Technical Issue Paper

Inclusion of Salmon in Fish Consumption Rates

DRAFT

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Acronyms & Abbreviations

DDT	dichlorodiphenyltrichloroethane
DEHP	di-2-ethylhexyl phthalate
DNA	deoxyribonucleic acid
DPE	dialkyl phthalate ester
Ecology	Washington State Department of Ecology
EDC	endocrine disrupting chemical
FAC	fluorescent aromatic compound
FCR	fish consumption rate
HCH	hexachlorocyclohexane
LDW	Lower Duwamish Waterway
PAH	polycyclic aromatic hydrocarbon
PBDE	polybrominated diphenyl ether
PBT	persistent bioaccumulative toxics
PCB	polychlorinated biphenyl
PCDD	polychlorinated dibenzo-*p*-dioxin
PCDF	polychlorinated dibenzofuran
PCN	polychlorinated naphthalene
PFC	perfluoroalkyl compound
POP	persistent organic pollutant
PSAMP	Puget Sound Assessment and Monitoring Program
SaSI	Salmonid Stock Inventory
SEM	Standard Error of Mean
TEQ	toxic equivalent
tPAH	total polycyclic aromatic hydrocarbon
tPCB	total polychlorinated biphenyl
TSD	Technical Support Document
WDFW	Washington Department of Fish and Wildlife

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Introduction

The Washington State Department of Ecology (Ecology) received many and divergent comments about including or excluding salmon from the default fish consumption rate for Washington State fish-consuming populations. Consideration of salmon consumption depends on several different technical- and policy-related factors, including salmon life cycle, salmon chemical contaminant body burden, and the importance of salmon to Native Americans. New technical information and comments were provided to Ecology to further evaluate issues related to the consumption of salmon. This Technical Issue Paper integrates information provided in the public review comments on the salmon life cycle and survival strategies with the information currently in the draft Fish Consumption Rates Technical Support Document (TSD). This integration and analysis will, in part, consider where the salmon contaminant body burdens are obtained in relation to the salmon life cycles and survival strategies. This Technical Issue Paper also examines factors that may affect decisions to include or exclude consumption of salmon in site-specific sediment risk management and cleanup decisions.

Analysis

This section presents a review of salmon life history, a summary of literature on where and when salmonids obtain contaminant body burdens, and an assessment of the adequacy of currently available information to support site-specific salmon consumption criteria or advisories. Each topic includes a brief summary of the information presented in the draft TSD, followed by a summary of the public comments received on that topic. The analysis then provides further reviews or information summaries for additional clarity on each technical topic.

I. Salmon life history review

The draft TSD, specifically Appendix E, provides background information about the life cycle and survival strategies of those salmonids that both occur in Washington State waters and are consumed in quantity by its residents. Reviewers of the draft TSD provided very few comments with respect to new or missing life history information. Rather, comments largely focused on where and when body burdens are accumulated in a given salmon's life. Body burden accumulation is discussed in the next section of this Technical Issue Paper. However, in an effort to provide additional species-specific information, a summary of available information comparing life histories is included here. While this section is not an exhaustive literature review for Pacific Northwest salmonids, it is a suitable summary for salmonid life history comparison that provides a foundation for the following section on salmonid body burdens.

A. Summary of life history information in the draft TSD

Appendix E of the draft TSD provided background information about the life cycle and survival strategies for Chinook, coho, pink, sockeye, and chum salmon, as well as steelhead and cutthroat trout (Ecology 2011). The draft TSD Appendix E tables provided a general overview of the salmonids reviewed. Table E-1 of the draft TSD summarized general rearing habitats and migrational behaviors, while Tables E-5 and E-6 provided summary information on seasonal occurrence, habitat use, and the range of life expectancy for each of the seven salmonids. Tables E-7 through E-10 provided creel data for freshwater and marine systems. Lastly, Tables E-11 through E-13 provided Salmonid Stock Inventory (SaSI) summaries, including stock-specific status for salmonids occurring near the Port Angeles Harbor and adjacent areas. SaSI is the Washington Department of Fish and Wildlife's (WDFW) standardized, uniform approach to identifying and monitoring the status of Washington's salmonid stocks.

B. Summary of additional life history information from the draft TSD comments

Very little new information on the life history of salmonids was provided in comments received on the draft TSD. However, one reviewer (NCASI 2012) referred to Fresh et al. (2005) for a summary of juvenile salmonid life history strategies. Even though this table provides a different display of available life history information, it was technically consistent with the tables provided in Appendix E of the draft TSD. However, one of the important points noted in their comments was that Chinook salmon not only display greater residency, but, as they mature, Chinook salmon tend to eat more fish than other salmon. This point is relevant for the following

sections of this document that discuss the regional and species-specific differences between salmon in their uptake of toxins.

Additionally, a few other comments received (Weyerhaeuser 2012; Nippon Paper 2012) referred to their support of the 2003 AMEC paper titled *Evaluation of the Fish Consumption Rate Selected by Oregon DEQ for the Development of Ambient Water Quality Data*. This paper, when referring to salmonid bioaccumulation in the Columbia River basin, noted that "most anadromous species spend only a small fraction of their lifetime in the Columbia River," with the majority accumulated in marine habitats.

Although the draft TSD was not intended to be a comprehensive review of the variable life history strategies of all Pacific Northwest salmonids, by watershed, and the degrees by which these differences could play a role in body burden accumulation, these comments do indicate that some additional life history summary would be helpful in this process. In an effort to more fully describe these differences, a slightly more comprehensive review of these life history strategies is provided in the following sections.

C. Enhanced summary of Puget Sound salmonid life history strategies

This summary is not intended to be an exhaustive literature review for Pacific Northwest salmonids, but rather a summary of relevant information to aid in the interpretation of contaminant body burdens and other issues discussed in subsequent sections of this Technical Issue Paper. It is not intended to provide a comprehensive review of habitat requirements, such as dissolved oxygen, stream depth/velocity, temperature, or turbidity, and the potential effects these may have on salmonid life stages. Seven species of salmonids were briefly reviewed in the draft TSD (Chinook, coho, sockeye, chum and pink salmon, and steelhead and cutthroat trout). Due to their relative absence as a human food resource compared to the other salmonids, this Technical Issue Paper does not include a life history review summary for cutthroat trout (similar to the exclusion of bull trout in the draft TSD).

Although each of the six species reviewed here are salmonids, their life history strategies can vary substantially. Table E-1 of the draft TSD indicated, for these six species, whether juveniles rear in rivers, estuaries, or lakes. It also indicated the general areas of migration: nearshore, continental shelf, or mid-oceanic. Table E-5 of the draft TSD provided additional life history detail for a variety of salmonid species, including general life expectancy. However, even with species-specific differences in their life histories, an aspect that each of these salmonids have in common is that they are anadromous. That is, they hatch from eggs in fresh water, mature in marine waters, then return to fresh water as adults to spawn. What follows is a more detailed species-specific summary than was provided in the draft TSD. Knowledge of where fish hatch, rear, migrate, and forage is important to understand how each of these species may differ in their accumulation of toxic body burdens.

When information is too voluminous for inclusion, the reader will be referred to the source for further review. For example, in 2002 WDFW updated the SaSI report by classifying the status of 489 Washington State salmonids and steelhead stocks (WDFW 2002). These SaSI status reports, along with other references, were briefly reviewed for general stock-specific background

information. For a detailed description of the data and summaries of these salmonid stocks, please see the WDFW SaSI web page (http://wdfw.wa.gov/fish/sasi/).

Some of the life history questions that arose during the draft TSD review process included seasonal occurrence, habitat use, distribution, foraging, and life expectancy. Relative to more resident species such as perch and starry flounder, salmonids have large and highly variable distributions over their lifespan; occurrence and habitat use are a function of the needs of a given lifestage. However, even range and age at out-migration can be highly variable within a given species (e.g., steelhead and coho juveniles, and resident Chinook). Relative to fish species that are much longer lived such as English sole, spiny dogfish, white sturgeon, sablefish, yelloweye rockfish, and rougheye rockfish, estimated to live as long as 22, 75, 104, 114, 121, and 205 years, respectively (Love 1996; Berkeley et al. 2004), salmonids have short life spans, generally living from 2 to 6 years. In addition, compared to other bony fish species, salmonids have very large eggs. This provides the developing embryos and alevins with sufficient food resources to survive until they begin foraging as fry. However, egg size is highly variable between salmonid species. This difference is important as body burden of lipophilic toxins can be transferred from adult salmon to their young via the fatty content of the eggs. The species-specific life history information that follows is intended to supplement the information previously provided in the draft TSD. For an in-depth summary of Chinook salmon life histories, please refer to Myers et al. (1998), Healey (1991), and Quinn (2005), among many others.

a. Chinook Salmon

Chinook salmon (*Oncorhynchus tshawytscha*) is the largest of the *Oncorhynchus* species, typically reaching 8 to 10 kg, although Chinook salmon they have been documented in excess of 45 kg (Healey 1991; Quinn 2005). Resident Puget Sound Chinook salmon, however, are typically on the smaller end of this scale. Chinook salmon occur throughout the northeastern Pacific coast, and are considered one of the most sought after of the salmon species by commercial and tribal fishermen, sport anglers, and human consumers.

Due to their relatively large size, Chinook salmon generally spawn in larger rivers or streams than other salmonids (Healey 1991; Quinn 2005). Chinook salmon can be highly variable between and within given watersheds. They have various in-migration (e.g., spring versus fall) and out-migration (e.g., ocean-type versus stream-type) times that can vary within a given system, stock, or run of fish (WDFW 2002; Healey 1991; Myers et al. 1998; Duffy 2003, 2009; Duffy et al. 2005; Redman et al. 2005; Quinn 2005). Spring Chinook typically produce stream-type juveniles, whereas fall Chinook typically produce ocean-type juveniles (Quinn 2005). In general, Chinook salmon adults return to their natal streams and rivers to spawn in spring or fall, although some summer runs also occur (WDFW 2002; Quinn 2005). With some exceptions, for Chinook populations in the state of Washington, ocean-type Chinook occur within Puget Sound and the lower Columbia River tributaries, while spring-type Chinook occur in tributaries further up the Columbia River (Myers et al. 1998).

The life history habits of juvenile Chinook salmon vary widely, and a full understanding and classification of these differences is still in progress (Redman et al. 2005). For this summary, a four strategy classification of behavior in emerging Chinook salmon is described here, with one strategy for stream-type, and three strategies for ocean-type.

Egg

Chinook salmon have the largest eggs compared to the other Pacific Northwest salmonids, ranging from 210 to 420 mg (Allen and Hassler 1986; Beacham and Murray 1993). The eggs of Puget Sound Chinook stocks are larger than eggs of Chinook that occur in most other watersheds (Myers et al. 1998). Adult ocean-type Chinook salmon, which are generally larger in size than stream-type Chinook, also appear to produce larger eggs (Myers et al. 1998). As a result of the relatively larger eggs, Chinook fry are also relatively large upon emergence, averaging 33 to 37 mm in length and ranging from 0.12 to 0.47 gram (Healy 1991; Myers et al. 1998; Quinn 2005).

Fry

After emergence, stream-type Chinook spend a year or more in the river before migrating downstream (Healey 1991; Myers et al. 1998; Duffy 2003, 2009; Duffy et al. 2005; Quinn 2005). Once entering the marine environment, stream-type Chinook spend very little time in the estuaries before migrating toward coastal waters (Duffy 2003, 2009; Duffy et al. 2005). Ocean-type fry display a very different type of behavior. Myers et al. (1998) summarized literature documenting three distinct phases of ocean-type juveniles migrating to marine habitats. One phase, or strategy, is the immediate type that migrates to the ocean soon after yolk resorption at 30 to 45 mm in length. During years of poor environmental conditions, another behavioral phase may occur, with ocean-type juveniles remaining in fresh water for a year, although this is relatively uncommon. The most common behavior for ocean-type fry migrants is to migrate to marine habitats at 60 to 150 days post-hatching, or as fingerling migrants, migrating downstream in the late summer or autumn of their first year. Emergent Chinook fry in freshwater habitats, like fry of other Pacific salmonids, depend on shaded nearshore habitat with slow-moving currents, where they forage on drift organisms, including insects and zooplankton (Healey 1991). In general, ocean-type parr (the freshwater stage of juvenile salmon, which usually occurs in the first one to two years of life) usually migrate to estuarine areas from April through July with some variability (peak out-migration occurring from May to early July), becoming smolts (juveniles that have transitioned from fresh water to salt water) soon after entering marine waters. Duffy et al. (2005) found that wild ocean-type Chinook out-migrate to Puget Sound waters from March to July, while hatchery Chinook occupy nearshore Puget Sound waters soon after release and in pulses from May to June. Once reaching the marine environment, they then spend a few weeks or longer rearing in the estuary (Duffy 2003, 2009; Duffy et al. 2005).

Juvenile

Due to their longer residence time in freshwater systems prior to out-migration, stream-type Chinook are much larger, averaging 73 to 134 mm, than ocean-type Chinook upon reaching the estuary (review in Myers et al. 1998). Entering the estuary at a larger size allows spring-type juveniles to move offshore more quickly than ocean-type juveniles (Healey 1991).

Ocean-type juveniles grow at a faster rate than do stream-type individuals (review in Myers et al. 1998). This may be due, in part, to food quality. Duffy (2009) found that insects provided a higher caloric content, and therefore promoted faster growth than other food resources such as decapod larvae for juvenile Chinook in Puget Sound. Upon entering marine habitats, hatchery-produced smolts occur at a larger size than do their wild counterpart (Duffy 2009). Once reaching the marine waters of Puget Sound, juvenile ocean-type Chinook occupy nearshore habitats from April to June, before shifting to more offshore habitats from July to September

(Duffy 2009). Further, Duffy (2009) found that the size of ocean-type juveniles immediately prior to this offshore movement was strongly related to survival. By early fall, it was presumed that juvenile Chinook salmon in Puget Sound either migrate towards the Pacific Ocean or to deeper waters of Puget Sound (Duffy 2009). Coastal rearing populations of juvenile Chinook salmon are largely piscivorous (fish eating), but also consume euphausiids, amphipods, copepods, pteropods, and cephalopods (Brodeur 1990).

Subadult

Once reaching the ocean, Chinook salmon are distributed in both coastal and offshore waters (Quinn 2005). In the ocean, ocean-type Chinook are distributed along coastal waters, whereas stream-type can be found offshore and throughout the central Pacific (Healey 1991; Myers et al. 1998). The diet of oceanic maturing Chinook consists mainly of squid, with fish, euphausiids and pteropods also present (Brodeur 1990). Those salmonids that mature and occur within coastal waters have a diet primarily composed of fish, with euphausiids, decapod larvae, and cephalopods also present (Brodeur 1990). Salmonids mature in oceanic and coastal waters from 1 to 6 years, although 2 to 4 years is more typical, before returning to their natal streams to spawn (Myers et al. 1998).

Adult

Mature adult Chinook salmon can return to their natal streams months in advance of spawning; however, both spring-run and fall-run fish begin spawning in the fall (Quinn 2005). Within much of the Puget Sound region, adult fall-run Chinook salmon start entering estuarine and riverine waters as early as August and begin spawning in their natal rivers and streams from mid-September to November, but this can continue through January (Myers et al. 1998; Quinn 2005). Spring-run Chinook salmon enter Puget Sound and Columbia River waters in April and May, although spawning does not begin until August and September (Myers et al. 1998). Upon entering these freshwater systems, ocean-type adults are larger than spring-type adults. It has been postulated that this is in part due to ocean-type juveniles occurring in the more productive estuarine environment at an earlier age than stream-type juveniles, or the additional 3 to 5 months longer that ocean-type adults remain in the marine environment prior to entering their natal streams (Myers et al. 1998; Duffy 2003, 2009; Duffy et al. 2005). It is likely that both of these factors play a role in the larger size of ocean-type adults.

Fat Content of Chinook

Fat content between salmonid stocks within a given system can vary substantially between years, seasons, sexes, and runs. Seasonal abundance of food in the ocean can alter size at entry as well as fat content upon entry. Within the Klamath River, Hearsey (2011) found that spring Chinook salmon, entering rivers months in advance of spawning, had much higher overall fat content compared to fall-run Chinook. However, due to their long period of freshwater residence prior to spawning, upon spawning, fall-run fish generally had a higher overall fat content. Hearsey (2011) found that male and female Chinook generally had the same fat content upon entry, but the females had a much lower fat content by the time spawning occurred. This is attributed to females using their fat reserves (muscle lipids and triacyglycerol deposits) during upstream migration and gonadal development of the eggs. Lipid content is an important factor as lipophilic contaminants can occur at higher numbers in these fish. Then as the female converts this energy

during gonadal development, the fatty eggs from females with higher body burdens receive maternal transferred contaminants at elevated levels.

b. Coho Salmon

Like other salmonids in Washington State, coho salmon (*Oncorhynchus kisutch*) are hatchery-reared and released throughout the state. Although some of the cited literature reviews hatchery-released fish, this life history summary is intended to focus primarily on *natural spawning* or *wild* fish behaviors.

Along the northeastern coast of the Pacific, coho salmon range from Monterey Bay, California, to Point Hope, Alaska, and the Aleutian Islands (Laufle et al. 1986). Coho salmon typically reach 3.5 to 4.5 kg (Sandercock 1991), although they have been documented to reach as many as 14 kg (Laufle et al. 1986). Sandercock (1991) found that adult coho returning to British Columbia waters ranged from 53 to 67 cm (21 to 26 inches). For populations in and around Washington State, returning adult coho salmon are generally 3-year-olds, and spend approximately 18 months in fresh water and 18 months in marine habitats (Sandercock 1991). A small percentage of sexually mature males (*jacks*) return to fresh water to spawn after only 5 to 7 months in the ocean. Compared to Chinook salmon, coho tend to spawn in smaller streams of modest gradient (Quinn 2005).

In general, coho salmon do not have the broad variation in life history habits that occurs in other salmonids such as Chinook and sockeye salmon and steelhead. With some variation, adult coho salmon generally return to their natal streams to spawn in fall (Laufle et al. 1986; Sandercock 1991; Quinn 2005). After emerging, the fry generally remain within freshwater streams for a year or two before migrating downstream. A more detailed summary of the life history characteristics of coho salmon is provided below. For an in-depth summary of coho salmon life histories, please refer to Laufle et al. (1986), Sandercock (1991), and Quinn (2005), among others.

Egg

For coho salmon populations, there is considerable variation in egg size within and among populations (Fleming and Gross 1990). In general, longer female body length within a population resulted in a larger egg produced. Along the Pacific coast, coho salmon have been shown to have a significant negative relationship between latitude and egg size (Fleming and Gross 1990). In other words, all other factors equal, coho salmon in California have larger, albeit fewer, eggs than those in Puget Sound, which are larger than those in systems further north. In general, coho salmon eggs within Washington State generally range from 160 to 295 mg, depending on location, and from 4.5 to 6.0 mm in diameter (Fleming and Gross 1990; Laufle et al. 1986; Quinn 2005).

Fry

Following hatching, coho alevin do not emerge from the gravel for 2 to 3 weeks (Laufle et al. 1986). Emergence has been detected from March to July (Laufle et al. 1986). Coho salmon fry are approximately 30 mm upon emergence (Quinn 2005). Although some fry migrate to marine waters soon after emergence, the majority disperse both up- and downstream, remaining in streams to rear as juveniles for one to two years before migrating downstream (Laufle et al.

1986; Quinn 2005). Following emergence, coho fry begin feeding on a variety of insects, including dipterans, ephemopterans, and plecopterans (Laufle et al. 1986). Fry that are not displaced (washed out) by freshets grow larger, reside longer, and establish territories within their natal freshwater systems (Sandercock 1991).

Juvenile

While residing in freshwater streams, the maturing juvenile coho diet progressively includes larger prey items to sustain their growth. At this stage their diet begins to include crustaceans and fish, including co-occurring salmonids (i.e., pink and chum salmon) (Laufle et al. 1986). In fact, when co-occurring with other similar-sized juvenile salmonids, juvenile coho are more aggressive and outcompete other salmonids, including juvenile Chinook, for food resources (Laufle et al. 1986; Sandercock 1991). As a result, juvenile coho grow at a faster rate than co-occurring salmonids of other species. Both age and size of juvenile coho salmon are believed to be triggers for downstream migration (Laufle et al. 1986). Within this region, coho smolts typically leave fresh water and migrate to marine habitats to enter the smolting process in the spring (April to June) (Sandercock 1991). Once entering marine waters, coho smolts spend little time rearing in estuaries, instead migrating toward coastal waters (Quinn 2005). Juvenile, adult, and subadult coho diets in marine waters tend to vary with fish size and coastal region occupied. Juvenile coho diets, while occurring in nearshore sublittoral habitats, primarily consist of decapod larvae, euphausiids, amphipods, polychaetes, and crustaceans (Fresh et al. 1981, as summarized by Laufle et al. 1986; Quinn 2005; Sandercock 1991). Juvenile and subadult coho occurring further offshore generally consume decapod larvae, euphausiids, amphipods, and fish (principally herring) (Fresh et al. 1981, as summarized by Laufle et al. 1986; Brodeur 1990).

Subadult

Although some coho salmon move to offshore waters, typically subadults continue to feed and mature in these coastal waters of the northeast Pacific (Quinn 2005). An additional group appears to rear in the Strait of Georgia, and possibly Puget Sound (Laufle et al. 1986). For those coho that move offshore, this migration appears to begin in July and August (Laufle et al. 1986). Coho captured in oceanic waters tended to have diets dominated by fish and squid, although euphausiids, amphipods, and pteropods were also present (Brodeur 1990). The majority of coho originating from Washington streams migrate to coastal waters off Oregon and Washington, with low numbers occurring in Oregon and British Columbia waters (Laufle et al. 1986). Very few Washington coho appear to migrate to Alaskan coastal waters (Laufle et al. 1986). Both subadult and adult coho salmon usually occur in the top 10 meters of marine water, except when these surface waters become too warm (Laufle et al. 1986).

Adult

Young adult coho occurring offshore of the Columbia River are generally larger than their Puget Sound conspecifics, which may be due in part to their preying almost exclusively on fish (i.e., anchovy, surf smelt, whitebait smelt, herring, and juvenile Chinook and rockfish), although diets of mature coastal coho can also include euphausiids, crab larvae, amphipods, and squid (Laufle et al. 1986; Brodeur 1990). While some adult male coho salmon return after spending only one summer at sea, the majority of coho return after spending two, and sometimes three, summers at sea (Laufle et al. 1986; Quinn 2005). There are some run timing differences between coastal and inland Washington stocks of coho salmon, but adults begin returning to estuaries and outlets of

their natal streams from July to September (Laufle et al. 1986). Except for earlier arriving jacks, sexually mature adults migrate up natal streams and rivers from August to November and spawn from November to December, and occasionally as late as February or March (Laufle et al. 1986; Sandercock 1991). In general, coho spawn in streams and small rivers that have relatively fast flow (Laufle et al. 1986; Sandercock 1991; Quinn 2005).

c. Sockeye Salmon

This section describes the general life history of anadromous forms of sockeye salmon (*Oncorhynchus nerka*); it does not describe life history patterns of land-locked sockeye salmon, known as kokanee. Mature adult sockeye salmon are small relative to other species in this region, reaching weights between 2 and 4 kg (4.4 and 8.8 lbs) (Quinn 2005). Along the coast of the northeast Pacific Ocean, sockeye salmon populations range from the Sacramento River in California to the Arctic (Burgner 1991). Within the state of Washington, a number of stocks exist, including Lake Pleasant, Ozette Lake, Lake Washington, and a few runs in the Columbia River drainage. Sockeye salmon have one of the most diverse patterns of life history among Pacific Northwest salmon species. For example, age at out-migration to marine systems from their natal streams not only varies between systems, and within systems, but can vary among related individuals. As a result, the summary presented here is considered a general overview of sockeye salmon life histories, not an all-inclusive review.

Sockeye salmon migrate from marine waters to natal freshwater systems in the summer months. Many times these systems include a *nursery lake*, in which juveniles rear and adults may hold prior to spawning. Adult sockeye salmon return to Lake Washington from June through August, with peaks from mid-June to mid-July (Newell 2005). When conditions are right, the adults migrate to suitable spawning habitat to dig a nest (redd) and spawn. In some systems sockeye salmon spawning can occur on lake beaches, inlets or outlets of lakes, and in outwash fans of lake tributaries (Gustafson et al. 1997). For an in-depth summary of sockeye salmon life histories please refer to Pauley et al. (1989), Burgner (1991), and Gustafson et al. (1997).

Egg

The number of eggs produced by a female sockeye salmon is relatively high (averaging 3,500), yet sockeye salmon produce some of the smallest eggs of the Pacific salmon (5.3 to 6.6 mm in diameter) (Pauley et al. 1989). As a result, when sockeye fry emerge, they are also small, averaging 26 to 29 mm (Quinn 2005). Lake Washington sockeye salmon eggs hatch approximately 51 to 124 days after fertilization. Hendry et al. (1998) found that incubation duration is strongly linked to water temperatures, with eggs incubating in warmer (12.5°C) waters hatching in less than half the time as those incubating in colder water (5°C).

Fry

The hatched alevin then take an additional 24 to 60 days to emerge from the gravel as fry, with warmer temperatures reducing the time for emergence. Sockeye salmon emerge as fry generally in April or May (Pauley et al. 1989), with some variability associated with temperature. As might be expected, fry length and weight have been found to be positively correlated with egg weight (Hendry et al. 1998). While there is some variability with post-emergent behavior (Gustafson et al. 1997), after emergence, fry generally migrate toward a lake that they will use as a nursery (and will migrate either upstream or downstream to reach a lake). However, some forms will

remain in the natal stream for a portion of their rearing. Regarding their entry into marine waters, two *types* of sockeye salmon occur: the ocean-type (or *sea-type*) that migrates to marine waters in the first year of their life, and the river-type that may rear in rivers for a year or more before migrating to marine habitats (Gustafson et al. 1997).

Juvenile

Once entering a lake system, juvenile sockeye begin preying upon available zooplankton and insect larvae. Juvenile sockeye in Washington generally migrate from their nursery lakes to marine habitats in March and continuing through June, with peak out-migration occurring in April and May (Appendix C-5 in Gustafson et al. 1997). Upon entering marine waters, estuarine use by juvenile sockeye salmon (smolts at this point) is limited, although some ocean-type sockeye may use these habitats before migrating toward coastal waters. Once entering salt water, juvenile sockeye salmon migrate northward to the Gulf of Alaska in coastal waters, but then by autumn move away from coastal habitats and use offshore waters for growth to maturation (Gustafson et al. 1997). In offshore marine waters, sockeye juveniles tend to disperse and not form defined schools (Burgner 1980, as cited in Pauley et al. 1989).

Subadult

Sockeye spend 2 to 4 years at sea before returning to their natal systems to spawn (Burgner 1991; Quinn 2005). Sockeye have long gill rakers to allow foraging on a variety of plankton species while in the ocean. As there is some dietary overlap between sockeye and pink salmon while at sea, during even-numbered years, when pink salmon abundance is relatively low, maturing sockeye salmon that migrated to the Bering Sea saw their diet of euphausiids, copepods, fish, and squid increase (Davis et al. 2005). For all years, and many regions, larger sockeye tended to have greater proportions of fish and squid in their diet (Brodeur 1990; Davis et al. 2005). For sockeye populations off the Oregon and Washington coasts, larval fishes (Osmeridae) and euphausiids can be dominant prey resources (Brodeur 1990). In other nearby regions, amphipods, copepods, and euphausiids were dominant (Brodeur 1990). As these fish reach maturity, they begin their return migrations from offshore and coastal waters towards the estuaries and river mouths of their natal river, streams, and lakes.

Adult

Upstream migration of sockeye stocks is highly variable depending on region and other factors, such as day length and water temperature (Burgner 1991). Adult sockeye salmon return to Lake Washington from June through August, with peaks from mid-June to mid-July (Newell 2005); however, these fish delay spawning until fall. Upon returning to these systems, reproductively mature adults average between 2 and 4 kg (4.4 and 8.8 lbs) (Quinn 2005). However, as reproductive sockeye that enter these systems exhibit little or no feeding behavior, some reduction in size may occur prior to their upstream migration to spawn in the fall. Within Lake Washington there are variations in sockeye salmon breeding behavior. Some of the returning adults hold in the lake for up to six months before spawning in the Cedar River that flows into the south end of the lake (Newell 2005). Other smaller populations, those that spawn in tributaries that flow into the north end of the lake or on the lake's beaches, spawn at different times (Newell 2005). This is believed to be a strategy for maximizing the survival of eggs, alevins, and fry as spawning timing is correlated with emergence timing, and therefore the best

environmental conditions to optimize survival for the next generation (Brannon 1987, as cited in Newell 2005).

d. Chum Salmon

Chum salmon (*Oncorhynchus keta*) have the broadest distribution of all salmonid species (Pauley et al. 1988) and range along the Northeast Pacific coast from Monterey Bay, California, to the Arctic Ocean (Pauley et al. 1988; Salo 1991; Johnson et al. 1997). Similar to pink salmon, adult chum salmon prefer to spawn in the lower reaches of their natal streams (Pauley et al. 1988; Quinn 2005). Chum salmon produce larger eggs than do the smaller sockeye and pink salmon (Beacham and Murray 1993; Quinn 2005). Similar to pink salmon or ocean-type Chinook, juvenile chum migrate from their freshwater redds to marine waters almost immediately after emergence (Pauley et al. 1988; Salo 1991; Johnson et al. 1997; Quinn 2005). Chum salmon generally live 3 to 5 years and are relatively large compared to other salmonids, second only to Chinook; chum typically average 3.6 to 6.8 kg (8 to 15 lbs) (Salo 1991; Quinn 2005) and records indicate they can attain weights of up to 20.8 kg (46 lbs) (Johnson et al. 1997). Adult chum lengths typically average 53 to 79 cm (21 to 31inches), although they have been reported to reach sizes in excess of 108 cm (42.5 in) (Johnson et al. 1997). What follows is a summary by lifestage for chum salmon, with a focus on those populations that occur in Washington State. For an in-depth summary of chum salmon life histories please refer to Pauley et al. (1988), Salo (1991), and Johnson et al. (1997).

Egg

Female chum salmon lay between 900 and 8,000 eggs (Pauley et al. 1988) that range in weight from 248 to 349 mg (Beacham and Murray 1993). These eggs are extremely sensitive to changes in the environment, with a high degree of mortality (up to 90 percent) in the developing eggs (Pauley et al. 1988). Depending on environmental conditions, the eggs hatch to become alevins 50 to 130 days later. The alevins remain in the gravel another 30 to 50 days, until their yolk sac is absorbed (Pauley et al. 1988). Having depleted the energy stores in their yolk sacs, alevins emerge from the gravel as fry in the spring (Pauley et al. 1988).

Fry

Emerging fry are relatively large, ranging from 32 to 38 mm (Quinn 2005). While in fresh water, these fry rely on aquatic insects as their primary food resource. Most chum salmon fry spend only a few days to a few weeks rearing in fresh water before migrating toward marine habitats from March to May (Pauley et al. 1988; Salo 1991; Johnson et al. 1997; Quinn 2005). A much smaller number of fry may rear in freshwater streams but migrate to marine waters by the end of their first summer. Chum salmon utilize estuarine habitats for a few more weeks before migrating to coastal, then offshore waters. Once reaching marine habitats, chum salmon form dense schools as they rear in nearshore habitats (Pauley et al. 1988; Salo 1991). The Hood Canal shoreline is said to serve as a nursery and rearing habitat for up to 25 percent of all chum salmon originating from Washington State rivers (Pauley et al. 1988). While in this environment, chum fry stay in very shallow, nearshore habitats and consume a number of epibenthic invertebrates, including gammaridean amphipods, harpacticoid copepods, cumaceans, and mysids (Pauley et al. 1988). This environment not only provides them with a readily available food resource, but also protects them from larger predators such as cutthroat trout. Most chum fry enter estuaries by June and leave them by mid to late summer.

Juvenile

By the time chum fry leave estuaries and begin moving to coastal waters, size becomes a key factor for their survival. Chum salmon that enter these waters when they are less than 55 mm are less likely to survive than larger juveniles (Pauley et al. 1988). For those fish that remain in estuaries through the summer, more typical sizes are 150 to 225 mm (Pauley et al. 1988). At this size juvenile chum generally begin to move to offshore neritic habitats, feeding on euphausiids, calanoid copepods, hyperiid amphipods, larvaceans, and fish larvae (Simenstad and Kinney 1978). A number of age 2 chum salmon do occur within Puget Sound waters (Pauley et al. 1988), although the absence of age 3 chum suggests that all chum salmon spend time rearing in the Pacific Ocean (Pauley et al. 1988).

Subadult

Once reaching coastal waters, the juvenile chum disperse and are widely distributed. Dietary studies of chum salmon along the British Columbia coast vary, with dominant food items of younger, maturing chum salmon including amphipods, euphausiids, pteropods, and fishes (Brodeur 1990). As chum grow larger and mature, their diet shifts to larger prey items, including amphipods, euphausiids, and crustaceans, but also an increase in squid and fishes (Brodeur 1990). In general, chum salmon originating from Washington streams and rivers, and rearing in the open ocean, do not return as mature adults until age 3 or 4 (Pauley et al. 1988).

Adult

Chum salmon can be reproductively mature as 3, 4, or 5-year-old fish (Pauley et al. 1988). In some systems, chum salmon are the last of the salmon to migrate upstream to spawn (Pauley et al. 1988). While most systems support only a summer and fall run of returning adult chum, Puget Sound rivers produce *early* (mid-August – October), *normal* (November – December), and *late* (January – March) runs (Pauley et al. 1988). In systems such as Hood Canal, chum salmon migration and spawning times are separated by up to a month, resulting in summer-run fish (spawning in early September to mid-October) and fall-run fish (spawning in early November to late December) (Johnson et al. 1997). Even though data are limited, coastal runs of chum salmon occur in October and November, with spawning taking place as late as December (Johnson et al. 1997).

As with other salmonids, adult chum may mill at a river's mouth, or estuary, for a period before initiating their upstream migration (Johnson et al. 1997). Once beginning their upstream migration, adult chum no longer continue to feed (Pauley et al. 1988). Chum salmon survival is limited once they enter fresh water. Studies have indicated that, once entering fresh water, adult chum may die within 11 days but may survive as long as a month (Pauley et al. 1988). Although chum salmon in Washington State generally spawn in the lower portions of rivers and streams, in some systems, such as the Skagit River, chum salmon migrate 170 km or more (Hendrick 1996, as cited in Johnson et al. 1997). After the female digs out a redd, and lays somewhere between 900 and 8,000 eggs that are immediately fertilized by a male, the pair defends the redd(s) until eventually dying in the following days.

e. Pink Salmon

Pink salmon (*Oncorhynchus gorbuscha*) are the most abundant salmon along the coast of the Northeast Pacific Ocean and are also the smallest at maturity (Bonar et al. 1989; Heard 1991; Quinn 2005). Mature adult pink salmon are approximately 1.0 to 2.8 kg (2.2 to 6.2 lbs) when they return to their natal streams to spawn (Bonar et al. 1989; Heard 1991; Quinn 2005). Pink salmon only live for 2 years, with very little variability. In systems south of the Fraser River, most pink salmon adults return to their natal streams in odd years (Bonar et al. 1989; WDFW 2002; Quinn 2005). Twelve of the thirteen pink salmon populations in Washington spawn only in odd years, with an additional even-year population occurring in the Snohomish River (Hard et al. 1996). Pink salmon are more abundant in the northern river systems (e.g., Nooksack, Skagit, Stillaguamish, and Snohomish Rivers) than in southern river systems (e.g., Puyallup and Nisqually Rivers) (Hard et al. 1996). Though less abundant, populations also occur in Hood Canal (e.g., Hamma Hamma, Duckabush, and Dosewallips Rivers) and the Strait of Juan de Fuca systems (e.g., upper Dungeness, lower Dungeness, and Elwha Rivers) (Hard et al. 1996).

As pink salmon adults spawn near river mouths, and fry migrate downstream immediately after emergence, this salmon species spends the least amount of time in fresh water (Bonar et al. 1989; Heard 1991). Although some smaller coastal and Columbia River runs occur, within Washington State two of the rivers supporting the largest pink salmon runs are the Snohomish and Puyallup. These two rivers support commercial netting and sport fishing, activities that occur in marine, estuarine, and freshwater portions of the respective systems.

Within four to six weeks of entering estuaries, the adults go through a transformation, with the males developing a large hump on their backs, enlarged heads, and the development of large teeth (Bonar et al. 1989; Heard 1991). The hump in male pink salmon is so pronounced compared to other salmonids it has resulted in the species being nicknamed *humpies*. Following spawning, the vast numbers of spawned out pink salmon begin to die off, with dead and dying adult pink salmon littering the banks and shallows. A variety of predators and scavengers (e.g., eagles, bears, and gulls) utilize this readily available food resource (Heard 1991). The remaining carcasses decay, with their bodies providing nutrients in the nearby downstream vicinity of their spawning grounds. A summary description of the life history characteristics of pink salmon is provided below. For an in-depth summary of pink salmon life histories please refer to Bonar et al. (1989), Heard (1991), and Quinn 2005).

Egg

The eggs produced by pink salmon are smaller (about 6 mm in diameter) than other larger salmonid species (Bonar et al. 1989; Quinn 2005). Depending on the region and in-stream temperatures, fertilized pink eggs can take from five to eight months before fry emerge and migrate downstream (Heard 1991). Accounting for some variability between years and systems, pink salmon eggs laid in August to October generally hatch between late January and early March (Hard et al. 1996). Newly hatched alevin remain in the gravel for a few weeks utilizing their yolk sac. These alevin can average 21.3 mm in length.

Fry

With some variability, pink salmon fry emerge from the gravel primarily in March and April (Hard et al. 1996). Once the yolk sac is depleted, the alevins emerge as fry some 41 to 64 days

(average 52 days) post-hatching. These newly emerged fish range from 29 to 33 mm long with an average length 31.5 mm (Heard 1991; Quinn 2005). There is very little or no freshwater rearing as pink salmon fry migrate seaward upon emergence from the gravel, and so their downstream migration also occurs in March and April (Hard et al. 1996). Pink salmon originating from Puget Sound and Hood Canal streams and rivers appear to use nearshore areas extensively for early rearing during their first few weeks of entry into marine habitats (Jewell 1966, as cited in Hard et al. 1996). While little is known about their behavior as the fry are exiting Puget Sound proper, Hiss (1994, as cited in Hard et al. 1996) found that fry occurrence in Dungeness Bay (near Sequim) peaked in April and they were gone by late May. These fish ranged in length from 35 to 75 mm. Findings suggest that most out-migrating pink salmon enter the open ocean by late summer or early fall (Hard et al. 1996). However, like some Chinook and coho, a small portion of the pink salmon population appears to adopt residency in Puget Sound for the marine phase of the life cycle (Hard et al. 1996).

Juvenile/Subadult

Pink salmon fry migrate so rapidly to the sea, and so little is known about the juvenile and subadult behavior at sea, that for pink salmon the juvenile and subadult life history categories are combined. Once reaching estuarine and marine habitats, pink salmon migrate toward the open ocean within the first couple of months. By September the majority of pink salmon migrate hundreds of miles out in the open sea to grow and mature (Hartt and Dell 1986, as cited in Hard et al. 1996; Bonar et al. 1989; Heard 1991). Stomach contents of ocean-caught pink salmon were found to include fish, amphipods, euphausiids, pteropods, salps, squid, crustacean larvae, chaetognaths, and polychaetes (Bonar et al. 1989; Brodeur 1990; Pearcy et al. 1984). They spend approximately eighteen months rearing in the open ocean before their eastward migration to their natal streams and rivers (Bonar et al. 1989; Heard 1991).

Adult

Adult pink salmon begin migrating toward the river mouth of their natal stream from June to September, with peaks in some systems, such as the Snohomish, in the month of August (Heard 1991; Hard et al. 1996). Most pink salmon returning to Washington rivers and streams are believed to travel east through the Strait of Juan de Fuca, with some additional use of the Johnstone Strait/Strait of Georgia corridor (Hard et al. 1996). Once reaching their natal streams, adult pink salmon, in general, do not migrate far upstream, preferring to spawn within a few miles of the estuary. However, in the Snohomish River pink salmon spawn as far upstream as the Sultan River (approximately 23 miles), in the Puyallup River primarily above 12.5 river miles, and in the Nisqually River main stem between river mile 22 and 40 (Hard et al. 1996). In Washington and southern British Columbia, spawning generally occurs from August to October (Hard et al. 1996). Adult pink salmon spawn in dense numbers near riffles with clean gravel, an activity that takes from one to eight days (Heard 1991). After spawning the adults aggressively defend their respective redds until they eventually die, 11 to 21 days later (Heard 1991).

f. Steelhead

Steelhead (*Oncorhynchus mykiss*) range from central California to the Bering Sea and Bristol Bay, Alaska (Pauley et al. 1986). This species can occur as both anadromous (steelhead) and resident (rainbow trout) fish (Pauley et al. 1986). This brief life history summary focuses on naturally spawning, or *wild*, steelhead populations, and not the resident rainbow trout or hatchery

produced stock of either form. A significant difference between steelhead and salmon is that steelhead, in fresh water, can maintain a life history as rainbow trout, and steelhead can be repeat spawners. Adult spawners of either steelhead or rainbow trout can produce either, or both, freshwater or anadromous juveniles (Quinn 2005). The discussion below focuses on the anadromous, or steelhead, form of the species.

Comparing the size of an average steelhead to a given salmon species needs to take into account the age of a given steelhead. Unlike some of the larger salmonids that die after spawning, steelhead can return to spawn in multiple years. As a result, steelhead can spawn up to four times and have been documented to live as long as 8 or 9 years (Pauley et al. 1986). Because steelhead grow larger in the productive marine environment, fish that stay in these habitats longer are typically larger. Studies investigating this have found that steelhead range in size from 47 cm (18.5 inches) for a 1-year saltwater resident to 88 cm (34.6 inches) for a 4-year saltwater resident (Maher and Larkin 1954, as cited in Pauley et al. 1986). Steelhead are prevalent throughout streams and tributaries of the Puget Sound and Columbia River (Pauley et al. 1986). Both winter and summer steelhead types, or races, occur within Washington State streams and rivers.

Typically adult steelhead return to streams and rivers in the winter or summer and spawn in the spring and summer, with fry emerging in just a few weeks. Upon emergence, steelhead typically rear in the freshwater streams and rivers between 1 and 3 years. Following their downstream migration to marine waters, these fish rear and mature in the ocean for 1 to 3 years before returning to freshwater systems as adults to spawn (Pauley et al. 1989; Quinn 2005). Because steelhead can be repeat spawners, the age and size of returning adults varies considerably. A summary description of the life history characteristics of steelhead is provided below. For an in-depth summary of steelhead life histories please refer to Pauley et al. (1986) and Quinn (2005).

Egg

Steelhead eggs are typically smaller than salmon eggs, with size varying based on maternal size and body condition. Though timing for egg laying and hatching varies between river systems and temperature conditions, eggs of both summer- and winter-run fish begin to hatch from April to June, 4 to 7 weeks following adult spawning. Alevins emerge soon after, rapidly absorb their yolk, and are free swimming within 3 to 7 days (Pauley et al. 1986). These newly emerged fish are active foragers on microscopic organisms, moving toward insects and larger prey items as they grow.

Fry

By the summer of their first year, steelhead fry are consuming bottom-dwelling aquatic and terrestrial insects (Pauley et al. 1986). As they continue to grow, young steelhead fry become parr. Steelhead parr can remain in fresh water from 1 to 4 years, although 2 to 3 years is more common. Steelhead parr actively forage from spring to fall but become relatively inactive during winter months (Bustard and Narver 1975, as cited in Pauley et al. 1986). It is at the parr stage that steelhead begin their downstream migration toward marine habitats.

Juvenile

Juvenile steelhead migrate downstream typically in spring (although this can be from January to July) of their second, third, or fourth years in freshwater habitats, finally entering marine waters

and becoming smolts. Size at smoltification in steelhead has been correlated with survival. Small steelhead entering marine habitats do not survive long. Ideally a steelhead smolt should be at least 14 to 16 cm (5.5 to 6.3 inches) to survive this critical period (Pauley et al. 1986). Once entering estuaries, juveniles migrate toward coastal waters for a short period before moving offshore and into the open ocean. While in the ocean, juvenile steelhead diet shifts again and includes amphipods, euphausiids, a variety of fish, and squid (Pauley et al. 1986; Brodeur 1990).

Subadult

While in the ocean, subadult steelhead grow rapidly. However, upon entering the ocean, instead of forming schools they disperse widely. As a result, little is known about their distribution in marine habitats, other than distribution conforming between the 5°C isotherm to the north and the 15°C isotherm to the south (Pauley et al. 1986). Subadult steelhead diet while in the ocean appears to vary between regions, which may be a factor of available food resources. For those fish that occur off Oregon and Washington, cephalopods represent nearly 80 percent of the diet with fish representing only 10 percent (Brodeur 1990). Similar aged steelhead in the Gulf of Alaska had diets that consisted of 63 percent fish and 31 percent squid (Brodeur 1990). Although Columbia River summer-run steelhead generally only spend one summer in the ocean, other stocks, including winter-run, spend up to 4 years in the ocean, although 2 to 3 years is more common (Pauley et al. 1986).

Adult

Stream-maturing (summer) adult steelhead typically enter rivers from August to September, remain in the river through fall and winter, then spawn the following spring (Pauley et al. 1986; Quinn 2005). Ocean-maturing (winter) steelhead in Washington return during March to April and may spawn within a month of entering fresh water (Pauley et al. 1986; Busby et al. 1996, as cited in Quinn 2005). Returning adult steelhead rarely eat and grow little if at all once entering fresh water to spawn (Maher and Larking 1954, as cited in Pauley et al. 1986). Unlike salmon, steelhead do not die after spawning and can spawn up to four times, although two to three is more common (Pauley et al. 1986). As a result, post-spawn adult steelhead migrate back toward marine habitats within a relatively short period of time after spawning.

II. Salmonid body burdens

Over the course of a given salmonid lifespan, these fish occupy a variety of habitats that meet specific needs for each lifestage. As they grow from one lifestage to the next, and move from one habitat type to the next, their growth is based on the available food resources (Healey 1991, Quinn 2005; Duffy 2009). During each period of growth, each lifestage has the potential to accumulate environmental toxins. This section reviews and summarizes the information provided in the draft TSD, and the comments received on the draft TSD. Finally, this section includes a summary review of salmonid body burden accumulation. This review refers back to the life history summaries described above in an effort to determine whether it may be appropriate to attribute body burden accumulation to specific sites.

A. Summary of salmonid body burden information in the draft TSD

The draft TSD was written to address human consumption of fish and not the biology of Washington State salmonids. However, some explanation of salmonid life history and general region of body burden accumulation is warranted. Appendix E of the draft TSD, titled *The Question of Salmon*, summarized the life cycle and survival strategies of selected Washington State salmonids.

Appendix E acknowledged that, by the year 2000, an estimated 58 percent of all salmon consumed worldwide was farmed salmon. However, as the draft TSD indicated, people of Washington State not only consume more salmon than other populations, but much of this salmon comes directly from wild-caught resources in the Pacific Northwest region. As a result, accumulation of body burden by non-farmed salmonids in Washington State is relevant when evaluating human health risks associated with consumption of the resource.

The Appendix E section titled *Salmonid Contaminant Body Burden* summarized the role that salmonids play in the distribution of bioaccumulative pollutants. Appendix E acknowledged that "Pacific salmon exposure to PBTs, and PCBs in particular are, in part, contingent on migratory patterns, residency time in Puget Sound, proximity of the salmon to contaminated sediments, waste sites, and different behavior and dietary patterns as the fish mature." Included in this summary was the finding of O'Neill et al. (1998) "…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." Further, indications are that more than 98 percent of the final body weight of most salmon is attained at sea. Appendix E cited the finding of O'Neill et al. (2006) that coastal migrants (coho and ocean-type Chinook) have greater body burdens than do more oceanic migrants (chum, pink, and sockeye). Further, this study found that resident Chinook, which tend to be ocean-type, fall-run fish, were found to have 2 to 6 times the amount of polychlorinated biphenyls (PCBs) as non-residents, and 5 to 17 times the polybrominated diphenyl ether (PBDE) burden. A final point made in Appendix E with respect to regional variations in accumulation is that tributaries in the far southern reaches of Puget Sound lengthen the time that these fish occur in the Sound. This is due to greater distances from natal streams to the ocean for both out-migrants and in-migrants.

B. Summary of salmonid body burden information from the draft TSD comments

Public review comments on the draft TSD represented a wide range of positions with respect to where and when in a salmon's life cycle it accumulates significant portions of its toxic body burden, and how this information should be incorporated into the draft TSD. These comments are summarized below.

One reviewer (Yakama 2012) noted that salmon have been shown to acquire contaminants in waters that are under Washington State jurisdiction. They pointed out that accumulations occur within fresh waters of the Columbia River for juveniles during their out-migration (LCREP 2007) and in estuarine and inland marine waters of Washington (O'Neill 2011, as cited in Yakama 2012).

Another reviewer (Exponent 2012) pointed out the draft TSD Appendix E appeared to support the conclusion that, for most salmon, body burden of bioaccumulative chemicals (e.g., PCBs, toxins, mercury) derives mostly from marine waters. They noted that "Washington waters/sediments may contribute to body burden depending on the species, run, chemical, life cycle characteristics, and range of environmental physical characteristics," and concluded that "variability, dominated by a lack of significant contribution, argues for evaluating the situation on a site-specific basis with the exclusion of salmon being the default."

A few comments received on the draft TSD (Weyerhaeuser 2012; Nippon Paper 2012) referred to their support of the 2003 AMEC paper titled *Evaluation of the Fish Consumption Rate Selected by Oregon DEQ for the Development of Ambient Water Quality Data* and this paper's relevance to the reviewed draft TSD. One of the points made by the AMEC (2003) document, with respect to freshwater and estuarine occurring fish, was that "If there is a permitted discharge to a freshwater body, the consumption of estuarine fish and shellfish is likely to be irrelevant. Similarly, if there is a discharge to an estuarine area, the freshwater fish upstream will likely not be affected. Thus the inclusion of rates of consumption of freshwater and estuarine finfish and shellfish is a very conservative assumption for these specific applications" (page 5).

The AMEC (2003) paper called into question the inclusion of anadromous fish, which are consumed by Columbia River Tribal members at rates of three times higher than resident fish species, according to the CRITFC (1994) fish consumption survey. They noted that many juvenile Chinook salmon in the Columbia River spend several months in the system before migrating to a marine feeding area, and that when they return as adults after 2 to 6 years, they generally do not feed during their upstream spawning migration, and therefore do not reach equilibrium with the surrounding environment. In other words, though potentially occurring within a discharge area, migratory fish species such as Chinook salmon do not occur in any site-specific region for a sufficient length of time to achieve equilibrium with regulated compound concentrations in the associated water column.

One reviewer (NCASI 2012) provided extensive comments, citing many of the same references that were cited in the draft TSD. They point out that different species and different runs of the same salmon species have very different life history strategies and will accumulate body burdens to differing degrees. They state that literature supports the position that the major fraction of persistent bioaccumulative toxic (PBT) burden carried by adult salmon originates from the open ocean. Their comments noted that resident Puget Sound Chinook, with higher body burdens, are an exception as they do not utilize open ocean habitats. Due to this difference, they noted that "…it might be appropriate to assess risk to select Puget Sound residents as a separate activity, and inclusion of salmon in an FCR [fish consumption rate] used in such a risk assessment may well be warranted." However, due to the large differences in life history, the reviewer felt that it is inappropriate to lump all species together as *salmon*, and should instead apportion numbers between salmon species. Their conclusion was that, based on the information provided above, the consumption of salmon should be excluded from any state-wide default fish consumption rate.

C. Salmonid body burden accumulations by life stages, rates, and location

This section includes a summary of the detailed technical literature review comments provided by one specific reviewer, and an additional literature review concerning salmonid body burden accumulation conducted during preparation of this Technical Issue Paper.

a. NCASI review comments (Should salmonid body burden be included as part of the fish consumption rate?)

A key question asked by a number of reviewers of the draft TSD was whether salmonid body burden accumulation is sufficiently understood to be included as part of the default fish consumption rate. One reviewer in particular, NCASI (2012), provided a summary of their literature review on where salmonids accumulate PBT chemicals. A summary of their review is included here, as well as an expanded review of additional literature, to further understand what the current knowledge is for the rate of uptake, locations where uptake occurs, and those salmonid species and life stages for which this information is available.

The NCASI (2012) comments included a table taken from Fresh et al. (2005), that compared the life history variations for six Washington State salmonid species (NCASI [2012] cited the Fresh paper as NOAA 2005). NCASI (2012) comments stated that… "These differences are potentially significant in that they may lead to differences in the mass (burden) of the chemical contaminants (e.g., PBT chemicals) ultimately accumulated by the salmon, and in the fraction of this ultimate burden accumulated in freshwater vs. saltwater." Section I.C of this Technical Issue Paper was prepared to provide an even greater understanding of what those life history differences are, where these six salmonid species occur at given stages of their life, and the principal food items consumed during each life stage. This Technical Issue Paper is not an exhaustive summary, but one that allows for comparison on an appropriate scale.

NCASI (2012) stated that, taken to the extreme, the life history differences of these salmonids imply that each run of each salmonid should be evaluated independently to determine where contaminants are accumulated. They further stated that this comparison may not be necessary, as the work of O'Neill et al. (1998), West and O'Neill (2007), and O'Neill and West (2009) indicated that the open ocean is the dominant pathway for PBT chemical uptake by salmonids. The NCASI review provided additional references that are included to show that the majority of contaminant burden in anadromous fish occurs in marine systems and not freshwater systems. A final, albeit very notable, distinction made in their review was the finding by O'Neill et al. (1998) that indicated a greater uptake of PBTs in Chinook, in both Puget Sound proper and its tributaries, relative to other salmonids. Findings such as this are likely attributable to two factors: (1) resident Puget Sound Chinook are generally ocean-type (rearing in marine waters rather than extensive periods in fresh water), and (2) they eat more fish, including contaminated herring stocks, as a part of their food resource than other salmonids.

b. Summary of investigations concerning salmonid body burden accumulation

There is growing evidence in the literature that Puget Sound fish, including salmonids, are experiencing biological effects attributable to contaminant exposure (McCain et al. 1990; Stein et al. 1995; Landahl et al. 1997; O'Neill et al. 1998; West and O'Neill 2007; O'Neill and West 2009; Hope 2012). Although there is evidence that adult salmon returning to spawn in

Washington waters have elevated body burdens of these contaminants, the origin of these contaminants is of central importance for resource management and risk reduction. What follows is a summary of selected papers that investigated body burden accumulation in salmonids.

Juvenile accumulation

In situ biomonitoring of caged, juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in the Lower Duwamish Waterway (Kelley et al. 2011):

> Kelley et al. (2011) conducted a series of 8 to 10 days in situ caged fish exposure studies in the Lower Duwamish Waterway (LDW) each July, over a 4-year period (2004–2007). The exposure period was chosen to be well below previous studies, indicating that residence time in these waters for naturally occurring juvenile Chinook tends to be much greater (ranging from 1 week to 2 months). Among other investigative methods, they used fluorescent aromatic compounds (FACs) in Chinook salmon bile to evaluate the relationship between contaminated sediment and ecological receptors for fish caged in the LDW. At each caged fish location they collected sediment and water sample data. Their findings indicated that biomarkers among field-exposed Chinook were greater than those in control sites. In fact, deoxyribonucleic acid (DNA) adduct analysis indicated there were significant differences between the test subjects and the controls, with the exception of 2007 data, a period when in-water contaminant levels were at their lowest. Further, tissue body burden of yearly mean and the standard error of mean (SEM) polycyclic aromatic hydrocarbon (tPAHs) were significantly different during the 2005 study period when some of the highest tPAHs were detected in water samples (Figure 1), which happened to coincide with the only time total PCBs (tPCBs) were detected in water samples. The findings of Kelley et al. (2011) indicated that juvenile Chinook, occurring for a relatively short period of time in a contaminated estuarine environment, can experience elevated contaminant body burden. Similar conclusions were reported by other authors, indicating that contaminant accumulation by salmonids can occur within freshwater and estuarine systems (Giesy 1999; Meador et al. 2002; Hardy and McBride 2004; Sethajintanin et al. 2004; Fresh et al. 2005; Johnson et al. 2007; Yanagida 2012).

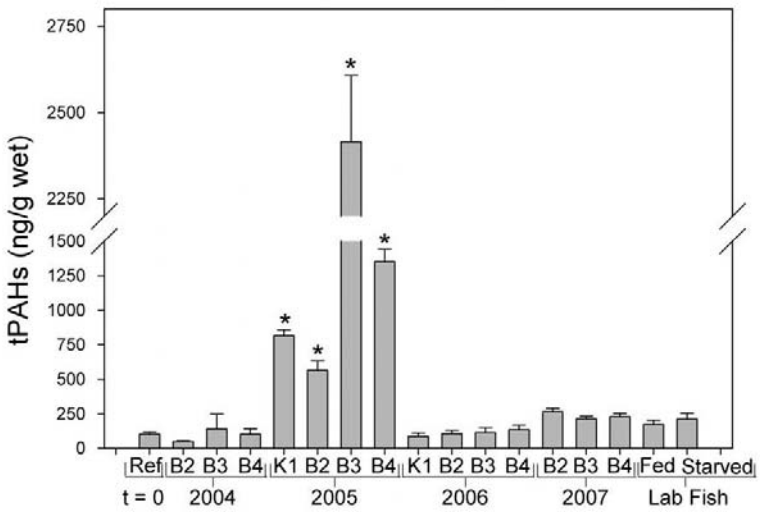

Fig. 5. Mean and SEM total PAHs detected in juvenile Chinook salmon tissue composites, illustrating the significant spike across stations in 2005, following an 8–10 days caged exposure (depending on study year) in the Lower Duwamish Waterway, compared to fish that were not exposed ($t = 0$). Fish that were caged at the Mukilteo lab ± feeding were also included. Typically 3–8 fish per were used per composite and $n = 4$ for each treatment group. *Statistically significant difference from control.

Figure 1. Mean and SEM total PAHs detected in juvenile Chinook salmon tissue composites

Source: Kelly et al. 2011

Studies of uptake, elimination, and late effects in Atlantic Salmon (*Salmo salar*) dietary exposed to di-2-ethylhexyl phthalate (DEHP) during early life (Norman et al. 2007):

> Norman et al. (2007) investigated the uptake, elimination, and late effects in Atlantic salmon where juveniles were exposed to orally administered, and food contaminated with, di-2-ethylhexyl phthalate (DEHP). They found diet was the major route for uptake of lipophilic compounds. In addition, they found that for this compound and its metabolite, salmon were able to excrete the compounds, with body burden concentrations approaching background within one week of exposure. The exposure levels in this study demonstrated that dietary exposure to DEHP could temporarily increase body burden, but if no longer exposed can excrete DEHP to levels more consistent with background, and have no late effects on growth or survival to adulthood. However, they did find that repeated exposure to very high doses that did not allow the fish to return to background levels could alter gonadal development in males.

In situ biomonitoring of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) using biomarkers of chemical exposures and effects in a partially remediated urbanized waterway of the Puget Sound, WA (Browne et al. 2010):

> Browne et al. (2010) investigated the contaminant effects of Duwamish Waterway PAHs and PCBs on caged juvenile Chinook salmon using in situ biomonitoring and molecular biomarker analysis. In July 2007, approximately 20 pre-smolt Chinook were placed in four cages for eight days at adjacent sites in the Duwamish. Biomarkers were compared to control cages of fish at an upstream hatchery. Prior to cage placement, sediment samples were collected and analyzed at the selected cage locations. High concentrations of total PAHs in sediments were detected at one site, whereas two other sites had relatively low concentrations. Waterborne PAHs at all of the sampling sites were relatively low (<1 ng/L). Sediment PCBs at the sites

ranged from a low of 421 ng/g to 1,160 ng/g, and there were no detectable waterborne PCBs at any of the sites (detection limit = 10 ng/L).

Browne et al. (2010) found no significant differences (<0.05) in biomarker gene expression in the Duwamish-caged fish relative to controls, although there was a pattern of gene expression suppression at the most heavily PAH-enriched site. The lack of a marked perturbation of mRNA biomarkers was consistent with relatively low levels of gill PAH-DNA adduct levels that did not differ among caged reference and field fish. Browne et al. (2010) found that there was low bioavailability of sediment pollutants for experimentally caged juvenile Chinook. Their conclusion was that these findings were potentially reflecting low waterborne exposures occurring at contaminated sites within the Duwamish waterway that have undergone partial remediation.

However, a limitation of the Browne et al. (2010) study may be duration of exposure. As the majority of Chinook populations in Puget Sound are ocean-type, fall-run fish, they generally enter estuaries at a smaller size and stay for a longer period than would spring type Chinook. A critical reviewer of this paper may propose an exposure period more consistent with naturally occurring pre-smolt Chinook to determine if the findings of no significant difference of PAHs and PCBs would stand.

Contaminant exposure in outmigrant juvenile salmon from Pacific Northwest estuaries of the United States (Johnson et al. 2007a):

Johnson et al. (2007a) investigated contaminant uptake in out-migrant juvenile salmon in the Pacific Northwest, including concentrations of PCBs, DDTs, PAHs and organochlorine pesticides in tissues and prey of juvenile Chinook and coho salmon from selected estuaries and hatcheries in the U.S. Pacific Northwest. Subyearling Chinook were collected using beach seines from five Washington and seven Oregon bays and estuaries from 1996 to 2001. Additional specimens were collected from hatcheries. Juvenile coho were collected from two Washington and three Oregon estuaries in 1998. In addition to tissue testing, bile metabolites and stomach contents were evaluated.

Johnson et al. (2007a) found that Chinook salmon had the highest whole body contaminant concentrations, typically 2 to 5 times higher than coho salmon from the same sites. Believed to be a function of high lipid content, hatchery Chinook body burdens of PCBs and DDTs were higher than estuarine Chinook salmon. Of the twelve estuaries where sampling occurred, concentrations of PCBs were highest in Chinook salmon from the Duwamish Estuary, the Columbia River, and Yaquina Bay. Each of these systems had fish exceeding the 2,400 ng/g lipid NOAA threshold for adverse health effects on fish. No significant differences were observed in PCB concentrations in coho salmon between sampling sites, though sample size was small.

Johnson et al. (2007a) found DDT concentrations in juvenile Chinook were highest in the Columbia River and Nisqually Estuary. PAH metabolites concentrations in bile were highest in Chinook captured in the Duwamish Estuary and Grays Harbor. When coho and Chinook salmon collected from the same sites were compared, ∑DDT concentrations were much lower in coho salmon. As PCBs, PAHs, and DDTs were consistently present in stomach contents at

concentrations correlated with contaminant body burdens from the same sites, it is believed that contaminants in estuarine food resources contribute to out-migrant body burden.

Persistent organic pollutants in outmigrant juvenile Chinook salmon from the Lower Columbia Estuary, USA (Johnson et al. 2007b):

Johnson et al. (2007b) investigated exposure to several persistent organic pollutants (PAHs, PCBs, DDTs, and other organochlorine pesticides) in out-migrant juvenile fall Chinook salmon in the Lower Columbia River. They also evaluated the potential for adverse effects on salmon and the estuarine food web. Three regions were chosen for the collection of whole body and gut content samples: Columbia River estuary, Longview, and the confluence of the Willamette and Columbia Rivers. Approximately 30 juvenile Chinook were collected via beach seine in the summers of 2001 and 2002. Additional fish were captured using a purse seine in the Columbia River estuary. Chinook captured included a mix of both hatchery and naturally spawned fish. Once captured, fish were sacrificed for whole body and gut content analysis. The entire stomach content was collected post-mortem.

Johnson et al. (2007b) found average whole body concentrations of PCBs in juvenile Chinook ranged from 1,300 to 14,000 ng/g lipid (Figure 2). Average whole body concentrations of DDT were extremely high, ranging from 1,800 to 27,000 ng/g lipid (Figure 3). Whole body PCB and DDT concentrations tended to be associated with fish size, not distribution by river mile (Figures 2 and 3). The authors concluded that this finding was a correlation with estuarine residence time, as larger fish required longer residence time. With respect to prey items collected from gut contents, PCBs, DDTs, and PAHs were all found in salmon stomach samples, indicating that prey is a source of exposure. The authors concluded that since whole body contaminant concentrations were poorly correlated with nearby sediment concentrations, pelagic as well as benthic sources are important in determining salmon exposure. The findings of Johnson et al. (2007b) indicate that concentrations of DDTs and PCBs are elevated in out-migrant juvenile Chinook salmon in the Lower Columbia River, relative to salmon from undeveloped Pacific Northwest estuaries.

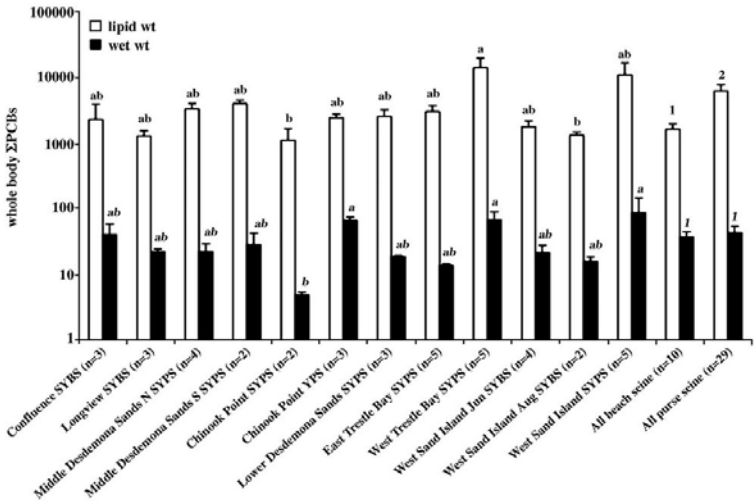

Fig. 4. Mean concentrations (±SE) of ΣPCBs (ng/g wet weight and ng/g lipid) in whole bodies of juvenile chinook salmon collected from the Lower Columbia River and Estuary. Beach seine samples are composites of 5–6 fish each, while purse seine samples are individual fish. Purse seine samples were collected in 2001 and beach seine fish were collected in 2002. Means with different letter designations are significantly different (ANOVA, Tukey–Kramer multiple range test, $p<0.05$); lower-case letters indicate comparisons among sites; upper-case letters indicate comparison between all beach seine and all purse seine fish.

Figure 2. Mean concentrations of total PCBs (ng/g wet weight and ng/g lipid) in whole bodies of juvenile Chinook salmon from the Lower Columbia River and Estuary

Source: Johnson et al. 2007b

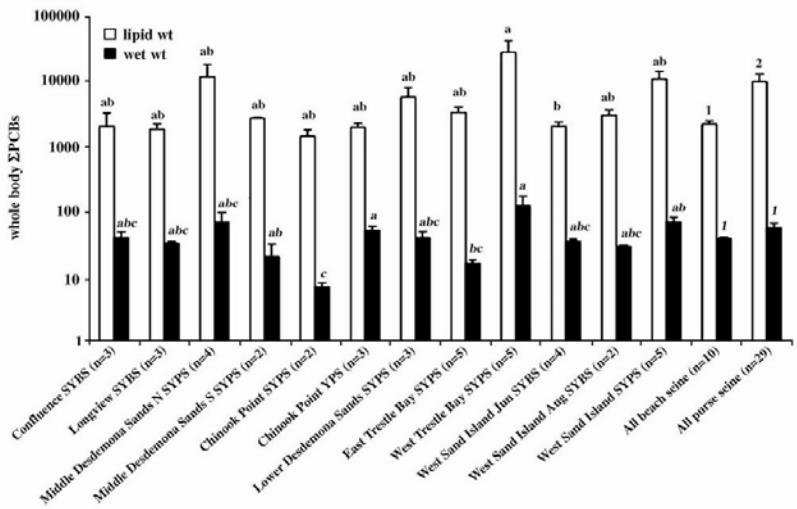

Fig. 6. Mean concentrations (±SE) of ΣDDTs (ng/g wet weight and ng/g lipid) in whole bodies of juvenile chinook salmon collected from the Lower Columbia River and Estuary. Beach seine samples are composites of 5–6 fish each, while purse seine samples are individual fish. Purse seine fish were collected in 2001 and beach seine fish were collected in 2002. Means with different letter designations are significantly different (ANOVA, Tukey–Kramer multiple range test, $p<0.05$); lower-case letters indicate comparisons among sites; upper-case indicate comparison between all beach seine and all purse seine fish.

Figure 3. Mean concentrations of total DDTs (ng/g wet weight and ng/g lipid) in whole bodies of juvenile Chinook salmon from the Lower Columbia River and Estuary

Source: Johnson et al. 2007b

Adult uptake and transfer of contaminants

Lipid reserve dynamics and magnification of persistent organic pollutants in spawning sockeye salmon (*Oncorhynchus nerka*) from the Fraser River, British Columbia (Kelly et al. 2007):

> Though accumulations of salmonid body burdens can and do occur during freshwater and estuarine occurrence of salmonids, the relative proportion of total adult body burden accumulated during juvenile stages has been questioned by some authors (O'Neill and West 2009). Kelly et al. (2007) investigated spawning sockeye salmon in the Fraser River. From June to October of 2001, they collected returning adult fish from as far downstream as 10 km, and as far upstream as approximately 1,200 km. Unfortunately, their complete methodology was not included in the paper, though their target analytes included PCBs and polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). Their study found that the Fraser River is not a major source of sockeye salmon body burden accumulation of PCBs and PCDD/PCDFs, and that marine food sources and pathways are the important factors of persistent organic pollutants (POPs) in returning adults. However, other important findings were that magnification of toxics occurs during the development of eggs. Findings showed a three-fold increase of lipid toxic equivalents (TEQs) in eggs from open-ocean samples to those taken during spawning. This suggests that lipid reserve depletion during upstream migration can increase PCB and PCDD/PCDF concentrations in eggs as the adult fish prepare to spawn.
>
> Kelly et al. (2007) conclude by noting that other globally distributed dioxin-like compounds and/or endocrine disrupting chemicals (EDCs) such as polychlorinated napthalenes (PCNs), polybrominated diphenyl ethers (PBDEs), hexachlorocyclohexanes (HCHs), endosulfans, dialkyl phthalate esters (DPEs), and perfluoroalkyl compounds (PFCs) are undoubtedly present in tissues of these salmon. Should magnification and maternal transfer of these compounds also occur during spawning, toxicological impacts would affect returning adults and early life stage development. Unlike legacy pollutants such as PCBs and PCDD/PCDFs, many of these other current use chemicals of concern can be extensively discharged into urban/agricultural receiving waters such as the Fraser River. Future research should, therefore, focus on accumulation patterns and the cumulative and/or synergistic effects of PCBs, PCDD/PCDFs, and other EDCs of emerging concern on the reproductive health and population dynamics of Pacific salmon.

Acquisition of polychlorinated biphenyls (PCBs) by Pacific chinook salmon: An exploration of various exposure scenarios (Hope 2012):

> Hope (2012) used models to examine 16 different scenarios to identify where Oregon State water quality standards in place for the protection of human health might be effective at reducing PCBs in adult fall Chinook salmon. Model scenarios assumed a 130-day juvenile residency in freshwater, 50-day juvenile residency in estuaries, and adult fall Chinook returning after three to four winters in the ocean (1,860 days). A simplified summary of what Hope (2012) applied includes a bioenergetics model and a bioaccumulation model with estimates of prey consumption rates to estimate contaminant levels in a given fish on a given day at a given location. The model scenarios assumed that prey of adult salmonids included 20 to 60 percent herring, a substantial PCB source for adult Chinook. However, it was not clear if the various model scenarios took into account the region-specific differences in

herring PCB burdens described by West et al. (2008). While acknowledging that interpreting models must be done with caution, Hope (2012) concludes that his model scenarios suggest a limited ability of the Oregon water quality standards to meet the expectation of reducing contaminant loadings in anadromous species (in this case fall Chinook).

Marine distribution, life history traits, and the accumulation of polychlorinated biphenyls in Chinook salmon from Puget Sound, Washington (O'Neill and West 2009):

One of the most important papers for understanding body burden accumulations of Chinook salmon in Puget Sound is O'Neill and West (2009). They focused on three primary objectives; (1) compare PCB levels from Puget Sound Chinook salmon with other West Coast populations, (2) evaluate whether PCB accumulation mainly occurred in the freshwater or marine habitats, and (3) quantify the relative importance of fish age, fish size (fork length), lipid content, and saltwater age (the number of winters spent in salt water) on PCB concentration. Maturing and subadult Chinook salmon were sampled in August and September from 1992 to 1996. Muscle samples (total of 204) were collected from 763 individual Chinook. Only a portion of the fish sampled were of naturally spawning runs, with hatchery fish representing 98 percent of fish that migrated to salt water as yearlings (30 percent of the total fish sampled). An aroclor analysis of the tissues was the selected method.

Though varying widely among samples, average concentration of PCBs measured in samples of skinless muscle tissue from subadult and maturing Puget Sound Chinook salmon was 53 ng/g fish tissue, which was three to five times higher than average concentrations reported for adult Chinook salmon from six other populations on the West Coast of North America (Figure 4) (O'Neill and West 2009). Chinook samples collected in the south and central portions of Puget Sound had the highest average concentrations (Figure 5). Rivers in the northern portion of Puget Sound, while still averaging approximately 40 ng/g, had the lowest concentrations of the seven separate groups within the Puget Sound sampling area (Figure 5).

When comparing regions of body burden accumulation, the analysis of O'Neill and West (2009) indicated that, even in the most highly PCB-contaminated river draining into Puget Sound, the Duwamish River, the vast majority (>96 percent) of PCB accumulation occurred in the marine environment, with little freshwater contribution. They noted that these findings are not surprising, given that Chinook salmon typically gain 99 percent of their total mass in marine habitats. They further estimated that yearling out-migrants (possibly stream-type fish) would acquire a similar percentage (>98.7 percent) of their total mass in marine habitats.

O'Neill and West (2009) found wide variations in contaminant burden for Puget Sound Chinook, suggesting that behavioral differences varied considerably among individual Puget Sound Chinook salmon. Variation may be related to fish size, and diet shifts that occur with size. They suggest that two mechanisms appear to be at work here: (1) growth dilution of PCB associated with the addition of weight accumulated by older fish, and (2) a reduction in dietary PCB inputs associated with feeding on cleaner prey resources offshore for these older Chinook.

That the variation of contaminant burden within Puget Sound is region-specific is an indication that there may be minimal straying, or some geographic isolation that occurs, between north and south sound resident Chinook. Because the pelagic food web in Puget Sound is more heavily contaminated than that in the coastal waters (West et al. 2008),

resident Puget Sound Chinook salmon, particularly those that occur within inner Puget Sound (an urbanized basin), experience a much more contaminated environment than non-resident populations. The urbanization of the inner Sound and the extended residence in these waters for Chinook originating from South Sound tributaries contributes to the findings that fish residing and feeding in central and southern Puget Sound probably would be exposed to higher PCB levels than fish feeding in northern areas of the sound. In an investigation of inland marine herring stocks, a substantial portion of subadult and adult Chinook salmon diets, West et al. (2008) found that Pacific herring from central Puget Sound are more highly contaminated with PCBs than those from northern Puget Sound and the southern Strait of Georgia. As a result, O'Neill and West (2009) conclude that the wide range of PCB levels observed for Puget Sound Chinook salmon reflects their degree of residency and distribution while feeding within the inland marine waters. Although the authors concluded that Puget Sound Chinook PCB burdens appear to be a function of duration of residency and distribution while feeding within the inland marine waters, they also stated that behavioral differences of individual fish with respect to diet, overwintering, and movement within the inland marine waters was not fully understood.

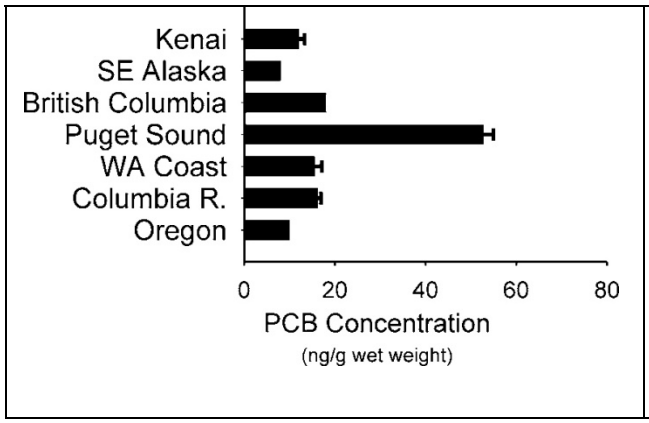

Figure 4. Mean PCB concentration in Chinook salmon fillets

Source: O'Neill and West 2009

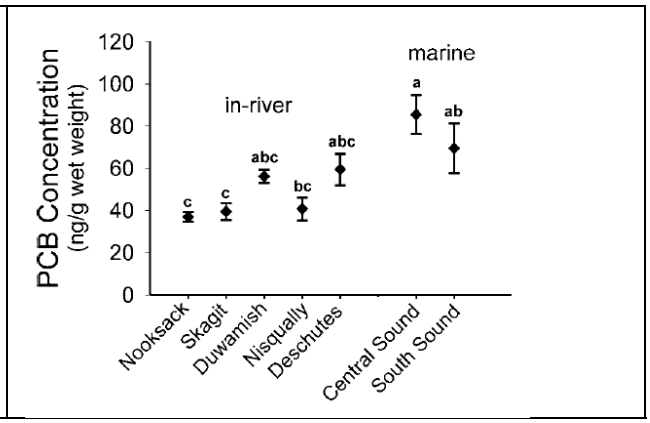

Figure 5. Mean PCB concentration in adult Chinook salmon returning to Puget Sound (in-rivers versus marine waters)

Source: O'Neill and West 2009
Error bars represent standard error around the means.

Persistent organic pollutants in Chinook salmon (*Oncorhynchus tshawytscha*); implications for resident killer whales of British Columbia and adjacent waters (Cullon et al. 2009):

In a study designed to investigate the effects of contaminated food resources for Southern Resident Killer Whales, Cullon et al. (2009) measured POP concentrations in Chinook salmon (*Oncorhynchus tshawytscha*). A total of nine smolts and 24 adult Chinook were collected in 2000 and 2001 over an area ranging from Johnstone Strait to southern Puget Sound, at the Deschutes hatchery. Adult Chinook were collected from the central Strait of Georgia, whereas Washington fish were collected at the mouth of the Duwamish River and at a Deschutes River hatchery. Once collected, samples were prepared and analyzed for stable isotope analysis, contaminant analysis, and lipid determination. Scale analysis showed that all but three of the adult Chinook appeared to migrate to marine waters in their first year.

Table 1. Estimated body burdens of persistent organic pollutants in returning adult Chinook salmon and Chinook smolts

Table 4. Estimated body burdens of persistent organic pollutants in returning adult chinook salmon (*Oncorhynchus tshawytscha*) from Johnstone Strait (n = 6) and Lower Fraser River (n = 6) (British Columbia, Canada); Duwamish River (n = 6) and Deschutes River (n = 6) (Washington, USA); and chinook smolts (n = 6) from the Strait of Georgia (British Columbia, Canada) and Puget Sound (n = 1 pool of 12) (Washington, USA). Body burden estimates calculated using POP lipid weight concentrations and whole fish lipid mass. Values represent mean ± standard error of the mean. One-way analysis of variance (ANOVA) tests were used to assess significant differences (α = 0.05) between the four adult salmon groups (ν = 23) and three adult groups for total dichlorodiphenyltrichloroethane (ΣDDT) and total hexachlorocyclohexane (ΣHCH) (ν = 17). Tukey post hoc tests were used to assess which groups differed (results in italics)

	Body burden (μg) (except for ΣPCDD and ΣPCDF)						
Sum congeners/ isomers[a] Group:	Strait of Georgia smolts	Johnstone Strait adults 1	Lower Fraser River adults 2	Puget Sound smolts	Duwamish River adults 3	Deschutes River adults 4	ANOVA test *(Tukey test)*
ΣPCBs as % returning burden	1.12 ± 0.40	141.54 ± 30.48 99.21%	537.58 ± 99.01 99.79%	0.03	216.32 ± 56.88 99.99%	339.62 ± 108.82 99.99%	0.017 *(1-2)*
ΣPCDDs (ng) as % returning burden	0.13 ± 0.04	8.99 ± 1.44 98.56%	10.14 ± 3.18 98.72%	0.005	5.50 ± 1.34 99.91%	9.76 ± 3.07 99.95%	0.194
ΣPCDFs (ng) as % returning burden	0.21 ± 0.10	8.07 ± 2.30 97.40%	23.94 ± 8.05 99.12%	0.001	8.21 ± 1.87 99.99%	11.48 ± 2.01 99.99%	0.018 *(1-2; 2-3)*
ΣPBDEs	NA[b]	NA	165.75	NA	54.34	NA	ND[c]
ΣDDT[d] as % returning burden	0.15 ± 0.08	24.11 ± 6.30 99.38%	44.46 ± 8.00 99.66%	0.01	107.96 ± 28.08 99.99%	NA	0.003 *(1-3)*
ΣHCH[e] as % returning burden	0.04 ± 0.02	35.01 ± 3.74 99.88%	6.68 ± 1.21 99.40%	0.001	9.32 ± 1.55 99.99%	NA	0.000 *(1-2; 1-3)*

[a] PCB = polychlorinated biphenyl; PCDD = polychlorinated dibenzo-*p*-dioxin; PCDF = polychlorinated dibenzofuran; PBDE = polybrominated diphenyl ether; DDT = dichlorodiphenyltrichloroethane; DDD = dichlorodiphenyldichloroethane; DDE = dichlorodiphenyldichloroethylene; HCH = hexachlorocyclohexane.
[b] NA = not analyzed.
[c] ND = statistical comparison not possible.
[d] ΣDDT includes DDT (*o,p′*-DDT, *p,p′*-DDT), DDD (*o,p′*-DDD, *p,p′*-DDD), and DDE (*o,p′*-DDE, *p,p′*-DDE).
[e] ΣHCH includes (α-, β-, γ-) HCH.

Source: Cullon et al. 2009

Based on their analysis, Cullon et al. (2009) concluded that 97 to 99 percent of PCBs, PCDDs, PCDFs, dichlorodiphenyltrichloroethane (DDT), and hexachlorocyclohexane (HCH) in returning adult Chinook were acquired during their time at sea, not in fresh water or estuaries (Table 1). However, it is important to note that the sample size for this investigation, considering the large area investigated, was very limited. An interesting finding was that even though they were found to have lower lipid concentrations, Chinook collected further south had higher POP concentrations than Chinook sampled in more northern areas.

Thirty years of persistent bioaccumulative toxics in Puget Sound; Time trends of PCBs and PBDE flame retardants in three fish species (West and O'Neill 2007):

West and O'Neill (2007) were interested in evaluating Puget Sound PCB tissue concentration trends in English sole, Pacific herring, and coho salmon. They combined, screened for comparable methodologies, and analyzed Puget Sound Assessment and Monitoring Program (PSAMP) data that had been collected over a 30-year period. As the needs of this issue paper are for salmonid accumulations, a review of the English sole is not presented. However, as herring are an important food resource for salmonids in Puget Sound, their summary is included. Data were regionally organized into North, Central, and South Puget Sound. The analysis of PCB concentrations in herring showed that northern Puget Sound fish had much lower concentrations than those in central and southern portions of the sound. Concentrations of PBDEs in Pacific herring were roughly one-half to one-third of their PCB concentrations, with concentrations from 2001 to 2006 of central Puget Sound herring ranging from 40 to 85 ng/g wet wt., total PBDEs. The authors note that there was no apparent time trend in any stock, as early data were very limited.

The summary review by West and O'Neill (2007) of historic data indicated that PCBs in muscle tissue of coho salmon in central Puget Sound decreased over time from over 200 ng/g wet weight in one composite sample from 1975 to 86 ng/g in 1987, and generally less than 50 ng/g in the 1990s. Data were not presented for coho occurring in southern or northern portions of the sound. In comparison to coho, Pacific herring from central and southern Puget Sound stocks have remained nearly three times that of coho salmon from central Puget Sound. No species analyzed were found to have a reduction in PCBs from 1990 through 2005. West and O'Neill (2007) hypothesized that the lack of a declining trend in PCBs over the past 15 years is the result of biotic recycling of PCBs through the food web.

Spatial extent, magnitude, and patterns of persistent organochlorine pollutants in Pacific herring (*Clupea pallasi*) populations in Puget Sound (USA) and Strait of Georgia (Canada) (West et al. 2008):

West et al. (2008) investigated the geographic distribution and magnitude of three POPs in three Puget Sound populations and three Strait of Georgia populations of Pacific herring. Their summary on herring is included due to the herring's importance as a food resource for selected species of adult salmonids. Methods included mid-water trawls from 1999 to 2004, collecting a total of 1,055 pre-spawn herring for all locations combined. They found Puget Sound herring were 3 to 9 times more contaminated with PCBs, and 1.5 to 2.5 times more contaminated with DDTs, than Strait of Georgia herring (Figure 6). The authors concluded, considering the distinct differences between the populations, that the stocks appeared to be

isolated from each other geographically, allowing for the environmental exposure to contaminants to be regionally expressed. Therefore, although herring represent a mobile source of POPs, they appear to stay regionally isolated. This is relevant to Puget Sound salmonid populations as heavily burdened Puget Sound herring are a notable source of bioavailable POPs in the Puget Sound food web, and their regional distribution may have a corresponding regional effect on their predators, including resident Puget Sound Chinook.

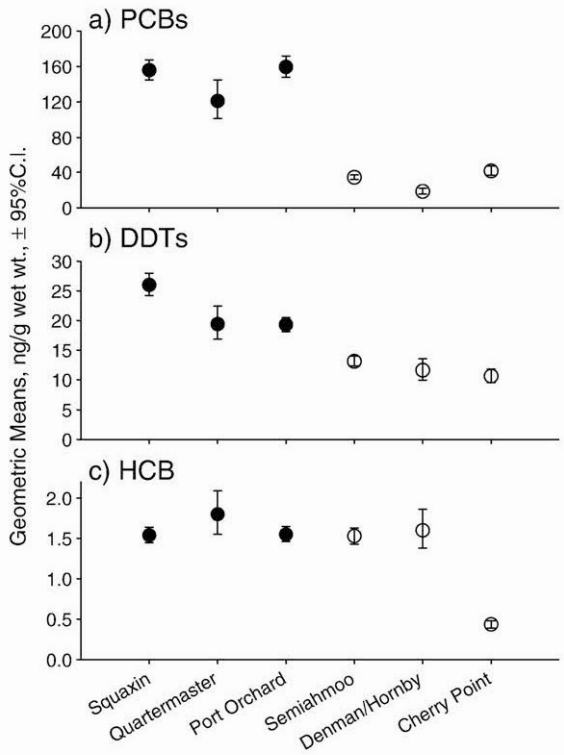

Fig. 2–(a–c). Concentration of a) PCBs, b) DDTs, and c) hexachlorobenzene (HCB) in six herring populations from the Puget Sound (filled circles) and Strait of Georgia (open circles). Symbols indicate geometric means, and vertical bars define 95% confidence intervals.

Figure 6. Concentration of PCBs, DDTs, and hexachlorobenzene in six herring populations from Puget Sound and the Strait of Georgia

Source: West et al. 2008

III. Can salmonid contaminant body burden be attributed to a specific location?

A central question related to site-specific consumption is: can a salmonid's body burden be attributed to a location in which it occurs for a specific time in its life?

The life history strategies of different salmon species, and runs within given salmon species, are highly variable. Life history variation between salmonids begins at a very early age. Slight differences occur between species due to the time it takes for a given egg to hatch, with pre-hatching duration differences affected by environmental conditions, as well as species-specific differences. In general, eggs take some number of weeks to hatch, and the alevins remain in the gravel for a few more weeks until they consume their yolk sac reserves. It is at emergence from the gravel where life history patterns begin to vary substantially between and within species. Some salmon, such as pink, chum, and ocean-type Chinook salmon, migrate downstream within the first few weeks, with some exceptions. Other species, such as stream-type Chinook, coho, and sockeye salmon and steelhead, remain in freshwater streams or rivers to rear for 1 to 3 years before migrating toward marine habitats. The differing behavior within species (e.g., stream-type vs. ocean-type Chinook) illustrates how difficult it is to make generalizations, even within a given salmonid species. Estuarine rearing is also highly variable between and within salmonids, with some species and types rearing for prolonged periods in these habitats, while others spend a few days to a few weeks during their shoreline out-migration. Salmonid food resources are also very different, which is likely a life history strategy that allows co-occurring species to partition the available resources and minimize direct competition. Some salmonids, both as juveniles and adults, use available planktonic food resources, some use epibenthic resources, while others as they grow larger are mainly piscivorous. Age at maturity varies between species; some species (pink salmon) reach maturity at age 2 with little variation. Other species are much more variable, reaching maturity at ages 3, 4, 5, or even 6 years of age (e.g., Chinook and chum).

A few salmonids (Chinook, coho, and pink) that originate from Puget Sound show some form of residency behavior (Laufle et al. 1986; Duffy 2003, 2009; Duffy et al. 2005). All or portions of these runs and/or stocks remain in Puget Sound waters for rearing and maturing, never migrating to coastal or open ocean waters. However, likely because their residency forms are less abundant than their ocean-going forms, much less is known about possible resident coho and pink salmon than resident Puget Sound Chinook. While non-resident Chinook may gain as much as 98 percent of their total weight while in the ocean (Quinn 2005), resident Chinook complete their entire life from egg to returning adult in their natal stream and Puget Sound. Therefore, body burden accumulation for resident Chinook salmon may be an indicator of environmental conditions within Puget Sound.

Due to widely varying life histories, most notably the regions where salmonids occur and their dietary preferences, it is not appropriate to group all salmonids into a single category to serve as site-specific indicators for contaminants. In fact, as a number of authors indicate, almost all salmonids accumulate the vast majority of their body burden at sea; accumulation at juvenile life stages in freshwater and estuarine habitats contributes a very limited proportion of the total accumulation. There is some regional potential, however, for resident Puget Sound Chinook salmon.

It is not surprising that O'Neill and West (2009) found greater than 96 percent of PCB accumulation in Puget Sound Chinook occurred in marine habitats. Even more noteworthy, when taking into account the life history of these fish, is the finding of O'Neill and West (2009) that Puget Sound Chinook have three to five times higher PCB concentrations than those of other west coast populations. Considering that the majority of salmonids originating in Puget Sound are ocean-type, meaning they rear only for a short time in fresh water before migrating to

estuarine and marine habitats, the total mass of a returning resident adult Chinook is primarily obtained in Puget Sound marine habitats. In addition, Puget Sound Chinook return to their natal streams to spawn having spent fewer years in marine habitats than some Chinook populations elsewhere. Therefore, Puget Sound resident Chinook salmon spend less time accumulating contaminants than many other populations, yet have a higher total body burden.

Another factor potentially relevant to this topic, briefly mentioned by a few authors but not investigated in detail, is the lack of understanding of whether there was a threshold response effect on juvenile salmonids exposed to contaminants while in freshwater and estuarine habitats. It is possible that the subadult and adult salmonids sampled for body burden analysis were those fish that did not experience behavioral and physiological abnormalities, post-exposure, that would have reduced their survival to adulthood. In other words, subadult and adult fish sampled may not be entirely representative of the naturally occurring juvenile population.

O'Neill and West (2009) showed that there is regional variation within Puget Sound waters and resident Chinook in more urbanized waters have greater body burdens. These findings suggest that a relationship does exist between contaminants and body burden in these fish. Nonetheless, due to their transient nature, these fish will probably not be able to serve as site-specific indicators. However, a more complete understanding of their duration of residency and distribution while feeding within specific regions of the inland marine waters may enable resident Puget Sound Chinook to serve as region-specific indicators in the future.

Summary

A review of the literature on northeast Pacific Ocean salmon body burden accumulation found that there were very few investigations of the origin of steelhead body burden and contaminants compared to other salmonids. Although other salmonids along the west coast and in Puget Sound have lower body burden concentrations of contaminants, Puget Sound Chinook salmon have elevated PCB levels that appear to correlate with specific regions within Puget Sound. Nearly 22 percent of the maturing and subadult Chinook salmon samples collected from Puget Sound by Meador et al. (2002) had PCB concentrations above an effects threshold identified for salmonid fishes (i.e., 2,400 ng/g lipids), which included endpoints such as reduced growth, altered enzyme and hormone levels, and increased mortality. O'Neill and West (2009) summarized that the most contaminated Puget Sound Chinook salmon in their investigation, believed to be Puget Sound residents, had concentrations comparable to Baltic Sea Atlantic salmon. Only Great Lakes salmon had higher concentrations of PCBs in North America, where Chinook salmon and coho salmon populations in the early 1990s were 20 to 30 times more contaminated with PCBs than the Puget Sound Chinook salmon investigated by O'Neill and West (2009). It is alarming that Puget Sound Chinook spend fewer years in marine habitats than many other salmonids, have a lower fat content in which lipophilic contaminants can be stored than spring-run Chinook, yet have much higher body burdens of PCB contaminants. These observations suggest that the food web within Puget Sound has a much higher concentration of PCBs than other rivers and estuaries in this region.

To understand where, when, and how salmonids accumulate their body burden, it is important to first note their life history, summarized in Section I, *Salmon Life History*. Regional occurrence is important: where do salmon occur over what portion of their life, and what are they doing in a given region that contributes to contaminant uptake (principally, what are they eating?). While there are many differences between salmonids originating from Washington State streams and rivers, salmonid diet and where subadults/adults occur while they are maturing appear to be the most important factors. The dietary resource of a maturing salmon when it is maximizing growth (by mass) appears to be the principal factor for its eventual total body burden. That does not mean that salmonids do not accumulate toxins as fry or smolts, as various authors have shown this occurs. However, relative to the total body burden by the time a salmon reaches a harvestable size, juvenile contaminant uptake does not appear to be a significant factor.

Salmonid diet is important to consider when studying the uptake of contaminants because some salmonids prey on food resources higher up the food chain than others, increasing the total biomagnification. For example, a large portion of the pink and sockeye salmon diet is composed of planktonic invertebrates. By the time these short-lived prey become food resources, they have not lived long enough, or consumed a sufficient number of other prey items, to increase their potential for toxic loads. However, the larger species, notably coho and Chinook, will consume prey items higher on the food chain (e.g., Osmeridae and Clupeidae), increasing their exposure risk. Maturing Chinook salmon, more than any other salmonid, is the most piscivorous. The diet of a subadult or adult Chinook salmon diet includes a substantial amount of fish species, herring (planktivores) in particular. Feeding higher on the food chain may take advantage of a higher caloric resource, but it also means prey items have lived longer (2 to 3 years) and consumed more organisms. As a result, prey resources such as herring have been exposed to more

contaminants and have an elevated body burden (West et al. 2008). For those salmonids preying on herring stocks in Puget Sound and the Strait of Georgia, the volume and origin of their food resources exposes them to the highest risk.

Studies have shown that the region in which a salmonid occurs during its growth from juvenile to subadult to adult is the most important factor for origin of contaminants in a given fish. For those salmonids that mature at sea, at least 96 percent of their POP body burden has been described as originating from oceanic waters. Studies have also shown that salmonids with the greatest burden are those that mature in polluted waters. Although some very small numbers of coho and pink salmon may not migrate to oceanic waters, the stock of greatest note is the resident Puget Sound Chinook. A number of authors showed that tissue analysis of this stock has a much higher body burden than ocean-migrating stocks. In addition, resident Puget Sound Chinook originating from southern Puget Sound tributaries have greater burdens than those to the north.

As noted above in Section III, the life histories of salmonids are too variable between and within species and the habitats they utilize to be used for site-specific evaluation. Ocean-maturing fish accumulate the vast majority of their body burden while at sea. However, for resident Puget Sound Chinook there does appear to be a correlation between salmon body burden and region of occurrence within the inland marine waters. Though the life history of these fish does not make them ideal candidates to serve as site-specific indicators, further understanding of their region-specific differences and origin of burden may enable them to serve as region-specific indicators in the near future.

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