An Evaluation of Potential Impacts of Chemical Contaminants to Chinook Salmon in the Green-Duwamish Watershed

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King County

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Prepared for:

Water Resource Inventory Area 9 Watershed Ecosystem Forum

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Acronyms

μg/Kg	micrograms per kilogram
μg/g	micrograms per gram
CEC	contaminants of emerging concern
cfs	cubic feet per second
CS0s	combined sewer overflows
CSL	cleanup screening level
cy	cubic yard
Ecology	Washington State Department of Ecology
ENR	enhanced natural recovery
EPA	U.S. Environmental Protection Agency
EW	East Waterway
FS	feasibility study
HPAH	polycyclic aromatic hydrocarbon
LDW	Lower Duwamish Waterway
ng/g	nanogram/gram
PAHs	polycyclic aromatic hydrocarbons
PBDE	polybrominated diphenyl ethers
PCB	polychlorinated biphenyls
PPCP	pharmaceuticals and personal care products
RI	remedial investigation
RM	river mile
ROD	record of decision
SCO	sediment cleanup objective
SQS	sediment quality standard
TBT	tributyltin
USGS	United States Geological Survey
WDFW	Washington Department of Fish and Wildlife
WQS	water quality standards
WRIA	water resource inventory area

Executive Summary

The 2005 Green-Duwamish Salmon Habitat Plan identified protection and improvement of sediment quality as a Tier 3 conservation hypothesis for salmon recovery. Although sediment clean-up was hypothesized to benefit Chinook salmon, limited scientific data were available on the potential impacts of sediment contamination on Chinook salmon productivity. Other habitat quality and quantity issues were more well-defined and identified as higher priority needs in the watershed. WRIA 9 commissioned this paper in 2017 – along with several other white papers – to address priority data gaps identified during the scoping of the 10-year update to the Salmon Plan. This paper summarizes research completed since the 2005 Plan was adopted on the potential impacts of chemical contaminants on Chinook salmon productivity in the Green-Duwamish watershed. The information is intended to inform identification and prioritization of recovery needs as WRIA 9 watershed partners update the 2005 Salmon Plan.

Contaminants are carried from sources to surface waters as well as within surface waters, by transport pathways. Contaminants can be carried to the Green-Duwamish receiving waters by point discharges (permitted industrial, stormwater and combined sewer overflows [CSOs] discharges), overland flow (stormwater runoff), groundwater, and direct atmospheric deposition, as well as by spills/leaks and bank erosion. Fish are exposed to chemicals through multiple routes including water passing through their gills and/or its ingestion, direct sediment contact and/or its ingestion, and/or through consumption of contaminated food. The importance of an exposure pathway to a fish is dependent on several variables primarily related to the chemical properties of the contaminant (e.g., hydrophilic, hydrophobic) and the ecology of the species of interest (e.g., diet, benthic or pelagic habits). Generally, water exposure and food consumption are the greatest exposure pathways to Chinook. Because juvenile Chinook spend a longer amount of time in the Green-Duwamish watershed than adult Chinook, their exposure to chemicals and risk of health impact are greater. In addition, juvenile Chinook are feeding during this period and consuming prey that are potentially contaminated.

Metals such as aluminum and selenium, have low toxicity under typical environmental conditions. Several other metals, such as copper, chromium, and lead, share similar acute symptoms resulting from disturbance of homeostasis. However, chronic exposure symptoms range widely from neurological and reproductive to sensory system and immune system impacts. Common classes of organic contaminants include pesticides, pharmaceuticals, phthalates, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers (PBDEs). Three commonly detected organic chemical contaminants in the Puget Sound Region are PCBs, PAHs, and PBDEs. There is a wide variety of possible health effects in fish from organic chemical exposure.

The available ambient water, sediment, and Chinook salmon tissue chemistry and sediment bioassay data collected in the Green-Duwamish watershed and the ecological assessments that use these data are reviewed in this report. Key information found from this review includes:

Observations of potential impacts of contaminants

- Chinook salmon return rates are substantially lower in contaminated estuaries, like the Duwamish, compared to uncontaminated estuaries.

Tissue chemistry/biomarkers

- Lower Duwamish Waterway (LDW) and East Waterway (EW) risk assessments did not identify risk of impaired growth or survival for juvenile Chinook salmon. However, the LDW risk assessment noted reduced immunocompetence may occur in juvenile Chinook migrating through the LDW.
- Subsequent studies, using more conservative assumptions, concluded PCBs may be causing health impacts in Chinook salmon.
- The risks of impacts to Chinook salmon from Chemicals of Emerging Concern (CECs) are unknown although these chemicals are likely present in wastewater discharges, and to a lesser degree stormwater discharges to the Green/Duwamish watershed.
- Relatively little juvenile Chinook tissue data have been collected or evaluated in the Duwamish Estuary in the last 10 years, and less data are available for the Green River. Tissue chemistry data indicate juvenile Chinook salmon are bioaccumulating contaminants while in the Duwamish Estuary. Tissue assessments suggest that PCB exposure may be causing sublethal adverse effects to juvenile Chinook salmon.

Sediment

- In the most contaminated areas of the LDW and EW, contaminated sediments are potentially impacting benthic invertebrates which could reduce the quantity or quality of food for juvenile salmon.
- Juvenile Chinook salmon in the Duwamish Estuary are exposed to sediments contaminated with PCBs, PAHs, some metals, and phthalates.
- In the Duwamish Estuary, PCBs are the most widespread sediment contaminant. Sediment contaminants in the Green River need more characterization. Based on existing data, sediment contamination is highest in Mill (in Kent) and Springbrook creeks and may be a concern to benthic invertebrates. Mill Creek (in Auburn) is less contaminated, and Jenkins, Newaukum, Covington, or Big Soos creeks are of little concern. Arsenic and BEHP concentrations most frequently exceeded the no-effects benthic sediment cleanup level (SCO) in Green River tributaries.
- Superfund cleanup of contaminated sediments will be an important step in reducing the exposure of aquatic life including Chinook salmon to contaminants, particularly PCBs. Sediment recontamination will remain a risk from dredging activities during cleanup of the LDW and EW.

Water chemistry

- Several water quality assessments have not identified any chemicals that are presenting notable risk to aquatic life. Of the chemicals investigated, mercury in water may be a chronic exposure risk for juvenile Chinook salmon in the Green River.

While tracking the LDW cleanup schedule, it is recommended that further direct work on Duwamish Estuary Chinook salmon be supported by the WRIA 9 group. Work completed before cleanup begins on the LDW and EW will provide a foundation for comparison with future data to measure how juvenile Chinook health and contaminant impacts change over time. This work will be most efficiently directed at Chinook diet and tissue chemistry, biomarkers and sublethal effect measurement and improvement of Chinook-specific effect thresholds.

In addition to ongoing support for cleaning up contaminants in sediments and limiting future contaminant transport to surface waters, specific recommendations for future work include:

- Conduct studies that measure contaminants in juvenile Chinook tissues and stomach contents at different life stages or residence times; e.g., in rearing habitat for Chinook, in restored habitat project areas, and where tributaries enter the Green River. This work will strengthen the small dataset available for risk evaluation.
- Focus new studies on contaminants known to be elevated in the Duwamish Estuary and for which substantial effects data are published for some salmonids (PCBs, PAHs) and opportunistically explore CECs, such as pharmaceuticals, in water and Chinook salmon to build a chemistry database. CEC analysis is costly, effects analysis tools are lacking, and substantial new data are necessary to begin risk evaluation for Chinook. Therefore, prioritizing known contaminants first will optimize resources.
- Establish one or more new tissue effect thresholds for PCBs that are Chinook-specific. Effects thresholds are a tool that allow chemistry results to be placed into the context of toxicity. PCBs are the most widespread contaminant in the Duwamish Estuary. Outside of Superfund risk assessments, there is only one published PCB effect threshold that has been developed to assess Chinook in this region. Given the highly variable assumptions made in defining an effects threshold, developing one (or more) new PCB thresholds would provide a more stable foundation for evaluating how PCBs are affecting Chinook survival.
- Support studies that examine other effects evidence (e.g., juvenile Chinook bioassays with Duwamish sediments, biomarkers) by providing in-kind or financial assistance. In addition to the types of evidence recently collected for Chinook salmon (tissue and stomach content chemistry concentrations), work on other lines of evidence that can demonstrate occurrence of contaminant effects. For example, encourage National Oceanic and Atmospheric Administration or Washington Department of Fish and Wildlife to conduct laboratory exposure of salmon for PCB, PBDE, PAH effect endpoints using Duwamish sediments.
- Tease out cause(s) of lower smolt-to-adult return (SAR) by collecting juvenile salmon when they leave the Duwamish Estuary and measure body mass, nutrition and stomach contents and compare to mass of Chinook salmon at release from hatcheries. This would test if food quality (e.g., benthic invertebrates) between hatcheries and Duwamish Estuary mouth may be reducing juvenile health and decreasing SAR.

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1.0 INTRODUCTION

The 2005 Green-Duwamish Salmon Habitat Plan identified protection and improvement of sediment quality as a Tier 3 conservation hypothesis for salmon recovery. Although sediment clean-up was hypothesized to benefit Chinook salmon, limited scientific data were available on the potential impacts of sediment contamination on Chinook salmon productivity. Other habitat quality and quantity issues were more well-defined and identified as higher priority needs in the watershed. WRIA 9 commissioned this paper in 2017 – along with several other white papers (Engel et al., 2017, Higgins 2017, Kubo 2017) – to address priority data gaps identified during the scoping of the 10-year update to the Salmon Plan. It summarizes research completed since the 2005 Plan was adopted on the potential impacts of chemical contaminants on Chinook salmon productivity in the Green-Duwamish watershed. The information is intended to inform identification and prioritization of recovery needs as WRIA 9 watershed partners update the 2005 Salmon Plan.

This report does not critique individual studies for the strength of their study design or sampling or analytical methods. This report does review the type and quantity of information available from published sources with the intent of summarizing any available evidence that Chinook salmon may be adversely affected by toxic contaminants as well as describing where the largest knowledge uncertainty lies.

The concepts of contaminant transport and exposure pathways are defined to provide context and general information on the potential health effects of specific metals and some common organic chemical contaminants in fish is included. Then, summaries are provided of available chemical contaminant and biomarker data measured in Green-Duwamish watershed water, sediment, and aquatic biota including evaluations of their impacts to Chinook salmon and/or their prey. Recent and thorough data compilations have been completed for water and sediment data and are used for efficiency. Relevant findings for Chinook salmon from Superfund ecological risk assessments are also included. There are several ongoing Green-Duwamish watershed policy programs and initiatives which have potential to influence or spawn new actions that influence contaminant sources or cleanup. These programs/initiatives are briefly described.

The majority of available contaminant information for the Green-Duwamish watershed comes from the Duwamish Estuary[1] because of investigations completed in the Lower Duwamish Waterway (LDW) Superfund Site and the West Waterway and East Waterway portions of the Harbor Island Superfund Site. The LDW Remedial Investigation (RI) was initiated in 2001 and completed in 2010 (Windward 2010) and the Feasibility Study (FS) was completed in 2012 (AECOM 2012). EPA released the Record of Decision (ROD) in 2014 (EPA 2014). Concurrently over this period, cleanup actions occurred in three of five Early Action Areas containing the highest levels of contamination. The LDW site is currently in pre-design phase before the remaining cleanup begins. A No Action Decision for the West

[1] The Duwamish Estuary includes the Lower Duwamish, East, and West Waterways.

Waterway unit of the Harbor Island Superfund Site (West Waterway) was issued by EPA in 2003 which did not require remediation for this site (EPA 2003). A supplemental RI was completed for the East Waterway unit in 2014 (Windward and Anchor QEA 2014). The draft East Waterway FS was completed in 2016 (Anchor and QEA 2016) and will be finalized in 2018 (pers. comm. Williston 2017).

Relatively little information is available across the entire Green-Duwamish watershed regarding how chemical contamination impacts Chinook salmon. Therefore, information is also presented as it relates to salmon or fish in general to provide context regarding the overall level of contamination in the watershed. There are studies that characterize chemical concentrations in water and sediment but these have not been tied directly to salmon impacts. Potential benthic community effects have been assessed with sediment chemistry and bioassay data. Most of the available data are for sediments in the Duwamish Estuary because sediments are considered the key medium of contamination driving human health and ecological risk in the respective Superfund sites. Studies that have measured contaminants in juvenile Chinook salmon are limited. In addition, data from a small number of studies are available that have investigated potential adverse health effects of contaminants in the Duwamish Estuary on salmon. Contaminant information from these studies is summarized within this report.

2.0 CONTAMINANT PATHWAYS

Contaminants are carried from sources to surface waters and also within surface waters, by transport pathways. Understanding which chemical transport pathways are most important assists in prioritization of sources. Once present in fish habitat, fish may be exposed to contaminants in various ways, some of which depend on their diet and behavior. The level of impact that contaminants have on Chinook salmon or other organisms is dependent on how the fish is exposed (i.e., the exposure pathway), contaminant quantity (i.e., dose) and the duration of exposure. The conceptual transport and exposure pathways for fish in the Green-Duwamish River are summarized below; these concepts are used throughout the document to discuss how chemical contaminants may affect salmon in the Green-Duwamish watershed.

2.1 Transport Pathways

Contaminants can be carried to the Green-Duwamish receiving waters by point discharges (permitted industrial, stormwater and combined sewer overflows [CSOs] discharges), overland flow (stormwater runoff), groundwater, and direct atmospheric deposition (Figure 1) as well as spills/leaks and bank erosion. Once in the Green-Duwamish River watershed, contaminants can be transported geographically or within the food web by different mechanisms such as tidal currents, sediment resuspension by vessel traffic, and trophic transfer (i.e., through the food web). Transport pathways are not sources themselves, but routes by which contaminants are moved from sources to receiving waters or between different geographic areas of receiving waters.

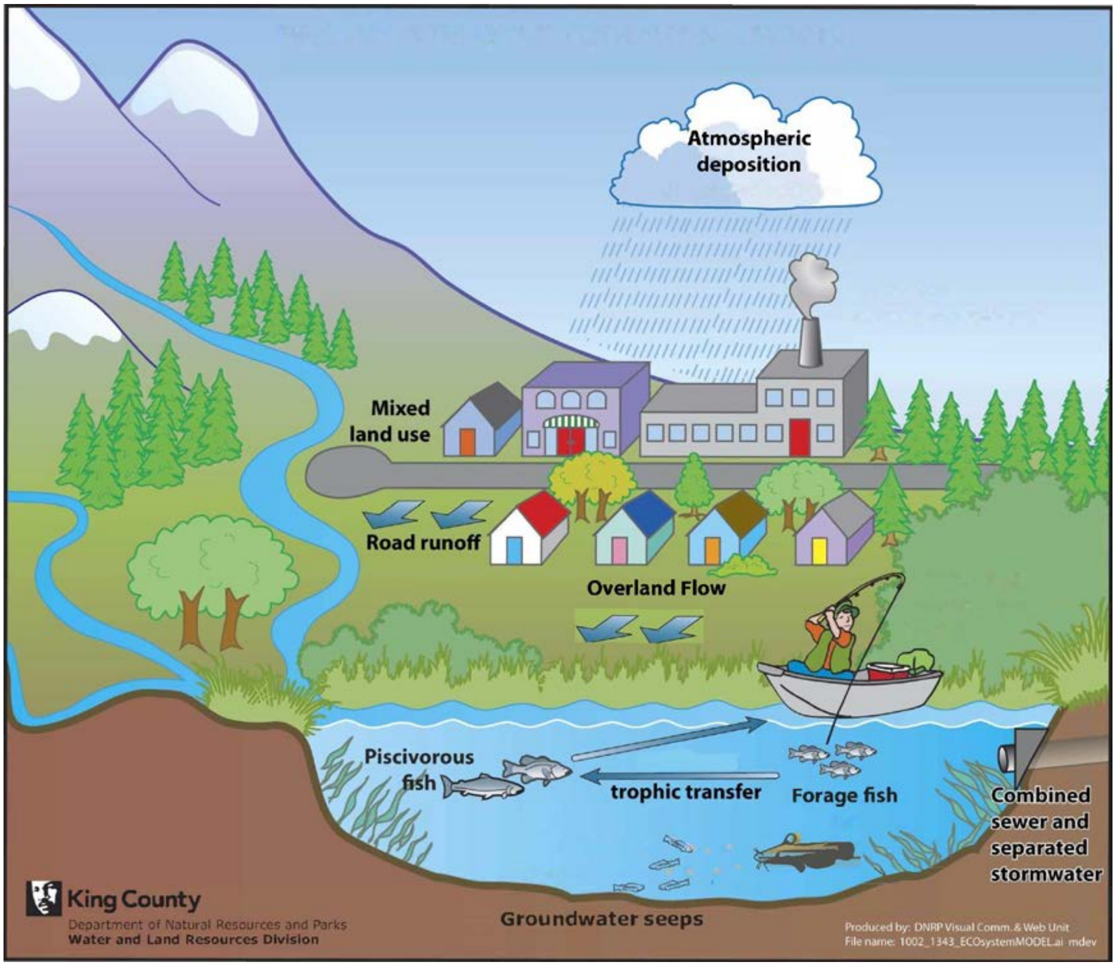

Figure 1. Conceptual transport pathways to Green-Duwamish River

2.2 Exposure Pathways

Fish are exposed to chemicals through multiple routes including water passing through their gills and/or its ingestion, direct sediment contact and/or its ingestion, and/or through consumption of contaminated food. The importance of an exposure pathway to a fish is dependent on several variables primarily related to the chemical properties of the contaminant (e.g., hydrophilic, hydrophobic) and the ecology of the species of interest (e.g., diet, benthic or pelagic habits).

For example, polychlorinated biphenyls (PCBs) are a group of chemicals that do not readily dissolve in water and tend to bind to solids due to their chemical properties. Therefore, PCBs tend to associate with sediments and accumulate in fish species that have close contact with the river bottom and/or consume benthic prey. These species experience higher exposure than those that reside in the water column and consume plankton or plants. These hydrophobic properties of PCBs result in their affinity for fatty tissue and their propensity to bioaccumulate. Therefore, fish that are piscivorous (i.e., consume other fish) tend to accumulate more PCBs than planktivorous or insectivorous fish.

Chinook salmon are not a demersal species (i.e., one living on bottom sediments) like English sole. Thus, direct contact with contaminated sediments is likely a relatively minor pathway. In general, water ingestion through feeding or respiration and food ingestion are primary exposure pathways for any life stage of Chinook salmon. Incidental sediment ingestion through feeding may be an important pathway for juvenile Chinook depending on their feeding strategy. Studies throughout Puget Sound indicate that juvenile Chinook are opportunistic feeders in estuarine and marine waters, appearing to feed on a wide variety of prey as opposed to showing clear preferences for a specific category of prey (e.g., plankton) like other juvenile salmon species (Fresh 2006; Nelson et al. 2013; Figure 2). Stomach contents of juvenile Chinook from the Duwamish Estuary sometimes contain mainly terrestrial insects (Morley et al. 2012) or annelid worms, midges and bivalve siphons (David et al. 2015, Cordell et al. 2006). Directly targeting benthic instead of pelagic food would increase contaminant exposure of Chinook salmon from incidental ingestion of sediment. Juvenile Chinook may shift their diet as different prey become available which would also shift significance of their food and sediment exposure pathways. The importance of the sediment ingestion pathway to juvenile Chinook is uncertain in the Green-Duwamish watershed and likely variable in space and time. Risk assessments for juvenile Chinook may conservatively assume their prey is 100% benthic invertebrates because this results in higher contaminant exposure from food ingestion than from assuming a plankton diet. Potential exposure pathways of juvenile Chinook in streams and rivers are illustrated in Figure 3.

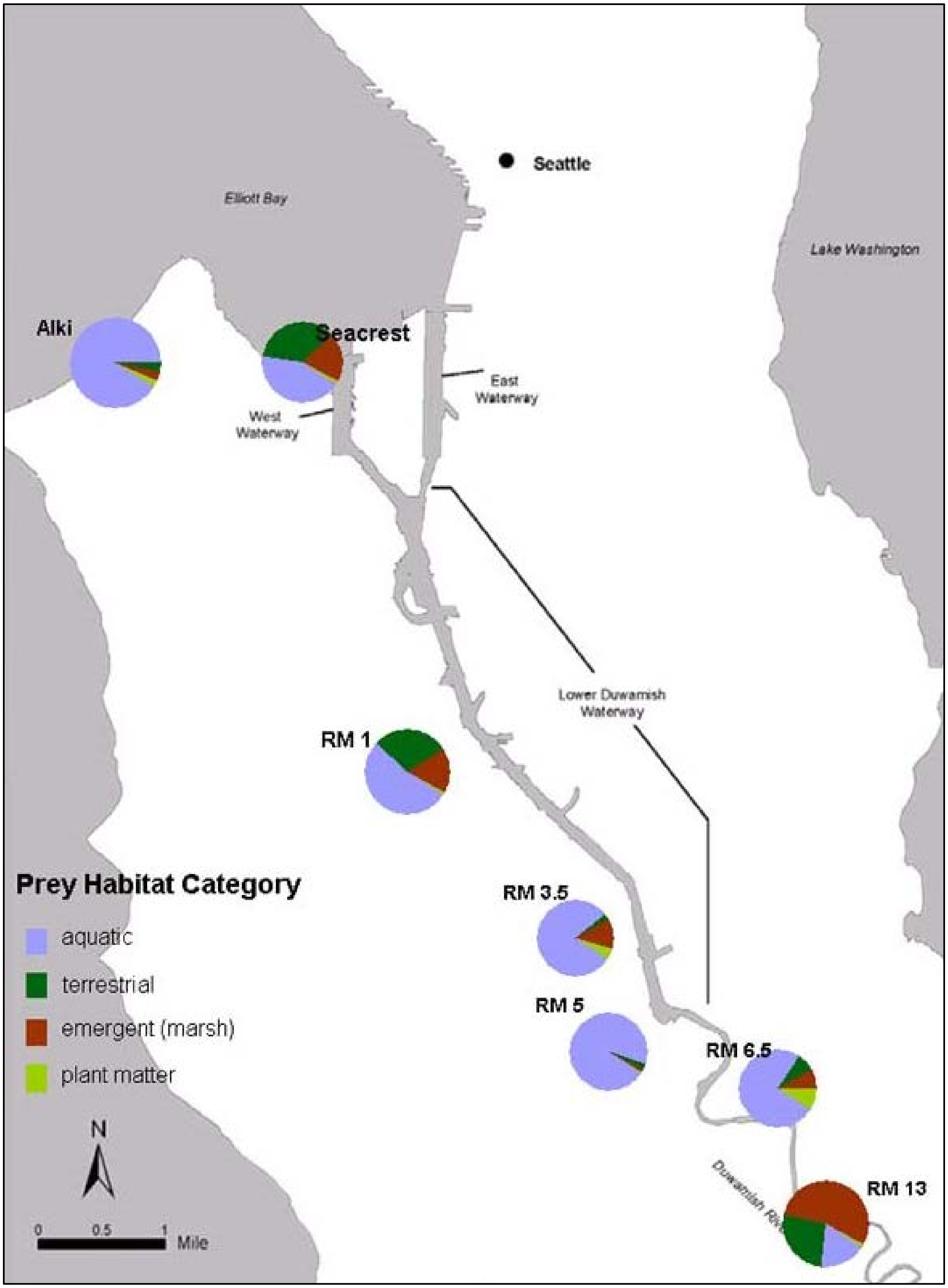

Figure 2. Invertebrate prey categories of juvenile Chinook salmon (n=321) from seven Duwamish Estuary locations (Nelson et al. 2013)

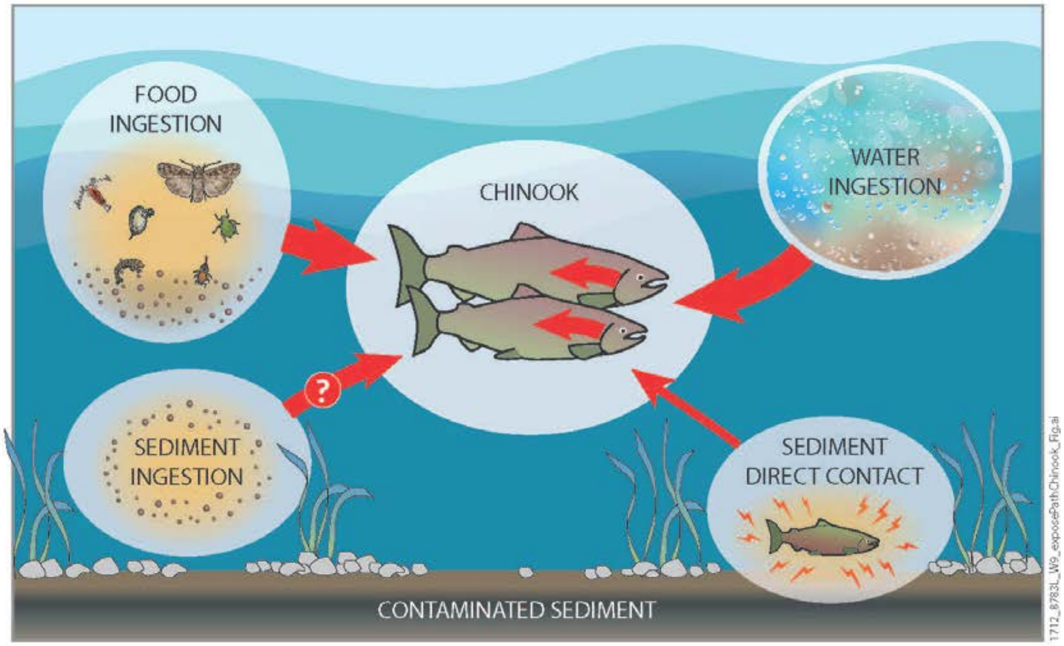

Figure 3. Contaminant exposure pathways to juvenile Chinook salmon. Arrow thickness denotes relative importance.

Life stage is a key factor that determines which exposure pathways are most important for salmon. The different life stages of Chinook salmon have varied feeding strategies and residence times. Adult Chinook salmon in the Green-Duwamish watershed are returning to spawn, no longer feeding and cumulatively spend relatively little time (i.e., 3–5 months) in the watershed (Engel et al. 2017). Juvenile Chinook salmon spend months to 1+ years in the Green River and days to months in the Duwamish Estuary (Figure 4). Also, juvenile Chinook consume a diet of benthic invertebrates and some zooplankton and terrestrial insects (Cordell et al. 2006), giving them greater dietary exposure, as well as residence time, than adult Chinook in the Green-Duwamish watershed.

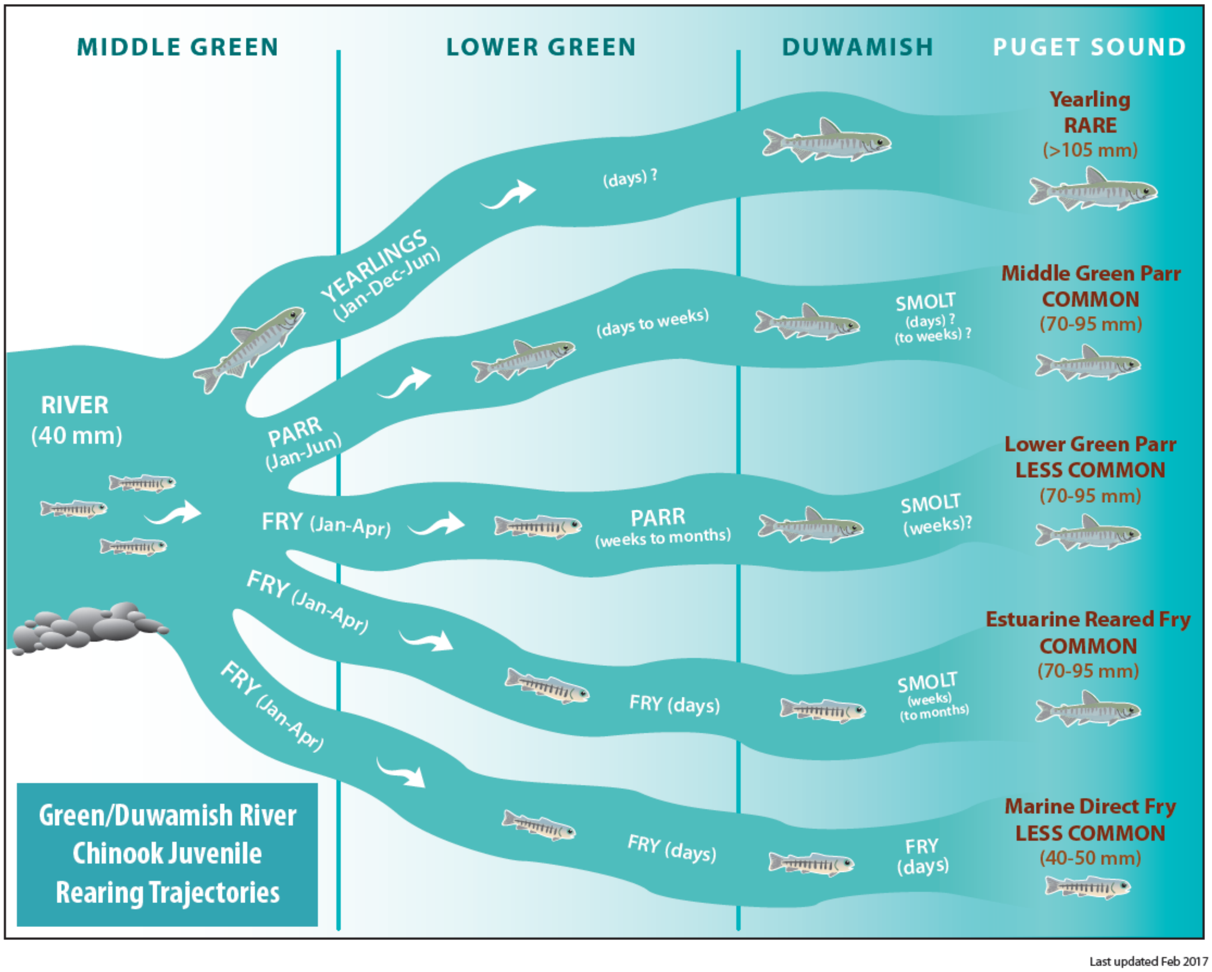

Figure 4. **Juvenile Chinook salmon residence times in the Green-Duwamish River (modified from Ruggerone and Weitkamp 2004)**

3.0 CONTAMINANT INFORMATION

This section provides a summary of contaminant concentrations measured in watershed media and evaluations of their risks to Chinook salmon through direct and indirect exposure pathways.

3.1 Background on Health Effects of Chemical Contaminants to Fish

Chemical contaminants can cause a variety of adverse effects in fish. Metals and organic chemicals are discussed separately in this section due to differences in their behavior and chemical properties, and, therefore, toxic effects. The following information applies to fish in general unless a particular species is mentioned. Mechanisms of acute toxicity and adverse effects of chronic exposure described here are primarily taken from a comprehensive review by Wood et al. (2012a and b) for metals and several local studies for organic chemicals. The mechanisms of metals toxicity in Chinook salmon and other marine/anadromous fish are not well understood (Wood 2012) but are informed by research on freshwater fish. Chinook salmon and other salmonids may be more or less sensitive to contaminants than freshwater species. Information specific to Chinook salmon are provided in this section, where available, particularly from local studies. However, an extensive literature search was not conducted on this topic. Therefore, this summary is not comprehensive and additional specific studies on adverse effects may be available for Chinook salmon. This information is intended to provide a general guide on health effects to fish.

Metals commonly measured as potential environmental contaminants from human sources include aluminum, arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, and zinc. All metals are naturally occurring but also have human sources. Some metals are essential, meaning they are necessary for biological life in small amounts; some are non-essential. Both types can be toxic to fish, but non-essential metals are more toxic (e.g., cause effects at lower levels). Metals in aquatic ecosystems can be in free, dissolved form (most bioavailable) or bound to solids (least bioavailable). Table 1 outlines some common sources and adverse effects of different metals on freshwater fish. Metals such as aluminum and selenium, have low toxicity under typical environmental conditions. Several other metals, such as copper, chromium, and lead, share similar acute symptoms resulting from disturbance of homeostasis but range widely in their chronic symptoms from neurological and reproductive to sensory system and immune system impacts.

Organic chemicals are those that contain carbon. The number of possible environmentally present organic contaminants outnumbers the possible metals contaminants by orders of magnitude. Common classes of organic contaminants include pesticides, pharmaceuticals, phthalates, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers (PBDEs). Three commonly detected organic chemical contaminants in the Puget Sound Region are PCBs, PAHs, and PBDEs. There is a wide variety of possible health effects in fish from organic chemicals. See Table 1 for examples of adverse effects caused by exposure to these compounds. Ionic imbalance refers to problems with osmoregulation with the surrounding waters, usually due to interruptions of ion pumps located in the gill.

Table 1. Common sources of common metals and organic chemical contaminants and their adverse effects on freshwater fish.

Contaminant	Naturally Occurring?	Common Non-natural Sources	Symptoms with Acute Mortality	Primary Chronic Exposure Effects
Aluminum	Yes	Mining, aerospace, many consumer products (Wood et al. 2012b).	Only in extreme pH: ionic imbalance, respiratory disturbance (Wood et al. 2012b).	Same as acute (Wood et al. 2012b).
Arsenic	Yes	Mining, smelter emissions (e.g. Asarco), treated wood, roofing materials (Wood et al. 2012b, Norton et al. 2011).	Acute mechanism not well understood in fish (Wood et al. 2012b).	Decreased growth rate, possible reproductive effects (Wood et al. 2012b).
Cadmium	Yes	Mining, smelting, roofing materials (Wood et al. 2012b, Norton et al. 2011).	Ionic imbalance, respiratory disturbance (Wood et al. 2012b).	Ionic imbalance, oxidative stress, possible reproductive impairment (Wood et al. 2012b).
Chromium	Yes	Pulp processing, electroplating, and products (e.g., stainless steel, spray paint) (WDOH 2017).	Mucus overproduction, ionic imbalance, respiratory disturbance (Wood et al. 2012a).	Spinal deformities, anemia, neurological damage and possible growth reduction (Wood et al. 2012a).
Copper	Yes	Mining, pesticides, fertilizers, brake pads, boat paint, roofing materials (Wood et al. 2012a, Norton et al. 2011).	Ionic imbalance, sensory impairment, reduced swimming speed (Wood et al. 2012a).	Reproductive impairment, general health decline from detoxification (elimination of toxins from body), oxidative stress (reactive oxygen damage repair), sensory impairment (smell and lateral line), immune suppression (documented in Chinook salmon) (Wood et al. 2012a).

Contaminant	Naturally Occurring?	Common Non-natural Sources	Symptoms with Acute Mortality	Primary Chronic Exposure Effects
Lead	Yes	Ammunition, lead shot, wheel weights, fishing sinkers, aviation fuel combustion (Norton et al. 2011).	Hypocalcemia and ionic imbalance (Wood et al. 2012b).	Reproductive impairment, general health decline from detoxification (elimination of toxins from body), oxidative stress (reactive oxygen damage repair), sensory (smell and lateral line) impairment, immune suppression, and mortality (Wood et al. 2012b).
Mercury	Yes	Thermostat and fluorescent lamp disposal, mining, smelters, industrial/commercial emissions, petroleum refineries (Wood et al. 2012b, Norton et al. 2011).	Breakdown of neural functions, and other physiological issues (Wood et al. 2012b).	Gonad growth impairment, spawning inhibition, reduced growth, gill damage, ionic imbalance, impaired digestion, nerve/brain damage, organ tissue damage (Wood et al. 2012b).
Nickel	Yes	Stainless steel, batteries, many consumer products, building materials, inks/dyes, electroplating, medical equipment (Wood et al. 2012a).	Loss of magnesium balance in kidneys, mortality (Wood et al. 2012a).	Reduced egg hatchability, organ tissue damage, respiratory distress (Wood et al. 2012a).
Selenium	Yes	Metals mining, fossil fuel refinement and use (EPA 2016).	Not seen in environment due to low acute toxicity (Wood et al. 2012a).	Developmental deformities (Wood et al. 2012a).
Zinc	Yes	Mining, galvanized steel and other metal products, roofing materials, tire wear (Wood et al. 2012a, Norton et al. 2011).	Calcium imbalance and mortality (Wood et al. 2012a).	Calcium imbalance, reduced growth, possible reproductive impairment (Wood et al. 2012a).
PCBs	No	Transformers, light ballasts, recyclers, paint, caulk, pigments (Ecology 2015).	Can’t accurately assess due to low solubility (Stalling and Mayer 1972.	Immune suppression (Arkoosh et al. 2001), reduced reproductive success, mortality (Eisler and Belisle 1996).

Contaminant	Naturally Occurring?	Common Non-natural Sources	Symptoms with Acute Mortality	Primary Chronic Exposure Effects
PAHs	Yes	Wood smoke, creosote-treated wood, vehicle emissions (Norton et al. 2011).	Not fully understood; cardiotoxicity of embryos (Incardona and Scholz 2005).	*English sole*: liver cancer and other liver disease, gonad development failure, inhibited ovarian development, reduced spawning success, disorientation, and mortality. *Juvenile Chinook*: reduced growth, embryo developmental abnormalities, cardiovascular problems, and immune suppression (Johnson et al. 2008).
PBDEs	No	Flame retardants on plastics, upholstery and foam (Ecology 2006).	Not applicable. PBDEs are not an acute contaminant.	Endocrine disruption, disease susceptibility (Arkoosh et al. 2010).

3.2 Chemical Contaminants in Water

Several studies have measured water chemistry in the Green River and Duwamish Estuary. Some of these studies have compared concentrations to Washington State water quality standards (WQS) for aquatic life. However, while the WQS are generally protective of 95% of aquatic species, and utilize salmonid data when available, they are not specific to Chinook salmon. Thus, WQS may be more or less protective of Chinook salmon. Therefore, these comparisons are general indications of water contamination. The results summarized below indicate which chemicals may potentially impact Chinook salmon in the Green-Duwamish watershed.

3.2.1 Duwamish Estuary

From 2009 to 2011, Ecology measured pesticides (weekly from March to September) in several Western WA streams including one in the Green-Duwamish watershed: Longfellow Creek (Ecology 2013). Few pesticides were detected in Longfellow Creek, but herbicides were most common (dichlobenil, trichlopyr, 2,4-D). Concentrations were compared to WQS, pesticide registrations toxicity criteria, and EPA National Recommended Water Quality Criteria (EPA 2006) for aquatic life. Only methiocarb (insecticide) concentrations in some samples showed the potential to be sublethally toxic to invertebrates. The study concluded toxic impacts to invertebrates could have population-level effects and reduce food availability for juvenile salmon.

3.2.2 Duwamish Estuary and Middle Green River

King County reviewed available water concentration data in the Green River and Duwamish Estuary published between 2000 and 2013 (King County 2017a). Locations for these water data are in Figure 5, except for 5 stations sampled in the East Waterway (EW) in 2008/2009 (Windward 2009). See Windward (2009) or Appendix C of King County (2017) for the mapped locations of these EW stations. Some of these datasets go as far back as the 1970s (Table 2). All samples were collected by King County, Ecology, or the East Waterway Group. More than 150 samples were analyzed for metals and other chemicals. The Lower Duwamish, East, and West Waterway data were compared to marine acute and chronic criteria due to their estuarine salinity; the Green River data were compared to freshwater acute and chronic criteria. Five samples exceeded freshwater chronic aquatic life standard for one metal (total mercury) in the Green River (GR 11.1, GR 40.6, GR 63.1) (Figure 5; Table 3). One East Waterway sample also exceeded the chronic aquatic life standard for total mercury (at EW-SW-1). One East Waterway sample exceeded the chronic aquatic life standard for tributyltin (TBT) (at EW-SW-2). No other metals exceeded aquatic life criteria. Detected organic chemicals included triclopyr (pesticide), estrone, 4 nonylphenol, and bis(2-ethylhexyl)adipate (endocrine disruptors), PAHs, PCB congeners, one dichlorobenzene, aniline, benzoic acid, benzyl alcohol, caffeine, phenol, and N-nitrosodimethylamine. However, all of these chemicals were infrequently detected except for PAHs and PCBs. It should be noted that when analyzed by the most sensitive method, PCBs are usually detected at some level in ambient waters because they are a ubiquitous contaminant. For organic chemicals with aquatic life criteria, none were exceeded.

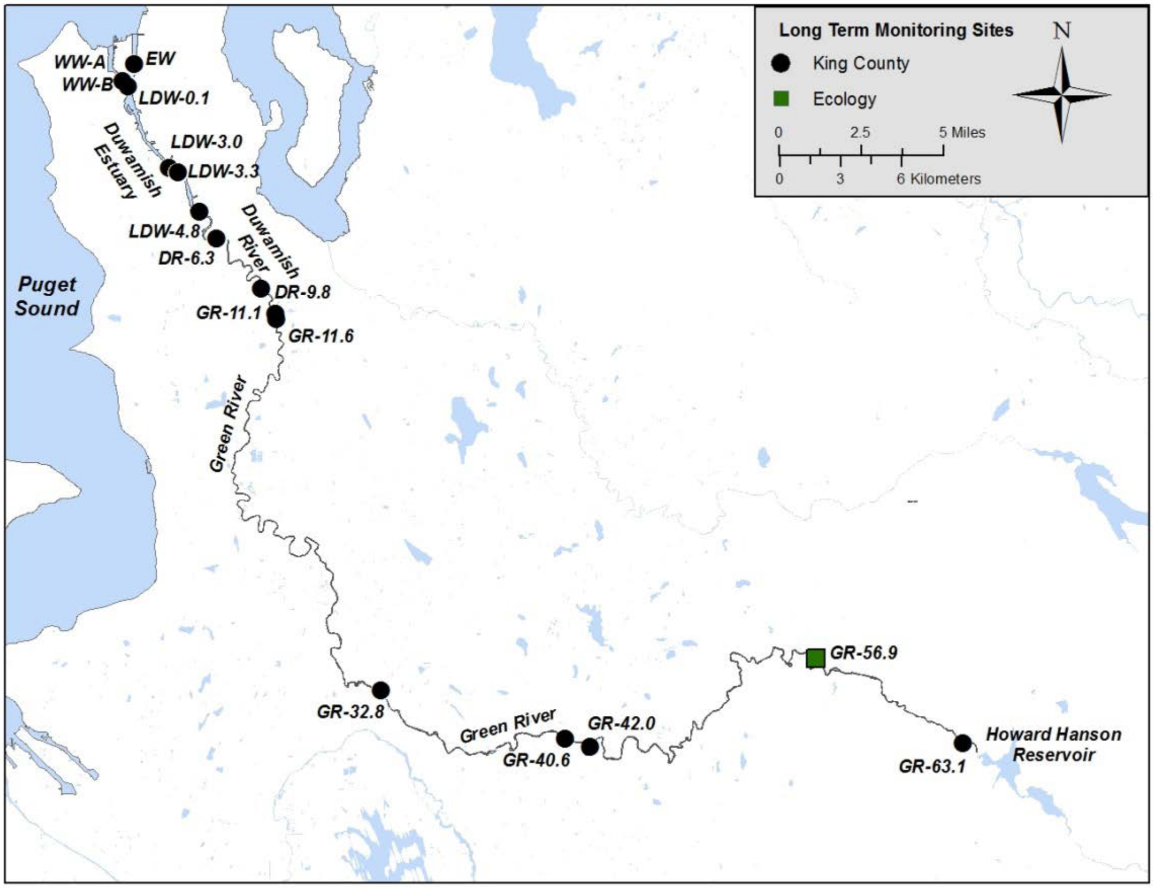

Figure 5. Water chemistry stations reviewed by King County (2017a) except for East Waterway Supplemental RI stations.

Table 2. Water chemistry sampling locations, sample depths and years sampled from King County (2017a)

Site ID	Station Locator	Agency	Description	River Mile[a]	Depths Sampled	Years Sampled
–	EW-SW-1	EWG	East Waterway – Between Terminal 102 and 104	–	Above and below 1 m	2008-2009
–	EW-SW-1 Flood tide	EWG	East Waterway – Between Terminal 102 and 104	–	Above and below 1 m	2008-2009
–	EW-SW-2	EWG	East Waterway – Off Terminal 25	–	Above and below 1 m	2008-2009
–	EW-SW-2 Flood Tide	EWG	East Waterway – Off Terminal 25	–	Above and below 1 m	2008-2009
–	EW-SW-3	EWG	East Waterway – Slip 27	–	Above and below 1 m	2008-2009
–	EW-SW-4	EWG	Lower East Waterway – east side of channel; moved to EW-SW-5 after Round 1	–	Above and below 1 m	2008
–	EW-SW-5	EWG	East Waterway – Slip 36; replaced EW-SW-4	–	Above and below 1 m	2008-2009
–	EW-SW-6	EWG	Lower East Waterway – middle of channel	–	Above and below 1 m	2008-2009
–	EW-SW-6 Flood tide	EWG	Lower East Waterway – middle of channel	–	Above 1 m	2008-2009
WW-a lower	LTKE03	King County	West Waterway – Upstream of the Spokane Street Bridge, middle of the channel	–	Below 1 m	2005–2013

Site ID	Station Locator	Agency	Description	River Mile[a]	Depths Sampled	Years Sampled
WW-a upper	LTKE03	King County	West Waterway – Upstream of the Spokane Street Bridge, middle of the channel	–	Above 1 m	2005–2013
WW-b lower	0305	King County	West Waterway – Upstream of the Spokane Street Bridge, on west side of channel	–	Below 1 m	1970–2004
WW-b upper	0305	King County	West Waterway – Upstream of the Spokane Street Bridge, on west side of channel	–	Above 1 m	1970–2004
LDW-0.1	LTLF04	King County	Lower Duwamish Waterway – At the south end of Harbor Island	0.1	Above 1 m	2003–2004
LDW-3.0	LTTL02	King County	Lower Duwamish Waterway – Duwamish Waterway Park	3	Above 1 m	2007–2010
LDW-3.3 lower	0307, LTUM03	King County	Lower Duwamish Waterway – 16th Ave. S Bridge	3.3	Below 1 m	1970–2013
LDW-3.3 upper	0307, LTUM03	King County	Lower Duwamish Waterway – 16th Ave. S Bridge	3.3	Above 1 m	1970–2013
LDW-4.8	LTXQ01	King County	Lower Duwamish Waterway – Upstream side of Boeing pedestrian bridge, mid span	4.8	Above 1 m	2009–2013
DR-6.3	0309	King County	Duwamish River – East Marginal Way Bridge at S 115th Street	6.3	Above 1 m	1970–2008
DR-9.8	FL319	King County	Duwamish River – Foster Links Golf Course, downstream of confluence with Black River	9.8	Above 1 m	2011–2012
GR-11.1	3106, A310	King County	Lower Green River – Bridge at Fort Dent Park upstream of Black River	11.1	Above 1 m	1970–2013
GR-11.6	0311, 09A080	King County, Ecology	Lower Green River – Renton Junction Bridge on West Valley Road at Highway 1	11.6	Above 1 m	1970–2013
GR-32.8	A319	King County	Lower-Middle Green River – Bridge on SE Auburn-Black Diamond Road, upstream of Soos Creek	32.8	Above 1 m	1972–2012
GR-40.6	B319	King County	Lower-Middle Green River – Bridge on 212th Ave SE, upstream of Newaukum Creek	40.6	Above 1 m	1993–2013
GR-42.0	FG319	King County	Lower-Middle Green River– Bridge at SE Flaming Geyser Road in Flaming Geyser State Park	42	Above 1 m	2011–2012
GR-56.9	09A190	Ecology	Upper-Middle Green River– Bridge on Cumberland-Palmer Road at Kanaskat	56.9	Above 1 m	1977–2012
GR-63.1	E319	King County	Upper-Middle Green River – Below Howard A. Hanson Dam, at USGS gage 12105900	63.1	Above 1 m	2001–2003

[a] River miles conform to the convention used in the RI/FS for the Lower Duwamish Waterway Superfund site. The starting point of RM 0 is at the southern tip of Harbor Island (Windward 2010).
EWG – East Waterway Group

Table 3. Summary of metals concentrations (mg/L) and WQS exceedances (bolded) in the Lower Duwamish Waterway and Green River (From Table 3-43 of King County 2017a)

Analyte	FOD	Mean	Maximum Detected	Max MDL
Antimony	53/187	0.117	0.153	0.5
Arsenic	176/230	1.19	1.41	0.5
Cadmium	57/230	0.071	1.45	0.1
Chromium, total	153/238	0.85	10.8	0.79
Copper	172/233	1.44	2.94	0.4
Lead	26/230	0.0702	0.45	2.3
Mercury	49/195	0.00069	0.0058	0.2
Mercury, total	113/232	0.00501	**0.0835****	0.2
Nickel	116/230	0.425	7.79	0.34
Selenium	56/189	0.188	0.38	1.5
Silver	4/226	0.0198	0.022	0.2
Zinc	161/240	6.16	16.9	0.5

Notes:
Metals concentrations are in dissolved form unless noted.
**** Exceeds freshwater (0.012) and marine (0.025) chronic aquatic life criteria**
FOD – frequency of detection (# samples detected/ total collected)
MDL – method detection limit

3.2.3 Lower Green River

The United States Geological Survey (USGS) sampled (Conn et al. 2015) whole and filtered water at Foster Links Golf Course RM 8 (same as station FL319 in Figure 6) during baseflow, storm flow and significant dam releases between November 2013 and March 2015. Composite samples were collected over 28 events and analyzed for metals, PAHs, PCBs, dioxins/furans, butyltins, volatiles and semivolatiles, and pesticides. Pesticides, butyltins, volatile and semivolatile chemicals were not detected except for methylene chloride and bis(2-ethylhexyl)phthalate (ubiquitous contaminants). Nine metals were frequently detected (>75% of samples). PAHs were infrequently detected and at low concentrations. PCBs and dioxins/furans were detected in most if not all samples. Concentrations were not compared to water quality standards. Chemical concentrations detected during storm events were consistently higher than at baseflow. Where detected, metals concentrations were higher during significant (>2000 cfs) Howard Hansen Dam releases compared to storm events. These dam releases send large water volumes from the Upper Green River downstream. Metals concentrations in unfiltered water samples generally increased with suspended sediment concentrations and were similar in filtered water samples across storms, significant dam releases, and baseline periods. These observations suggest that sediment-bound metals are more important than the dissolved fraction.

The frequent detection of metals is not unusual given their natural occurrence. The most noteworthy findings of this study are the consistently higher chemical concentrations in storm events relative to baseflow and higher estimated chemical loads during significant dam releases relative to storm samples. The storm versus baseflow results align with similar studies in other areas of Puget Sound (King County 2013, Ecology and King County 2011) and suggest that stormwater contributes substantially greater contaminant loads than baseflow. Higher metals loads during significant dam releases relative to stormflow indicate that dam flow regulation plays an important role in controlling loading and exposure of juvenile Chinook salmon to metals. The higher sediment bound fraction indicates metals are being stored in sediments behind Howard Hansen Dam and these solids are occasionally released with large dam openings.

3.2.4 Lower and Middle Green River and Tributaries

King County (2014a) evaluated water quality in the Lower and Middle Green River and 4 tributaries (Mill Creek in Auburn, Soos Creek, Black River and Newaukum Creek) (Figure 6). Significantly higher dissolved arsenic concentrations were measured in Mill Creek than in the mainstem at Flaming Geyser or Foster Links, or in Newaukum Creek during storm events. Concentrations of total PCBs and PAHs increased with distance downstream during storm events. Significantly higher total high molecular weight polycyclic aromatic hydrocarbon (HPAH) concentrations were detected in the Black River during storm events compared to the mainstem at Flaming Geyser or in Newaukum and Soos Creeks. Total PCB concentrations were highest in the Black River (at the Pump Station) compared to Mill, Newaukum and Soos Creeks and the two mainstem locations although differences were not statistically significant. All measured total PCB and arsenic concentrations were below the Washington State freshwater aquatic life WQS.

3.2.5 Middle and Upper Green River

King County conducted a 2013 study of Middle and Upper Green River water quality (King County 2015) sampling between Kanaskat-Palmer and 20 miles upstream of the dam (Figure 7). Results showed water concentrations of arsenic increase with distance downstream during storm events. All measured arsenic concentrations were below the Washington State freshwater aquatic life WQS. Concentrations of total PCBs and PAHs increased during storm events with distance downstream. All measured total PCB concentrations were below the Washington State freshwater aquatic life WQS (there were no applicable aquatic life standards for PAHs at the time of the report).

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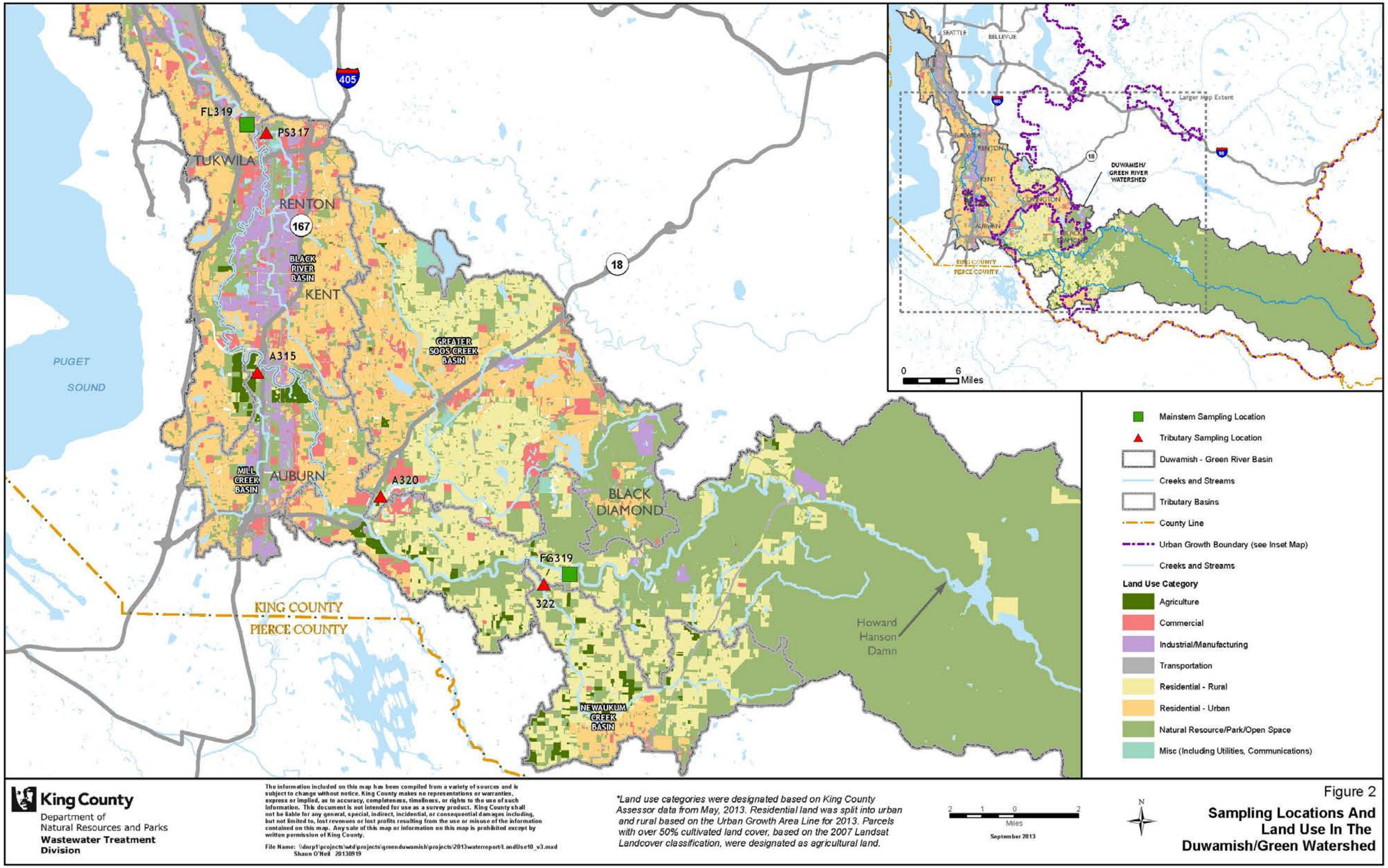

Figure 6. King County sampling stations in the Lower and Middle Green River (King County 2014a)

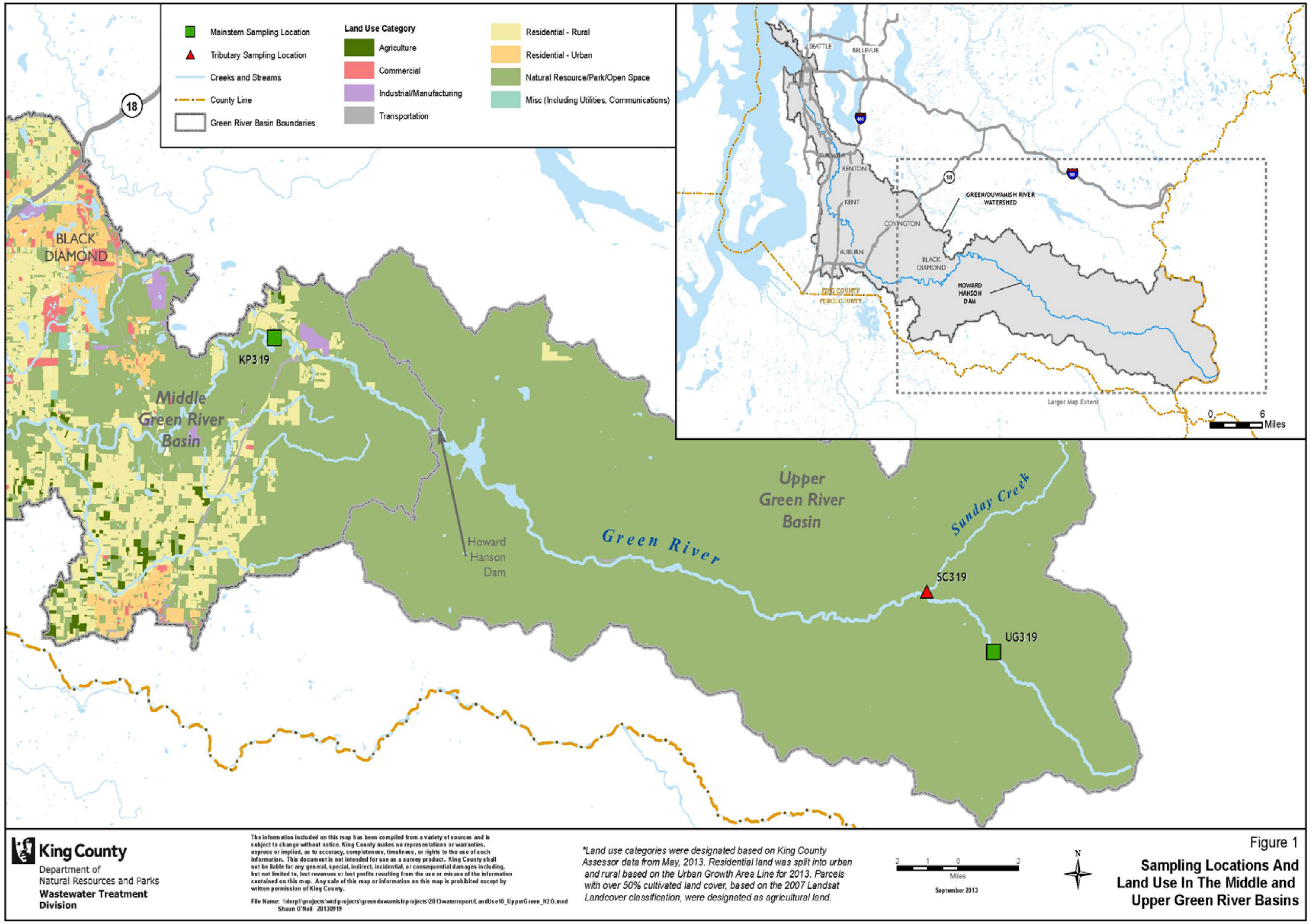

Figure 7. King County sampling stations in the Middle and Upper Green River (King County 2014b)

3.2.6 Duwamish-Green Sub-basins

King County (2005) conducted an aquatic life screening risk assessment for the Green River in 2005 using existing metals and organic contaminant data collected by King County and USGS from 1999 through 2003. These data included a mix of grab and composite water samples collected from 67 stations during baseflow and storm flow spanning all sub-basins from the Duwamish Estuary to just below Howard Hansen Dam in the Upper Green (see Figure 3-1 http://your.kingcounty.gov/dnrp/library/2005/KCR1883.pdf). Chemical data were available for nutrients, metals and several organic chemicals (phenols, PAHs, PCBs, pesticides, and other volatile and semivolatile chemicals). Quartiles and 5th and 95th percentiles of resulting concentrations were compared to (in hierarchical order): Washington State WQS (WAC 173- 201A 2003 version), EPA National Recommended Water Quality Criteria (EPA 2002), an EPA toxicity database (AQUIRE) or other thresholds from the scientific literature. Of the 187 chemicals targeted, 127 were never detected in any water samples. For 10 chemicals, at least one sample exceeded the selected risk threshold, but most had low exceedances (percentile concentration/threshold ratios <2). It was concluded that metals and organic chemicals posed minimal risk to aquatic life.

3.3 Chemical Contaminants in Sediments

Some contaminants in sediments have been demonstrated to cause toxic effects in fish. For example, Puget Sound sediments contaminated with PAHs have been linked to toxic effects in English sole, a benthic species (Johnson 2000). For salmon and other non-benthic species that occupy the water column, their direct sediment exposure is lower than a benthic species, but to what degree is uncertain. However, juvenile salmon sometimes consume benthic invertebrates which can increase their chemical exposure relative to planktonic prey. In addition, a decline in benthic populations due to contamination may theoretically decrease the food quantity or quality for juvenile salmon. Therefore, sediment contamination may directly or indirectly impact Chinook salmon.

King County conducted a sediment chemistry study of the Green River (King County 2014b) and completed a review of all available watershed sediment chemistry data (King County 2017a). Sediment chemistry data were compared to Washington State Marine Sediment Management Standards (WAC 173-204-320), more specifically known as the Sediment Quality Standard (SQS) and the Cleanup Screening Level (CSL) (WAC 173-204-562). The SQS is a "no benthic effects" level while the CSL is a "minor benthic effects" level. The SQS is equivalent to a benthic sediment cleanup objective (SCO) used to develop a sediment quality goal for Washington State sediment cleanup sites. While there are no established freshwater sediment standards in Washington State, freshwater benthic cleanup levels, also referred to as SCO and CSL (WAC 173-204-563) have been developed. These standards and benthic cleanup levels were developed based on chemical concentrations that cause adverse effects to benthic invertebrates. Results of the King County (2017a) review do not reflect removal of contaminated sediments that has occurred from early action cleanups in the LDW.

3.3.1 Duwamish Estuary

King County (2017) summarized existing sediment data collected between 1991 and 2013, comparing sediment chemistry results for Duwamish Estuary (King County 2017a) to benthic sediment standards described above (SQS and CSL). Figure 8 shows where any chemical exceeded the SMS; the metals and key organic chemical exceedances are summarized below.

- All eight metals with benthic sediment standards exceeded the CSL in the East Waterway and LDW: arsenic, cadmium, chromium, copper, lead, mercury, silver, and zinc.
- The majority of the SMS exceedances were north of RM 1.3 in the LDW.
- Several metals exceeded the CSL at two additional locations in the LDW, the west inlet at RM 2.2 and south of the Jorgensen Forge cleanup area between RM 3.7 and RM 3.9.
- Cadmium exceeded the CSL approximately 50 m southwest of the Duwamish/Diagonal cleanup area and in the west inlet located at RM 2.2 in the LDW.
- Mercury was widely dispersed and exceeded the CSL throughout the East Waterway, in the LDW between RM 0.0 and RM 1.3 (exceedances detected between RM 0.2 and RM 0.6 and RM 0.9 and RM 1.2), throughout the west inlet of the LDW at RM 2.2, south of the Jorgensen Forge cleanup area (RM 3.7 to RM 3.9), and in the LDW near the head of Slip 6.
- The frequency of sediment standards exceedances was highest in the East Waterway and LDW for total PCBs and next highest for bis(2-ethylhexyl)phthalate. Exceedance of PAH sediment standards was frequent in the LDW and tended to be within 50 m of shore.

3.3.2 Green River

King County (2014b) collected and analyzed sediment samples from 2008 to 2012 in tributaries of the Green River. Of 58 samples collected, 24 exceeded the no effects level (freshwater benthic SCO) for one or more contaminants including three metals (arsenic, nickel and cadmium), bis (2-ethylhexyl)phthalate, di-n-octylphthalate, and total PCBs (Figure 8). Bis (2-ethylhexyl)phthalate and arsenic were the two chemicals with the highest frequency of exceedance. Tributaries included Big Soos Creek, Covington Creek, Jenkins Creek, Newaukum Creek, Springbrook Creek, Mill Creek in Kent and Mill Creek in Auburn. Creeks located in the most urbanized areas (e.g., Mill in Kent and Springbrook) generally had a greater number of freshwater benthic SCO exceedances than the lesser developed creek basins. Four stations were located in the Green River mainstem but there were no exceedances of freshwater benthic SCO at these locations.

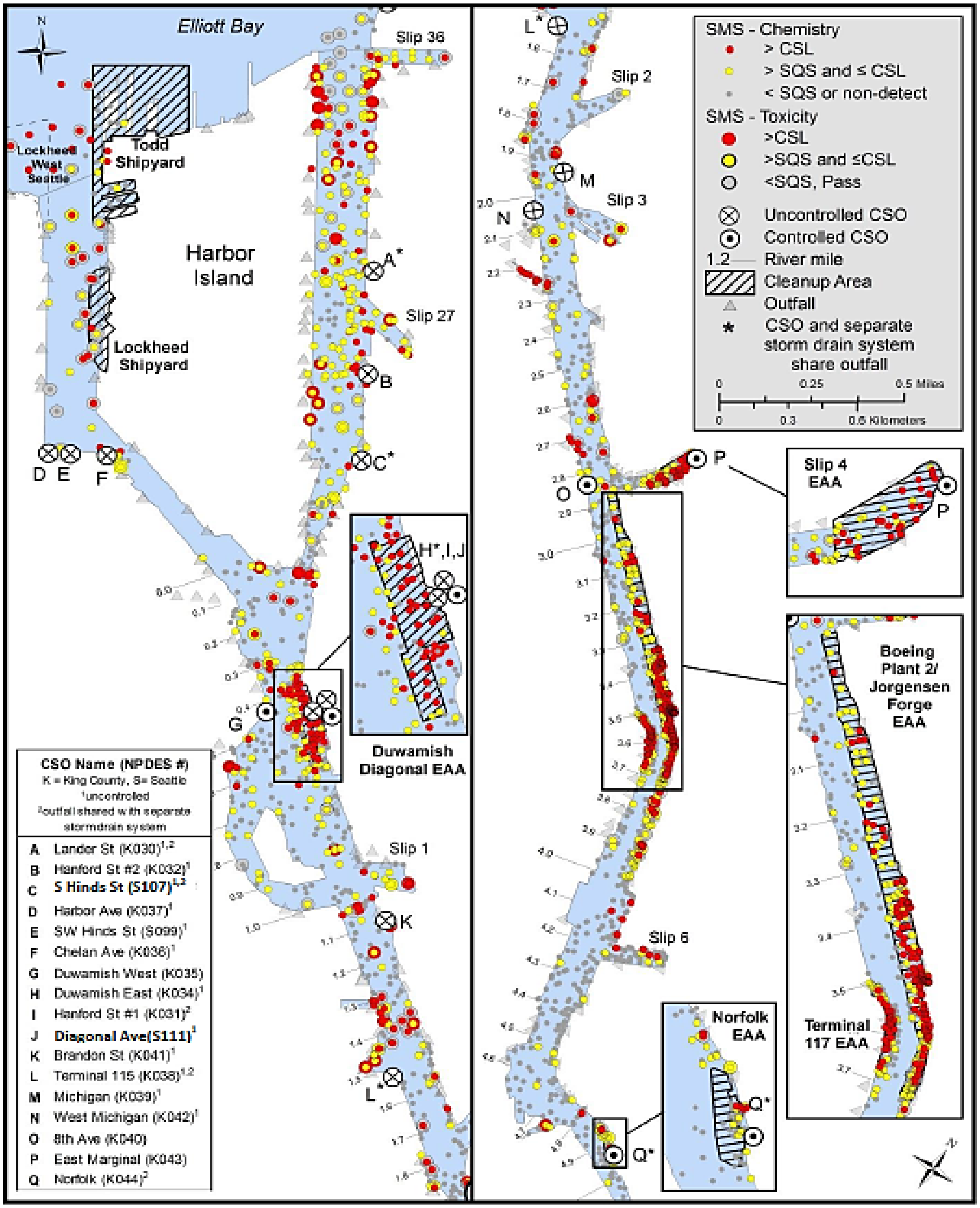

Figure 8. Surface sediment stations (collected 1991-2013) with benthic exceedances along the East, West, and Lower Duwamish waterways before EAA remediation actions. Original Sources: AECOM 2012, Windward and Anchor QEA 2014, Urban Waters Initiative (Ecology 2009), and PSEMP Database (Ecology 2015).

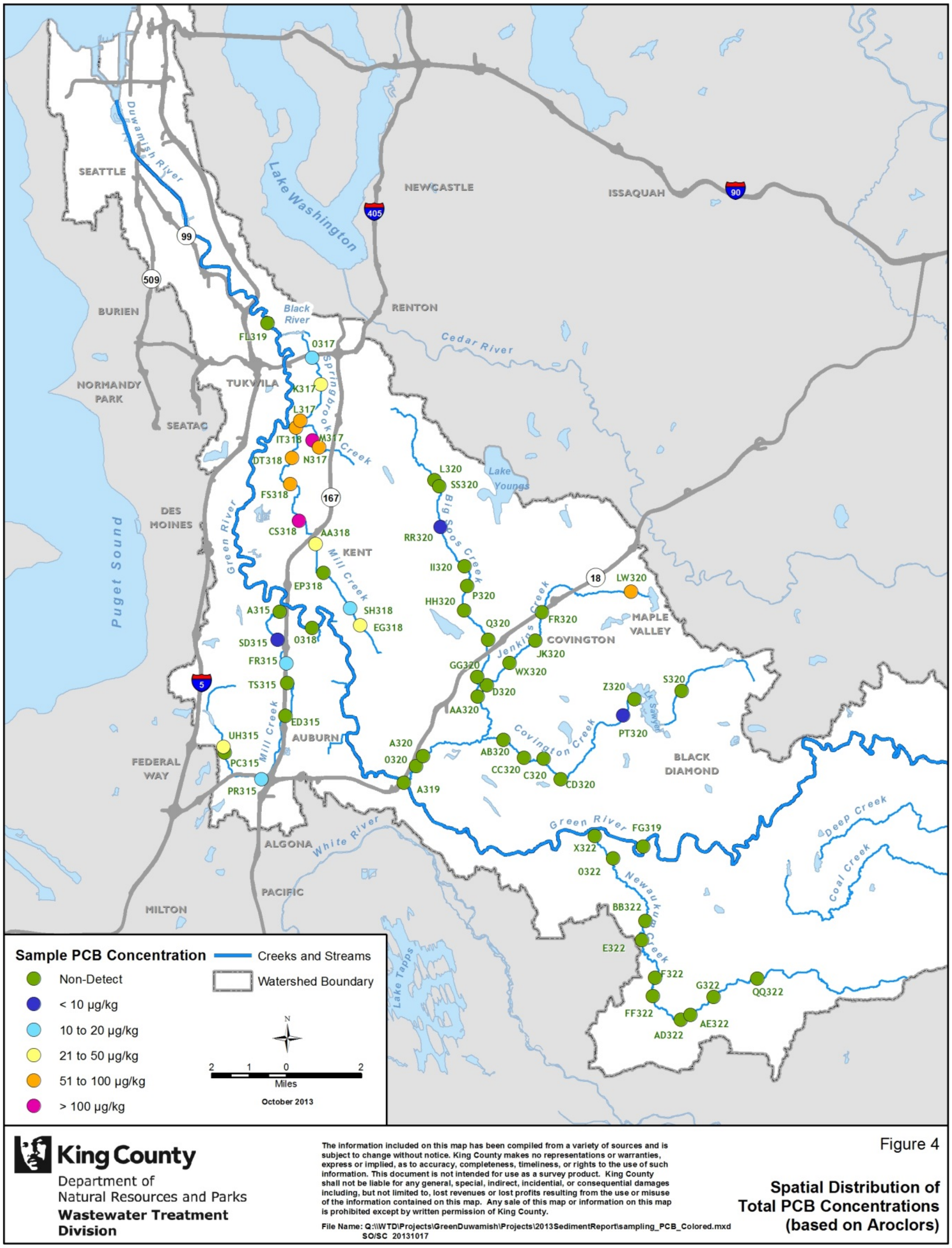

Figure 9. Total PCB concentrations in Green River tributary and mainstem sediments (King County 2014b).Two stations with highest concentrations exceed SCO.

3.3.3 Early Action Areas in LDW

Based on identification of highly contaminated areas during the first phase of the LDW RI, five Early Action Areas (EAA) were selected by EPA and Ecology for early cleanup. Together, cleanups at all five EAAs cover 29 acres and are expected to reduce the LDW area-weighted average surface sediment PCB concentration by approximately 50% (EPA 2014). The status of cleanup actions in these areas is summarized below. See Figure 5 for locations of each EAA.

Slip 4

- Approximately 10,000 cubic yards (cy) of PCB-contaminated sediments were dredged and 3.4 acres were capped with clean sand, gravel, and granular activated carbon amended filter material, during October 2011 through January 2012, by the City of Seattle (with participation by The Boeing Company) under an Administrative Settlement Agreement and Order on Consent (consent order) (Seattle 2015). Upland plantings were also completed in 2012. A net gain of 1.1 acres of intertidal, shallow subtidal and riparian habitat resulted.
- Dredging and capping was monitored with one brief exceedance of the turbidity standard during placement of clean cap sand. The City of Seattle has been monitoring the cap and documented recontamination (exceedance of SMS) with PCBs in Years 1 and 3 (Seattle 2015). In-water construction activities in Year 3 may have influenced the surface sediments on the cap (pers. comm. Schuchardt 2017). Year 4 monitoring was completed, but did not include sediment chemistry (Seattle 2016).

Terminal 117

- Cleanup was performed by City of Seattle and Port of Seattle (Port of Seattle project website http://t117.com). The Port of Seattle work was completed in 2015 and included dredging of 8,000 cy of sediment followed by backfill with clean sand, and removal of 36,000 cy of upland and bank soil (AECOM 2016). As source control actions, the City of Seattle completed cleaning of residential yards in 2013 and finished cleaning adjacent streets and stormwater infrastructure construction in 2016. A monitoring and maintenance plan is currently being developed with EPA. Habitat restoration is planned to occur in 2018 (pers. comm. Florer 2017).

Boeing Plant 2/Jorgensen Forge (Across from Terminal 117)

- The Boeing Company initiated cleanup of river sediment and the shoreline of Boeing Plant 2 in 2013. Substantial upland source control actions were completed before 2013, including building structure removal, joint compound replacement, storm drain cleaning and installation of stormwater treatment systems (pers. comm. Anderson 2017). 163,000 cy of sediment was dredged (and backfilled with clean sediment) from the nearly 1-mile-long property footprint (Amec Foster Wheeler et al. 2016). Shoreline soils impacted by organic chemicals were removed and replaced with salmon habitat features including riparian and intertidal plants, along with large woody debris features (Amec Foster Wheeler 2014). The project was completed in 2015.

- The Boeing Company has completed the first year post-remediation monitoring data report (Amec et al. 2016). Concentrations of all metals and organic chemicals including PCBs were below the no effect threshold (SQS). As expected, deposition of sediments is occurring on the surface of the clean backfill; 22 of 40 samples showed increases in PCB concentrations after one year. http://www.boeing.com/resources/boeingdotcom/principles/environment/pdf/duwamish_backgrounder.pdf
- The Jorgensen Forge site is adjacent to Boeing Plant 2. In 2014, in-water sediments were dredged and bank material was removed and backfilled with clean materials. Several rounds of post-cleanup surface and subsurface sediment sampling have documented sediment PCB concentrations above cleanup levels (>SQS). EPA and Earle M. Jorgensen are currently negotiating an amendment to the Agreed Order to establish how remaining contamination will be addressed (Chu, pers. comm. 2017).

Diagonal CSO/Storm Drain

- King County remediated 7 acres by dredging and capping in 2003/2004 (EBDRP 2015); a total of 68,000 cy of contaminated sediment was removed. Contamination of the surrounding sediments after dredging resulted in placement of a thin layer of clean sand, called an enhanced natural recovery (ENR) area, in 2005, to reduce contaminant concentrations in surface sediments.

- King County monitored the site and the surrounding sediments pre- and post-remediation through 2012. The largest storm drain to the LDW discharges to this area, in addition to City of Seattle and King County CSOs; sediment concentrations near the outfall have varied over time. Sediment PCB concentrations in a portion of the capped area remain consistently low. However, concentrations in other portions of the capped area are variable year-to-year and sometimes exceed the PCB marine SQS. The area-wide mean PCB concentration across remediated areas was 61 µg/Kg dw in 2010 falling within an anthropogenic background concentration for urban areas of 40-90 µg/Kg dw calculated in the LDW FS (AECOM 2012). PCB concentrations in the ENR area have been consistently low. Monitoring reports can be found here: http://www.kingcounty.gov/services/environment/wastewater/sediment-management/projects/DuDi.aspx

Norfolk CSO

- King County completed cleanup in the river at Norfolk CSO in 1999 including dredging 5,190 cubic yards of sediment and backfilling with clean sediment. Sediment monitoring of the cleanup area was conducted for 5 years (project website: http://www.kingcounty.gov/services/environment/wastewater/sediment-management/projects/Norfolk.aspx).

- Monitoring in the early years identified the adjacent Boeing site storm drain as a source of PCBs to the Norfolk site (EBDRP 2005). The Boeing Company conducted dredging in 2003 to remediate this area. They also conducted source tracing and added treatment to the storm drain. After the last year of monitoring in 2004, two PAH compounds and PCBs were identified as chemicals at the Norfolk site that exceeded SQS. Monitoring Reports can be found here: http://www.kingcounty.gov/services/environment/wastewater/sediment-management/projects/Norfolk.aspx

Natural background for total PCBs in Puget Sound sediments is 2 ug/Kg dw and is based on concentrations in areas without influence of local human activity. This is also the total PCB cleanup level established by EPA for the LDW.

Figure 10 is an updated map of benthic exceedances in the LDW with outdated EAA area data removed. Benthic SMS exceedances by any chemical are most numerous and widespread below RM 2.9. Above RM 2.9, benthic SMS exceedances are generally clustered around RM 3.7-4.2 and RM 4.8-5.0 and exceedances of only the SQS are scattered in between.

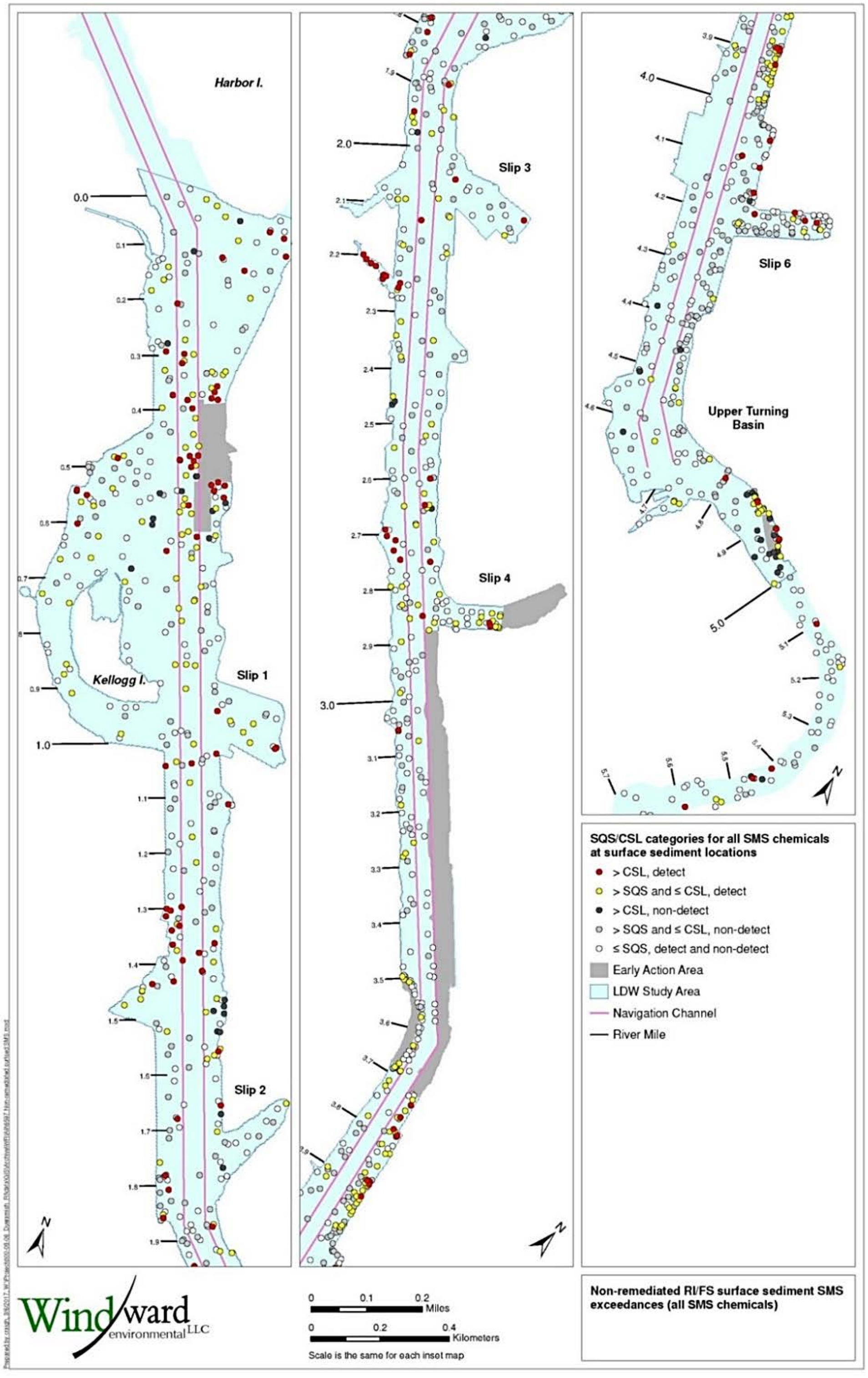

Figure 10. Updated map of SMS exceedances for the LDW surface sediments in non-remediated areas (Windward unpublished; Data through 2010).

3.4 Benthic Community Health Assessment

As mentioned earlier, Chinook salmon can be exposed to contaminated sediments by direct ingestion, direct contact, or eating contaminated food, such as benthic invertebrates. In addition, the adverse effects of chemical contaminants on the benthic community can theoretically reduce the quantity or quality of food for fish like juvenile salmon. However, studies were not identified in the Green-Duwamish watershed that examine potential effects of benthic community reductions on fish diets or health. Studies that have sampled benthic community[2] taxonomic composition and tested sediments for chemistry and toxicity to benthic invertebrates are summarized here. Only studies that cover the Duwamish Estuary were located.

- Taylor et al. (1999, as cited in Windward and Anchor QEA 2014) characterized epibenthic invertebrate taxa residing in intertidal habitat of the lower 2 miles of the Duwamish Estuary including East Waterway. At the three intertidal areas sampled, most taxa were identified as potential salmon prey.
- Benthic community sampling was conducted in the 1990's at Kellogg Island, Duwamish/Diagonal CSO-storm drain, and the LDW Turning Basin. Areas of Kellogg Island demonstrated high abundance and species diversity relative to the Turning Basin and the Duwamish/Diagonal CSO-storm drain sites (Cordell et al. 1994 and 1996, Parametrix and King County 1999). The area sampled at Duwamish/Diagonal has since been remediated (see Section 3.3.3), but benthic community sampling was not part of the post-remediation monitoring activities.
- Paired sediment chemistry and benthic invertebrate toxicity testing were completed for the East Waterway RI (Windward and Anchor QEA 2014). Comparison of chemistry and toxicity test results to SMS indicated that approximately 21% of the EW area likely cause adverse effects to benthic invertebrates. Potential minimal adverse effects were indicated for 39% of the area and no adverse effects were indicated in approximately 40% of the EW area.
- The East Waterway RI also assessed risk to benthic invertebrates by measuring chemical concentrations in tissues and comparing them to effect concentrations. Adverse effects for benthic invertebrates were indicated for TBT in 2 of 12 areas sampled and potential minor adverse effects were indicated for total PCBs in 10 of 13 areas sampled.
- The East Waterway RI also examined volatile chemicals by comparing porewater chemistry data to effects concentrations. Napthalene was identified as likely causing adverse effects to benthic invertebrates in one location. No other volatile chemicals were concluded to present risk of adverse effects.

[2] Benthic community assessments for contaminants have a different purpose than sampling for and calculation of the Benthic Index for Biotic Integrity (BIBI) (Karr 1998; Fore et al. 2001, Karr & Chu 1999, Kleindl 1995, Morley & Karr 2002). The BIBI is a biological indicator of stream condition integrating multiple stressors of chemical and non-chemical pollution, hydrologic conditions, and physical habitat characteristics. Contaminant assessments of benthic community health are more specific to contaminant effects and involve measurement of sediment chemistry, benthic invertebrate community taxonomic analysis, and/or sediment bioassays.

- Toxicity tests on benthic invertebrates in the LDW (Windward 2010) resulted in 30 of 48 samples that failed the SQS criteria for toxicity. Comparison of sediment chemistry and toxicity test results to SMS indicated (see Map 4-16 in RI for SMS results):
    - no adverse effects to benthic invertebrates were expected in 75% of the LDW area,
    - adverse effects are likely in 7%[3] of the LDW area, and
    - adverse effects are uncertain in 18% of the LDW area.
- The LDW RI also examined volatile chemicals by comparing porewater chemistry data to effects concentrations. Cis-1,2-dichloroethane was identified as potentially causing adverse effects to benthic invertebrates in one location. No other volatile chemicals were concluded to present risks of adverse effects in porewater.

3.5 Chemical contaminants in Chinook Salmon and their Diet

Chinook salmon tissue chemistry data has been collected by Washington Department of Fish and Wildlife (WDFW) (O'Neill et al. 2015), by Nelson et al. (2013) as part of the Juvenile Salmon Survival Study, and by the LDW Group and EW Group as part of Superfund RIs (Windward 2010, Windward and Anchor QEA 2014). Assessment of adverse effects on fish can be conducted using whole body tissue, bile or other organ chemistry, stomach content chemistry, toxicity tests and/or biomarkers that indicate exposure. Some chemicals do not bioaccumulate because they are metabolized or otherwise broken down in fish. For example, it is inappropriate to assess risk to fish from parent PAHs based on fish tissue concentrations because these chemicals are quickly metabolized resulting in tissue concentrations that do not reflect exposure (Johnson et al. 2008). Exposure to PAHs is more accurately assessed by measuring PAH metabolites in liver bile or PAHs in stomach contents. The WDFW and King County Chinook tissue and the LDW and EW Chinook tissue chemistry results are summarized here. All fish tissue concentrations are based on wet weight.

- Juvenile Chinook salmon appear to be exposed to significantly more copper and lead in the Duwamish Estuary than those in the Nisqually, Skagit and Snohomish River systems as reflected by gill concentrations (O'Neill et al. 2015). However, this study could not differentiate Duwamish Estuary from upstream exposure in the Green River. Gill tissue concentrations are indicative of the water exposure pathway. Cadmium and nickel concentrations in LDW Chinook gills were not significantly different compared to the other river systems sampled. Zinc levels in LDW Chinook gills were lower than those from the other three major river systems in Puget Sound.
- Juvenile Chinook salmon wholebody concentrations suggest that more of their PCB and DDT burden is contributed from the Duwamish Estuary and/or Elliott Bay than

[3] The sediment assessment was updated with more recent data in the LDW FS, resulting in a lower area of 4% with likely adverse effects.

from Puget Sound (O'Neill et al. 2015). Juvenile Chinook from offshore locations in Puget Sound (>0.5 km from shore in Whidbey Basin and south) had significantly lower concentrations of PCBs and DDTs than the LDW or Elliott Bay locations. However, PCB concentrations in Chinook salmon collected from nearshore Elliott Bay were higher than in fish from the Duwamish Estuary. The average total PAH concentrations of juvenile Chinook stomach contents were significantly higher in the LDW and Elliott Bay than in the Skagit or Nisqually River systems.

- Nelson et al. (2013) summarized a 2003 juvenile Chinook sampling effort in the Duwamish Estuary, Lower and Middle Green rivers and Elliott Bay. Twenty six composite samples each containing 6 to 32 subyearling Chinook salmon were analyzed for PCBs and mercury. Hatchery and wild fish were identified and sorted before compositing and analyzed separately. Average PCB levels in hatchery fingerlings from the Duwamish Estuary (29 µg/Kg) were less than half the levels in wild fingerlings (77 µg/Kg). Average PCB levels in Elliott Bay wild (27 µg/Kg) and hatchery Chinook salmon (25 µg/Kg) were similar to each other and slightly higher than Lower Green River wild (14 µg/Kg) and hatchery fish (15 µg/Kg). In theory, the longer residence time of wild Chinook salmon in the Duwamish Estuary may increase their bioaccumulation of PCBs relative to hatchery Chinook salmon. The PCB levels across all samples of wild Chinook salmon from the Duwamish Estuary were highly variable (7.4 to 225 µg/Kg). Mercury levels in juvenile Chinook were low and did not vary by sampling location or fish origin.
- King County (2017a) reviewed all fish and shellfish tissue data used in the LDW and EW RI's and summarized tissue data for PCBs in juvenile Chinook salmon and other fish. These data were collected in the Green-Duwamish watershed from 1998 to 2007. Whole wild and hatchery juvenile Chinook salmon collected from East Waterway (12 composite samples) and LDW (24 composite samples) contained variable levels of PCBs with an average concentration up to 50 times lower than in adult English sole, the fish species measured with the highest PCB concentrations (Table 4). English sole fillet samples contain lower concentrations than wholebody samples; this is due to preferential partitioning into fatty tissues. Chinook tissue were also analyzed for pesticides and TBT. TBT was not detected in juvenile Chinook. These tissue chemistry data were used to inform the LDW and EW ecological risk assessments. See Section 3.6 for LDW and EW Chinook salmon risk assessment results.

Table 4. Total PCB concentrations (µg/Kg wet) in juvenile Chinook salmon relative to English Sole in the East Waterway and LDW (King County 2017a).

Fish Species	Tissue Type	FOD	Minimum	Maximum	Mean
East Waterway					
English sole	Fish whole body	13/13	1,460	7,900 J	3,200
English sole	Fish fillet (with skin)	20/20	409	5,700	1,700
Juvenile Chinook salmon	Fish whole body	12/12	7.4	91.5	59
Lower Duwamish Waterway					
Juvenile Chinook salmon	Fish whole body	24/24	6.9	1,200	140

FOD – frequency of detection (# samples detected/ # analyzed)

- O'Neill et al. (2015) measured PCBs, PAHs, and PBDEs in composite samples of juvenile Chinook stomach contents. One sample was collected in the LDW estuary, two from nearshore (Elliott Bay) and one from offshore (Puget Sound). The authors estimated dietary effects thresholds of 3,800 ng PAHs/g for altered growth and 12,200 ng PAHs/g for altered growth and plasma chemistry based on Meador et al. (2006). The single Chinook stomach content sample collected in the Duwamish Estuary did not exceed the effect thresholds for PAHs. One of two stomach content samples collected in Elliott Bay exceeded the PAH threshold.
- O'Neill et al. (2015) calculated PBDEs effects ranges for increased disease susceptibility (greater than or equal to 470 to 2,500 ng/g lipid) and for altered thyroid hormone levels (greater than or equal to 1,492 to 2,500 ng/g lipid) in whole juvenile Chinook based on Arkoosh et al. (2013) and Arkoosh et al. (2010). None of the Duwamish Estuary juvenile Chinook tissue samples exceeded either threshold. One of 10 samples in Elliott Bay exceeded the PBDE effects threshold.
- From 1996 through 2001, Johnson et al. (2007) measured PCBs, DDTs, and PAHs in juvenile Chinook in the Duwamish Estuary (1998 and 1999 only) and other estuaries of Puget Sound. Results show increased exposure in the Duwamish compared to Puget Sound. PAH metabolites were also higher in Duwamish juvenile Chinook than any of the other 5 estuaries sampled on Washington's coast (Skokomish, Nisqually, Grays Harbor, Willapa Bay). PAH metabolites may be relatively higher in the Duwamish Estuary due to urban development.

It is important to note that chemicals of emerging concern (CECs) have been detected in Puget Sound (Miller-Schultze et al. 2014) and waters of the Duwamish Estuary (King County 2017b). The definition of CECs varies, but EPA defines them as "chemicals and other substances that have no regulatory standard, have been recently 'discovered' in natural streams (often because of improved analytical chemistry detection levels), and potentially cause deleterious effects in aquatic life at environmentally relevant concentrations" (EPA 2008). Hormones, pharmaceuticals and personal care products (PPCPs), and industrial process chemicals are examples of CECs and are rarely targeted in environmental surveys. Yet, many of them have been documented as endocrine system disruptors in fish. Available information on CECs as pollutants in the Greater Puget Sound is limited to source pathways (e.g. wastewater), ambient surface waters, sediments, and invertebrate and fish tissue chemistry concentrations. A recent study of CECs by King County (2017b) found 17 of 130 CECs were detected in surface waters of the Duwamish Estuary (4 stations sampled). The first and only survey of pharmaceuticals and personal care products (PPCPs) in Puget Sound Region wholebody fish tissue detected several (37 of 150) of these chemicals in juvenile Chinook salmon (Meador et al. 2016). Meador et al. (2016) detected more PPCPs in juvenile Chinook salmon than in staghorn sculpin in the areas sampled: Sinclair Inlet, Puyallup Estuary, and Nisqually Estuary. These data suggest preferential bioaccumulation of CECs in juvenile Chinook salmon. The reasons for this are unknown but could be related to differences in prey, habitat, life stage, and/or metabolic processes.

3.6 Modeled and Observed Adverse Effects on Chinook

Ecological risk assessments conducted under Superfund have estimated the likelihood that contaminants in the LDW and EW would cause adverse effects to juvenile Chinook salmon using a standard and simple model of exposure and effects. These models consider effects that directly influence mortality and growth. In addition to the risk assessments, several field and laboratory studies have investigated adverse effects of contaminants in juvenile Chinook or juvenile coho salmon. Findings of these studies are summarized below.

3.6.1 Modeled adverse effects

An ecological risk assessment was conducted for both the LDW and EW RIs. In these assessments, risks to juvenile Chinook salmon from contamination in the waterways were evaluated (Windward 2007; Windward and Anchor QEA 2014). The LDW and EW risk assessments determined that the direct water contact and dietary exposure pathways were the greatest exposure pathways to juvenile Chinook salmon (Figure 11).

The LDW ecological risk assessment concluded that cadmium, arsenic, copper, and vanadium in juvenile Chinook salmon food pose low risk of adverse effects on survival or growth; effects levels were not exceeded but no-effects levels were exceeded. These four metals are not bioaccumulative. Other chemicals, such as PCBs and PAHs, were determined not to pose risk of impaired growth or survival to juvenile Chinook based on a screening step that uses conservative (i.e., high) exposure assumptions and no-effect thresholds (Windward 2007). The risk assessment included an uncertainty assessment, which acknowledged reduced immunocompetence may occur in juvenile salmonids migrating through the LDW. However, this risk assessment was not able to determine if a particular contaminant was the cause of the immunocompetence effect observed in the field.

Similar to the LDW assessment, the EW ecological risk assessment concluded adverse effects to juvenile Chinook salmon growth and survival were unlikely from arsenic, mercury and TBT in surface water and were at low risk in their diet from cadmium, chromium, copper, and vanadium. Risks from cobalt, nickel, and dibenzofuran were concluded to be unknown because there was not sufficient toxicity information to assess them. Other chemicals, such as PCBs and PAHs, were determined not to pose risk of impaired growth or survival to juvenile Chinook (the same methodology discussed above for the LDW Ecological Risk Assessment was used) (Windward 2012).

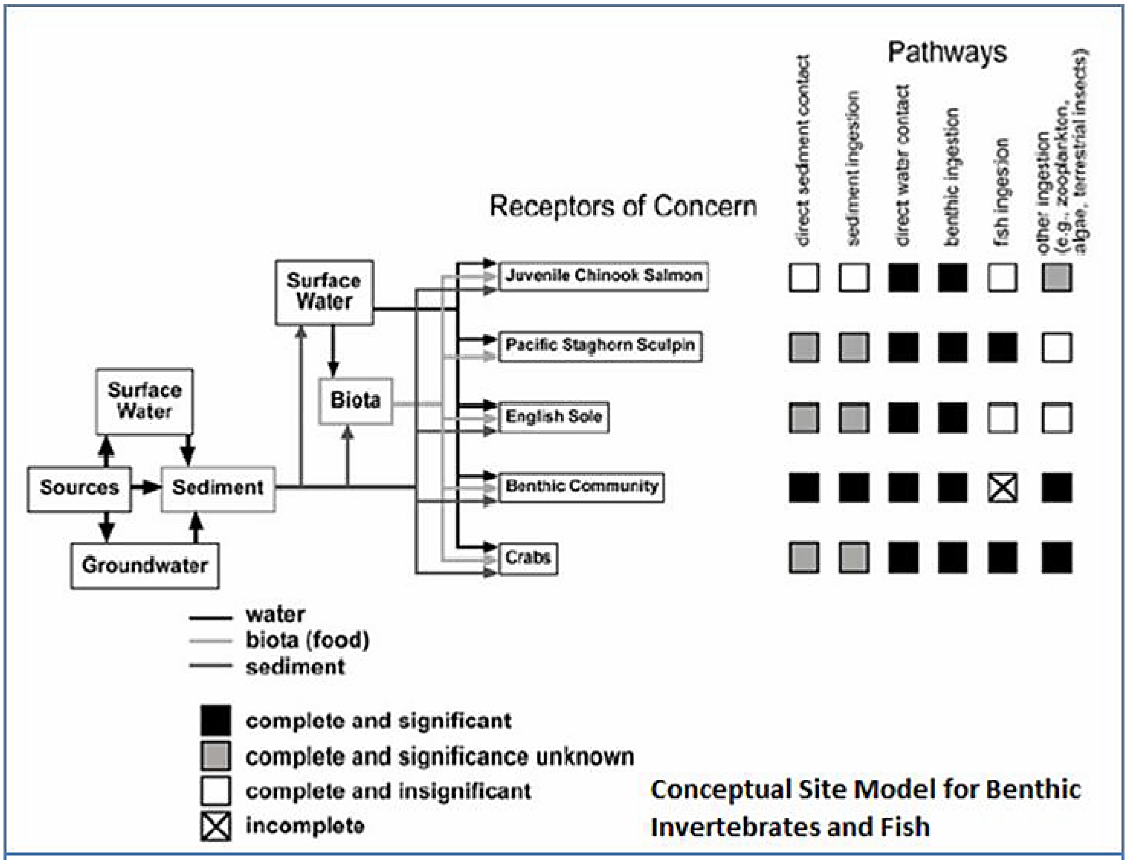

Figure 11. Conceptual Site Model and Pathways for Juvenile Chinook from LDW Baseline Risk Assessment (Windward 2007)

Some effect thresholds have been calculated for juvenile Chinook salmon for purposes of comparison with PCB, PBDE, and PAH tissue concentrations. Although not an established tissue standard, Meador et al. (2002) statistically derived a lipid-normalized tissue effects threshold in juvenile Chinook for PCBs of 2400 ug/Kg lipid based on biochemical and immune system effects. This threshold was exceeded by juvenile Chinook sampled in the Duwamish Estuary in 1998 and 1999 (Johnson et al. 2007). More recently, in 2013, 25% (1 of 4) of juvenile Chinook samples from the Green-Duwamish watershed exceeded this effects threshold (O'Neill et al. 2015).

3.6.2 Observed Adverse Effects

Juvenile Chinook salmon from the Duwamish Estuary have been observed with immunosuppression, reduced resistance to disease and decreased growth rates (Arkoosh et al. 2001, Johnson et al. 2008). It is uncertain if these changes were caused by an individual contaminant (e.g. PAHs) or a mixture. The observed biochemical changes do not indicate adverse health effects by themselves (Johnson et al. 2007).

A type of pre-spawn mortality observed in coho is linked to stormwater and has been documented in small tributaries of the Green River and Duwamish Estuary where Chinook salmon are not found. There is a specific suite of pre-spawn mortality symptoms which result in mortality of male and female coho before spawning. This is an acute mortality event associated with storm events and the cause is currently suspected to be chemical(s) in vehicle tires (Du et al. 2017). Local researchers have demonstrated that the symptoms are induced by urban stormwater runoff (Scholz et al. 2011, Spromberg et al. 2015, McIntyre et al. 2016) and eliminated by stormwater infiltration through bioretention soils (McIntyre et al. 2016). This phenomenon has not been observed in other co-occurring salmonids (e.g. chum). Local studies have demonstrated that urban highway stormwater runoff induces cardiotoxicity, reproductive effects and mortality in juvenile coho and other, non-salmonid fish (McIntyre et al. 2015, McIntyre et al. 2014) which can be eliminated by infiltration through bioretention soils (McIntyre et al. 2015, McIntyre et al. 2016). Chinook salmon is not a species that has been tested; thus, it is uncertain how they are affected. These studies indicate that stormwater runoff is potentially toxic to Chinook salmon in streams. The absence of impact to chum salmon also demonstrates how one salmon species can be much more sensitive to chemical contaminants than others.

Meador (2014) analyzed Puget Sound coho and Chinook salmon hatchery release and return data to compare smolt-to-adult return rates (SAR) in contaminated and uncontaminated estuaries. Ten hatcheries located upstream of contaminated estuaries and 12 located upstream of uncontaminated estuaries were identified for this study. Three of the selected hatcheries (Soos, Crisp and Keta creeks) are located in the Green-Duwamish watershed. The Duwamish Estuary was categorized as a contaminated estuary. Thirty eight years of hatchery SAR data (1972–2008) were statistically compared for Chinook and coho grouped across years and year-by-year. A significantly lower SAR (45% lower) was calculated for Chinook from contaminated compared to uncontaminated estuaries across all years or year-by-year; these statistical differences in SAT were not found for coho in the same estuaries.

4.0 CURRENT AND FUTURE ACTIONS

Several ongoing programs and projects are planning actions in the Green-Duwamish watershed which may provide additional contaminant information relevant to Chinook salmon and/or may influence contaminant concentrations. Perhaps the two largest activities that will improve Duwamish waterway conditions are the LDW and EW sediment cleanups. The LDW cleanup plan will addresses 412 acres of contaminated sediment through a combination of active remediation and monitored natural attenuation. The EW cleanup plan is anticipated to be issued by EPA in the next year, which is expected to include remediation of a large portion of the EW. In addition to the LDW cleanup, King County and the City of Seattle's Our Green/Duwamish Program and Ecology's Pollutant Loading Assessment are developing tools and strategies to address water quality in the Green-Duwamish watershed.

4.1.1 The LDW Superfund Cleanup

EPA's Record of Decision contains the LDW cleanup plan (i.e. Selected Remedy) which includes the following actions (EPA 2014).

- 105 acres of dredging or partial dredging and capping;
- 24 acres of capping;
- 48 acres of enhanced natural remediation (placing clean sand to speed up the rate of natural recovery; and
- 235 acres of monitored natural attenuation

Figure 12 illustrates the geographic areas where each type of activity will occur in the LDW. These actions in combination with EAA cleanups are predicted to reduce PCB contaminant concentrations by 90% or more in sediment, fish, and shellfish. The cleanup is estimated to require 7 years of construction to complete followed by 10 more years for monitored natural recovery. Currently, the LDW Group (City of Seattle, King County, Port of Seattle, and the Boeing Company) and EPA are conducting pre-design studies which include:

- Collection of water, sediment, and biota data to establish baseline conditions prior to the sediment cleanup;
- A survey of waterway users to understand how this may affect sediment transport and remediation technology selections (e.g., current and anticipated tug and barge activities in the LDW);
- Documentation of piers and other structures that may affect remediation design; and
- Collection of supplemental sediment and bank data to assist Ecology with source control.

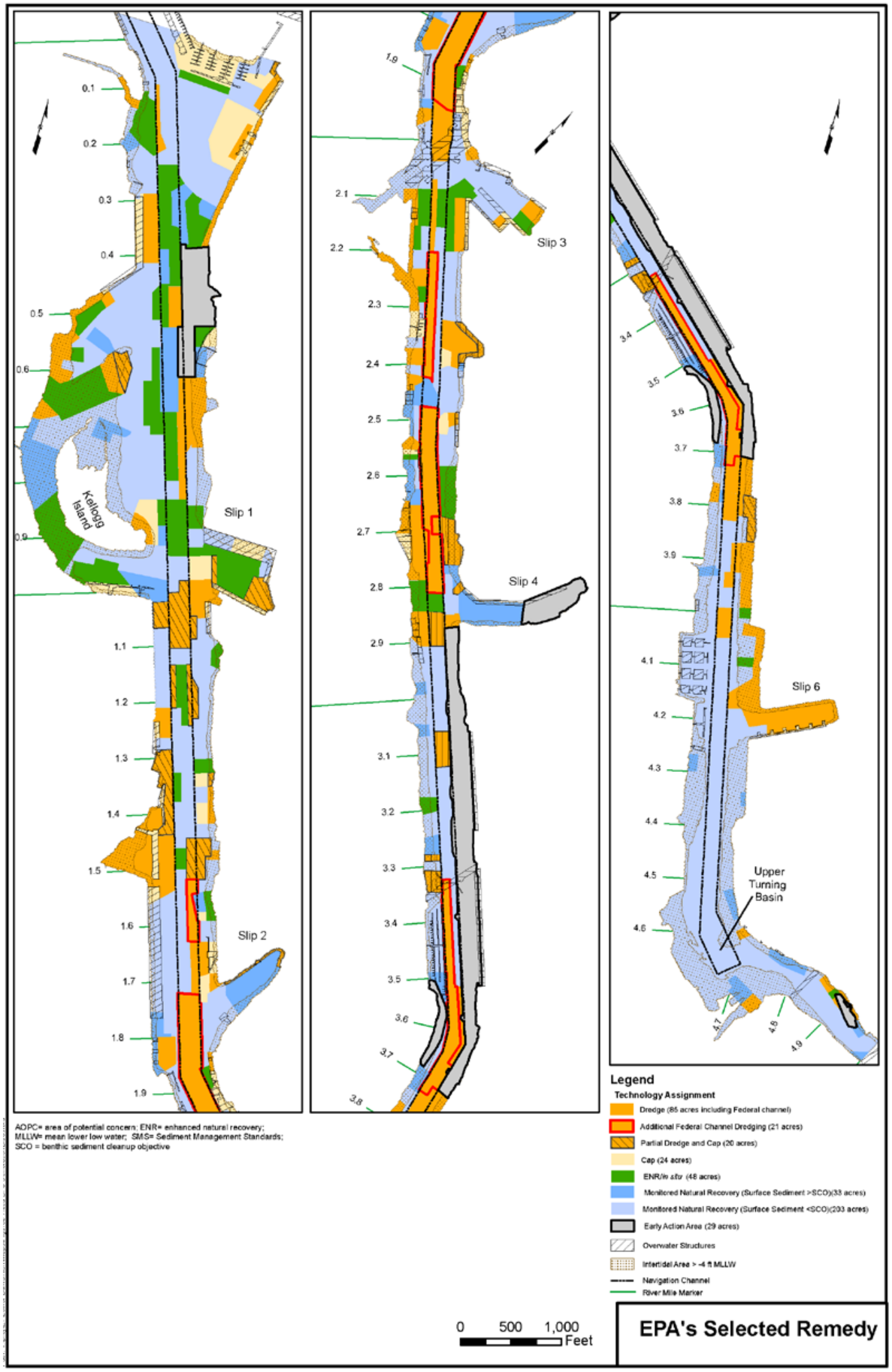

Figure 12. Remedial Actions in the EPA Selected Remedy for the LDW (EPA 2014)

Collection of new water, sediment, and biota data will provide more current contaminant data that could be used to update the information on Chinook salmon exposure levels provided in this report. The next step in the cleanup process will be remedial design sampling and engineering plans for the cleanup construction activities followed by the construction and long-term monitoring.

4.1.2 The EW Superfund Cleanup

The FS for the EW is currently being completed. The FS develops a range of remedial alternatives to clean up contaminated sediments and provides relative rankings for each based on various Superfund cleanup criteria (e.g., long-term effectiveness, short-term impacts, and implementability). EPA will then develop a proposed plan for sediment cleanup and after a public comment period, EPA will then issue a Record of Decision outlining the selected remedy for cleaning up contaminated sediments in EW. The Proposed Plan is expected to be issued in 2018.

4.1.3 Our Green/Duwamish

This project was initiated by King County and City of Seattle. The purpose is to develop a strategy to coordinate the many different efforts in the Green-Duwamish watershed with the objective of protecting and restoring its air, land, and waters (https://ourgreenduwamish.com/). An inventory of projects and programs (Phase I) was conducted in 2015. Workshops were held in 2016 and an initial Watershed Strategy was completed in 2017. The priority topics needing more work were identified as stormwater, open space, climate change, and air quality. Recommendations for actions for each of these topics were made, with the most attention focused on stormwater. Our Green/Duwamish will be developing a final strategy and implementation plan for additional stormwater control in the watershed.

4.1.4 Green-Duwamish Pollutant Loading Assessment

Ecology and EPA are leading the Pollutant Loading Assessment (PLA) for the Green-Duwamish watershed which began in 2012 (Ecology Focus Sheet 2014; https://fortress.wa.gov/ecy/publications/SummaryPages/1410053.html). This project is intended to provide information useful for addressing water quality issues in the watershed that will remain after the LDW Superfund Site cleanup. Clean Water Act violations and contaminated water upstream of the LDW are projected to persist after cleanup is completed. Therefore, EPA and Ecology are working with technical experts and stakeholders in the region to develop models that can:

- Develop a modeling tool to assess pollutant loads from different sources (point and diffused)
- Better understand the relationship between water, sediment and fish tissue quality
- Predict improvements in water, sediment and tissue quality expected to occur as a result of management actions

This effort will occur in phases over several years. As of early 2017, a modeling project plan has been completed (TetraTech 2016) and the watershed model is in development (TetraTech 2017).

5.0 UNCERTAINTY

This section discusses key types of uncertainty associated with the information presented in this document. Measurement uncertainty is associated with data/sample collection methods and analysis for any field or laboratory study conducted. Results of desktop statistical analyses and modeling studies (e.g., ecological risk assessments) also have an inherent quantifiable error. This document does not evaluate each study presented here for these data quality uncertainties. Instead, it evaluates the collective knowledge uncertainty in relation to this document's objective: to assess whether there is evidence that Chinook salmon health is or is not adversely impacted from contamination in the Green-Duwamish watershed. The primary sources of uncertainty discussed are data quantity (completeness of spatial coverage, number, and representativeness of samples) and Chinook salmon effects assessment methods (effect threshold development/selection and endpoints evaluated).

5.1 Data Quantity

When considering sample density, the majority of information gathered to characterize contamination in the Green-Duwamish watershed has been on sediment chemistry and benthic invertebrate community health within the Duwamish Estuary. Sediment and benthic community health data are available at lower densities for the Green River subbasins. These contaminant data are helpful in describing exposure of juvenile Chinook salmon to contamination via their diet (benthic invertebrates), direct sediment contact, and incidental sediment ingestion. The benthic community assessments are also helpful in describing if there might be a reduction in benthic invertebrate food for Chinook salmon from contaminant impacts. Collection of water chemistry data has been very limited in scope and frequency throughout the watershed. The existing data provide some confidence that contaminant exposure to juvenile Chinook or other aquatic life is not a substantive chronic problem, but little certainty that acute or chronic exposures are not problematic under certain flow conditions and/or in some tributaries.

Since 2000, 66 juvenile Chinook salmon composite tissue samples have been processed and analyzed for the studies reviewed in this report; however, all but 4 of these were sampled more than 10 years ago. With several Lower Duwamish remediation projects completed during this time, these older data may represent higher exposures than current conditions. Most of the available juvenile Chinook tissue chemistry data are from the Duwamish Estuary where chemical risk is likely highest.

It is most efficient to remain focused on evaluation of Chinook salmon impacts from toxic contaminants in the Estuary before evaluating Chinook upstream. The overall higher spatial density of environmental data from the Duwamish Estuary likely represents the highest risk exposure scenario given this areas' more industrialized land use history compared to any area of the Green River. However, there may be more localized, small scale, but relatively contaminated sediments in some areas of the Green watershed that have not been identified to date. This seems unlikely but possible given the limited sampling conducted in this relatively large watershed.

5.2 Chinook Effects Assessment Methods

5.2.1 Effect Thresholds

Several studies reviewed here have compared contaminant concentrations to WA state standards (e.g., WQS, SMS). The WQS were developed to be protective of aquatic life while the marine sediment standards and freshwater and marine benthic cleanup standards were developed to protect benthic invertebrates. The WA state WQS and SMS were derived using effect thresholds for many different species. However, Washington State WQS (last issued in 2006) have not kept pace with EPA's updates in criteria. For example, the freshwater copper WQS is still calculated based only on hardness whereas EPA has updated their freshwater acute and chronic aquatic life copper criteria to account for the influence of dissolved organic carbon concentrations (i.e., using the Biotic Ligand Model). It is unknown how well WQS protects Chinook salmon absent incorporation of modern toxicity information into the WQS. Because they protect benthic invertebrates, the sediment standards do not include any fish toxicity data. Therefore, studies summarized in this report comparing sediment chemistry to SMS reflect how contaminants may impact the health of benthic invertebrate populations, an important food source for juvenile Chinook. However, these data are not directly relevant for evaluating adverse impacts of contaminants on Chinook health. More meaningful are the Chinook tissue data and measures of chemical effect. However, many sources of uncertainty present themselves in the interpretation of these data.

There are no existing Washington State (or federal) regulatory standards for tissue concentrations that are protective of fish (some exist for protection of human health or wildlife). Therefore, effect thresholds for fish tissue assessments require project-specific derivation and these efforts can result in very different threshold values for the same contaminant and species of interest. This is partially because of uncertainties in the many assumptions required to identify an effect threshold. For example, the LDW screening ecological risk assessment (Windward 2007) used the highest no-effect thresholds from published studies compared to the maximum measured chemical concentrations in juvenile salmon. The intent for the risk assessment thresholds was to estimate a value below which adverse effects to Chinook salmon would not occur. The final selected threshold for PCBs was 27,000 ug/Kg tissue wet weight based on mortality in spot fish. During the EW risk assessment screening, a lower effect threshold for PCBs was identified (1,400 µg/Kg) based on survival of pinfish[4]. Criteria leading to these threshold selections were defined based on several assumptions, such as that growth and mortality effects are protective but reproductive effects do not need consideration because juvenile salmon do not grow to reproductive age in the LDW or EW. Other examples of assumptions included:

[4] The 1,400 µg/Kg no effect level was based on applying an uncertainty factor of 10 to an observed adverse effects level of 14,000 µg/Kg ww in pinfish (Hansen et al 1971).

- Only used tissue concentrations provided in study; none were estimated,
- effects study data on any fish species can be considered, not just salmonids or Chinook,
- the highest qualifying no-effect concentration below the lowest qualifying effect concentration should be used for endangered species assessment,
- and effect and no-effect concentrations should be in wet weight, not lipid normalized.

The rationale for the appropriateness of these and other assumptions is provided in the LDW and EW ecological risk assessments (Windward 2007, 2012) and is not the subject of discussion here.

In comparison, Meador et al. (2002) estimated a PCB Chinook salmon tissue effects threshold for sublethal effects using different assumptions that resulted in 2.4 µg/g lipid, equivalent to approximately 144 µg/Kg tissue wet weight (assuming 6% lipid). Criteria leading to this threshold selection were defined based on assumptions such as the 10th percentile concentration of biological effect studies is protective of individual Chinook salmon. Other example assumptions used by Meador et al. (2002) included:

- that 75% of an injected Aroclor PCB dose or 50% of ingested food dose is adsorbed into body tissues (used to estimate tissue concentrations from injection or food exposures if not reported),
- only salmonid species effects studies should be used to calculate an effects threshold,
- a PCB effect concentration should be lipid normalized before evaluation,
- lipid content, to allow lipid-normalization, was estimated from the literature for different Chinook salmon lifestages (adult, fry and juvenile),
- and immune system/biochemical effects should be considered, but mortality and growth effects excluded.

Several other assumptions are described in Meador et al. (2002).

These three different PCB effect thresholds (27,000 µg/Kg, 1,400 µg/Kg and 140 µg/Kg) were generated using different assumptions including different target endpoints (growth and survival versus biochemical changes). Biochemical endpoints are more sensitive and provide additional protection than other endpoints, but their link to individual health and survival is more tenuous than growth, reproduction, and survival endpoints. In this comparison, the no-effect thresholds (27,000 and 1,400 µg PCBs/Kg) are much higher than the effect threshold (144 µg PCBs/Kg); the largest difference is two orders of magnitude. This comparison highlights one reason tissue effect thresholds are highly uncertain and can result in different conclusions regarding the potential risk of effects.

The quantity of available exposure and effect studies for salmonids is much lower than for other fish species. Often, available salmon studies are limited to rainbow trout, a species bred captively for mass production and questionable in its representation of wild salmon. For example, six dietary exposure studies were identified for the LDW ecological risk assessment of arsenic in fish (Windward 2007). All but one of these tested rainbow trout and the remaining species was striped bass, a non-salmonid.

Very few effect thresholds have been developed for the numerous CECs that are documented to adversely impact fish. Therefore, although these chemicals have been detected in Puget Sound and its urban estuaries, there is currently no established method for interpreting measured concentrations.

5.2.2 Exposure Pathways

Chinook salmon can be exposed to contaminants through respiration (uptake through gills), dietary ingestion of prey, and incidental ingestion of sediment. Exposure through gill uptake can be significant for contaminants like many metals; thus, gill tissue concentrations can provide valuable information. The most uncertain estimation is for direct exposure to sediments through ingestion. However, this pathway is usually a small contribution to total exposure. The dietary pathway for fish is often of significant magnitude for certain chemicals, but it is difficult to accurately quantify exposure from this pathway. Some studies measure chemical concentrations in dietary components (e.g., stomach contents, invertebrate prey) which can have high natural variability due to individual preferences and food availability. Even with this information, there is uncertainty in the chemical uptake rate from food into fish tissue that is challenging to characterize. Dietary exposure assessment may be more valid than salmon tissue assessments if the contaminant(s) present are metabolizable by fish, such as with PAHs. Using tissue chemistry data to estimate exposure has the advantage of integrating accumulation from all exposure pathways. Thus, it is found useful when assessing bioaccumulative chemicals.

5.2.3 Multiple Contaminant Effects

It is rare for only one chemical contaminant to be elevated in natural surface waters, especially in urban environments like the Duwamish Estuary. The effects of exposure to contaminant mixtures on fish are poorly understood and can only be assessed for a limited number of related chemicals (e.g., dioxins). Chemicals can have additive, antagonistic or agonistic effects but the net effect of multiple contaminants on fish are unknown. For this reason, biomarkers or evidence of adverse health in fish are sometimes used to evaluate contaminant effects. Perhaps the largest challenges in using biomarkers are determining which environmental contaminant causes the measured effects and if the observed effects impact the health and long-term survival of the fish. Lastly, the combined effect of chemical exposures and other stressors, such as higher temperatures and low dissolved oxygen, on fish is also difficult to assess.

6.0 DISCUSSION AND CONCLUSION

Observations of potential impacts of contaminants to juvenile Chinook salmon:

- Chinook smolt-to-adult (SAR) return rates have been found to be significantly lower in contaminated estuaries, like the Duwamish, relative to uncontaminated estuaries.

Tissue chemistry/biomarkers

- LDW and EW risk assessments did not identify risk of impaired growth or survival for juvenile Chinook salmon. However, the LDW risk assessment noted reduced immunocompetence may occur in juvenile Chinook migrating through the LDW.
- Subsequent studies using more conservative assumptions concluded PCBs may be causing health impacts.
- The risks of impacts to Chinook salmon from CECs are unknown although these chemicals have been detected in the Lower Duwamish Estuary.
- Relatively little juvenile Chinook tissue chemistry data have been collected or evaluated in the Duwamish Estuary in the last 10 years, and even less data are available for the Green River. Available tissue chemistry data indicate juvenile Chinook salmon are bioaccumulating contaminants while in the Duwamish Estuary. Tissue assessments suggest that PCB exposure may be causing sublethal adverse effects to juvenile Chinook salmon.

Sediment

- In the most contaminated areas of the LDW and EW, contaminated sediments are potentially impacting benthic invertebrates which could reduce the quantity or quality of food for juvenile salmon.
- Juvenile Chinook salmon in the Duwamish Estuary are exposed to sediments contaminated with PCBs, PAHs, some metals and phthalates.
- In the Duwamish Estuary, PCBs are the most widespread sediment contaminant. Sediment contaminants in the Green River need more characterization. Based on existing data, sediment contamination is highest in Mill (in Kent) and Springbrook Creek and may be a concern to benthic invertebrates. Mill Creek (in Auburn) is less contaminated and Jenkins, Newaukum, Covington or Big Soos creeks are of little concern. Arsenic and BEHP concentrations most frequently exceeded the no-effects benthic sediment cleanup level (SCO) in Green River tributaries.
- Superfund cleanup of contaminated sediments will be an important step in reducing the exposure of aquatic life including Chinook salmon to contaminants, particularly PCBs. Sediment recontamination will remain a risk from dredging activities during cleanup of the LDW and EW.

Water chemistry

- Several water quality assessments have not identified any chemicals that are presenting notable risk to aquatic life. Of the chemicals investigated, mercury in water may be a chronic exposure risk for juvenile Chinook salmon in the Green River.

A qualitative summary of information on contaminant risk to juvenile Chinook salmon reviewed in this report is presented in Table 5. The summary considers whether the completed assessments using each data type are directly reflective of risk to Chinook salmon, the level of risk posed to Chinook by the contamination, and how much knowledge uncertainty is associated with the information.

Considering the low sample density and spatial distribution of water samples across the whole Green-Duwamish watershed, uncertainty associated with water data is concluded to be high although risk based on existing data appears to be low (Table 5). The risk from sediment contamination in the LDW and EW to Chinook from direct ingestion has not been quantified but is likely low relative to other pathways. However, the knowledge uncertainty on this risk is high due to limited information available on sediment consumption during feeding activities. Sediments in the LDW and EW are well characterized, but the impacts of sediment contamination on Chinook salmon are highly uncertain because direct exposure data are unavailable. The impacts of sediment contamination in some areas of LDW and EW on benthic invertebrates is high[5] (adverse impacts) to moderate (minimal impacts) potentially reducing Chinook salmon food quality or quantity. The knowledge uncertainty regarding how these benthic impacts affect Chinook salmon is high. Chinook tissue and biomarker data are the most directly relevant to Chinook salmon. Tissue chemistry assessments using these data in the LDW and EW RIs concluded low contaminant risks while the most recent assessment by WDFW indicates PCBs may be adversely affecting juvenile Chinook. Due to low sample density and effects assessment methods, knowledge uncertainty is high.

Only water and sediment chemistry data were identified as available from the Lower and Middle Green River subbasins (Table 5). Aquatic life assessments suggest overall chemical exposure to Chinook salmon is low. The risk from sediment contamination in the Lower and Middle Green River to Chinook salmon from direct ingestion has not been quantified, but is likely low relative to other pathways. The knowledge uncertainty on this risk is high due to limited information available on sediment consumption during feeding activities. Similarly in the Upper Green, only water chemistry data are available and the overall chemical exposure appears low. The knowledge uncertainty associated with these data is high due to low sample density and lack of updated Chinook-specific thresholds in the WQS.

Table 5. Summary of Information available on contaminant risk to juvenile Chinook.

Duwamish Estuary	Chinook specific assessment?	Risk Level	Uncertainty	Notes
Water	No – Aquatic Life	Low	High	Low data volume; not evaluated with updated Chinook-specific thresholds.

[5] Risk definitions used here are not equivalent to regulatory definitions used in Superfund process.

Duwamish Estuary	Chinook specific assessment?	Risk Level	Uncertainty	Notes
Sediments – Direct Exposure	None completed	Low	High	Lack of exposure data; unknown and indirect effect on Chinook.
Sediments and Benthic Invertebrates	No – Indirect exposure via prey	High (for 4% of LDW);Moderate (for 18% of LDW); Low in other areas	High	Large volume, indirect and unquantified effect on Chinook; multiple lines of evidence.
Tissue/Food/Biomarkers	Yes	Moderate (PCBs)	High	Small data volume and highly uncertain effect thresholds.
SAR (return rates)	Yes	High	High	Contaminants as cause for low SAR unconfirmed. Need further analysis and other lines of evidence.
Low to Mid-Green				
Water	No – aquatic life	Low	Moderate	Small data volume; Black River levels highest for PCBs and PAHs.
Sediments – Direct Effect	No	Low	High	Lack of exposure data; unknown and indirect effect on Chinook.
Sediments and benthic invertebrates	No – Indirect effect on prey	Low in mainstem and most tributaries; moderate in Springbrook and Mill (Kent) creeks.	High in mainstem; Moderate in tributaries.	Indirect and unquantified effect on Chinook; Low sample density in mainstem; >10 per creek.
Upper Green				
Water	No – aquatic life	Low	High	Small data volume; not evaluated with Chinook-specific thresholds.

Relatively recent tissue chemistry data, biomarkers, and smolt-adult-return rate analysis provide multiple lines of evidence, although from only a handful of studies, that juvenile Chinook may experience adverse effects from contaminants in the Green-Duwamish watershed. However, substantial basic knowledge uncertainties are associated with these studies. Recent Chinook tissue assessments are based on only one published Chinook-specific effects threshold for PCBs, one for PAHs and one for PBDEs. Additional studies are needed to bound the uncertainty in relating tissue thresholds and effects in juvenile Chinook. The biomarkers measured by Johnson et al. (2008) and (Arkoosh et al. 2001) need to be connected to Chinook survival and repeated in additional studies. Additional work is needed to demonstrate that lower SARs for Chinook in contaminated estuaries like the

Lower Duwamish result partly or wholly from contaminants and not lack of refugia, food, slower growth or other factors.

Considering all of the information reviewed in this report, findings relevant to chemical contaminants and Chinook are:

- The Chinook salmon smolt-to-adult return rates have been found to be significantly lower in contaminated estuaries (including the Duwamish Estuary), relative to uncontaminated ones.
- Duwamish Estuary Chinook salmon are more contaminated than those in other Puget Sound waterbodies;
- Duwamish Estuary juvenile Chinook salmon may experience adverse effects from contaminants; reduced immunocompetence may occur in juvenile salmonids migrating through the LDW. Better effects data are needed to evaluate effects from PCBs and additional contaminants. No information on potential impacts of CECs on salmon are available for WRIA 9 although limited data show some are present in the Duwamish Estuary.
- Biomarkers, demonstrating contaminant exposure, have been observed in LDW Chinook salmon.
- Benthic invertebrates in some areas of the Duwamish River experience adverse effects from contamination. Therefore, it is possible this could reduce food availability for juvenile Chinook salmon and/or shift diet composition.
- Generally, water and sediment contaminant concentrations increase with distance downstream making the Upper Green the least contaminated and Duwamish Estuary the most contaminated;
- In general, tributaries with evidence of highest sediment contamination are the most urbanized (Springbrook and Mill [in Kent] creeks).

7.0 RECOMMENDATIONS

Although there are several substantial knowledge uncertainties related to contamination in the Green-Duwamish watershed, the highest risk to Chinook salmon from chemical contaminants is most likely in the Duwamish Estuary. Focusing future Chinook salmon work on this part of the watershed will increase the likelihood of success in determining if contaminants are impacting Chinook survival. However, contamination in the Lower Green River, while less severe than the Duwamish River, may also impact Chinook survival. Therefore, supplementing Duwamish Estuary sampling with some in the Lower Green River is recommended to provide context on relative spatial contributions and inform if management of chemical contamination upstream of the LDW will be necessary.

While tracking the LDW cleanup schedule, it is recommended that further direct work on Duwamish Estuary Chinook salmon be supported by the WRIA 9 group. Work completed before cleanup begins on the LDW and EW will provide a foundation for comparison with future data to measure how juvenile Chinook health and contaminant impacts change over time. This work will be most efficiently directed at Chinook diet and tissue chemistry, biomarkers and sublethal effect measurement and improvement of Chinook-specific effect thresholds. Although any single type of exposure or effect measurement may have substantial uncertainties, collectively, multiple lines of evidence can more accurately characterize chemical impacts on Chinook salmon.

Recommendations for Future Work:

- Conduct studies that measure contaminants in juvenile Chinook tissues and stomach contents at different life stages or residence times; e.g., in rearing habitat for Chinook, in restored habitat project areas, and where tributaries enter the Green River. This work will strengthen the small dataset available for risk evaluation.
- Focus new studies on contaminants known to be elevated in the Duwamish Estuary and for which substantial effects data are published for some salmonids (PCBs, PAHs) and opportunistically explore CECs, such as pharmaceuticals, in water and Chinook salmon to build a chemistry database. CEC analysis is costly, effects analysis tools are lacking, and substantial new data are necessary to begin risk evaluation for Chinook. Therefore, prioritizing known contaminants first will optimize resources.
- Establish one or more new tissue effect thresholds for PCBs that are Chinook-specific. Effects thresholds are a tool that allow chemistry results to be placed into the context of toxicity. PCBs are the most widespread contaminant in the Duwamish Estuary. Outside of Superfund risk assessments, there is only one published PCB effect threshold that has been developed to assess Chinook in this region. Given the highly variable assumptions made in defining an effects threshold, developing one (or more) new PCB thresholds would provide a more stable foundation for evaluating how PCBs are affecting Chinook survival.
- Support studies that examine other effects evidence (e.g., juvenile Chinook bioassays with Duwamish sediments, biomarkers) by providing in-kind or financial assistance. In addition to the types of evidence recently collected for Chinook

salmon (tissue and stomach content chemistry concentrations), work on other lines of evidence that can demonstrate occurrence of contaminant effects. For example, encourage National Oceanic and Atmospheric Administration or WDFW to conduct laboratory exposure of salmon for PCB, PBDE, PAH effect endpoints using Duwamish sediments.

- Tease out cause(s) of lower SAR by collecting juvenile salmon when they leave the Duwamish Estuary and measure body mass, nutrition and stomach contents and compare to release mass of Chinook salmon from hatcheries. This would test if food quality (e.g., benthic invertebrates) between hatchery and Duwamish Estuary mouth may be reducing juvenile health and decreasing SAR.

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