Spatial Trends in the Concentration of Polychlorinated Biphenyls (PCBs) in Chinook (*Oncorhynchus tshawytscha*) and Coho Salmon (*O. kisutch*) in Puget Sound and Factors Affecting PCB Accumulation: Results from the Puget Sound Ambient Monitoring Program

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Introduction

Polychlorinated biphenyls (PCBs) are among the most ubiquitous and persistent contaminants in aquatic ecosystems worldwide. Even though only an estimated 1% of the total PCBs produced have reached the oceans so far (Stone 1992), PCBs are everywhere in aquatic systems (Phillips 1964) including remote polar aquatic ecosystems where PCBs are transported via atmospheric processes (Hammar 1989). PCBs were manufactured prior to 1975 and used extensively as industrial coolants and in electrical transformers, where they were frequently mixed with oils and greases. Since 1976, PCB manufacture has been banned in the U.S., but they persist in the aquatic environment and their high toxicity continues to cause concern for aquatic life, especially fish.

The Washington Department of Fish and Wildlife (WDFW) monitors concentrations of 101 contaminants in marine fishes in Puget Sound, including chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*), as part of the Puget Sound Ambient Monitoring Program (PSAMP). This effort is implemented by a multi-agency consortium of scientists and natural resource managers who assess and monitor the environmental health of the Puget Sound ecosystem (Puget Sound Water Quality Authority 1995; Puget Sound Water Quality Action Team 1998). This monitoring has documented that PCBs are one on the few contaminants that accumulate in chinook and coho salmon from Puget Sound. WDFW continues to monitor PCB concentrations in adult chinook and coho salmon because of their importance in the Puget Sound ecosystem and in recreational and commercial fisheries. Prior to these PSAMP studies, PCB exposure and accumulation in chinook and coho salmon from Puget Sound were not well studied. The aim of PSAMP is to assess spatial and temporal trends in PCB exposure in these species by annually monitoring PCB concentrations in the edible muscle tissue of adult fish at various locations throughout Puget Sound.

Exposure to PCB-contaminated sediments and food are primary pathways for accumulation of PCBs in fish (Varanasi et al. 1992). However, various biotic and abiotic factors affect the degree of exposure and accumulation. Exposure to PCBs may be affected by the proximity of fish to contaminated sediments and prey, the magnitude of contamination in their habitats, fish movement patterns, trophic status, growth rates, duration of exposure (i.e., lifespan or fish age), and bioavailability of PCBs (Jensen et al. 1982; Hammar et al. 1993; Stow et al. 1994; Bentzen et al. 1996). Furthermore, although fish may be exposed to PCBs, species-specific metabolism and detoxification of PCBs, reproductive and maturational patterns (e.g., sex and age of first reproduction), and the level of body fat (i.e., percent lipids) can affect the degree to which these PCBs accumulate in tissues, and have adverse effects (Masnado 1987; Larsson et al. 1991; Varanasi et al. 1992; Loizeau and Abarnou 1994; Bentzen et al. 1996; Larsson et al. 1996).

In the Pacific Northwest PCBs have been detected in Pacific salmon from various locations in Alaska (NMFS unpublished data, John Stein, personal communication) and the Columbia River (Tetra Tech. Inc. 1996), suggesting a widespread source of PCBs in this areas. Pacific salmon are anadromous and throughout their lives may be exposed to PCBs in fresh water, estuarine, or marine areas. Although specific migratory patterns of these species vary, chinook and coho salmon are spawned in freshwater, live there for 3 to 15 months after emergence as embryos from gravel nests, and subsequently migrate to marine waters. PCB

concentrations in prey consumed by salmon may vary in these habitats. In fresh water, young chinook and coho salmon consume aquatic insects and crustaceans but as these fish smolt and enter the estuary they consume a wider variety of invertebrates and larval fish (Higgs et al. 1995). Adult salmon in marine waters continue to eat invertebrates but they consume more epipelagic fish (Higgs et al. 1995), increasing the likelihood of PCB biomagnification in their tissues. The amount of time each species or population spends at sea varies widely, but for both species the majority of their growth occurs in marine waters (Groot and Margolis 1991) before they return to their natal streams to spawn.

PCBs are lipophilic, typically concentrating in the fatty tissues in fishes (Varanasi et al. 1992), and thus PCBs may readily accumulate in muscle tissue of adult chinook and coho salmon because of their relatively high lipid content. However, the lipid content in the muscle tissue in adult salmon in marine waters decreases rapidly as they approach fresh water and reach reproductive maturity, particularly in females (Hendry 1998). Thus, the lipid content of the muscle tissue, the sex of the fish, and the degree of maturation may all affect PCB accumulation in chinook and coho salmon.

One of the main objectives of PSAMP is to assess species-specific and location-specific differences in PCB accumulation in adult chinook and coho salmon. However, meaningful comparisons of PCB concentration in tissues of chinook and coho salmon from different Puget Sound locations can only be made after an accounting of the factors described above that could affect PCB accumulation at these locations. The purpose of this paper was to model the accumulation of PCBs in chinook and coho salmon from Puget Sound. In addition to unspecified location effects that may be associated with proximity to and magnitude of PCB contamination, we estimated the contribution of percent body weight as lipids, the gender and age of the fish, and the hatchery or wild origins of the fish. First, we compared differences in PCB concentrations between adult chinook and coho salmon sampled from marine areas of Puget Sound and from five Puget Sound rivers. Then, for coho salmon we evaluated the effects of tissue lipid content and sampling location on PCB accumulation. At a subset of the sampling locations we evaluated the effects of gender and the hatchery or wild origins on the PCB accumulation in coho salmon. An insufficient number of samples was collected to fully assess which aspects of the chinook salmon's complicated life history affect PCB accumulation in that species, and therefore only preliminary analysis on the effects of fish age and percent lipids are presented for that species in this paper.

Materials and Methods

Sample Locations and Preparation

Adult chinook and coho salmon were sampled from five "in-river" locations (including near-shore estuarine and river locations) where the captured fish were presumed to be returning to their natal streams and various offshore "marine" locations in central and southern Puget Sound where the fish's natal stream was unknown (Figure 1). Fish were purchased from licensed fish buyers and treaty tribal fishermen in the late summer and early fall of 1992–1995. Nooksack, Skagit and the Duwamish/Green rivers were sampled in all years but the Nisqually and Deschutes rivers were only sampled in 1993, 1994, and 1995. Whole salmon were transported on ice to the laboratory where we tagged, measured (fork length, nearest cm), weighed and then removed some of their scales for age-estimation (detailed below). The fish were then wrapped individually in aluminum foil, placed in plastic bags and stored on ice for up to 10 days until tissues were removed for contaminant analyses.

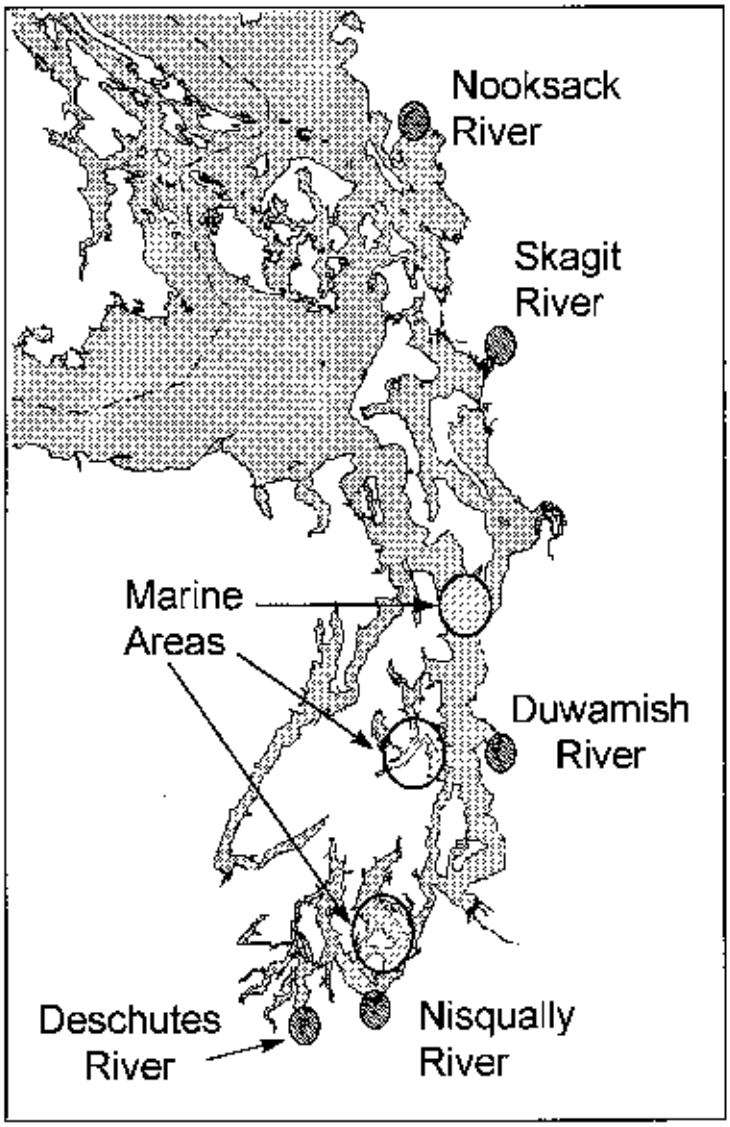

Figure 1. Five in-river and three marine locations sampled by PSAMP for coho and chinook salmon, 1992–1995.

Composite muscle tissue samples of chinook and coho salmon were prepared by collecting equal amounts of skinned muscle tissue from individual fish and combining the tissue in pre-cleaned jars to make one composite sample as detailed in the Puget Sound Estuary Program protocols (Puget Sound Estuary Program 1986). Utensils and work surfaces were cleaned and then rinsed with isopropyl alcohol between each sample. Muscle tissue composites were frozen at -20_ C. prior to analysis. The number of fish comprising a composite varied from one to five individuals among years. In 1992 and 1993, fish from an individual location were composited randomly, without regard to sex, fish age or hatchery or wild origin, but in 1994 and 1995, fish of like sex and origin were combined in composites. A minimum of six composite samples was prepared for each species per sampling location per year.

The pattern and spacing of circuli on the scales were used to estimate the total age of the fish and the year in which the fish migrated to sea. For example, a coho salmon that went to sea in its second year and returned to spawn in its third year had a freshwater age of two, and a total age of three (designated 3_2). A four-year-old chinook that went to sea in its first year of life and had a freshwater age of one

would be designated 4_1. Also, for those fish that went to sea in their second year, the pattern of growth rings was used to classify the fish as hatchery or wild in origin.

Chemical Analyses

Chemical analyses for PCBs were completed according to PSEP protocols (Puget Sound Estuary Program 1996b). Briefly, all tissue samples delivered to the chemical laboratory were homogenized in a blender and PCBs were extracted from fish samples by sonication with a methylene chloride and acetone mix. All extracts were "cleaned" by gel permeation chromatography. PCBs were analyzed using gas chromatography-electron capture detection (GC/ECD), with a dual narrow-bore column (0.25 mm) suited to analyzing low concentrations (1992,1993, and 1994), or with an ion trap detector (1995) . Aroclor mixtures were used as standards for quantifying PCB concentrations. Matrix-based detection limits were determined for the muscle tissue by adding standards to representative instrument-ready sample matrices. All chemistry data were reported as the concentration per wet weight of tissue in g/kg (ppb).

Lipids were determined by a modified crude fat determination using acid hydrolysis. The tissue sample was mixed with sodium sulfate, extracted with a sonic probe using a mixture of methylene chloride and acetone, filtered through a bed of sodium sulfate powder, and the solvent was allowed to evaporate. Percent lipids were then determined gravimetrically and reported as percent of total weight.

Quality Assurance and Quality Control (QA/QC)

An independent QA/QC chemist reviewed tissue chemistry data and detailed findings were presented to WDFW. In general, the QA/QC chemist reported that the chemical laboratory followed the PSEP protocols for chemical analyses of organic contaminants in fish tissue (Puget Sound Estuary Program 1996b) and produced good quality data on PCB concentrations in chinook and coho salmon.

Data Analyses

The percent lipids and the mean fish age were computed for the fish comprising each composite sample. All statistical analyses on lipid-specific PCB concentrations were conducted using Mean Composite Age (MCA), and Composite Percent Lipids (CPL).

A two-way Analysis of Variance was used to assess whether observed PCB concentrations varied significantly between chinook and coho and between marine- and river-caught fish within a species. For coho salmon, linear regression analysis was used to model accumulation of PCBs in coho in marine waters and in fish returning to Puget Sound rivers, with stepwise (forward) variable selection (Kleinbaum and Kupper 1978). Variables modeled included CPL and dummy variables that were used to estimate location-specific variability in tissue contaminants. A t-test of log-normalized PCB data was used to test the significance of differences in PCB means between marine-caught coho salmon from central Puget Sound and south Puget Sound.

Because of limited sampling size, variation associated with the hatchery or wild origin status and the sex of the fish (gender) could not be assessed for coho at all locations. For those stations with sufficient sample sizes and ranges of lipid values, wild and hatchery fish were analyzed separately using linear regression to estimate the contribution of lipid content and sampling location on PCB accumulation. Dummy variables were used to estimate the location effect in lipid-specific PCB concentrations.

The potential effects of fish gender on lipid-specific PCB-accumulation, separate from effects associated with location or the hatchery or wild origins, were assessed by analyzing wild coho salmon samples from the Deschutes River with linear regression. Variables in the model included percent lipids and a dummy variable for sex.

Linear regression analysis with log-normalized lipid data was used to model the relationship between PCBs and CPL for chinook salmon. Data from all locations were combined for that species.

Results

From 1992 to 1995, we collected 178 chinook and 157 coho composite-samples from adult fish from five in-river locations and from several marine locations in Puget Sound. PCBs were detected in both salmon species from both location types. Chinook salmon from marine locations had the greatest mean concentration of PCBs (74.2 µg/kg), followed by chinook salmon from in-river locations (49.1µg/kg), coho salmon from marine locations (35.1 µg/kg), and coho salmon from in-river locations (26.5 µg/kg; Figure 2, Table 1).

Table 1. Average total PCB concentrations (µg/kg) in coho and chinook salmon sampled from in-river and marine location types. Sample sizes in parentheses.

	Location Type		
Species	Marine	In-River	Grand Mean
Chinook	74.2 (34)	49.1 (144)	53.9 (178)
Coho	35.1 (32)	26.5 (125)	28.3 (157)
Grand Mean	55.3 (66)	38.6 (269)	41.85 (335)

Each of these differences was statistically significant; that is, the mean concentration of PCBs for each species-location combination was significantly different from the others (two-way analysis of variance using log-transformed PCB data, $p=0.05$ for species-location interaction). In addition, the average concentration of PCBs in chinook salmon (controlling for the effects of location type) type was significantly greater than coho salmon (53.9 µg/kg versus 28.2 µg/kg; $p<0.001$; Figure 2 and Table 1), and the average concentration of PCBs in salmon from marine locations (controlling for the effects of species) was significantly greater than in-river locations (55.3 µg/kg versus 38.6 µg/kg; $p<0.001$; Figure 2 and Table 1).

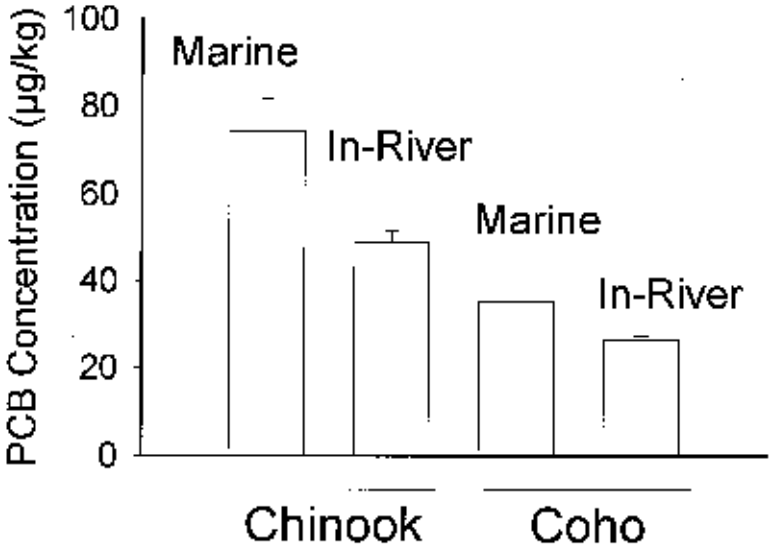

Figure 2. Average total PCB concentration (with standard errors) for chinook and coho salmon in marine and in-river locations of Puget Sound, 1992–1995.

Coho Salmon

We evaluated or attempted to control for the effects of four important potential factors on PCB accumulation in coho salmon; composite percent lipids (CPL), location, hatchery/wild origin, and gender. Variability in fish age was not an important factor for coho salmon. All individual coho salmon we sampled were three-year-olds that went to sea in their second year, which was typical of most coho salmon returning to spawn in Puget Sound streams.

We observed a significant, positive correlation of total PCBs with CPL for four in-river locations (Figure 3a). Using forward stepwise linear regression analysis and dummy variables to isolate location effects, CPL and sampling location accounted for 61% of the total variation in these PCB concentration data (CPL transformed using natural log, $p<0.001$). Slopes of fitted regression lines were equal among locations, however, intercepts for Deschutes and Nisqually Rivers were significantly greater than for Skagit and Nooksack Rivers. This means that the pattern of PCB increase with CPL was the same for all locations. However, for a given CPL, PCB concentrations were highest in coho salmon from the Nisqually River, followed by coho from the Deschutes River (southern Puget Sound locations), and the Skagit and Nooksack rivers (northern Puget Sound locations; Skagit and Nooksack regression lines were coincident).

PCBs in coho salmon from the Duwamish Waterway did not exhibit a significant correlation with CPL as did the other four in-river locations (scatterplot omitted from Figure 3a). Mean PCB concentration of samples from the Duwamish Waterway (in central Puget Sound) independent of lipids was 27.3 µg/kg, which was intermediate between the southern locations (Deschutes and Nisqually rivers; 30.8 and 29.6 µg/kg) and the northern locations (Skagit and Nooksack rivers; 25.1 and 20.1 µg/kg).

Like the in-river locations, PCB concentrations in coho salmon sampled from marine locations from central Puget Sound were positively correlated with CPL (Figure 3b, $r^2=0.32$, $p=0.007$). However, those from marine locations in southern Puget Sound were not (Figure 3b, $p>0.05$). Because CPL apparently did not contribute to variability in the southern Puget Sound samples, we ignored that factor in comparing PCB concentrations between the two marine locations. Average PCB concentrations in southern Puget Sound samples (60.6 µg/kg) were significantly greater than central Puget Sound marine-caught samples (35.1 µg/kg; t-test of log-normalized PCB data, $p<0.001$). Eight of twelve southern Puget Sound samples exceeded the greatest PCB concentration from central Puget Sound (Figure 3b).

In addition to location-specific effects, the origin (whether wild or hatchery) may have contributed to variability in PCB concentration. The samples used to describe fish location-specific variation in PCB concentration for coho salmon (Figure 3) were composed of 55 wild, 50 hatchery and 52 mixed-origin samples. To evaluate potential influence of origin on PCB concentration, we re-plotted the relationship between PCBs and CPL presented in Figure 3a for wild and hatchery-origin coho salmon separately (Figure 4). Sample sizes and ranges of CPL were sufficient to model location-specific PCB:CPL relationships for wild-only coho salmon from three in-river locations (Deschutes, Nisqually, and Skagit rivers, Figure 4a), and hatchery-only coho salmon from two locations (Nisqually and Nooksack rivers, Figure 4b).

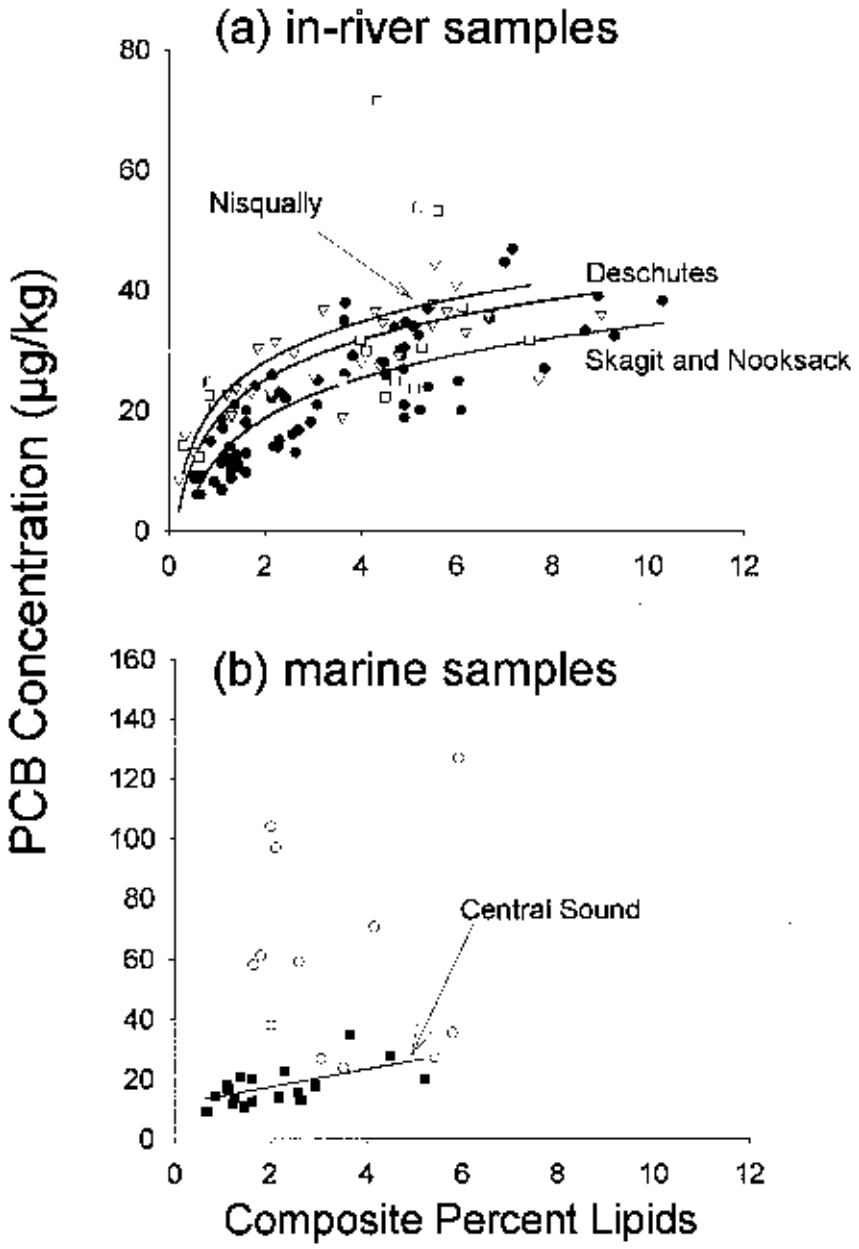

Figure 3. Relationship between total PCBs and tissue lipid content for coho salmon sampled from (a) in-river locations: Nisqually River (open squares), Deschutes River (open triangles), and combined Skagit and Nooksack Rivers (filled circles) and (b) marine locations: central Puget Sound (filled squares) and southern Puget Sound (open circles). Lipid data were log-transformed to linearize data for in-river samples. Forward stepwise linear regression analysis using dummy variables to isolate location effects was used to compute correlations and generate regression lines shown.

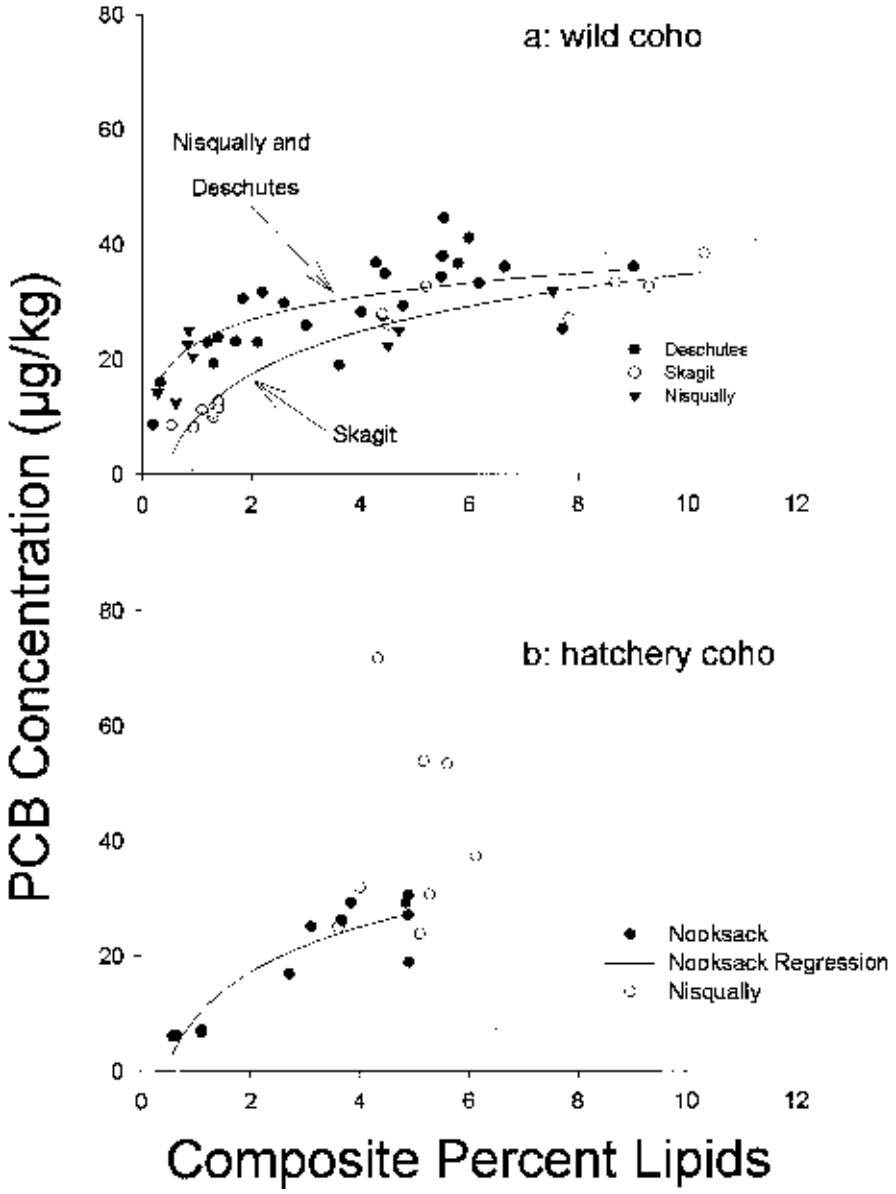

Figure 4. Relationship between total PCBs and tissue lipid content for (a) wild and (b) hatchery coho salmon from in-river locations. Forward stepwise linear regression analysis with log-linearized lipid data and dummy variables was used to estimate correlation coefficients and generate regression lines. Lines for wild Nisqually and Deschutes coho salmon were coincident (not significantly different from each other). The PCB:lipid correlation for Nisqually hatchery coho was not significant ($p>0.05$).

Wild-only coho salmon exhibited a strong correlation between PCBs and CPL, and the north-to-south gradient of increasing CPL-specific PCB concentrations was consistent with that previously observed for the combined wild and hatchery coho (Figure 4a, $r^2=0.64$, $p<0.001$). However, for hatchery-only coho salmon, we observed a strong correlation ($r^2=0.83$, $p<0.0001$) between PCBs and CPL for Nooksack River fish but not for coho from the Nisqually River ($p>0.05$, Figure 4b). Unexplained variability in lipid-specific PCB concentration for these hatchery coho salmon from the Nisqually River was similar to that observed for the coho from the Duwamish River (not shown). At the Duwamish location, samples consisted mostly of hatchery or mixed hatchery/wild origin fish (Table 2).

Thus, some hatchery fish, especially those from central and southern Puget Sound, appear to accumulate PCBs differently than wild coho salmon.

Table 2. Number of composite tissue samples collected from adult coho salmon from in-river and marine locations in Puget Sound, 1992–1995.

Location Type	Station	Wild-Origin			Hatchery-Origin			Mixed-Origin		
		Male	Female	Mixed Sex	Male	Female	Mixed Sex	Male	Female	Mixed Sex
	Nooksack River	1	1	1	5	2	5	3	0	7
	Skagit River	5	2	7	3	1	1	2	0	6
In-river	Duwamish River	0	1	1	8	2	4	1	1	7
	Nisqually River	1	1	6	3	2	3	0	0	2
	Deschutes River	11	10	7	n/a	n/a	n/a	n/a	n/a	2
Marine	Central Sound	0	0	0	0	0	5	1	0	14
	Southern Sound	0	0	0	4	2	0	4	0	2

To further investigate potential effects of hatchery/wild origin without interference from unexplained location effects, we compared PCB accumulation between hatchery- and wild-origin coho salmon at a single location, the Nisqually River (Figure 5). This was the only location that had sufficient sample sizes and ranges of CPL to compare PCBs from hatchery and wild coho salmon. Again, we observed a relatively strong correlation of PCBs with CPL for wild fish (r^2=0.54, p=0.023), but not for fish of hatchery origin. In addition, PCBs in three of the seven Nisqually hatchery-origin samples were substantially higher (roughly two times greater) than any wild Nisqually sample. Essentially, this means that average PCB concentrations were higher in hatchery fish and hatchery-origin fish were responsible for much of the relatively high CPL-specific PCB concentrations observed for combined hatchery and wild coho salmon from the Nisqually River in Figure 3a.

To examine the effects of gender independent of location and hatchery or wild origin, we plotted PCB concentration versus CPL for wild fish from a single location, the Deschutes River. This location was the only one where we had collected sufficient numbers of composites of both sexes (11 males and 10 females; Table 2) across a relatively wide range of lipid values. Scatter plots (not shown for brevity) revealed no apparent disparity in the relationship of total PCBs and lipids between males and females. Thus, there was no evidence that gender of coho salmon affected the observed location-specific variation in PCB concentration.

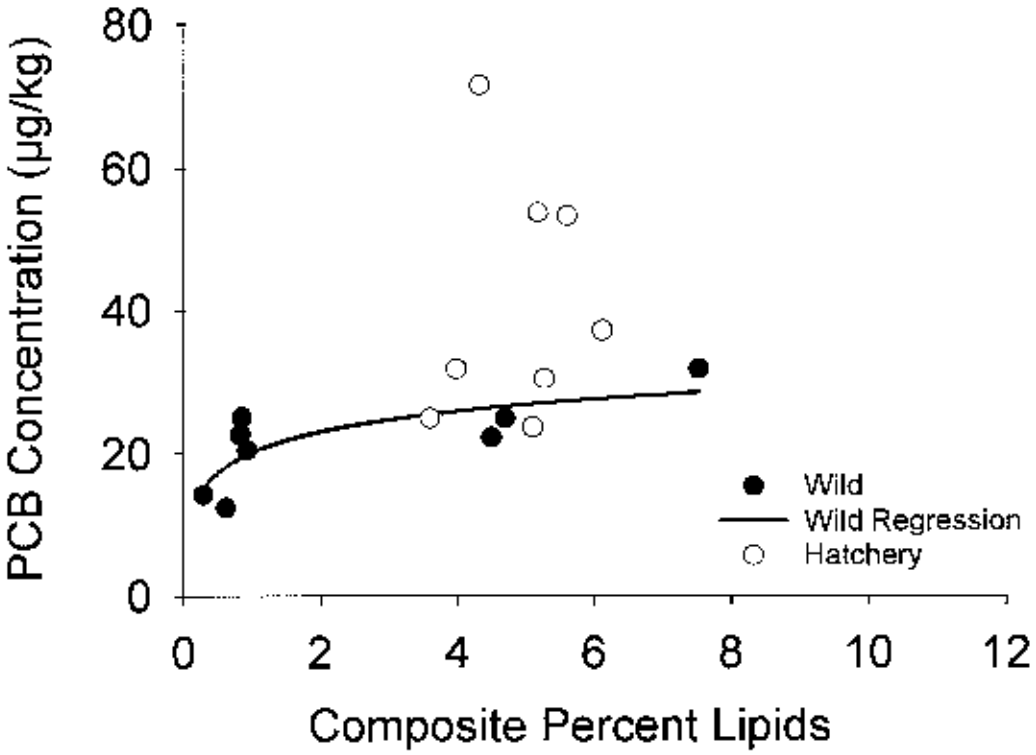

Figure 5. Relationship between total PCBs and tissue lipid content for wild coho salmon from the Nisqually River. Scatter plot of hatchery coho overlain for comparison. Linear regression analysis on log-linearized lipid data was used to fit line to wild coho data. The correlation for hatchery data was not significant ($p>0.05$).

Chinook Salmon

Evaluating the factors that affect PCB accumulation in chinook was more difficult because of their relatively complex life history. Most of the chinook salmon were three or four years old, but they ranged from two to five years old overall. The amount of time these fish spent in rivers, estuaries, and marine environments varied considerably. Most of the chinook salmon were ocean-type fish that went to sea in their first year of life, but some of the three- to five-year-olds were stream-types that went to sea in their second year. Chinook salmon were combined in composite-samples to create 44 stream-type, 93 ocean-type and 41 mixed-type life-history samples (Table 3). All but one of the stream-type fish were of hatchery origin; the origins of the ocean-type chinook were unknown because characteristics specific to their scale patterns preclude this type of determination.

Table 3. Number of composite tissue samples collected from adult chinook salmon from in-river and marine locations in Puget Sound Rivers, 1992–1995.

Location Type	Station	Stream Type: Wild Origin	Stream Type: Hatchery Origin	Ocean Type (unknown origins)	Mixed Fish Type (unknown origins)
	Nooksack River	0	1	24	3
	Skagit River	1	9	10	9
In-river	Duwamish River	0	11	16	6
	Nisqually River	0	3	16	1
	Deschutes River	0	14	10	10
Marine	Central Sound	0	2	8	8
	Southern Sound	0	3	9	4

Insufficient numbers of sample composites with unique combinations of origin, age, and life-history type prevented us from fully evaluating the effect that these factors might have on accumulation of PCBs in chinook salmon. Future sampling efforts will be designed to isolate factors by sampling individual fish or creating homogenous composites. Preliminary results for the present samples suggest that, for ocean-type chinook salmon, PCB concentration varied with fish age (data not shown) and only for four-year-old fish did PCB concentration increase with lipid content in the muscle tissue (Figure 6). PCB concentrations in stream-type fish (all ages and locations combined) were also not correlated with lipid content (data not shown).

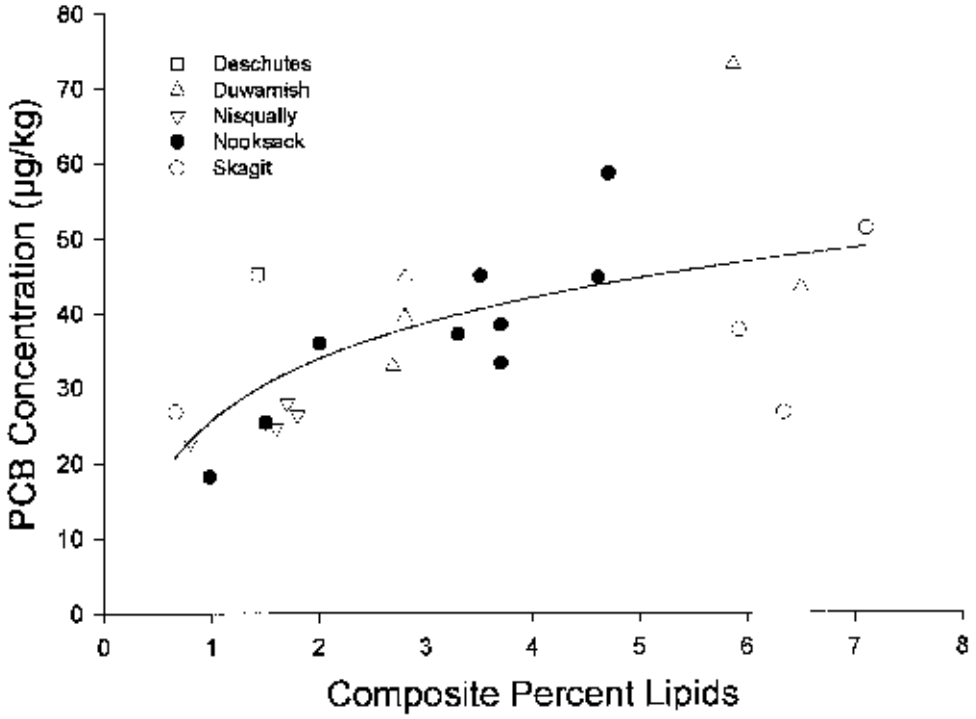

Figure 6. Relationship between total PCBs and tissue lipid content for four-year-old ocean-type chinook salmon from five in-river locations. Linear regression analysis with log-linearized lipid data was used to compute correlation coefficient for all locations combined.

Discussion

We investigated a number of factors as possible correlates with concentration of PCBs in muscle tissue of chinook and coho salmon from various marine and in-river locations in Puget Sound. We observed that chinook salmon had significantly higher PCB concentrations than coho salmon and within each species, PCB concentrations were higher in fish caught in marine areas than in-river areas (Figure 2, Table 1). For coho salmon, lipid content and sampling locations accounted for most of the observed variation in PCB concentrations (Figure 3). The location differences in PCB concentrations in these fish appears to be associated with a north-south location effect and the hatchery or wild origin of the fish (Figures 4 and 5). Male and female coho salmon accumulated PCBs similarly. Also fish age and year of migration to sea was not a factor affecting PCB accumulation in coho salmon because all of the fish were three-year-olds that went to sea in their second year of life. For chinook salmon, however, our preliminary review of the data suggests that the age of the fish may affect PCB accumulation. Average PCB concentrations in chinook salmon varied among fish ages with the highest concentrations occurring in three-year-old ocean-type fish and four-year-old stream-type fish. But, PCB concentration in muscle tissue increased with lipid content only for four-year-old fish that went to sea in their first year (ocean-type, see Figure 6).

Meaningful comparisons of PCB concentrations in tissues of chinook and coho salmon from different Puget Sound locations, and throughout time, can only be made with some understanding of their life history traits and how variation in these traits may affect exposure to and accumulation of PCBs in these species.

Because of their anadromous life-history, Puget Sound chinook and coho salmon occupy three distinct habitat types during their lifetimes, each of which may present different PCB exposure potential: (1) freshwater habitats, where eggs hatch and fry develop; and (2) Puget Sound, where smolts enter marine waters to feed and reside for some time during migration to (3) ocean habitats. Thus, inter- and intra-specific variation in movement patterns, and age at reproduction will affect the amount of time populations of chinook and coho salmon spend in different habitats and, subsequently, their potential PCB exposure.

The higher average PCB concentrations we observed in chinook than coho salmon may be the result of differences in: (1) the total time each species spends in fresh water, Puget Sound, and oceanic waters; (2) fish age; (3) diet; and (4) tissue lipid content. Chinook and coho salmon differ in their migration patterns and habitat use. Typically, Puget Sound coho migrate from fresh water to the sea in their second year, followed by a relatively brief estuarine (river-mouth) residence and about one to two years in Puget Sound, the southwest coast of Vancouver Island or the northern Pacific coast of Washington. They return as three-year-olds to spawn in their natal streams. Unlike coho salmon, juvenile chinook salmon may go to sea in their first or second year (ocean- or stream-type juveniles) and may return to spawn as two-, three-, four-, and five-year-olds. Stream-type juvenile chinook salmon reside in fresh water for a full year prior to their seaward migration in their second year, make limited use of estuaries, and tend to migrate to the North Pacific Ocean. Ocean-type juvenile chinook (the predominant form in Puget Sound rivers) migrate to sea in their first year of life (at a smaller size than the stream-type smolts), spend more time in estuaries, and have a more coastal distribution during their period at sea (Healy 1991). Because of these differences in their ages and migration patterns, chinook salmon in Puget Sound generally spend more time in marine waters than do coho salmon.

We suggest that chinook and coho salmon accumulate most of their PCB body-burden in the marine waters of Puget Sound and the ocean, and because chinook salmon live longer and stay at sea longer than coho salmon they accumulate higher PCB concentrations in their muscle tissues. Combining our data with those of Varanasi et al. (1993), we estimated that the likely contribution of PCBs to adult salmon body burdens attributable to movement though freshwater and estuarine habitats as young was negligible. Varanasi et al. (1993) demonstrated that chinook salmon smolts migrating out to Puget Sound through one of its most polluted estuaries (the Duwamish Waterway) were exposed to PCBs at a maximum concentration of approximately 260 µg/kg in 1989. Based on mean size of those smolts, we

estimated their body burdens at 1.4 g PCB per smolt. The chinook salmon adults we sampled in 1992 and 1993 were probably either of the same cohort, or within one year of the same cohort, of those sampled by Varanasi et al. (1993) in 1989. Assuming that 55% of the adult body mass was muscle tissue (we used estimates for sockeye salmon, *Oncorhynchus nerka* from Gilhousen (1980) and using our average PCB concentration and weight of chinook salmon returning to the Duwamish River, we estimated a total body burden of 130 g PCB per adult. Hence, the smolt body burden we estimated from Varanasi et. al. (1993), (1.4 µg/smolt) accounted for only 1.1% of the total PCB body burden estimated for adult chinook salmon. In other words, according to these computations and assumptions, about 99% of PCBs in adult chinook salmon returning to spawn in the Duwamish/Green River watershed were accumulated by the fish in the marine waters of Puget Sound or the Pacific Ocean.

Diet differences between chinook and coho salmon in marine waters may further account for some of the observed differences in PCB concentrations between these fish. Both species consume a wide variety of invertebrate (e.g., euphausiids, hyperiid amphipods, crab larvae) and fish (e.g., Pacific herring and Pacific sand lance) prey. However, adult chinook salmon tend to consume a greater percentage of fish than coho salmon (Fresh et al. 1981; Peterson et al. 1982; Beacham 1986; Higgs et al. 1995), resulting in a longer food chain for chinook salmon. The more piscivorous nature of adult chinook salmon may increase their exposure to PCBs because of biomagnification of the contaminants in the food web. Bentzen et al. (1996) observed that PCB and DDT concentrations in lake trout were proportional to tissue lipid concentrations (as we have seen) but the magnitude of the concentrations varied, due to either food chain length or differences in contaminant loading. Other researchers have demonstrated the importance of trophic status in accumulation of persistent pollutants like PCBs in freshwater salmonids and marine fishes (Young et al. 1980; Borgmann and Whittle 1992; Hammar et al. 1993; Madenjian et al. 1993; Madenjian et al. 1994; Davenport 1995; Kidwell et al. 1995; Stow 1995; Kidd et al. 1998).

Although, tissue lipid levels were correlated with PCB concentration for both chinook and coho salmon, the range of lipid levels observed between species were similar (grand means of 3.4% and 3.1%), suggesting that this factor did not contribute substantially to the species-specific PCB differences we observed.

Variability in any number of the above factors may account for the range of PCB concentrations we observed between these species, and between the in-river and marine fish. It is impractical to account for all such factors given sampling schemes typical of monitoring programs. However, we have observed that for coho salmon, location of capture, tissue lipid concentration, and possibly hatchery/wild origin are important factors in interpreting PCB concentration data.

PCBs were proportional to lipid levels in coho salmon from four of five in-river Puget Sound locations; however, the magnitude of lipid-specific PCB concentration depended on location. Coho salmon (hatchery and wild fish combined) from the Nisqually and Deschutes rivers had higher lipid-specific PCB concentrations than coho from the Nooksack and Skagit rivers (Figure 3a). Many physical or environmental differences distinguish these four watersheds, however. One of the most obvious is their north-to-south distribution. Coho salmon from the southern Puget Sound rivers (Deschutes and Nisqually) had greater lipid-specific PCB concentrations than from the northern rivers (Skagit and Nooksack). In addition, marine-caught coho salmon from southern Puget Sound had higher PCB concentrations than those from central (that is, more northern) Puget Sound areas (Figure 3b).

These patterns may be related to intraspecific variability in migration patterns or the total time coho salmon spend in Puget Sound versus oceanic waters. Puget Sound habitats likely present a greater potential exposure of PCBs to salmon than oceanic habitats, based on the presence of urban and industrialized areas and known contamination hot spots in Puget Sound. If so, then salmon that spend more time in Puget Sound than oceanic waters may experience greater exposure to PCBs. Salmon originating from southern Puget Sound watersheds must travel a greater distance in Puget Sound before they reach oceanic waters during their out-migration and during their return spawning migration to natal watersheds. In addition, it is likely that prey consumed in central and southern Puget Sound would have higher PCB concentrations due to the larger number of locations in central and southern Puget Sound

with PCB-contaminated sediments (Puget Sound Water Quality Action Team 1998). Salmon originating from northern watersheds have a shorter migration to oceanic waters, and they do not have to pass through polluted areas as do the salmon from more southern watersheds.

The total time a salmon spends in Puget Sound, or, its "residency," is unknown and probably highly variable (see Buckley 1969; Buckley and Haw 1978). Some outmigrating wild salmon may naturally remain resident in Puget Sound year-round (termed "resident salmon" by anglers). The population of wild resident salmon is thought to be naturally low. Fishery managers have, since the 1970s, attempted to increase populations of resident Pacific salmon by delaying the release of juveniles for a period ranging from several weeks to over a year. This practice, it is thought, tends to inhibit the out-migration of salmon, providing a year-round fishery for Puget Sound anglers (Appleby and Doty 1995).

Although the overall correlation of PCBs to lipids was fairly strong for coho salmon (Figures 3a and 3b), a number of composite samples did not fit the patterns well (Figures 3b, 4b, and 5). These "outlying" composites were composed entirely of hatchery-origin fish or fish of unknown origin. It is possible that these hatchery-origin samples were delayed-release fish that were "resident" in Puget Sound and thus experienced a greater exposure to PCB contamination. We were unable to determine with confidence whether any of our sampled salmon had been resident in Puget Sound. However, the life history of a significant portion of hatchery-origin coho (more than four million per year from 1983 to 1993) and chinook salmon (one million or more per year since 1974) have been manipulated to encourage residency (Appleby and Doty 1995).

The Duwamish River is the most polluted of the five in-river areas we sampled, yet coho salmon from relatively unpolluted locations had both higher (Deschutes and Nisqually rivers) and lower (Skagit and Nooksack rivers) concentrations of PCBs. The PCB concentrations of coho salmon from the Duwamish were intermediate between those from the southern and northern locations, supporting the geographic trend noticed in the lipid-specific data. The lack of a correlation between lipids and PCB concentration in muscle tissue for the Duwamish fish may results from the collection of hatchery fish at this location; four were hatchery-origin, two were wild, and nine were of mixed hatchery and wild origin.

Health of Pacific Salmon in Puget Sound

The effects of PCB accumulation on the health of chinook and coho salmon from Puget Sound are unknown. Salmon typically metabolize lipids as a source of energy during their spawning migrations, so fish closer to spawning generally have lower levels of lipid in their muscle tissues (see review in Brett 1995) and (consequently) lower PCB concentrations. However, accumulated PCBs may be transferred to the eggs and the resulting concentrations may be high enough to reduce reproductive success in individual fish. A study of chinook salmon in Lake Michigan (Ankley et al. 1991) showed that hatchery success decreased with increased PCB concentration in eggs. Chinook and coho salmon from Lake Michigan (Stow et al. 1994) had about 10 times the PCB concentrations in their muscle tissue that we observed in Puget Sound salmon. It is unknown whether PCB concentrations in Puget Sound salmon are transferred to eggs in high enough concentrations to affect hatching success and survival of fry.

Several studies have documented that juvenile salmonids in highly contaminated areas in Puget Sound (Duwamish River and Hylebos Waterway) are exposed to higher concentrations of organic contaminants, including PCBs, than fish from hatcheries and reference areas (McCain et al. 1990; Varanasi et al. 1993; Stein et al. 1995; Collier et al. in press). Furthermore, chinook salmon from the Duwamish estuary showed suppression of immune function, increased mortality after disease challenge, and impaired growth (Arkoosh et al. 1991; Varanasi et al. 1993). A recent laboratory study (Arkoosh et al. 1994) showed that exposure to chlorinated hydrocarbons and PAHs may impair immunocompetence of juvenile chinook salmon. Although exposure to contaminants is correlated with reduced growth rates and short-term survival, the effects on long-term marine survival and abundance of salmon populations are unknown.

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