude and 3.3 m in latitude. These results are within USGS National Mapping Standards of an average horizontal accuracy of 5 m for maps at a scale of 1:10,000.

**Protocol 3:** Digitize map features. By the end of FY 2004, 19 T-sheets were complete in the digitizing of their spatial features.

**Protocol 4:** Classify habitat features. We developed a cover classification system that incorporated the classes presented in Shalowitz (1962) plus elevation and ancillary modifiers (Table 19). We attempted to maintain a classification system closest to what the original surveyors intended while separating out wetland and other features of interest for spatial modeling, change analyses, and resource managers. For instance, a class of scrub-shrub wetlands is classified as a wooded marsh (class code = 3, Table 19), as discussed in Shalowitz (1962), plus a modifier of scrub-shrub (feature 2 = q, Table 20), which refined, yet maintained, the original map symbology.

Table 19. Full habitat classification system for T-sheets (not all classes visible in Figure 70). Italicized cover classes were not listed or discussed in Shalowitz (1962).

Class code	Cover class	Class code	Cover class
1	Marsh	16	Sandflat
2	Submerged marsh	17	Rocky bluff/bluff
3	Wooded marsh	18	Depression
4	Tidal channel/body of water	19	Road
5	Lake	20	Orchard
6	Pine	21	Cultivated fields
7	Woodland	22	<i>Pasture</i>
8	Shrubs	23	Dwellings
9	Reef	24	<i>Barren</i>
10	stream/river	25	Unknown
11	Grass	26	<i>Unclassified</i>
12	Sand and sand dunes	27	Levee
13	<i>Sand dunes, grasses</i>	28	<i>Mixed forest</i>
14	<i>Sand dunes, wooded</i>	29	<i>Overwater structure</i>
15	Sand	30	Eroded bank

Table 20. Modifiers denoting elevation and ancillary information.

Feature 1		Feature 2	
code	Elevation	code	Ancillary descriptor
a	Subtidal or below MLLW	h	Wharf
b	Intertidal or between MLLW and MHW	i	Pilings
c	Floodplain or above MHW but below 1st contour	j	Log boom
d	Upland	k	Sparse
e	Uncertain	l	Grasses
		m	Wooded
		n	Developed
		o	Undeveloped
		p	Sand
		q	Scrub-shrub

**Protocol 5:** Edge-match all T-sheets into one seamless dataset. To produce one seamless dataset of historical habitats, each of the T-sheet datasets had to be edge-matched. The edge features of the 11 T-sheets often resulted in hundreds of meters of overlap between two adjacent maps. Because of the temporal separation of the time of the surveys between the maps and to maintain the original survey results, edge-matching did not result in the creation or movement of any habitat feature boundaries. For this reason, steps or discontinuity in the features will sometimes occur at the boundary of each T-sheet. However, to reduce the discontinuity, effort was made to find a common point of where feature boundaries intersected, and at this point, a clip or slice occurred to remove the overlap.

**Protocol 6:** Create an error and certainty grid. Sources of uncertainty and error were tracked during each step in the processing of the data. This resulted in the development of spatially explicit grids so that users may trace the confidence of the data. For instance, each feature identified from the map received a level of confidence during the interpretation of the map symbology. Of the values 1 through 4, 1 is the highest level of confidence and 4 is the lowest. Over 95% of the features had a certainty of 1 (Figure 76). Of the 30 habitat classes, wooded symbology was often the most difficult to determine as either coniferous or deciduous forest, which was true for both upland and wetland forested classes (Figure 77). Therefore, users may choose to accept or decline specific features or regions based on an easily accessible level of confidence.



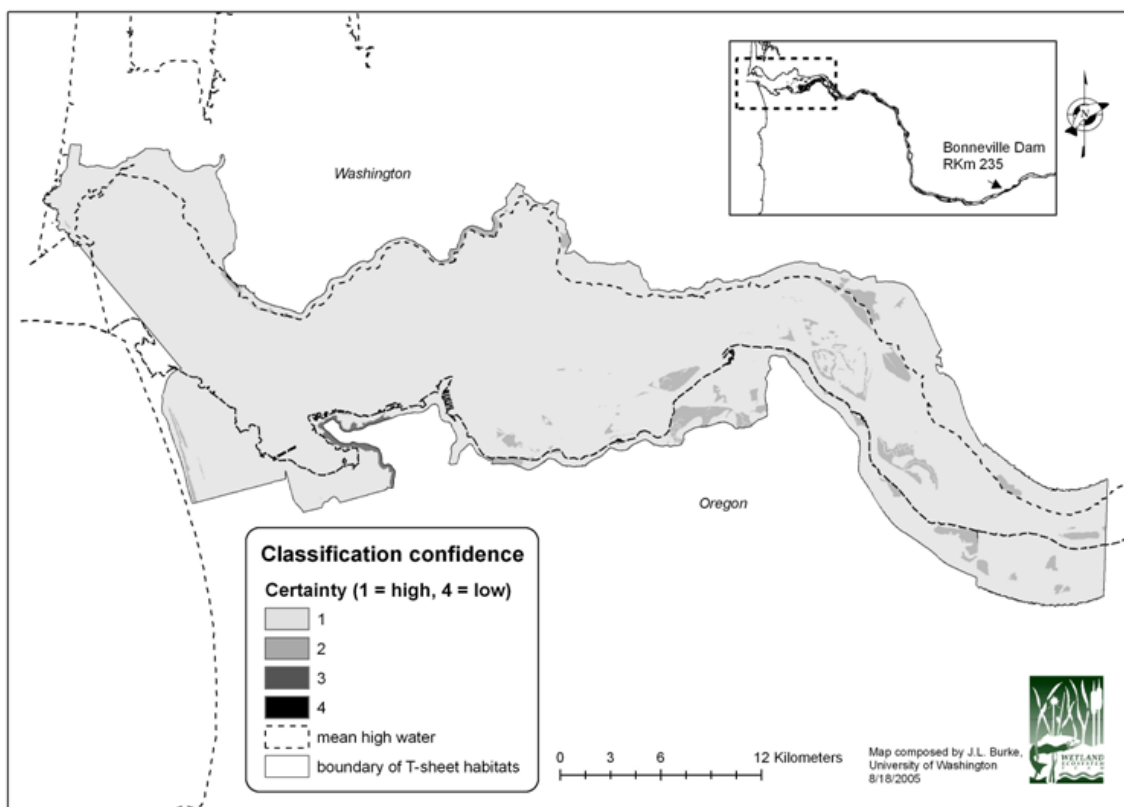


Figure 76. Grid of certainty in interpretation of symbology.

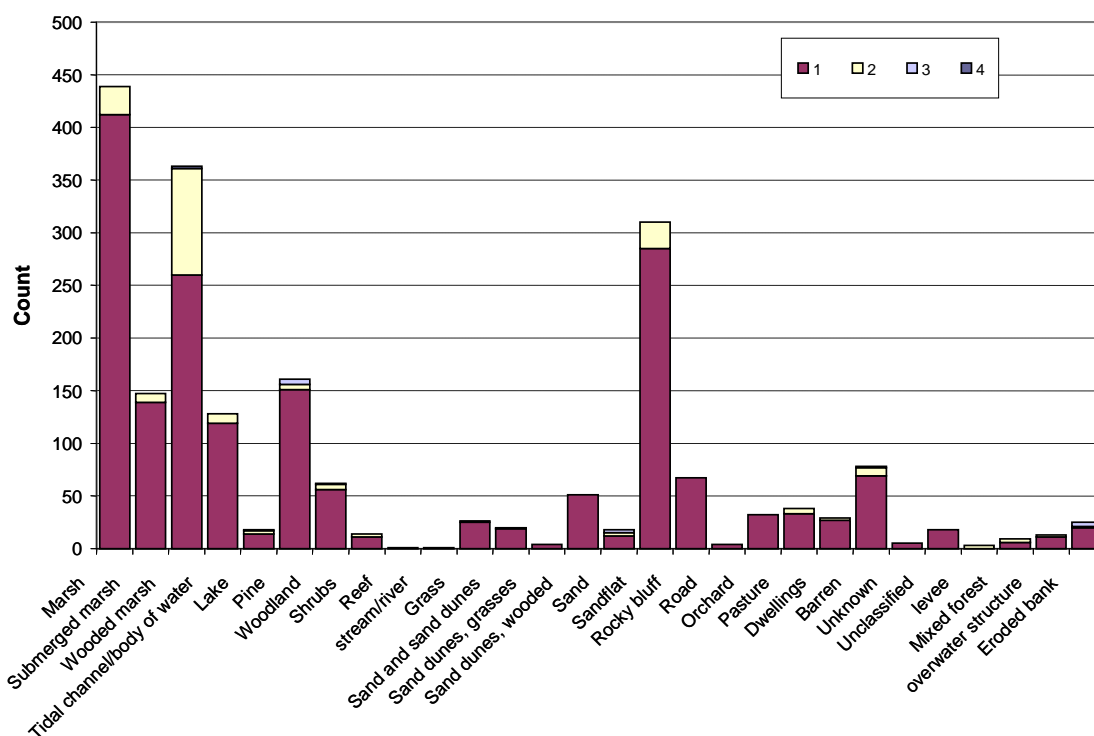


Figure 77. Certainty associated with the interpretation of map symbology by cover class. Certainty ranked from 1 (most confidence) to 4 (least confidence).

## **Conclusions**

By incorporating the best available technology and lessons from past efforts, we have generated the most rigorous and detailed reconstruction to date of historical habitats in the lower Columbia River and estuary. Development of the protocols resulted in high spatial accuracy and will provide a dataset with high usability for researchers and managers. The habitat reconstruction project presented several different levels of data that are relevant to restoration and monitoring efforts in the estuary. For instance, in addition to the spatially explicit cover classes presented in a GIS, information that can be extracted from the seamless dataset includes floodplain boundaries, complexity, and historical spatial and geomorphic structure of the wetlands and floodplain. Further, the preliminary dataset generated from the FY 2004 tasks will enable us to distribute the data for review by potential users so that we can further refine our methods, classification, and distributed product. The spatial accuracy and resolution of the ecosystem reconstruction will provide a dataset comparable to contemporary data for continuing evaluation of changes in the geographic distribution, amounts, and classes of estuarine and floodplain habitats available to juvenile salmonids.

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## APPENDIX

Appendix Table 1. Common and scientific names of fish species captured in beach-seine and trap-net samples

Common Name	Scientific Name
American shad	<i>Alosa sapidissima</i>
Banded killifish	<i>Fundulus diaphanus</i>
Bay pipefish	<i>Syngnathus leptorhynchus</i>
Black crappie	<i>Pomoxis nigromaculatus</i>
Chinook salmon	<i>Oncorhynchus tshawytscha</i>
Chum salmon	<i>Oncorhynchus keta</i>
Coho salmon	<i>Oncorhynchus kisutch</i>
Common carp	<i>Cyprinus carpio</i>
Cutthroat trout	<i>Oncorhynchus clarki</i>
Dungeness crab	<i>Cancer magister</i>
English sole	<i>Parophrys vetulus</i>
Eulachon	<i>Thaleichthys pacificus</i>
Largemouth bass	<i>Micropterus salmoides</i>
Largescale sucker	<i>Catostomus macrocheilus</i>
Longfin smelt	<i>Spirinchus thaleichthys</i>
Northern anchovy	<i>Engraulis mordax</i>
Northern pikeminnow	<i>Ptychocheilus oregonensis</i>
Pacific herring	<i>Clupea harengus pallasi</i>
Pacific lamprey	<i>Lampetra tridentata</i>
Pacific sand lance	<i>Ammodytes hexapterus</i>
Pacific sanddab	<i>Citharichthys sordidus</i>
Pacific staghorn sculpin	<i>Leptocottus armatus</i>
Pacific tomcod	<i>Microgadus proximus</i>
Peamouth	<i>Mylocheilus caurinus</i>
Prickly sculpin	<i>Cottus asper</i>
Rainbow trout (steelhead)	<i>Oncorhynchus mykiss</i>
River lamprey	<i>Lampetra ayresi</i>
Saddleback gunnel	<i>Pholis ornata</i>
Sand roller	<i>Percopsis transmontana</i>
Sand sole	<i>Psettichthys melanostictus</i>
Snake pricklyback	<i>Lumpenus sagitta</i>
Sockeye salmon	<i>Oncorhynchus nerka</i>
Speckled dace	<i>Rhinichthys osculus</i>
Speckled sanddab	<i>Citharichthys stigmaeus</i>
Starry flounder	<i>Platichthys stellatus</i>
Surf smelt	<i>Hypomesus pretiosus</i>
Threespine stickleback	<i>Gasterosteus aculeatus</i>
Topsmelt	<i>Atherinops affinis</i>
Walleye surfperch	<i>Stizostedion vitreum</i>
Whitebait smelt	<i>Allosmerus elongatus</i>
Yellow shiner perch	<i>Cymatogaster aggregata</i>

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