Fish Distribution, Abundance, and Behavior along City Shoreline Types in Puget Sound

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Abstract.—Shoreline modifications, such as bulkheads, riprap, and overwater structures, have altered many of the natural habitats in nearshore urbanized areas surrounding coastal cities, including those in Puget Sound, Washington. The effects of such structures on ecological processes are poorly known, especially those impacting juvenile salmonids *Oncorhynchus* spp. The goal of our study was to compare the relative abundance and behavior of juvenile salmonids and other fishes along various modified and undeveloped shoreline types. We used enclosure nets and snorkel surveys to sample fishes during high tides in areas adjacent to shore at five main habitat types: cobble beach, sand beach, riprap extending into the upper intertidal zone, deep riprap extending into the subtidal zone, and the edge of overwater structures. Bottom-dwelling fishes exhibited the only significant differences in density among cobble beach, sand beach, and riprap that extended into the upper intertidal zone. This suggests that substrate type and slope are important influences on fish densities when shoreline modifications only extend into the upper intertidal zone. Differences in pelagic fish density and behavior were more evident when shoreline modifications extended into shallow subtidal waters, truncating the shallow-water zone and creating deep water at the shoreline. We typically found higher fish densities, larger schools of salmon, and fewer terrestrial riparian insects in salmon diets at these sites. Juvenile salmonids avoided swimming beneath overwater structures, whereas surfperch (family Embiotocidae), crabs (infraorder Brachyura), and sculpins (family Cottidae) were observed beneath or adjacent to pilings. Overall, our results indicate that shoreline modifications have the greatest effect on nearshore fish assemblages when the alterations extend from the supratidal zone into the subtidal zone. Our data suggest that the differences in fish behavior and usage between modified and unmodified shorelines were caused by physical and biological effects of the modifications, such as changes in water depth, slope, substrate, and shoreline vegetation.

Studies of ocean-type juvenile Chinook salmon *Oncorhynchus tshawytscha* in the Pacific Northwest indicate that they use estuarine and nearshore habitats early in their out-migration and rearing periods (Simenstad et al. 1982; Healey 1998; Brennan et al. 2004). Where tidal floodplains and estuaries have been highly modified and are unavailable for natural rearing, marine shorelines may take on more of a role in providing rearing habitat. This is particularly true of central Puget Sound, Washington, where most of the deltas and estuaries are highly modified (Emmett et al. 2000; Simenstad and Cordell 2000). Juvenile Chinook salmon are found along these shorelines from late January through September, peak out-migration usually occurring in June and July. There is little specific information on whether or not juvenile salmon preferentially use or avoid certain types of shorelines and what functions the different shoreline types provide them. Research conducted in the Puget Sound region suggests that juvenile Chinook salmon and

chum salmon *O. keta* prefer shallow areas along estuarine and marine shorelines, including beaches, mudflats, and beds of eelgrass *Zostera marina* (Simenstad et al. 1982; Simenstad and Cordell 2000). However, in urban settings, it is unknown how juvenile salmon behavior is influenced by the diversity of anthropogenic structures and impacts. Do salmon select some habitats and avoid others, or are they randomly distributed along the shoreline?

The purpose of this study was to compare abundance and behavior of juvenile salmon and other fishes among various marine shoreline habitat types near the city of Seattle, Washington. Shorelines within Seattle city boundaries are considerably more modified than elsewhere in Puget Sound, as between 84% and 97% of the shoreline is modified by retaining structures (Weitkamp et al. 2000) compared with one-third for all of Puget Sound (Bailey et al. 1998). There are several other large cities occupying shoreline habitat within the greater Puget Sound–Georgia Basin area, including Olympia, Tacoma, Anacortes, and Bellingham, Washington, and Vancouver, British Columbia. We focused on five common types of shorelines: cobble beach, sand beach, riprap extending into the upper intertidal zone, deep riprap extending into the

subtidal zone, and the edge of overwater structures. Sampling was conducted during high tides on habitats directly bordering the shoreline, either in intertidal areas or in shallow subtidal areas in cases where modified embankments truncated the shallow-water habitat. A secondary goal was to collect stomach contents of juvenile salmon for indication of habitat use based on diet composition. The results were intended to be useful to resource managers who need to identify potential impacts of nearshore development on salmon, prioritize recovery actions, and identify approaches that provide maximum protection to those nearshore marine areas that are important to juvenile salmon. This is especially relevant because of the listing of Puget Sound Chinook salmon as a threatened species in March 1999 by the National Marine Fisheries Service (NMFS).

Shoreline modifications have been shown to affect fish and invertebrates in freshwater, estuarine, and coastal systems. Most studies in freshwater show negative impacts on fish abundance and diversity with increased shoreline development (Knudsen and Dilley 1986; Weaver and Garman 1994; Brazner 1997; Madejczyk et al. 1998; Schmetterling et al. 2001; Garland et al. 2002; Tabor and Piaskowski 2002; Friesen et al. 2003; Scheuerell and Schindler 2004; Wei et al. 2004), although increased structural complexity associated with shoreline development can sometimes have the opposite effect (Beauchamp et al. 1994; Jennings et al. 1999; Friesen et al. 2003). Fewer studies have focused on fish in estuarine and coastal systems. These indicate that shoreline developments can negatively impact (Able and Manderson 1998; Duffy-Anderson and Able 1999; Peterson et al. 2000), or at the least alter, fish communities (Guidetti et al. 2002). Such studies have not been conducted on fishes in the Pacific Northwest or on juvenile salmonids once they migrate past freshwater reaches. Impacts on invertebrate assemblages can additionally affect community patterns (Glasby 1998; Spalding and Jackson 2001; Davis et al. 2002; Cruz Motta et al. 2003; Sobocinski 2003) that may have cascading ramifications through trophic and other community interactions. Physical alterations associated with truncating and retaining the intertidal zone can include degrading intertidal habitat and shoreline vegetation, limiting the sediment supply, and reflecting wave energy, which can increase erosion and coarsen sediments (Thom et al. 1994; Douglass and Pickel 1999).

Most prior sampling for shoreline-oriented juvenile salmon in the Puget Sound region has been conducted with beach seines in targeted habitats (e.g., seagrass) or with fyke nets in estuarine channels associated with river mouths. The traditional method of fish sampling on Puget Sound beaches has been with 37-m-long beach seines (Simenstad et al. 1991), which have the following associated problems: (1) they are only effective for sampling certain habitat types, such as shallow, uniform sediment (gravel, sand) beaches at specific tide elevations; (2) density estimates can be severely compromised by varying sampling efficiencies on different substrates and water depths (Rozas and Minello 1997); (3) they can easily get snagged on submerged rocks or other obstacles as they are being hauled; (4) both floating and sinking beach seines have been used, depending on the target fish assemblages (Simenstad et al. 1991), which can complicate sampling efficiency (especially at deepwater sites); and (5) they are "instantaneous" measures of fish assemblage structure and density and, as such, do not supply information about more prolonged behavior and feeding activities in specific habitats. Therefore, interpreting diet composition from beach seine catches is limited, as the fish could easily have been feeding elsewhere.

Rozas and Minello (1997) found that using enclosure nets for estimating densities of small nekton in shallow estuarine habitats provided the most reliable quantitative data and comparability between sites and studies (also see Cicchetti and Diaz 2000). Snorkel surveys and other visual census techniques for assessing fish abundance have been used effectively in freshwater stream, lake, and marine coral reef environments (Slaney and Martin 1987; Hankin and Reeves 1988; St. John et al. 1990; Graham 1992; Beauchamp et al. 1994; Tabor and Piaskowski 2002) but have been less widely used in estuarine and shallow-water marine settings (MacDonald et al. 1986; Harmelin-Vivien and Francour 1992; Haggarty 2001; Davis et al. 2002). We used enclosure nets and snorkel surveys to assess habitat usage by fishes directly along marine and estuarine shorelines within the Seattle city limits.

Methods

Study sites and experimental design.—Fish sampling was conducted weekly between May 12 and August 1, 2003, during peak out-migration of juvenile Chinook salmon. Sampling locations were all within Seattle city boundaries (Figure 1). Study sites were selected based on habitat characteristics included in the Washington Department of Natural Resources ShoreZone Inventory (WDNR 2001), Washington Department of Energy oblique aerial photographs (WDOE 2000), city of Seattle high-resolution aerial photographs (image source, Triathlon Inc., Seattle), and field verification. Site location was determined by choosing sites that had a minimum shoreline length of 200 m and that were

stratified with respect to the other habitat type locations along the entire Seattle shoreline to minimize spatial variability and "clumping" of habitat types, to the extent possible, based on existing urbanization patterns (Figure 1).

Cobble beach, sand beach, and riprap sites were sampled with enclosure nets and snorkel surveys, and deep riprap and overwater structure sites were only sampled with snorkel surveys, as water depths at the sites were too deep for use of enclosure nets. The "deep riprap" habitat type included sites where riprap extended from the supratidal zone into the subtidal zone, and "riprap" sites were those at which the riprap only extended from the supratidal zone into the upper intertidal zone with exposed beach at low tide. Overwater structures included in this study were large apartment or business complexes constructed on piers, ranging in area from 582 to 4,866 m^2.

Sampling techniques were different on alternate weeks, depending on tidal elevations at spring and neap tides. During spring tides, enclosure nets and snorkel surveys were both used because the sites dewatered at low tide, allowing retrieval of fish from the nets. Eight sites were sampled during spring tide series: three each of sand beach and riprap and two of cobble beach. During neap tides, we conducted snorkel surveys at all sites and habitat types. A total of 15 sites were sampled (3 of each habitat type).

Means for spring tides were +2.8 m for high water and −0.3 m for low water, while neap tides were +2.9 m for high water and +1.8 m for low water. Horizontal Secchi disk readings were almost identical between tide weeks, averaging 4.90 m for neap tides and 4.92 m for spring tides. Spring tide surveys were always in the morning (mean time, 0835 hours), and neap tide surveys were always in the afternoon (mean time, 1532 hours) and were centered around high slack tide. Total mean salinity and temperature readings were 27.7‰ and 13.7°C, respectively, at the surface of the water column and 28.7‰ and 12.8°C at the bottom of the water column.

Enclosure nets.—The presence and abundance of fish along shallow-water shorelines were tested with enclosure nets. This method consisted of deploying a 60-m-long, 4-m-high, 0.64-cm-mesh net around poles to enclose a 400-m^2 rectangular section of the shoreline; the water's edge formed the fourth side of a rectangle. The poles were installed at low tide on the day before net deployment to minimize disturbance at the time of sampling. The net was set at high tide on the following morning. Fish were removed from the enclosed sample area with either a small pole seine (1.2 × 9.1 m; 0.64-cm mesh) or dip nets as the tide ebbed, usually starting at midtide a few hours after net
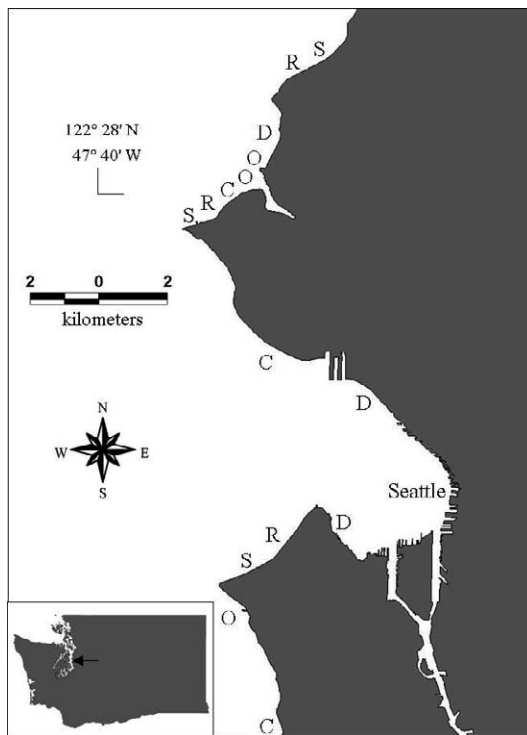

FIGURE 1.—Location of study sites in Puget Sound, Washington, and main habitats sampled in 2003: C = cobble beach, S = sand beach, R = riprap, D = deep riprap, and O = overwater structure. Gray shading represents land, and white represents water. Inset is the state of Washington; the arrow points to the area of enlargement.

deployment. All fish were removed before low tide. Nonsalmonid fishes and crabs (infraorder Brachyura) were identified, counted, and released. Salmonids were designated as either of unmarked "wild" or marked "hatchery" origin. Those fish marked with adipose fin clips, coded wire tags, or both were assumed to be hatchery produced. Unmarked fish with intact fins and no tags were assumed to be naturally produced wild fish. Some undetermined error was associated with this method, as a small fraction of hatchery fish were unmarked or incompletely marked. Fork lengths (FLs) of salmonids were recorded to $n = 5$ for each species, and marked or unmarked status. Standard lengths of all other fish were recorded (to $n = 20$). Crabs were measured for carapace width.

The data resulting from the enclosure-net sampling produced per-unit volume densities of fish and crabs on each segment of shoreline sampled. Volume was estimated by measuring the exact lengths of each side of the net, the water depth at the poles when the net was set, and the water depth at shore (if not zero; e.g.,

because of riprap embankment), assuming a steady slope from shore to the poles.

Stomach contents of juvenile salmonids were sampled by gastric lavage for up to $n = 5$ of each species, and marked or unmarked status. Gastric lavage has been shown to sample 100% of food items and to have no adverse long-term effects in salmonids (Twomey and Giller 1990). This method consisted of first placing fish in a tray of seawater with a small amount of the anesthetic tricaine methanesulfonate (MS-222) for approximately 30 s. Once sedate, each fish was removed from the tray and its FL was measured. Gut contents were then flushed from the stomach by use of a modified garden pump sprayer with a custom nozzle and filtered seawater. Stomach contents were washed into a 106-µm sieve and fixed in 10% buffered formaldehyde solution. Fish were immediately placed in a bucket of seawater for recovery (approximately 2–3 min) and released. Stomach contents were sorted and identified with a dissecting microscope in the laboratory. The degree of digestion was noted for each sample, and the prey items were ranked based on a modified index of relative importance (IRI; Pinkas et al. 1971; Simenstad et al. 1991) that was calculated as follows: %total IRI = %frequency of occurrence × (%numerical composition + %gravimetric composition).

Snorkel surveys.—Presence and behavior of fish were observed by snorkeling along transects parallel to shore. Surveys were conducted near high slack tide to maximize proximity to shoreline habitats. On each sampling date, four total transects per site were conducted (two transects each by two snorkelers). Because successful observations required 2.5-m visibility, all transects attempted with Secchi disk readings below 2.5 m were omitted from the analyses. Transects were 75 m long and were typically situated at a water depth of 1.5 m; distance from shore was measured with a measuring tape. At modified shorelines with steep banks (e.g., deep riprap), transects were conducted 3.0 m from shore and the water depth was measured with a weighted measuring tape. Overwater structures were surveyed by snorkeling 2.0 m away from the edge of the structure (not underneath) and measuring the water depth.

Fish counts were standardized by transect length and visibility (number/[transect length × horizontal Secchi depth]). Data collected during snorkeling transects included transect direction (compass point); direction of observations (away from shore, toward shore); fish identification and number; approximate fish length (2.5-cm increments); water column position of fish (surface, midwater, bottom); distance from observer to fish (m); water depth at fish location (m); substrate type (sand, gravel, cobble, boulder, riprap, riprap–sand

interface, kelp); fish behavior (schooling, swimming away, fleeing, feeding, inactive, hiding); and specific location and movement if next to an overwater structure or piling (within 1 m or directly on piling for crabs and sculpins [family Cottidae]). Fish behavior categories were defined as (1) schooling—fish that were located in a single school; (2) swimming away—fish that swam at a moderate rate; (3) fleeing—fish that swam very rapidly; (4) feeding—fish that were observed to be feeding; (5) inactive—fish that displayed no observable behaviors or movements; and (6) hiding—fish that hid around rocks, in crevices, and among other bottom structures.

Overlap of fish observations with the habitat type characteristics of water column position and substrate type was estimated with a modified percent similarity index (PSI; Cailliet and Barry 1978; Hurlbert 1978) that was calculated as follows:

$$\text{PSI} = \sum_{i=1}^{n} \text{miminum}(p_{xi}, p_{yi}),$$

where p_{xi} = percentage of habitat type i observed with fish x and p_{yi} = percentage of habitat type i observed with fish y.

Environmental measurements.—Surface and bottom water salinity and temperature were taken with a portable YSI meter (YSI, Inc., Yellow Springs, Ohio). Water visibility was estimated by determining horizontal Secchi disk readings during snorkel surveys. Daily weather patterns were qualitatively observed. High and low tidal heights and times were recorded, as predicted by the program Tides and Currents.

Statistical analysis.—Data were entered into Excel (Microsoft Corporation, Redmond, Washington) and analyzed with univariate statistics in the program S-Plus. Analysis of variance (ANOVA) tests ($\alpha = 0.05$) were used to analyze measured levels of fish densities at habitat types. For significant results, Tukey's test for multiple comparisons was used to identify specific differences between all possible pairs of means (Zar 1996). Snorkel densities were log transformed before ANOVA, as recommended by Zar (1996), to minimize effects of a positively skewed distribution and variations proportional to the means. When assumptions of normality and homogeneous variances were not met, the nonparametric Kruskal–Wallis k-sample test was used; this was the case for the length data. Snorkel densities were also analyzed with multivariate nonmetric multidimensional scaling (NMDS) ordination using PC-ORD to identify patterns in multivariate groupings of the entire fish assemblage (McCune and Grace 2002). Snorkel densities were also log transformed for multivariate analysis. After ordination, a

TABLE 1.—Functional groupings and mean lengths (mm fork length for salmonids, standard length for all others; carapace width for crabs) of fish and crabs collected with enclosure nets in Puget Sound (2003) and used for analysis. Species with an asterisk were only seen during snorkel surveys. Marked salmon were presumed to be of hatchery origin, and unmarked salmon were presumed to be wild.

Group	Common name	Scientific name	Mean length (mm)
Juvenile salmon	Chinook salmon	*Oncorhynchus tshawytscha*	Unmarked, 97.2 Marked, 89.4
	Coho salmon	*O. kisutch*	Unmarked, 132.4 Marked, 151.6
	Chum salmon	*O. keta*	61.0
	Cutthroat trout	*O. clarkii*	172.0
Forage fishes	Surf smelt	*Hypomesus pretiosus*	76.8
	Pacific sand lance	*Ammodytes hexapterus*	98.7
	Pacific herring	*Clupea pallasii*	97.3
Other nearshore fishes	Bay pipefish	*Syngnathus leptorhynchus*	189.5
	Tubesnout	*Aulorhynchus flavidus*	171.3
	Threespine stickleback	*Gasterosteus aculeatus*	35.0
Surfperches	Striped seaperch	*Embiotoca lateralis*	190.8
	Pile perch	*Rhacochilus vacca*	166.3
	Shiner perch	*Cymatogaster aggregata*	73.5
	Kelp perch	*Brachyistius frenatus*	85.5
Flatfishes	English sole	*Parophrys vetulus*	73.1
	Starry flounder	*Platichthys stellatus*	74.8
	Rock sole	*Lepidopsetta bilineata*	130.5
	Sand sole	*Psettichthys melanostictus*	186.1
	Pacific sanddab	*Citharichthys sordidus*	203.0
Other demersal fishes	Pacific staghorn sculpin	*Leptocottus armatus*	86.9
	Fluffy sculpin	*Oligocottus snyderi*	46.4
	Padded sculpin	*Artedius fenestralis*	69.7
	Buffalo sculpin	*Enophrys bison*	114.7
	Great sculpin	*Myoxocephalus polyacanthocephalus*	113.0
	White spotted greenling	*Hexagrammos stelleri*	91.0
	Lingcod*	*Ophiodon elongatus*	101.3
	Rockfishes*	*Sebastes* spp.	18.8
	Spotted ratfish*	*Hydrolagus colliei*	53.8
	Pricklebacks*	*Stichaeidae* spp.	26.3
Gunnels	Penpoint gunnel	*Apodichthys flavidus*	130.6
	Saddleback gunnel	*Pholis ornata*	122.0
	Crescent gunnel	*Pholis laeta*	135.2
Crabs	Dungeness crab	*Cancer magister*	74.3
	Red rock crab	*C. productus*	56.0
	Graceful crab	*C. gracilis*	50.1
	Yellow shore crab	*Hemigrapsis oregonensis*	16.0
	Northern kelp crab	*Pugettia producta*	40.3

multiresponse permutation procedure (MRPP) was used as a nonparametric test of differences between groups. The MRPP produces two test statistics that are useful in interpreting results: a *P*-value similar to an ANOVA test and an *A*-statistic, which measures the homogeneity between groups. When *A* equals zero, within-group heterogeneity is equal to that expected by chance; when *A* is greater than zero, the heterogeneity within groups is greater than that expected by chance. Indicator species analysis was also used in PC-ORD to identify the most influential taxa.

Results

Enclosure Nets

Fishes and crabs were classified by functional groups for analysis (Table 1). Densities were analyzed with ANOVA for the main effect of habitat type at the high intertidal zone (cobble beach, sand beach, riprap). The only functional group from enclosure-net sampling that was significantly different among habitat types was flatfish density (Figure 2; $P = 0.0045$). There were also no significant differences in juvenile salmonids based on species or their unmarked or marked status. Surfperches (family Embiotocidae) dominated the fish densities at cobble beaches, although this finding was not statistically significant. A Tukey's test of multiple comparisons for flatfish showed that densities were higher on sand beaches than on either cobble beach or riprap. This difference was driven mostly by juveniles ($P = 0.021$) as opposed to adults ($P = 0.092$; 100-mm standard length demarcation). The English sole was the dominant flatfish species.
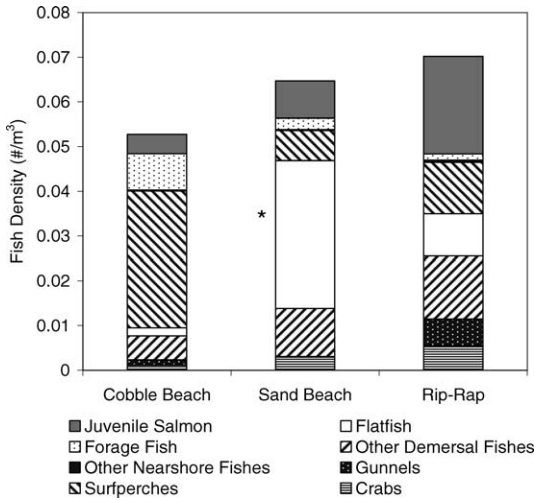
FIGURE 2.—Mean densities of fish functional groups sampled by enclosure nets at high intertidal habitat types in Puget Sound, Washington, 2003. Flatfish are the only significant grouping (an asterisk denotes significantly higher density). Order of the shading patterns in the bars for the functional groups follows that of the legend (top to bottom, left to right).
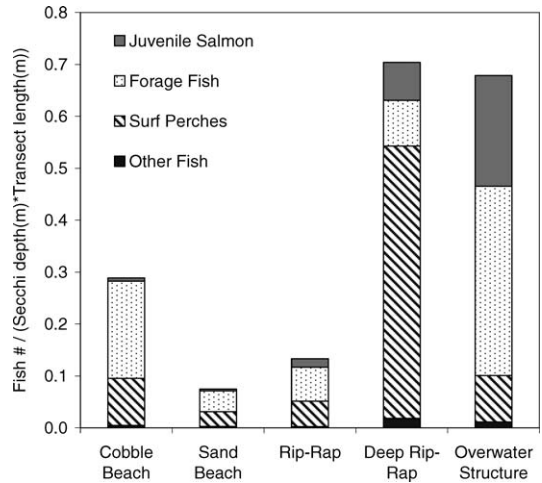

FIGURE 3.—Mean densities of fish functional groups sampled by snorkel surveys at high intertidal habitat types in Puget Sound, Washington, 2003. Statistics are represented in Table 2.

Mean length data for all species are given in Table 1. Lengths of Chinook salmon were analyzed by habitat type using the nonparametric Kruskal–Wallis test. Mean lengths were significantly different between habitat types ($P = 0.0004$); fork lengths at riprap sites were the lowest (89.2 mm), followed by sand beach (97.9 mm) and cobble beach (99.2 mm). Regression analysis showed that Chinook salmon and chum salmon increased in size through time (marked Chinook salmon: $R^2 = 0.65$, $P < 0.001$; unmarked Chinook salmon: $R^2 = 0.36$, $P < 0.05$; chum salmon: $R^2 = 0.85$, $P < 0.0005$), while the FLs of coho salmon *O. kisutch* exhibited no significant trends.

Juvenile salmonid densities varied somewhat with timing of out-migration. Chum salmon were abundant at the start of sampling and decreased to low numbers by the end of June. Marked Chinook salmon had a sharp peak the first week of June and then dropped to medium levels for the remainder of the sampling. Unmarked Chinook salmon had more constant densities; the highest numbers occurred in late June and July. Marked and unmarked coho salmon occurred at relatively low numbers, and the highest densities were found in late June.

Water volume sampled by the enclosure nets ranged from 157 to 681 m³. Volumes at riprap sites were significantly greater than those at sand and cobble beaches (means = 519, 372, and 337 m³, respectively)

as a result of steeper slopes caused by riprap embankments.

Snorkel Surveys

Fishes and crabs were also placed in functional groups for analysis of the snorkel survey data (Table 1). Densities were analyzed with ANOVA for the main effect of habitat type at high intertidal habitats (cobble beach, sand beach, riprap, deep riprap, overwater structure). Overall densities were significantly higher at deep riprap and overwater structure sites than at sand beach, riprap, and cobble beach sites (Figure 3; Table 2). All functional groups (except for forage fishes: $P = 0.054$) were significantly different ($P < 0.05$) among habitat types.

Multivariate analysis by NMDS ordination on densities of the entire fish assemblage further illustrated the differences between deep riprap and overwater structures versus other habitat types (Figure 4). The final stress for a three-dimensional solution was 14.59% ("quite satisfactory" according to the guidelines of McCune and Grace [2002]), and the instability value was 0.00470 after 44 iterations for the final solution. All three axes explained 72.9% of the variation (31.8, 21.2, and 20.0%, respectively). The MRPP analysis showed significant separation between habitat types ($P < 0.00000001$; $A = 0.14$). This illustrates that there are significant ecological differences between the species assemblages at the habitat types, as community ecology values for A can commonly be less than 0.1 even when P-values are significant (McCune and Grace 2002). Surfperches and

TABLE 2.—Significant differences in functional group and juvenile salmonid densities from snorkel surveys in Puget Sound (2003) based on ANOVA and Tukey's test for multiple comparisons on main habitat type. Letters designate significant differences, where the order of letters denotes higher densities (e.g., x < y < z) and common letters indicate nonsignificance (e.g., xy not significantly different than x or y). Dash indicates no significance.

| Functional group | P-value | Main habitat type | | | | |
		Cobble beach	Sand beach	Riprap	Deep riprap	Overwater structure
Overall densities	1.1×10^{-16}	x	x	x	y	y
Forage fishes	0.054	–	–	–	–	–
Other nearshore fishes	0.00017	x	x	x	y	xy
Surfperches	1.0×10^{-16}	x	x	x	y	x
Flatfishes	0.000013	x	y	xy	x	x
Other demersal fishes	0.011	xy	x	y	xy	xy
Gunnels	0.0035	x	x	x	y	x
Crabs	0.000011	y	x	x	xy	x
Overall juvenile salmonids	1.0×10^{-16}	x	x	x	y	z
Chinook salmon	0.0000024	x	x	x	y	x
Chinook–coho salmon	0.0000041	x	x	x	xy	y
Chinook–chum salmon	0.00014	x	x	x	x	y
Chum salmon	0.000001	x	x	x	x	y

juvenile salmon were the major indicator taxa driving the model (59.3 and 62.2 indicator values, respectively; $P = 0.001$ for each).

Identification of salmon to species level was sometimes difficult, as it was often hard to see distinguishing characteristics because of water turbidity and short viewing time. Therefore, identifications were often made in broader categories (Figure 5). The main

salmonid categories (Chinook, Chinook–coho, Chinook–chum, and chum salmon) were all significantly different for habitat type ($P < 0.05$). Tukey's tests for multiple comparisons on habitat type indicated higher densities of salmonids at deep riprap and overwater structure categories (Table 2).

Juvenile salmonids also occurred in larger school sizes at overwater structures (Figure 5). Salmonid
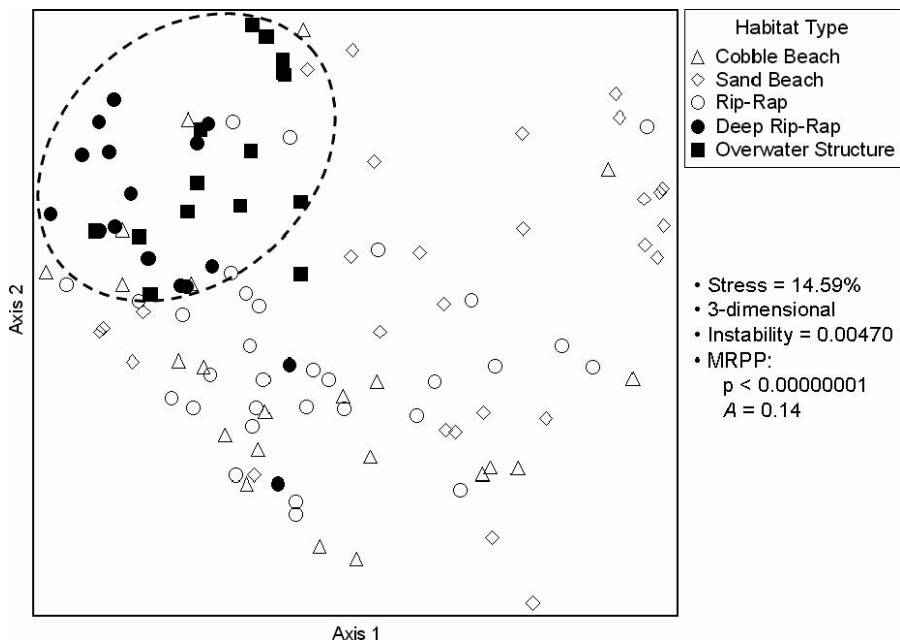

FIGURE 4.—Multivariate nonmetric multidimensional scaling ordination of mean snorkel densities (two major axes shown) of fishes in Puget Sound, Washington, 2003. The hatched circle outlines habitat types that have shoreline modifications extending into the subtidal zone. The multiresponse permutation procedure (MRPP) is a nonparametric procedure that tests for differences between groups.
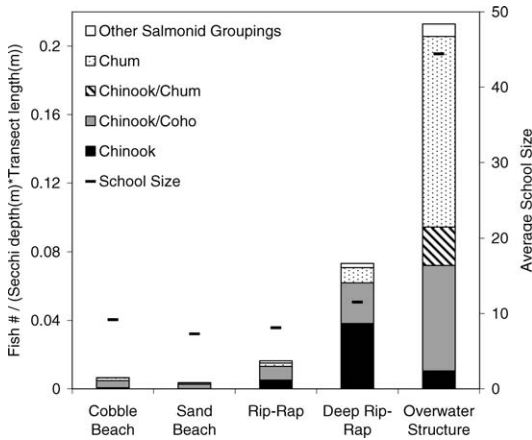
FIGURE 5.—Mean densities and school sizes of juvenile salmonids sampled by snorkel surveys at high intertidal habitat types in Puget Sound, Washington, 2003. Statistics are represented in Table 2. Order of the shading patterns in the bars follows that of the legend.

groupings were not equally represented at all sites, but when combined the overall juvenile salmonid mean school sizes were significantly different with regard to habitat type ($P < 5 \times 10^{-11}$). Tukey's tests showed that school size associated with overwater structures was significantly greater than for other habitat types.

Behaviors of juvenile salmon during snorkel surveys consisted mostly of schooling or swimming away (Figure 6). There were some observations of feeding and few of fleeing and inactive behavior. The greatest incidence of feeding was observed at the deeper sites, mainly at overwater structures, deep riprap, and riprap. Feeding was typically characterized by salmon darting to the surface, presumably to feed on neuston.

Juvenile salmonid categories containing Chinook salmon and coho salmon were located at either the middle or surface of the water column and were more at the surface at deep riprap sites (Figure 6). Chum salmon were always located at the surface except at overwater structures, where they were sometimes found in the middle of the water column. Juvenile salmonids were almost never located at the bottom of the water column; there was only one occurrence near the bottom for Chinook–coho salmon at an overwater structure.

Behavior, water column position, and substrate type summarized across all habitat types for functional groupings of fish and crabs are illustrated in Table 3. These data were used to indicate overlap of water column position and substrate types of juvenile salmonids with those of other fish. Water column positions of Chinook–coho salmon overlapped more

with surfperches and forage fishes in midwater than did the positions of chum salmon, which occurred mostly on the surface (Table 4). However, for substrate type, chum salmon did overlap most with forage fishes. Although bottom-dwelling fishes were separated in water column position from juvenile salmonids, flatfish and other demersal fishes did have fairly high overlap with Chinook–coho salmon and chum salmon based on substrate type. Although most observations comprised separate schools of fishes, juvenile Chinook salmon, coho salmon, and chum salmon sometimes occurred in mixed schools and were also observed infrequently in mixed schools with threespine sticklebacks, Pacific sand lances, Pacific herring, shiner perch, and pile perch.

Locations of fish observations relative to position of overwater structures were recorded, when possible, depending on visibility and time of viewing. Most juvenile salmonids were found away from the edge of the overwater structure or at the edge, and only one school was observed underneath a structure (Table 5). Surfperches were also typically observed away from or at the edge of structures, but did have the highest percentage of observations underneath (11%) and were sometimes associated with pilings (32%). Of the other species, only Pacific sand lances were observed (once) underneath overwater structures; most fish were observed either away from or at the edge of structures (Table 5). Crabs and sculpins were rarely observed, and the majority were located around pilings.

Overwater structures and deep riprap sites had significantly deeper water than other habitat types at the shoreline, and therefore these transects were closer to shore (Table 6). Visibility measured by horizontal Secchi disk readings was also typically better at deep riprap and overwater structures. Two of the overwater structure sites were relatively close to freshwater input (Figure 1), resulting in significantly lower surface salinity readings at overwater structure sites.

Diet Analyses

Prey of juvenile salmonids consisted of a diverse array of insects, marine invertebrates, and fishes (Figure 7). Prey items were grouped by ecological category to determine their source. Chinook salmon were the only salmon species with large amounts of terrestrial riparian prey (36% IRI; adult insects, mostly Chironomidae, Psocoptera, and Lepidoptera). Marine benthic–epibenthic prey accounted for approximately half of Chinook salmon diets (primarily the amphipod *Photis* spp. and nereid worms), while marine plank-tonic–neritic prey was less abundant (15% IRI; mostly Cirrepedia exuviae and larvaceans *Oikopleura* spp.). Coho salmon contained marine benthic–epibenthic and
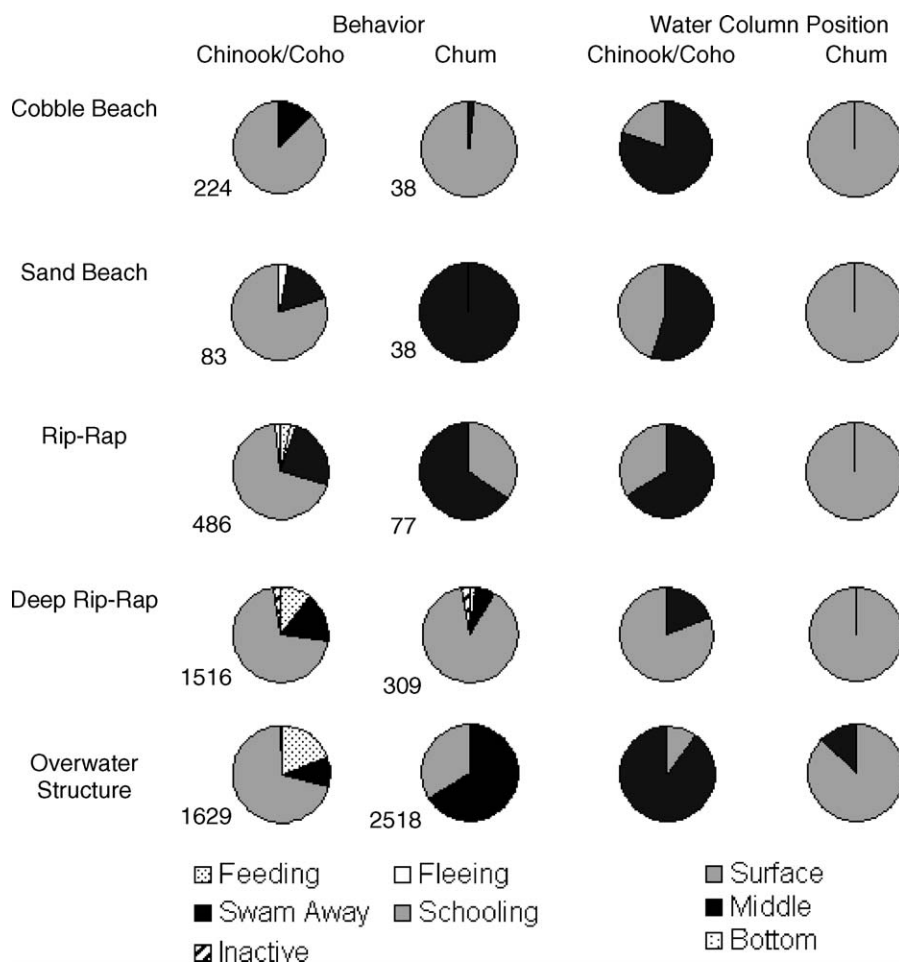
FIGURE 6.—Behavior patterns and water column position of juvenile salmonids at main habitat types in Puget Sound, Washington, 2003. Species identifications are lumped into general categories of Chinook–coho salmon and chum salmon. Sample sizes (numbers of fish) are shown in the lower left corners of the behavior graphs.

planktonic–neritic prey taxa similar to those found in Chinook salmon, plus a large amount of unidentified digested copepods (40% IRI). The majority of chum salmon prey was derived from marine planktonic–neritic sources (79% IRI; primarily the cyclopoid copepod *Corycaeus anglicus*, along with other copepods and invertebrate larvae).

Chinook salmon diet by site was also separated into categories based on shoreline retainment to examine effects of shoreline type on prey. Sites with intertidal or supratidal retaining structures had almost identical prey type compositions, mostly made up of marine benthic–epibenthic taxa (Figure 7). In contrast, Chinook salmon from unretained sites had few marine benthic–epibenthic prey and much more terrestrial riparian and planktonic–neritic prey. Mean digestion rankings for

prey items from juvenile Chinook salmon were 75–100% intact, indicating much of the prey was fresh and not heavily digested.

Discussion

The effects of shoreline modifications on nearshore fish communities and other ecological processes have been a challenging topic to address. This is mainly because of the difficulty in effectively sampling shoreline structures in a way that is quantitatively comparable with more natural habitats. Because of the extensive habitat alteration that occurs along urban shorelines in many coastal estuaries, it is important that we address the resulting gap in knowledge.

The results of our study suggest that the numerical and behavioral responses of fishes to shoreline

TABLE 3.—Behavior, water column position, and substrate type of fish and crab functional groupings based on snorkel survey observations summarized for all habitat types in Puget Sound, 2003. Juvenile salmonids are separated into categories of chum salmon and Chinook–coho salmon.

Observation	Chum	Chinook–coho salmon	Forage fishes	Other nearshore fishes	Surf perches	Flatfishes	Other demersal fishes	Gunnels	Crabs
Behavior									
Hiding (%)	–	–	–	–	0.004	1	9	29	–
Inactive (%)	0.3	1	0.1	63	17	52	46	57	96
Feeding (%)	0.2	12	–	5	0.2	–	–	–	3
Schooling (%)	41	72	89	31	77	–	–	–	–
Swam away (%)	59	14	1	1	4	31	31	14	0.5
Fleeing (%)	–	1	10	0.3	1	16	13	–	–
Water column position									
Surface (%)	89	42	32	34	1	–	–	–	–
Middle (%)	11	58	52	9	61	1	7	–	–
Bottom (%)	–	0.03	16	56	38	99	93	100	100
Substrate type									
Sand (%)	12	39	12	3	11	43	31	7	18
Gravel (%)	34	16	27	2	11	44	30	–	5
Cobble (%)	23	10	33	8	14	7	22	14	40
Boulder (%)	9	0.1	18	16	2	–	4	29	11
Kelp (%)	–	–	–	0.2	0.004	–	–	–	2
Riprap–sand interface (%)	13	8	2	1	15	7	2	7	7
Riprap (%)	9	27	8	69	48	–	11	43	17
Total counts (n)	2,980	3,938	19,766	604	22,334	75	54	14	229

modifications in Puget Sound depend on the degree to which the modifications extend into the tidal zone. When riprap extended only into the upper intertidal zone, the one significant density difference found in enclosure-net data was that juvenile flatfish (mostly English soles) were more abundant at sand beaches. Higher water volumes were sampled with enclosure nets at riprap sites because of their steep embankments and greater slopes, which truncate the intertidal zone. It follows that intertidal juvenile flatfish habitat is lost when this zone is retained with riprap. During snorkel surveys along high intertidal habitats, cobble beaches had higher numbers of crabs than did sand beaches and riprap, and riprap had more demersal fishes (sculpins). These between-habitat differences, which were restricted to bottom-dwelling fishes, suggest that changes in substrate type and slope that accompany shoreline modifications are important factors for demersal fish species when shoreline modifications occur in the upper intertidal zone. Conversely, we found no differences in any pelagic fish densities.

More differences between habitats occurred where shoreline modifications extended from the supratidal zone into the subtidal zone. Riprap that extended into deeper water and overwater structures had greater water depths than the other habitat types. Snorkel surveys at these sites occurred directly along the interface of the structure and the water because there was almost no shallow-water, low-gradient habitat (mean transect water depth = 2.4–3.0 m). Fish densities at deep riprap and at the edge of overwater structures were different than those of other habitat types, having higher overall fish densities than sand beaches, cobble beaches, and shallow riprap. The fish assemblages also exhibited this same overall separation of habitat types, as illustrated by ordination analysis.

TABLE 4.—Overlap (%) of water column position and substrate types between juvenile salmonids and other fish groups in Puget Sound (2003), as measured by the percent similarity index.

Observation	Chum salmon	Chinook–coho salmon	Forage fishes	Other nearshore fishes	Surfperches	Flatfishes	Other demersal fishes	Gunnels	Crabs
Water column position									
Chum salmon	–	53	59	44	12	1	7	0	0
Chinook–coho salmon	53	–	84	44	59	1	7	0	0
Substrate type									
Chum salmon	–	55	80	33	60	59	78	47	65
Chinook–coho salmon	55	–	48	41	66	69	71	51	57

TABLE 5.—Location of fish observations near edges of overwater structures in Puget Sound (2003). Categories are defined as under = more than 1 m underneath edge of overwater structure, edge = within 1 m under or away from edge of structure, and away = more than 1 m away from edge of structure.

Fish group and species	Proximity to overwater structure			Count of observations	Percent associated with pilings
	Under (%)	Edge (%)	Away (%)		
Juvenile salmonids					
Chinook–coho salmon	2	20	78	46	
Chinook salmon		17	83	6	
Chinook–chum salmon		80	20	5	
Chum salmon		50	50	26	
Other salmonid groupings		11	89	9	
Total	1	30	68	92	
Surfperches					
Shiner perch	8	35	58	52	27
Pile perch	17	45	38	29	38
Striped seaperch	14	43	43	14	36
Other groupings		83	17	6	33
Total	11	42	48	101	32
Other fishes					
Threespine stickleback		7	93	15	
Pacific sand lance	14	29	57	7	
Larval fish			100	4	
Sculpin		100		4	75
Smelt		50	50	4	
Red rock crab		100		3	67
Bay pipefish			100	1	
Dungeness crab		100		1	100
Gunnels			100	1	
Kelp crab		100		1	
Pacific herring		100		1	
Starry flounder			100	1	

Similarly, differences in juvenile salmonid densities were only observed when shoreline modifications extended into the subtidal zone. Within the overall fish assemblage, juvenile salmonids were one of the major indicator species driving the separation of habitat types in the ordination analysis. The results of the univariate analysis also showed that overall juvenile salmonid densities from snorkel surveys were significantly different among habitat types; specifically, densities were higher at the edge of overwater structures and deep riprap than at other habitat types. Densities of most salmonid species groupings were also higher at the edge of overwater structures than at other types, and definite Chinook salmon identifications were higher at deep riprap than at other types.

Juvenile salmonids were rarely observed (1%) underneath overwater structures. Two possibilities that we cannot confirm based on our data were that (1) fish were actively selecting and occupying edges of overwater structures and deep riprap and (2) fish were concentrated in such areas because of the loss of shallow-water habitat or because the structures interrupted their movement. Because (1) the depths during fish observations were significantly greater at deep riprap (2.4 m) and overwater structures (4.4 m) than at the other habitat types and (2) observations at these sites were at the land–water interface because of the presence of structures, we effectively observed every fish at that depth range. At low-gradient habitat types, water depths at fish observations were shallower (1.6–

TABLE 6.—Environmental measurements from snorkel surveys at main habitat types in Puget Sound (2003). All measured variables are significantly different using ANOVA tests; order of letters denotes specific differences (e.g., w ≠ x ≠ y ≠ z) and common letters indicate nonsignificance (e.g., xy not significantly different from x or y).

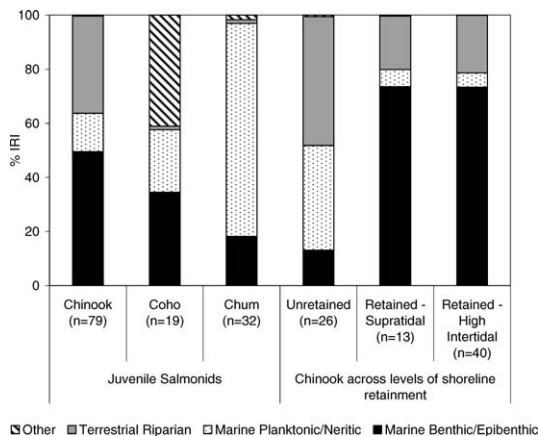| Habitat type	Mean transect distance from shore (m)	Mean water depth at fish (m)	Mean Secchi depth (m)	Surface salinity (‰)	Bottom salinity (‰)
Cobble beach	17.2 z	1.6 z	4.3 z	28.7 z	28.8 z
Sand beach	12.9 y	1.7 z	4.8 yz	28.7 z	28.9 z
Riprap	7.7 x	1.7 z	4.7 z	28.8 z	28.9 z
Deep riprap	4.8 w	2.4 y	5.9 x	27.5 z	28.2 y
Overwater structure	3.4 w	4.4 x	5.4 xy	23.7 y	28.6 yz

FIGURE 7.—Composition of prey (grouped by ecological categories) consumed by juvenile salmonids (Chinook, coho, and chum salmon) and Chinook salmon across levels of shoreline retainment in Puget Sound, Washington, 2003. "Other" refers to highly digested, unidentified prey plus other unassigned ecological categories (in the case of coho salmon, all copepods most likely in the marine planktonic–neritic category).

1.7 m) and distances from shore were significantly greater than at deep riprap and overwater structures (7.7–17.2 m). Therefore, fish were only observed in a fraction of the depth range observed at deeper stations, as allowed by the field of vision (mean Secchi disk reading = 4.3–4.8 m). Due to the nature of the habitat alterations at modified sites, it is not possible to standardize fish counts with identical depth and distance contours at all of the different habitat types.

However, the data we collected address our primary goal of quantifying fish use directly along the shoreline. When shoreline-oriented juvenile salmonids encounter an overwater structure or deep riprap, they must swim under the structure, inhabit deeper water, or move on. Our finding of larger juvenile salmon school sizes near overwater structures suggests that when they inhabit this deeper water, they change their behavior. This may have implications for within-species competition, feeding behavior, and susceptibility to predation. An alternative hypothesis is that the higher numbers and schooling behavior of the juvenile salmon at overwater structures were influenced by their proximity to freshwater, as two of these sites were closer to the Lake Washington out-migration corridor than the other sites. This effect cannot be isolated, since the different habitat types are unequally represented as determined by urbanization patterns.

Most fish, including juvenile salmon, were not usually observed underneath overwater structures as far as light attenuation allowed observations (~2 m).

Juvenile salmon were most often observed away from the edge and toward open water. This supports the premise that juvenile salmon avoid overwater structures because they physically block normal movement patterns or decrease light levels (Simenstad et al. 1999). Surfperches, crabs, and sculpins were the only taxa associated with the area underneath the structures and around pilings.

The fish assemblages associated with deep riprap can be attributed to the structure created by the riprap. This habitat had the highest densities of surfperches and gunnels (family Pholidae); these fishes are commonly found around (surfperches) and in (gunnels) complex habitats with interstitial spaces. We found that these fishes occupied the middle to bottom regions of the water column and appeared to use the riprap for refuge and feeding. Similarly, other nearshore fishes (threespine stickleback, tubesnout, bay pipefish) were more abundant at deep riprap sites than at cobble beaches, sand beaches, and higher-elevation riprap. These affinities are less clearly explained than those of fish that directly use the structure but they may be related to habitat attributes associated with deep riprap (e.g., feeding on invertebrates associated with micro- and macroalgae).

We found that most juvenile salmonids were located from the middle of the water column to the surface and were either schooling or swimming away. Juvenile salmonid categories containing Chinook salmon and coho salmon were located more at the surface at deep riprap sites, perhaps because of underlying riprap structure and associated fishes, some of which could potentially be predators. At other habitat types, these salmon were more distributed between the middle of the water column and surface. Chum salmon were surface oriented and were only observed in the middle of the water column at overwater structures, probably because of the greater water depths caused by the truncation of the intertidal zone.

Juvenile salmonids were often found schooling together; mixed schools of Chinook salmon, coho salmon, and chum salmon were observed regularly. We also observed mixed schools of juvenile salmonids, forage fishes, and surfperch. The extent to which interspecific schooling is beneficial to these salmonids is unknown, but the general benefits of schooling probably apply in these cases (Pitcher and Parrish 1993). Such observations of multiple-species schools are a benefit of snorkel surveys, because this kind of information is lost with traditional net sampling techniques. Another advantage of snorkel surveys compared with net sampling is that they provide detailed information on behavior and location of individual fish species and species groups. This type

of information (e.g., Table 3) might be useful in focusing future sampling to answer questions about how fish partition habitats (e.g., Table 4) and what types of habitats might be considered for conservation and restoration for target fish species.

In enclosure nets, fish were held for a mean of 2.75 h. Therefore, the diet samples probably represent food items obtained at the habitat types sampled, especially since much of the prey was largely undigested (e.g., 75–100% intact in juvenile Chinook salmon). In samples taken with "instantaneous" techniques, such as beach seining, specific feeding location is unknown. Marine benthic–epibenthic and terrestrial riparian taxa were the two largest contributors to juvenile Chinook salmon diets. These results, including many of the major prey taxa found, are similar to those found by Brennan et al. (2004) in a comprehensive collection of Chinook salmon diets from central Puget Sound beaches. In our study, terrestrial riparian insect prey was most abundant at sites without intertidal or supratidal shoreline retaining structures. Marine benthic–epibenthic prey organisms were most common along shorelines that were modified by retaining structures. In snorkel surveys, we observed increased instances of surface feeding by juvenile salmonids at sites with modifications and deeper water (most at overwater structures, followed by deep riprap and riprap); this result may be an artifact of the greater numbers of fishes and the greater depth of the water column at these sites, which made fish movement to the surface more noticeable.

Because much of the Puget Sound shoreline has been altered by armoring and backshore development, there has probably been a decreased input of terrestrial-derived salmon prey to Puget Sound. Two recent studies have shown a significant reduction in supra-littoral insect communities in areas where shoreline vegetation has been removed in association with armoring (Romanuk and Levings 2003; Sobocinski 2003). These findings, combined with our data that show fewer terrestrial riparian prey in diets of Chinook salmon at retained habitats, suggest that input of terrestrial prey is reduced by shoreline armoring and overwater structures. Such a limiting factor on a key prey component of juvenile Chinook salmon may lessen their rearing capabilities in nearshore areas in this system and may have cascading effects on fish growth and survival.

Most comparable shoreline studies in the literature originate from fluvial or lotic systems rather than estuarine or marine systems. Several recent studies have examined similar issues involving juvenile salmonids in nearby freshwaters. Based on snorkel surveys and above-water observations, Tabor and Piaskowski

(2002) found that juvenile Chinook salmon in Lake Washington avoided armored banks. In a study of fishes in the lower Willamette River using beach seines and electrofishing, Friesen et al. (2003) found that juvenile salmonids preferred alcoves and natural habitat types (although their methods did not sample the entire water column, so modified banks with deep water at the shoreline were underrepresented). Several other studies in the western United States have found higher juvenile salmonid abundances at natural shorelines than at riprap banks (Knudsen and Dilley 1986; Schmetterling et al. 2001; Garland et al. 2002). In these studies, which were conducted in streams and lakes, the salmon were smaller and more dependent on shallow water, which may have contributed to their avoidance of altered shorelines. The juvenile salmon in our study were larger and more pelagic (MacDonald et al. 1986), which may have resulted in less dependence on shallow-water habitats than during freshwater residence.

Our results were similar to those found elsewhere for some nonsalmonid fishes. For example, our finding of more surfperch around structures was similar to that of Friesen et al. (2003) for sunfishes (families Centrar-chidae and Elassomatidae), which preferred artificial habitats such as riprap and pilings. Other studies have similarly shown that some fish are more abundant at artificial shorelines that have high structural complexity (Beauchamp et al. 1994; Jennings et al. 1999). Such effects are not universal; Peterson et al. (2000) found that alteration of marshes with bulkhead and rubble reduces the abundance and diversity of most nekton along the Gulf Coast of Mississippi. In a study of overwater structures, Able and Manderson (1998) used small traps in the Hudson River estuary and found fish abundance and species richness to be low under large commercial piers; decreased growth rates and foraging of juvenile fishes were also found in such areas (Duffy-Anderson and Able 1999). Although the effect of pier size is not well understood, there appears to be some consistency in fish responses to the low light levels and barriers to movement patterns caused by overwater structures.

Scales of analysis are always a factor in any research design. Haggarty (2001) used snorkeling, above-water observations, and seines in the Burrard Inlet estuary (Vancouver, British Columbia) and found that juvenile Chinook salmon preferred larger substrates. However, this was dependent on the landscape scale (site versus basin). Davis et al. (2002) used snorkel surveys in San Diego Bay (California) and found that the hard substrates of riprap can extend the range of open-coast species into what used to be soft-sediment bays. Such landscape effects are especially important when examining the overall effects of habitat modifications.

Jennings et al. (1999) used electrofishing and seining and found that riprap in Wisconsin lakes increased species richness at the site level owing to complex structural habitat with interstitial spaces. However, when there is too much riprap at the expense of other habitats, this causes an overall reduction in species diversity at the landscape scale, leading to detrimental cumulative effects. This could be important for our study area, as between 84% and 97% of the shoreline is modified by retaining structures within the Seattle city limits (Weitkamp et al. 2000) and one-third of the shoreline is modified for all of Puget Sound (Bailey et al. 1998). Fish probably do not respond only to the structures along the shoreline. Jennings et al. (1999) concluded that fish respond to a suite of habitat characteristics that are the result of the structures. The results of our study also suggest that fish responses are caused by a number of factors, such as water depth, substrate type, bottom slope, and vegetation.

Understanding how mobile fish, such as juvenile salmon, use complex habitats and nearshore landscapes is notoriously difficult. However, given the economic and cultural importance and generally declining stocks of salmon, it is important to continue to develop methods that provide more information on juvenile salmon use of these habitats and landscapes. We found that when conducted in tandem, enclosure nets and snorkel surveys provided additional information that is not available from standard net sampling techniques. These methods allowed us to illustrate differences in nearshore fish use of five different habitat types as well as the increased effects that shoreline modifications can have as they extend from the supratidal zone to the subtidal zone. Adoption of similar methods for routine monitoring of fish assemblages at human-impacted shorelines will yield information useful in developing salmon recovery plans and habitat conservation and restoration techniques. To summarize our data, substrate type and slope were an important influence on bottom-dwelling fish densities when shoreline modifications only extended into the upper intertidal zone, whereas effects on pelagic fish densities and behavior were more evident when shoreline modifications extended into shallow subtidal waters. It is apparent that many factors can affect salmon and other fishes that use urbanized shorelines, and these factors should be addressed in future research efforts. They include (1) proximity to freshwater and out-migration corridors and varying tidal heights, (2) effects of structures on life history stages and predation risk, (3) effect of landscape versus site scale of analysis, and (4) effects of shoreline modifications at varying water depths and distances from shore contours.

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