Stormwater Quality in Puget Sound

Impacts & Solutions in Reviewed Literature

UPDATED SEPTEMBER 2021

The Nature Conservancy
Washington

Washington State University

By Cailin Mackenzie, Jasmine Prat, Jenifer McIntyre, Emily Howe, Jessie Israel

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Puget Sound, the largest estuary in the United States, nurtures a unique, complex interchange between land and sea, connecting the Cascade and Olympic mountains to the open Pacific Ocean.

MUCH OF THIS CONNECTION OCCURS THROUGH FRESHWATER, with 19 river drainage basins navigating diverse terrain to feed the Sound. More than 100 years of industrial pollution and urban development have affected the water quality of Puget Sound. The largest ongoing source of pollution to Puget Sound is stormwater runoff, annually contributing more than 370 billion gallons of water draining off of urban land-uses (Ecology & King County 2011). The impacts of stormwater on overall water quality in Puget Sound has direct implications for Puget Sound wildlife. Urban stormwater runoff is harmful to a variety of marine organism, particularly Pacific salmon populations, and can also impact human health. If increased treatment and prevention measures are not taken to mitigate stormwater runoff, water quality will continue to decline. While mitigation measures typically occur locally, the complexity and scale of the problems range from multi-city to multi-national. Management and policy around those mitigation measures need to match the range of scales, transcending local, state, and international decision-making (Levin et al., 2020). Likewise in regional efforts to address Puget Sound stormwater pollution in marine ecosystems, mitigation planning and implementation need to be coordinated across the numerous stormwater jurisdictions and not occur discretely within them.

Puget Sound makes a vibrant home for approximately 4.2 million people and continues to undergo rapid urban expansion. Puget Sound holds more than half of Washington State's population and is expected to add more than a million people by 2040 (Puget Sound Regional Council 2018). Furthermore, 82% of Puget Sound's population live on just 3% of the regions' land area in what are known as 'urban growth areas' (WDNR 2015). This population increase and urbanization alters the natural habitat of the Puget Sound in a variety of ways, including: impervious surface area increases, generation of urban runoff, industrial waste, and livestock runoff, armored shorelines, and overharvesting of fish, shellfish, and timber (Zank et al. 2016). Urban stormwater runoff is generated from precipitation on impervious surfaces such as roads, sidewalks, and roofs. As the precipitation is unable to infiltrate the ground it runs off the surface picking up pollutants as in moves across the surface. Impervious surfaces therefore cause a hydrologic shift from what was predominantly a subsurface flow of water through the ground to a surface flow, increasing the volume and velocity of urban stormwater runoff (Arnold and Gibbons 1996, Paul and Meyer 2001, Barbosa et al. 2012). For example, a 2-year storm in an area with 10% impervious surface area produces the same volume of runoff that a 10-year storm does in a forested area (City of Seattle 2015). An increase in stormwater runoff leads to an increase in sediment, nutrient, and contaminant transport as the runoff picks up chemical pollutants from our roads, buildings, and yards, before emptying into Puget Sound.

For most toxic pollutants, surface runoff contributes the largest loading to Puget Sound (Ecology & King County 2011). The consistent flushing of runoff toxicants into the water system impacts local marine species. For example, 100,000 acres of shellfish beds were closed in in 2017 in Puget Sound due to water quality attributed primarily to urban runoff (U.S. EPA 2019). Urban road runoff toxicity has been linked to coho salmon mortalities for multiple decades (Kendra and Willms 1990) and also affects their invertebrate prey (McIntyre et al. 2015). Coho salmon (*Oncorhynchus kisutch*) have been found to be particularly sensitive to urban runoff toxicity, (McIntyre et al. 2018) dying prematurely at rates of 70-90% when returning to urban streams to spawn

(Scholz et al. 2011). This phenomenon puts local populations of coho salmon at risk for extirpation (Spromberg and Scholz 2011).

Stormwater runoff is the principal contributor to water quality pollution nationwide (National Research Council 2009), and virtually all urban streams and rivers feeding Puget Sound have been affected by stormwater runoff toxicity (Booth et al. 2004). Stream health, as represented by benthic index of biological integrity (B-IBI), decreases in Puget Sound watersheds as total impervious surface area increases (Booth et al. 2004). More recent research has found increased risk in coho pre-spawn mortality and decreases in macroinvertebrate richness along an urban gradient in the Puget Sound basin (Peter et al. *In Prep*). The relationship between impervious surface and stream condition has been quantified by the "10 percent rule"; a threshold of roughly ten percent of impervious area in a watershed linked to aquatic habitat degradation (Klein 1979, Booth and Jackson 1997, Paul and Meyer 2001, Wang et al. 2001). Road density and number of road-crossings have been shown to be better predictors of deteriorated stream health than total impervious surface, highlighting the significance of roads and road runoff as a threat to aquatic communities (Alberti et al. 2007, Johnson et al. 2013).

It's important to invest in solutions that improve water quality in Puget Sound to protect local wildlife, as well as human health. Stormwater treatment with soil infiltration has been shown to eliminate toxic responses like the urban runoff mortality syndrome in coho salmon (Spromberg et al. 2016) and cardiovascular toxicity in developing fish (McIntyre et al. 2016a). Soil infiltration is a common feature of green stormwater infrastructure (GSI), and City of Seattle and King County, the most populous areas of Puget Sound, are currently pursuing the goal to manage 700 million gallons of stormwater with GSI by 2025 (King County & Seattle Public Utilities 2019).

We currently spend about $100/capita annually on managing stormwater runoff in the Puget Sound region (Visitacion, Booth, & Steinemann 2009). Restoring the Puget Sound basin to hydraulically function like a forest and soak in rainfall is estimated to cost $650 million annually over a 100-year implementation timescale, or 14 billion annually under a 30-year implementation timescale (King County 2014a). However, there is also significant economic costs of inaction. For example, annual losses due to polycyclic aromatic hydrocarbon (PAH) exposure alone are estimated to be between $4.4 and $12.1 billion in Washington (Ecology & WDOH 2012), and every dollar spent to reduce lead exposures in the United States is estimated to produce $17-$221 in benefits (Bennett et al. 2016).

Improving water quality will benefit entire trophic systems, from benthic communities to resident Orca whales and people. Flow control is a critical partner to water quality treatment to minimize the negative impacts of urban stormwater runoff including stream flashiness, combined sewer overflows (CSOs), and flooding – however, flow control is not a focus of this review. This report analyzes what is known about toxic pollutants in urban stormwater runoff in Puget Sound and their impacts on Puget Sound biota. The question of how much treatment is needed and where to put it is discussed as well, and recommendations for action and research are presented.

I. What We Know

Decades of research on toxic contaminants and their impacts provide the foundation to improve the health of Puget Sound. Toxics are released from their sources and travel along pathways to ultimately reach Puget Sound and contribute to its total pollutant loading. This section presents an overview of what we know about toxic contaminants in Puget Sound, including their sources, loadings, pathways, and impacts including toxicity, tissue accumulation, presence in water and sediment, and human health effects.

Toxics Loading to Puget Sound

Toxic chemicals in Puget Sound waters and sediments have been studied for decades. The Washington State Department of Ecology (Ecology) is the regulatory agency charged with carrying out the federal Clean Water Act for the state, monitoring and regulating toxics in Washington's waters. From 2006 to 2011, the Ecology worked with partners to conduct a comprehensive estimate of the sources, releases, pathways, and loadings to Puget Sound of select toxic chemicals (Ecology & King County 2011). The studied contaminants were chosen based on documented history and potential to harm Puget Sound ecosystems. For each pollutant studied, major sources, annual releases in the Puget Sound basin, annual loadings to Puget Sound, and major pathways to the Sound determined by this study are presented in Table 1 (Ecology & King County 2011; Ecology 2015a). The studied pollutants are arsenic, cadmium, copper, lead, mercury, zinc, polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), polychlorinated dibenzodiodioxins and dibenzofurans (PCDD/Fs), dichlorodiphenyltrichloroethane (DDTs), polycyclic aromatic hydrocarbons (PAHs), diethylhexyl phthalate (DEHP), triclopyr (an herbicide), nonylphenol (detergent), petroleum, oil and grease.

As a note, this loading study analyzed total PAHs using a list of 16 'priority PAHs' created by the Environmental Protection Agency (EPA) in 1976. Recent questions have been raised about the relevancy of this list, which has widespread use in the scientific community. Shortcomings of this list include the absence of several highly toxic, commonly occurring PAHs, absence of alkylated derivatives despite evidence of toxicity, and absence of heterocyclic aromatic compounds. An alternate list of 99 compounds has been proposed for use in scientific assessments. The list consists of 40 PAHs (including the 16 EPA PAHs), 23 NSO-heterocyclic compounds, 6 heterocyclic metabolites, 10 oxy-PAHs, and 10 nitro-PAHs (Andersson & Achten 2015). Due to the limitations of the 'priority PAH' list, loading of PAHs to Puget Sound may be far higher than the values estimated in Table 1.

Table 1. Sources, releases, loadings, and pathways of select toxics to Puget Sound (Ecology & King County 2011)

TOXIC	PRIMARY SOURCES	TOTAL RELEASE (T/YR)	TOTAL LOAD (T/YR)	MAJOR PATHWAYS	MEDIAN LOADINGS FROM SURFACE RUNOFF (T/YR)
ARSENIC	Mining, industrial air emissions, wood treated with chromated copper arsenate, roof materials	0.8[a]	14-25	Stormwater	16.9
CADMIUM	Roofing materials	1.0	0.05-0.53	Groundwater, air deposition	0.01
COPPER	Pesticides and fertilizers, brake pads, roofing materials, boat paint, plumbing components	180-250	33-80c	Stormwater	30.6*
LEAD	Ammunition, loss of fishing sinkers & wheel weights,	520	3.6-12		Stormwater
MERCURY	Improper disposal of consumer products, crematoria and industrial air emissions	0.5	0.11-0.37	Stormwater	0.136

ZINC	Roofing materials, vehicle tires, motor oil	1,500	140-200	Stormwater	106.47*
PCBS	Electrical equipment, leakage and spills, caulking, paints & coatings	2.2	0.003-0.02	Stormwater	0.005*
PBDEs	Flame retardants: furniture, computer monitors, residential & commercial indoor sources	0.7	0.028-0.054	Air deposition, wastewater	0.005*
PCDD/Fs	Burn barrels	0.000009	NA	NA	
DDTs	NA	NA	0.0025-0.032	Stormwater	0.026
PAHs	Wood smoke; creosote treated wood including pilings, bulk-heads, railroad ties, utility poles; vehicle emissions	310	0.19-1.0c	Groundwater, stormwater	0.383*
DEHP	Polymer off-gassing, air emis-sions, roofing materials	17	2.0-3.2	Stormwater	1.959
TRICLOPYR	Herbicide applications	150	0.64-0.69	Stormwater	0.719
NONYLPHENOL	Air emissions from detergents	0.18	0.023-0.024	Stormwater	0.025
PETROLEUM	Motor oil drips and leaks, improper oil disposal, gasoline spillage during fueling	9,300	330-500	Stormwater	345
OIL & GREASE	NA	NA	8,500-11,000	Stormwater	8,469

a Recent estimates of As contribution from roofing materials alone >20 t/yr (McIntyre et al. 2019)
* Values from Ecology 2015

There is important supplementary information on toxic loadings available in reviewed literature:

- Vehicles drip an estimated 7 million quarts of motor oil into Puget Sound waterways every year, and petroleum is estimated to represent over half of all toxic pollution in Puget Sound stormwater (Puget Soundkeeper 2015).
- Vehicles emit an estimated 84,000 kilograms (kg) of PAHs every year in Washington (Ecology & WDOH 2012)
- Brake friction releases 68,700-80,000 kg of copper, 11,800-17,000 kg antimony, 9,800-13,900 kg zinc, and 100-200 kg nickel in the Puget Sound basin yearly (Ecology 2013b).
- Tire wear contributes an estimated 80 tons per year of zinc loading to Puget Sound (Whiley 2011).
- Fecal loading to Puget Sound has not been estimated in reviewed literature.
- Contaminants of emerging concern (CECs) including pharmaceuticals, personal care products, and endocrine disrupting chemicals (EDCs) were not reflected in Ecology & King County's loading study.
- If the two wastewater effluents studied in a Central Sound study are representative, there are 44,000 kg of CECs entering Puget Sound every year in wastewater alone (Meador et al. 2016).
- Out of 172 waterbodies in King County that are listed as impaired because of fecal bacteria, only 59 have some type of pollution control plan in place (Watson 2019).

There is an association between fecal coliform levels and urbanization in Puget Sound (Ecology 2015b). A Western Washington study found fecal coliform samples to have an overall median of 350 (cfu/100mL), with urban land-use categories (high-density residential, commercial, industrial) samples all exceeding the 200 (cfu/100mL) standard for waters in secondary contact recreation category (Ecology 2015b).

It is important to note that annual loadings do not encompass all of Puget Sound pollution – annual loadings contribute to Puget Sound's total toxic burden. Possible fates of toxics entering Puget Sound include being metabolized in tissue, bioaccumulated in tissue, incorporated in sediment, volatized, degraded, or conserved in marine waters. Reductions of annual toxics loading to receiving waters does not reduce these legacy loads. Legacy loads of pollutants exist throughout Puget Sound that require mitigation. For example, contaminated sediments in the Thea Foss and Wheeler-Osgood Waterways cost the City of Tacoma $105 million to remediate (PSP 2010).

Stormwater Monitoring and Chemical Detection Methods

As previously noted, Ecology is the delegated state agency responsible for implementing the federal Clean Water Act in Washington State. Ecology fulfills its requirements under the Act through the Water Quality Assessment (WQA) which compares all available data from Ecology's monitoring programs and data submitted by external entities to water quality and sediment standards (Ecology 2020). Because the assessment relies on measurement of targeted contaminants for which standards exists, any presently unidentified toxicants and toxicants for which a standard has not been set may be impacting water quality are unregulated.

The ability to identify toxicants responsible for observed adverse effects in complex mixtures such as stormwater is imperative to ultimately regulating impacts of stormwater on biota in Puget Sound. High resolution mass spectrometry (HRMS) is increasingly being used to detect unidentified organic chemicals in water and fish tissues. This non-target approach was used to characterize the occurrence of 87 CECs in Puget Sound (Tian et al. 2021). The method has also been used to detect hundreds of unique chemicals absorbed by adult coho salmon experimentally exposed to road runoff (Du et al. 2017), and 57 chemicals have been associated with the coho salmon urban runoff mortality phenomenon through co-detections in water samples and fish tissues when mortality events occur (Peter et al. 2018). Most recently, nontarget HRMS was used in concert with effect-directed analysis to identify a ubiquitous, previously unknown chemical associated with tire rubber, 6PPD-quinone, that causes acute mortality in coho salmon (Tian et al. 2021). This is a clear example of the insufficiency of current regulation paradigms that are limited to a relatively small list of chemical toxicants to monitor.

Identifying strong relationships between contaminant concentrations may help to reduce monitoring and assessment efforts. In the Western Washington Phase 1 (NPDES) Stormwater Permit (Ecology 2015b) a comprehensive Principle Component Analysis of the pollutant data from stormwater and storm sediment samples in Western Washington indicated several contaminant groups were closely related. Parameters that appeared to be positively correlated include:

- PAHs and dichlobenil
- Copper, zinc, total lead, total suspended solids (TSS), Biological Oxygen Demand (BOD), and total phosphorus
- Cadmium, dissolved lead, and turbidity
- Total Kjeldahl nitrogen (TKN) and pentachlorophenol
- Hardness, conductivity, surfactants, and ortho-phosphate

In addition to reducing monitoring efforts, the ability to use one pollutant as a proxy for other contaminants could buy-down the overall costs of future water quality monitoring, decision support tools or remote sensor technologies.

Sources of Toxics to Puget Sound

The deterioration of Puget Sound quality is due in part to the sources that release toxic contaminants in the Puget Sound basin and contribute to the overall pollutant loadings to the Sound. The load is the amount (mass) of a pollutant that is discharged into a water body during a period of time (i.e. tons of sediment per year). Source releases are typically 10 to 10,000 times larger than loadings due to dilution, deposition, and degradation. Sources of toxics in Puget Sound are most clearly attributable to the different ways land is used (Rau 2015) – developed land is a much larger source of pollution than undeveloped land. Monitoring of water, sediment, and tissue contamination in Puget Sound generally shows increased concentrations of toxic chemicals proximate to urbanized areas, and decreased contamination proximate to undeveloped areas (Ecology 2011).

Coho salmon pre-spawning mortality rates increase along an urban gradient associated with road and traffic density (Feist et al. 2017). Benthic degradation in freshwater (Morley 2000) and marine (Bilkovic et al. 2006) habitats increases with increasing impervious surface area (Booth et al. 2004). Even areas with low development (5-10% impervious) show significant benthic degradation in streams (Cuffney et al. 2010). In a California study comparing runoff from similar watersheds differing in degree of development, the urbanized watershed consistently produced runoff with higher volume and toxicity than the undeveloped watershed (e.g. Bay et al. 2003).

Within urbanized areas, commercial and industrial land uses are generally bigger sources of toxic contaminants than residential uses:

- Commercial and industrial runoff is usually contaminated with metals, sediments, and anthropogenic organic pollutants including phthalates, PAHs, and other hydrocarbons (City of Seattle 2015). In a Puget Sound study, toxic chemicals were detected most frequently and at highest concentrations in commercial/industrial sub-basins (Ecology 2011). A study of PCB loading to Lake Washington found PCB loading was correlated with commercial and industrial development (King County 2013b). According to monitoring data from National Pollutant Discharge

Elimination System (NPDES) Phase I permittees, metals, hydrocarbons, phthalates, total nutrients, fecal coliform, pentachlorophenol, and PCBs were detected more frequently and in higher concentrations in commercial and industrial samples than residential samples (Ecology 2015b). A Puget Sound study of sediment pore water toxicity to sea urchin fertilization observed greatest toxicity in industrial harbors, intermediate toxicity in rural bays, deep-water passages, and urban bays, and lowest toxicity in deep basins (Long et al. 2012). A Southern California study observed that industrial runoff had the highest metal flux among all land use types including agricultural, commercial, residential, and transportation (Tiefenthaler, Stein, & Schiff 2008).

- Residential runoff is generally contaminated with road-based pollutants, as well as pesticides, surfactants, nutrients from fertilizers, sediment from gravel or dirt driveways, and bacteria and viruses from animal waste (City of Seattle 2015). According to data from NPDES Phase I permittees, residential runoff had higher concentrations of dissolved nutrients than commercial/industrial runoff (Ecology 2015b). Improper vehicle management is another source of stormwater toxicants. In Puget Sound, 11% of vehicle owners and 28% of boat owners seldom or never check their vehicle for leaks. Additionally, 35% of vehicle owners always, usually, or sometimes wash their vehicle in the driveway, street, or parking lot, adding toxics to the storm system (PSP 2015b).
- Agricultural runoff can often contain pesticides, metals, and nutrients. Metal and nutrient concentrations were higher in agricultural runoff than residential runoff in a Puget Sound study (Ecology 2011). A Southern California study reported agricultural runoff had higher mean storm flux of total suspended solids (TSS), copper, zinc, and lead than residential land uses (Tiefenthaler, Stein, & Schiff 2008). Agricultural land uses can also contribute nutrients and veterinary pharmaceuticals from livestock excretion.

There is important supplementary information on toxic sources available in reviewed literature:

TRANSPORTATION

- Highway runoff consists of thousands of chemical features (Du et al 2017).
- Road density and number of road-crossings have been shown to be better predictors of deteriorated stream health than total impervious surface, highlighting the significance of roads and road runoff as a threat to aquatic communities (Alberti et al. 2007, Johnson et al. 2013).
- Coho prespawn mortality is correlated with local road area (Feist et al. 2011) as well as traffic intensity (Feist et al. 2017). Experiments confirm that road runoff is highly toxic to coho salmon (e.g. McIntyre et al. 2015; Spromberg et al. 2016; Chow et al. 2019) and their prey (McIntyre et al. 2015).
- Street surfaces are major potential sources of bacteria in urban runoff, mainly due to pet and wildlife waste (Pitt 1998). Runoff from the 520 bridge over Lake Washington has sizable concentrations of fecal coliform and E.coli, attributable to vehicular sources as well as bird droppings (King County 2005).
- Vehicles are the primary source of pollutants in road runoff – leaks release oil and grease, exhaust produces PAHs, tire wear produces zinc, brake pad wear produces copper, and metallic wear, battery leakage, and wheel balance weights produce lead (City of Seattle 2015).
- Vehicles emit an estimated 84,000 kilograms (kg) of PAHs every year in Washington (Ecology & WDOH 2012)
- Vehicles drip an estimated 7 million quarts of motor oil into Puget Sound waterways every year, and petroleum is estimated to represent over half of all toxic pollution in Puget Sound stormwater (Puget Soundkeeper 2015).
- Brake pad wear can account for up to half of the copper entering Puget Sound streams and lakes (Ecology 2013b). 84% of copper released from brake pads in Puget Sound is released on urban roads (Whiley 2011).
- Brake friction releases 68,700-80,000 kg of copper, 11,800-17,000 kg antimony, 9,800-13,900 kg zinc, and 100-200 kg nickel in the Puget Sound basin yearly (Ecology 2013b).
- Tire wear contributes an estimated 80 tons per year of zinc loading to Puget Sound (Whiley 2011).
- 82% of tire wear in the Puget Sound basin is released on urban roads (Whiley 2011). The average tire emits 30% of its tread rubber into the environment, and tire wear rates range from 0.006 to 0.09 g/km per tire (Wik & Dave 2009).
- Chemicals leaching from tire wear particles are most chemically similar to toxic stormwater samples, relative to other motor vehicle contaminant sources (Peter et al. 2018).
- Tire wear and antifreeze are significant sources of benzothiazoles (Reddy & Quinn 1997).
- Asphalt pavements produce higher loads of copper and zinc than concrete pavements, probably because carbonates and hydroxides in concrete adsorb copper and zinc. Asphalt can leach zinc. Concrete increases mobility of particulates like total suspended solids (TSS) and lead (Murphy, Cochrane, & O'Sullivan 2015).

BUILDINGS

- Building siding is an important source of lead, copper, cadmium, and zinc in stormwater runoff (Davis, Shokouhian, & Ni 2001).
- Roofing material is a common source for leaching metals such as arsenic, copper, and zinc into stormwater (Winters et al. 2015). Runoff from several tested roofing materials

in Puget Sound basin demonstrated elevated concentrations of copper, arsenic, lead and zinc (Ecology 2014a), but values for some metals were lower than those estimated in the 2011 loadings assessment by Ecology & King County. In contrast, CCA-treated wood shingles were found to be a greatly underappreciated source of arsenic in the basin (McIntyre et al. 2019). Copper and zinc in runoff from existing roofing, siding, and accessories like gutters and chain link fencing in Lacey, WA were recently monitored to provide better estimates of these metals in runoff from urban areas of Puget Sound (Ecology 2019). In a study comparing the metals leaching from residential and commercial roofing materials common in Puget Sound, most arsenic and copper was estimated to be contributed by residential roofing materials (McIntyre et al. 2019), whereas most zinc was from commercial roofing.

→ 88% of exterior caulk sampled from San Francisco Bay Area buildings had detected PCBs, and 40% of samples had PCB concentrations exceeding 50 ppm. PCB distribution in San Francisco was estimated at 4.7 kg per building. These findings are consistent with other studies identifying high PCB concentrations in concrete and masonry buildings built between 1950 and 1980 (Klosterhaus et al. 2014).

→ The sources of PCBs in stormwater likely include clusters of older buildings, mostly commercial and industrial, that have PCB-containing exterior coatings (King County 2013b). Exterior coatings, including flashing, caulks, and sealants, have not been studied widely in Puget Sound (Futurewise 2016).

YARDS

→ Approximately 50% of Puget Sound residents apply pesticides every year. The most treated pests are weeds, moss, insects, and ants (WSDA 2014). 29% of Puget Sound residents always, usually, or sometimes use weed and feed, 30% use herbicides, 18% use insecticides, 18% use moss killers, and 44% use fertilizers (PSP 2015b). The most commonly applied pesticides in every category are:

- Herbicides: glyphosate (36.6%) and 2,4-D (31.1%)
- Moss control products: ammonium salts of fatty acids (32%) and potassium laurate (20%)
- Insecticides: pyrethroids (58.4%) and neonicotinoids (26.3%)
- Ant control: cyfluthrin, indoxacarb, fipronil, bifenthrin, and imidacloprid (WSDA 2014)

→ Pet waste is a significant source of fecal pollution to Puget Sound. There are over 1 million dogs in the Puget Sound region. Pets produce over 22,000 kg of waste every day in Seattle only, and a single gram of pet waste contains 23 million fecal coliform bacteria (Puget Soundkeeper 2015). 42% of Puget Sound pet owners always or usually dispose of pet waste somewhere other than the trash, like compost piles, and 19% of pet owners seldom or never pick up yard dog waste (PSP 2015b).

OTHER SOURCES

→ Wildfires are a potential source of metals in stormwater runoff. Wildfires increase the mobility of lead, iron, copper, and zinc: the dissolved ratio of these metals was higher in wildfire runoff than urban runoff in a California study. Concentrations of copper, zinc, lead, iron, and vanadium (both dissolved and soluble) were all significantly higher in runoff from burned areas compared with runoff from adjacent unburned natural areas (Pinedo-Gonzalez et al. 2017). The impact of Washington wildfires on stormwater runoff in Washington has not been studied. However, PAHs are generated from burning wood in wildfires, woodstoves, or fireplaces (Ecology & King County 2011).

→ Cigarette butts make up 22-46% of visible litter worldwide, and 76% of publicly smoked cigarettes are littered. Cigarette butts can leach toxics including nicotine, PAHs, ethyl phenol, and metals. Smoked cigarette butts can be acutely lethal to fish; one study found that just one butt per L was sufficient to kill half of test fish (Slaughter et al. 2011). Another study determined that one cigarette butt can contaminant 1000 L of surface water above predicted no-effect concentrations for nicotine. Nicotine causes liver damage in fish (Green, Putschew, & Nehls 2014).

→ Artificial turf has been shown to leach metals into stormwater. Turf runoff was acutely toxic to water fleas and fathead minnows, with toxicity linked to zinc concentrations that exceeded acute aquatic life criteria (Connecticut DEP 2010). A study of turf infill in King County parks found that crumb rubber infill leached 110 organic chemicals and 14 metals, with As, Cu, Zn, and N-nitrosodiphylamine at concentrations above water quality standards (Colton 2019).

→ The main source of pharmaceuticals in receiving waters is sewage effluent, which can enter stormwater runoff via CSOs, faulty septic systems, and biosolids applied as fertilizers (Gaw, Thomas, & Hutchinson 2014). Improper waste disposal can also contribute sewage contaminants to Puget Sound: 64% of boat owners and 56% of RV owners in Puget Sound seldom or never dispose of wastewater in approved facilities (PSP 2015b). Factors that increase pharmaceutical concentrations in marine water and sediment include proximity to wastewater treatment outfalls, high effluent outfalls, and increasing size of adjacent urbanized areas (Gaw, Thomas, & Hutchinson 2014). In a Central Sound study, the most important source of CECs was wastewater, and other potential sources included leaky septic systems, stormwater runoff, industry, aquaculture, landfills, biosolids, and agriculture (Meador et al. 2016).

Toxic Pathways to Puget Sound

Stormwater is the most important pathway to Puget Sound for most toxic contaminants, transporting more than half of the Sound's total known toxic load (Ecology & King County 2011). During a robust Puget Sound monitoring study, toxic chemicals were detected more frequently and at higher concentrations during storm events compared with baseflow for diverse land covers, pointing to stormwater pollution (Ecology 2011). The Puget Sound basin has over 4,500 unnatural surface water and stormwater outfalls, 2,121 of which discharge directly into the Sound (WDNR 2015). Although stormwater was not determined to be a "major pathway" for PBDE loading to Puget Sound (Ecology & King County 2011), stormwater was the second largest pathway for PBDEs into Lake Washington, which then feeds into Puget Sound via Lake Union (King County 2013a). Stormwater was also determined to be an important pathway for PBDEs to King County receiving waters (King County 2016).

According to one study (King County 2016), the sources and pathways estimated to be most important to King County receiving waters differ slightly from the 2011 loading study. The most important pathways for different contaminants were:

- Upstream watersheds and stormwater —lead, mercury, PBDEs, PCBs
- Upstream watersheds—nutrients, solids, arsenic, phthalates
- Creosote-treated pilings—PAHs
- Uncontrolled CSOs—fecal coliform
- Boats—copper

Antecedent dry period, season, and first flush effects are important factors for most contaminants in stormwater runoff. In Puget Sound, most precipitation falls between October and March. Higher contaminant concentrations and loads in runoff were observed from March to September, indicating the influence of antecedent dry periods and therefore seasonality to build up pollutants (Ecology 2015b). This seasonal trend was not observed for PAHs, phthalates, and pesticides. In Puget Sound, longer antecedent dry periods are correlated with higher concentrations of metals (Ecology 2014a), ortho-P, dissolved organic matter, PAHs, and TSS (McIntyre et al. 2014). In Southern California, early season storms produced significantly higher metal flux than late season storms (Tiefenthaler, Stein, & Schiff 2008) and stormwater produced by the first storm of the year was more than three times as toxic as subsequent storms (Bay et al. 2003).

Higher pollutant concentrations during the beginning of single storm events, called first flush effects, have been consistently reported in highway runoff (Kayhanian et al. 2012). First flush effects have been observed for tire wear particles (Wik & Dave 2009), benzothiazoles (Reddy & Quinn 1997), metals (Tiefenthaler, Stein, & Schiff 2008), and aquatic toxicity (McQueen et al. 2010; Kayhanian et al. 2008). In the Puget Sound region, a study tracking 35 stormwater-chemicals in urban streams found that the chemicals increased to high levels well in advance of the rise in the hydrograph (Peter et al. 2020).

Stormwater is an important pathway for CECs that were not studied in the Ecology & King County 2011 study. In a Sound-wide monitoring study of CECs, 17 detected contaminants in estuarine water were absent from wastewater effluent, suggesting other important pathways like stormwater runoff (Meador et al. 2016). In a California study of CECs in mussel tissue, tissue concentrations in waters receiving stormwater input were significantly higher than those not receiving stormwater. Increasing concentrations of alkylphenol, PBDEs, and perfluorinated compounds were correlated with increasing urbanization and proximity to stormwater outfalls (Dodder et al. 2013).

Other major pathways for toxics loading to Puget Sound are groundwater, air deposition, and wastewater. Groundwater loads are estimated to be an order of magnitude lower than stormwater runoff for most chemicals. Air deposition is an important pathway only for PBDEs and PAHs with high molecular weight, which tend to be adsorbed to particulate matter. Wastewater treatment plants are important pathways only for phthalates, PBDEs, and likely other pharmaceuticals unaddressed in the Ecology & King County 2011 loading study. These pathways are not a focus of this report.

Parameter Similarities

Western Washington Phase 1 (NPDES) Stormwater Permit (Ecology 2015) authors did a comprehensive Principle Component Analysis (PCA) of the pollutant data from stormwater and storm sediment samples collected between 2007 and 2013. The grouping of parameters used in the PCA of water concentrations indicated that some parameters were closely related across the sites. Parameters that appeared to be positively correlated include:

- PAHs and dichlobenil
- copper, zinc, total lead, TSS, BOD, and total phosphorus
- cadmium, dissolved lead, and turbidity
- TKN and pentachlorophenol
- hardness, conductivity, surfactants, and ortho-phosphate

These correlations may offer the ability to use one pollutant as a proxy for other contaminants and buy-down the overall costs of future water quality monitoring, decision support tools or remote sensor technologies.

Stormwater Impacts to Puget Sound

Toxic contaminants in stormwater runoff have a wide range of impacts on the health of Puget Sound. This section will present information on: the toxicity of stormwater pollutants to Puget Sound organisms; the presence of stormwater pollutants in Puget Sound tissues, waters, and sediments; and the impact of stormwater pollutants on human health.

It is important to note that the presence of toxic contaminants in stormwater runoff does not directly translate to impacts that are derived from laboratory studies. Impacts from the complex mixture of stormwater runoff may be more or less severe than those from laboratory studies based on factors that are physical, chemical, and biological. These include, for example, temperature, abiotic ligands that bind contaminants and reduce their bioavailability, interactions among contaminants, and the size, life stage, diet, and condition of exposed organisms. Nonetheless, the following list shows the potential for toxicity from contaminants known to be carried in urban runoff.

Table 2. Toxicity overview of Puget Sound contaminants (Ecology & King County 2011)

POLLUTANT	TOXICITY OVERVIEW
6PPD-QUINONE	Acutely lethal to coho salmon
ARSENIC	Toxic to mammals
CADMIUM	Toxic to freshwater organisms, can concentrate in shellfish seafood at levels harmful to people
COPPER	Interferes with salmonid sense of smell even at low concentrations, reducing capacity to return to their birth-place, find mates, and avoid predators
LEAD	Persists and bioaccumulates, affecting animals (especially waterfowl) and humans (affected behavior, high blood pressure, and impaired brain devel-opment, reproduction, and growth)
MERCURY	Linked not only to nervous system damage but also to kidney and liver dam-age and possibly cancer Bioaccumulates, can contaminate seafood (methyl mercury)
ZINC	Fatal to young salmon and adult salmon in high concentrations
PCBs	Bioaccumulate to disrupt thyroid hormone levels and harm immune, nervous, and reproductive systems in humans and wildlife
PBDEs	Affect development, reproduction, and survival of many species, accumulates in fish, orcas, and people
PCDD/Fs	Toxic to humans and animals, cause cancer, disrupt endocrine systems, and harm reproduction and development May build up in fish populations and affect seafood
DDTs	Decreases bird survival by making egg shells too thin, persists
PAHs	Causes sublethal effects on embryos and marine fish
DEHP	Harms male reproductive systems in humans and animals
NONYLPHENOL	Mimics estrogen and reduces reproduction in aquatic organisms
PETROLEUM	Toxic to algae, invertebrates, fish (especially eggs and larva), causes suble-thal effects for birds and mammals, reduces reproductive success for inver-tebrates, fish, birds, and mammals, and can also damage plants and stop seed germination

According to data from NPDES Phase I permittees in Puget Sound, dissolved copper, dissolved zinc, and PCBs in discharges to receiving waters exceeded chronic aquatic life criteria in 50%, 36%, and 41% of stormwater samples respectively (Ecology 2015b). These criteria are derived from national standards based on an average concentration across a 4-day period. They are not designed to protect all species, but rather 95% of species across a diversity of genera.

A wide range of toxic effects have been observed in diverse Puget Sound biota, from primary producers to higher trophic animals. Species-specific toxicity information was available in reviewed literature for the species and contaminants listed in Table 3. It is important to note that blank spaces in Table 3 do not mean that those contaminants are not toxic to Puget Sound biota. Rather, no information is available.

Table 3. Availability of toxicity data for Puget Sound biota in reviewed literature

	STORMWATER	COPPER	ZINC	PAHS & OIL	PCBS	PBDES	PESTICIDES	CECS	SURFACTANTS	6PPD-QUINONE
PRIMARY PRODUCERS		X	X	X	O		X	X		
BENTHIC BIOTA	X	X	X	X			X	X		
MUSSELS		O	O	O	O			X		
SEA URCHINS	X	X	X							
COHO SALMON	X	X	X				X			X
CHINOOK SALMON	O	X	X	X	X	X	X		X	
PINK SALMON				X						
STEELHEAD TROUT	O	X	X	X			X			
CUTTHROAT TROUT							X			
PACIFIC HERRING				X	O					
ENGLISH SOLE				X	X			X		
HARBOR SEALS			O		X	O				
KILLER WHALES					O	O				

X – direct evidence of toxicity in reviewed literature   O - indirect or correlative toxicity data only

Toxicity information available in reviewed In a study comparing runoff toxicity in freshwater and marine species, toxic responses were correlated among freshwater species and among marine species, but not between freshwater and marine species, suggesting different toxicants or toxic mechanisms (Kayhanian et al. 2008).

Toxic Impacts to Puget Sound Organisms

Toxicity information available in reviewed literature is organized here by Puget Sound organism. For toxicity information organized by contaminant, including data for Puget Sound and non-Puget Sound organisms, please see the appendix.

PRIMARY PRODUCERS

Toxicity to primary producers has been observed for many metals including copper and zinc, PAHs, and pesticides. Eelgrass (*Zostera marina L.*) is a critically important plant in Puget Sound, stabilizing sediments, filtering marine waters, providing spawning grounds for Pacific herring, shelter for Dungeness Crab, migration corridors for juvenile salmon, and feeding and forage habitats for waterbirds (WDNR 2012). It can even reduce the effects of ocean acidification. Due to high metal uptake and sensitivity to stressors, eelgrass has been identified as an indicator species for Puget Sound health (PSP & PSEMP 2015). Eelgrass rapidly accumulates metals from surrounding waters, and growth rates are inhibited by exposure to mercury, copper, cadmium, zinc, chromium, and lead (in order of descending toxicity) (Lyngby & Brix 1984), and nitrogen fixation has been affected by mercury, nickel, and lead (Brackup & Capone 1985). Metal exposure results in increased accumulation in green and red seaweed and can cause significant impairment of photosynthetic parameters compared to controls (Jarvis & Bielmyer-Fraser 2015). Copper at lower concentrations than those measured in Puget Sound has been shown to cause toxicity and affect photosynthetic function in five Australian seagrass species (Prange and Dennison 2000). Several studies have shown that copper exposure can affect morphology, reduce growth, inhibit photosynthesis, and cause mortality in seagrass (WDNR 2012). Zinc exposure can reduce seagrass growth (Lyngby & Brix 1984). A study exposing sea lettuce (Ulva lactuca) to increasing concentrations of tire leachate demonstrated photosynthesis impairment and an accumulation of zinc. The concentrations of zinc in tire leachate were measured, and separate exposures to equivalent concentrations of zinc produced significantly less phototoxicity, suggesting that organic contaminants of the leachate contributed to the impairment (Turner & Rice 2010).

Organic contaminants including PAHs also affect seagrasses (WDNR 2012). Direct contact with oil has caused reduced growth, leaf senescence, reduced photosynthesis, and mortality (Jacobs 1988). PAHs also reduce nitrogen fixation (Brackup & Capone 1985). Herbicides have been shown to affect photosynthesis and respiration in eelgrass (WDNR 2012). One German study found correlation between herbicide levels and declining seagrass beds (Bester 2000).

BENTHIC BIOTA

Toxicity to benthic communities has been observed for stormwater runoff as well as PAHs, pesticides, and contaminants of emerging concern (CECs). In Puget Sound, there has been net degradation in streams ranked "excellent" and net improvement in streams ranked "fair" according to the B-IBI data (PSP & PSEMP 2015).

One study found that urban road runoff can be acutely lethal to wild mayfly larvae (Baetis sp.) (McIntyre et al. 2015). Amphipod mortality is significantly correlated with sediment PAH, DDT, and chlordane (Anderson et al. 2007). CECs can cause benthic microalgal decline (Gaw, Thomas, & Hutchinson 2014).

Several components of tire wear debris, which is present in stormwater runoff, can be bioavailable and toxic to benthic organisms as well as fish, pelagic filter-feeders, and plants (Wik & Dave 2009).

MUSSELS

Contaminants of emerging concern can reduce mussel byssus strength (Gaw, Thomas, & Hutchinson 2014).

SEA URCHINS/ SAND DOLLARS

Toxicity to sea urchin (*Strongylocentrotus purpuratus*) fertilization has been observed at road runoff concentrations as low as 6% (Kayhanian et al. 2008; Bay et al. 2003). A study of parking lot runoff documented toxicity to sea urchin fertilization in all samples (Greenstein, Tiefenthaler, & Bay 2004). In a study of sediment pore water toxicity on sea urchin fertilization, an area of 10.7 km2 of the Puget Sound study area was determined to be toxic (Long et al. 2012). In a similar study with sand dollars, embryos developed abnormally when exposed to sediment elutriate from most of the 37 sites sampled in urban-impacted bays of Puget Sound (Meador et al. 1990). Abnormalities ranged from 15-100% of embryos, with a median of 90.6% and were related to organic contaminants.

Copper and zinc - alone and in combination with cadmium and nickel, were lethal to sea urchin larvae at concentrations that can be found in stormwater runoff (Phillips et al. 2003).

COHO SALMON

Toxicity to coho salmon (*Oncorhynchus kisutch*) has been observed for stormwater, copper, zinc, and some pesticides.

Coho salmon spawners returning to urban streams display erratic behavior like surface swimming, gaping, fin splaying, and loss of orientation and equilibrium. Affected fish die within hours, and female carcasses retain over 90% of their eggs (Scholz et al. 2011). Salmon that arrive in streams during extended dry periods of a week or more often become symptomatic and die with the next rain. An eight-year monitoring effort in Puget Sound streams found that coho pre-spawn mortality occurred at a rate of 0.9% in a rural stream and ranged from 60% to 100% in urban streams (Scholz et al. 2011). Untreated urban road runoff produces 100% mortality in experimentally exposed coho spawners (Spromberg et al. 2016). The City of Bellevue and Muckleshoot Tribe tagged and released coho spawners from the Issaquah Hatchery into two creeks – one with less impervious area (20%; Coal Creek), and one with more impervious area (40%; Kelsey Creek). The Coal Creek transplants had 41% spawning success rate in 2013 and 20% in 2014, whereas the Kelsey Creek transplants had 0.3% spawning success rate in 2013 and 0% in 2014 (City Bellevue 2015). Blood parameters of coho spawners exposed to roadway runoff had reduced pH, decreased sodium and chloride concentrations, and greatly elevated hematocrit compared with controls exposed to clean well water (McIntyre et al. 2018). Similar changes were seen in adult coho exposed to a tire leachate, suggesting that tires are the source of chemicals in stormwater that causes the pre-spawning mortality (McIntyre et al. Accepted).

A model of the effects of pre-spawning mortality of coho spawners on populations and metapopulations found that a 20% mortality rate was estimated to result in local population extinction in 135 years. The higher the mortality rate, the shorter the time to extinction: mortality at a rate of 60% results in extinction in 22 years, 70% in 16 years, 80% in 12 years, and 90% in 8 years. "Local population extinctions were predicted across the range of PSM rates that have been recently documented in Puget Sound urban streams" (Spromberg & Scholz 2011). Coho populations were projected to persist longer with slower rates of land development, as well as increased straying between populations. The more populations experienced low levels of coho spawner mortality, the higher the chance of metapopulation extinction: "for example, a single population experiencing 50% coho mortality reduced the overall metapopulation abundance by 23%, whereas 2 populations experiencing mortality at half the rate (25%) reduced the metapopulation abundance by 38%" (Spromberg & Scholz 2011). These population estimations reflect the impacts of stormwater on coho spawner mortality only, and do not account for impacts at other life stages.

Stormwater runoff also causes acute lethal toxicity in juvenile coho salmon.

Roadway runoff produced 100% mortality in juvenile coho salmon within 12 hours (McIntyre et al. 2015). The acute mortality and blood chemistry response to stormwater runoff exposure in juvenile coho is comparable to the response of adult coho salmon, and juveniles transferred to clean water after development of surface swimming died at the same rate as those that remained in stormwater (Chow et al 2019). Stormwater has also been found to impact lateral line development in coho embryos (Young et al. 2018).

In a study of juvenile coho outmigrating through estuaries with different levels of contamination, there were no significant differences in survival between outmigration through contaminated and uncontaminated estuaries (Meador 2013).

Copper in freshwater affects juvenile coho salmon olfactory function (Baldwin et al. 2003). By interfering with predator avoidance behavior, copper olfactory toxicity significantly decreases the likelihood of juvenile coho surviving a predator attack (McIntyre et al. 2012). Dissolved copper concentrations lower than frequently found in stormwater runoff can disrupt fish behavior – including critical behaviors like development, reproduction, and predator avoidance – and has the potential to reduce reproductive success at the population level (Hecht et al. 2007). At high enough concentrations, copper can cause acute mortality in coho (Chapman & Stevens 1978). Copper tends to bind strongly to organic matter (Santore et al. 2001, McIntyre et al. 2008), and would not often be bioavailable in stormwater runoff and receiving waters.

Dietary zinc intake has been linked to reduced growth, increased feeding, and decreased expression of hsp-70 in coho salmon (Bowen, Werner & Johnson 2006). Zinc exposure can also cause mortality when bioavailable (Chapman & Stevens 1978).

Toxicity of the insecticide phorate to coho salmon depends on salinity – toxicity was increased 32-fold in marine coho compared to freshwater coho (Lavado, Maryoung, & Schlenk 2011). Coho parr exposed to environmentally realistic concentrations of IPBC fungicide showed altered behavioral and physiological alarm reactions (Tierney et al. 2006). Juvenile coho olfactory function is impaired by low concentrations (<1 μg/L) of the pesticide chlorpyrifos (Sandahl et al. 2004). Similar concentrations of chlorpyrifos also significantly reduce brain and muscle acetylcholinesterase (AChE) activity, reducing activity levels and feeding behavior (Sandahl et al. 2005).

Mixtures of commonly co-occurring pesticides at environmentally realist concentrations can produce synergistic effects on the survival (Laetz et al. 2009) and behavior of juvenile coho (Laetz et al. 2013), which are modulated by temperature (Laetz et al. 2014).

CHINOOK SALMON

Toxicity to chinook salmon has been observed for stormwater, copper, zinc, PAHs, PCBs, PBDEs, pesticides, and surfactants. In a study of outmigration through estuaries of different levels of contamination, juvenile chinook migrating through contaminated habitats exhibited 45% lower marine survival than those migrating through uncontaminated habitats. From 1998-2008, the smolt-to-adult return rate was on average 2.1-fold higher for chinook salmon traveling through uncontaminated estuaries than contaminated estuaries (Meador 2013).

A small percentage (6%) of juvenile chinook exposed to roadway runoff from three rain events died during a 24-h exposure. It is expected that sublethal effects will occur in juvenile chinook exposed to stormwater (French B, NOAA-NWFSC, *unpublished data*).

Copper, zinc, and cadmium can individually cause mortality in juvenile chinook. Juvenile chinook are most vulnerable to mortality caused by these metals during their swim-up life stage (Chapman 1978).

Dietary PAH intake by juvenile chinook can alter growth, plasma chemistry, and lipids, and significantly reduce average fish weight at high doses (Meador et al. 2006). Reduction in fish size and reduced lipid stores have large ramifications on chinook survival (Meador et al. 2006). Immunity to pathogens is significantly decreased in juvenile chinook after PAH exposure (Arkoosh et al. 2001; Reynaud & Deschaux 2006).

Juvenile chinook exposed to PCBs show significantly reduced pathogen resistance compared to control fish (Arkoosh et al. 2001). In a Sound-wide study, 10-100% of juvenile chinook sampled from sites with the highest contamination showed adverse effects that may result from PCB exposure. Response to PCBs include reduced growth and altered hormone and protein levels (WDFW 2015). Dietary exposure to contaminants including PCBs was shown to increase the acquisition rate of infection by a factor of 2.2 and increase disease-related mortality in outmigrating chinook in the Columbia River Basin. This increased host-susceptibility is estimated to significantly reduce population abundance in the basin (Loge et al. 2005).

Juvenile chinook salmon fed environmentally relevant concentrations of PBDE congeners were more susceptible to infection and mortality during bacterial challenge than control fish (Arkoosh et al. 2010; Arkoosh et al. 2015). In a Sound-wide study, 100% of chinook sampled from the Snohomish River in Everett, the river system with the highest PBDE levels, showed increased disease susceptibility and altered thyroid hormone production. 10% of chinook sampled from the Duwamish, Hylebos, and Snohomish systems, the three most PBDE-contaminated estuaries, showed increased disease susceptibility (WDFW 2015).

Juvenile chinook show high sensitivity to current-use insecticides – toxic responses include mortality, immune response, inhibited brain and muscle enzyme activity, and changes in liver and muscle gene expression (Eder et al. 2009). Environmentally relevant pesticide exposures may reduce growth and size at ocean entry of juvenile chinook, reducing intrinsic productivity of modeled ocean-type chinook. Juvenile exposure to organophosphate insecticides was modeled to reduce spawner abundance by 73% in 20 years. Exposure to carbamate pesticides produced less severe results due to faster recovery time in chinook (Baldwin et al. 2009).

Several CECs were detected in juvenile chinook tissue in Central Puget Sound at concentrations that could be expected to cause adverse effects in fish (Meador et al. 2016). A metabolomic analysis showed that metabolism was differentially affected in urban vs reference sites (Meador et al. 2018; Meador et al. In Press). In subsequent laboratory studies, juveniles exposed to mixtures of CECs from the Puget Sound study showed impairments to growth and other indicators of metabolic stress (Meador et al. 2018), as well as mitochondrial dysfunction (Yeh et al. 2017). Juvenile chinook exposed to sediment contaminated with the surfactant HCBD showed 28% mortality when pathogen-challenged, compared to 16% mortality in the control group (Arkoosh et al. 2001).

PINK SALMON

PAHs are toxic to pink salmon. Cardiotoxicity caused by PAH-exposure may have been a significant contributor to the pink salmon fishery collapse in Prince William Sound after the Exxon Valdez oil spill (Incardona 2015). Pink salmon embryos exposed to PAHs show delayed growth and 15% lower marine survival (Heintz et al. 2000). Pink salmon embryos exposed to trace levels of crude oil develop permanent heart abnormalities and reduced cardiorespiratory function as juveniles, causing significant survival and population consequences (Incardona et al. 2015).

STEELHEAD TROUT

Steelhead trout are the anadromous form of rainbow trout. Toxicity to rainbow trout has been observed for stormwater runoff, copper, PAHs, and pesticides. In a study of Indian Creek, rainbow trout alevin survival was 4% just downstream of a stormwater outfall and 60% just upstream of the outfall, despite no significant differences in B-IBI scores. Individually, metal and PAH concentrations did not exceed water quality thresholds, suggesting that an unknown chemical or chemical mixture was responsible for alevin mortality (Ecology 2014b). Among juvenile steelhead exposed for 24 h to roadway runoff from three rain events, 7% died during exposure and an additional 17% died in clean water during the following 24 h, compared with no mortality in controls (French B, NOAA-NWFSC, *unpublished data*).

Dissolved copper can impair olfactory function in hatchery and wild steelhead trout at thresholds similar to those for coho salmon (Baldwin et al. 2011). Inhibition of brain AChE activity from chlorpyrifos (an organophosphate pesticide) exposure in steelhead is similar to that for coho salmon (Sandahl & Jenkins 2002).

PAH exposure can cause immune system changes in rainbow trout (Reynaud & Deschaux 2006). Rainbow trout fed a diet contaminated with PAHs showed lower survival when pathogen challenged and also showed changes in AhR activation and oxidative stress–higher doses increased biomarker response (Bravo et al. 2011). Toxicity of some pesticides to rainbow trout is higher in high salinity environments (Lavado, Maryoung, & Schlenk 2011).

CUTTHROAT TROUT

The acetylcholinesterase (AChE) inhibiting pesticide carbaryl reduced brain and muscle AChE activity in a dose-dependent manner in seawater phase cutthroat trout, which resulted in decreased survival in encounters with predators (Labenia et al. 2007). Trout did not show an avoidance behavior to carbaryl.

PACIFIC HERRING

Toxicity to Pacific herring has been correlated with concentrations of PAHs and PCBs, and was observed in response to stormwater exposure. Cardiotoxicity caused by PAH-exposure may have been a significant contributor to the pacific herring fishery collapse in Prince William Sound after the Exxon Valdez oil spill (Incardona et al. 2015). Pacific herring embryos exposed to low doses of crude oil showed pericardial edema, cardiac arrhythmia, and mortality that seriously impaired cardiac function seriously impacts swimming performance and survival (Incardona et al. 2009). Observed mortality in a study of Puget Sound Pacific herring was highest in areas with the highest PAH concentrations, and two sample sites with long-documented herring embryo mortality were also the sites with the highest PAH concentrations. Herring embryos in these areas had PAH residues exceeding those in San

Francisco Bay herring after the Cosco Busan oil spill. Several samples had PAH levels within previously established health effect thresholds for sublethal effects including yolk sac edema, premature hatching, malformations, genetic damage, smaller size, inhibited swimming, and mortality (West et al. 2014). PCB concentrations in 86% of Central Sound herring and 63% of South Sound herring were above toxic risk thresholds (PSP & PSEMP 2015). Herring embryos exposed to roadway runoff from 5 days post fertilization (dpf) to hatching at 11 dpf were smaller than control embryos and displayed cardiac anomalies consistent with oil exposure (Harding et al. *2020*).

ENGLISH SOLE

Toxicity to English sole has been observed for PAHs, PCBs, and CECs. English sole fed a PAH-contaminated diet showed significantly reduced growth rates, 10-fold lower than rates in control fish (Rice et al. 2000). PAH and PCB exposure has been linked to decreased reproductive function and immune response, and increased disease in Puget Sound. These responses could impact flatfish populations in Puget Sound, including reduction in sub-population size (Johnson et al. 1998).

In Puget Sound, a study of English sole detected xenoestrogen exposures at 75% of sites, correlated with proximity to stormwater, industrial, CSO, and wastewater discharges. High estrogen exposure was correlated with later spawning compared to samples with low exposure- late spawning affects gamete survival. Exposure has also been linked to reduced sperm production, sperm quality, and fertilization success (Johnson et al. 2008).

HARBOR SEALS & ORCA WHALES

Zinc has been shown to compromise seal immune systems and decrease blubber thickness (Anan et al. 2002). In a study of organic pollutant concentrations in Puget Sound harbor seals, PCBs were documented in the highest concentrations and posed the largest health risk to harbor seals (WDFW 2011a). Observed contaminant concentrations in Puget Sound harbor seal pups affect several seal health indicators: vitamin A, estrogen receptor-alpha, heat shock protein 70, and peroxisome proliferator-activated receptor. PCB contamination has been linked to decreased immune function in harbor seals.

The population of southern resident orca whales has varied from 71 individuals in 1974, 97 in 1996, 78 in 1001, 85 in 2008 (Krahn et al. 2009) and 73 in 2019 (Center for Whale Research, 2020). The population was listed as endangered in 2005 after the population declined by 20% from 1996 to 2001 (Northwest Marine Fisheries Service 2008). PCB concentrations in Puget Sound orcas have "easily surpassed" toxic thresholds established for harbor seals, indicating risk of toxicity (Ross et al. 2000). Reduction of toxics loading was identified as a key recovery strategy (Northwest Marine Fisheries Service 2008).

Organic contaminants like PCBs and PBDEs have been linked with "impaired reproduction, skeletal lesions, kidney damage, tumors, premature birth and skin lesions" in marine mammals like harbor seals and orca whales (WDFW 2011a). In 2009, all southern resident killer whales except for three recent mothers exceeded health-effects thresholds for total PCBs (Krahn et al. 2009). Four juvenile whales exceeded this threshold by factors of 2-3.6, indicating high maternal transfer and increased risk for health effects due to high exposure during rapid development. Population models predict that reproductive and immune system impacts of PCB accumulation in killer whales threaten the long-term viability of >50% of the world's orca whale populations, and pods near urban areas are at high risk of population collapse (Desforges et al. 2018).

PUTATIVE TOXICS IN STORMWATER RUNOFF

One approach to determining the identity of toxic chemicals in a mixture is the Toxicity Identification Evaluation (TIE) (US EPA 1991). Kayhanian et al. (2008) concluded that toxicity of urban highway runoff in Los Angeles to a variety of organisms was primarily due to copper and zinc in 80% of samples and surfactants in 10% of samples. Similarly, the TIE of stormwater samples from an urban creek feeding Santa Monica Bay in California identified zinc as the primary toxicant to sea urchin fertilization (Bay et al. 2003). In contrast, mixtures of metals (including copper and zinc) at concentrations present in urban road runoff were not sufficient to induce pre-spawn mortality symptoms in coho salmon spawners. Neither were mixtures of metals and low-molecular weight PAHs (Spromberg et al. 2016).

Coho spawner mortality is most closely correlated with the proportion of local roads, impervious surfaces, and commercial property type within a drainage basin, indicating that coho spawners are being killed by "as-yet unidentified toxic chemical contaminants" that reach coho spawning habitat through stormwater runoff (Feist et al. 2011). A risk assessment of prespawn mortality in the Puyallup River watershed found that urbanized regions with high impervious surface posed the greatest risk to coho spawners (Hines & Landis 2014). Similarly, pathogen-associated disease, noninfectious lesions, insecticides, stream temperature, dissolved oxygen, and other conventional water quality indicators do not seem to cause the coho prespawn mortality syndrome (Scholz et al. 2011). Finally, pesticides in stormwater are insufficient to cause coho prespawn mortality (King et al. 2013).

Mussel mortality in Puget Sound is weakly correlated with both impervious surface and road area, which was correlated with increased PAHs, PCBs, lead, copper, and zinc (WDFW 2014b).

Tire leachates toxic to daphnids assessed by TIE determined that zinc and non-polar organic compounds were primarily responsible for the observed toxicity (Wik & Dave 2009).

The pathophysiological response of coho salmon exposed to tire leachate was indistinguishable from that of coho exposed to stormwater (McIntyre et al. Accepted). The primary driver of toxicity in tire leachate and stormwater runoff has now been identified as 6PPD-quinone – a transformation product of the common tire additive 6PPD (Tian et al. 2021). Much more work is needed to confirm whether 6PPD-quinone plays a role in the toxicity of urban stormwater runoff to other salmon and nearshore marine species.

Tissue Data

Data on tissue concentrations in Puget Sound biota are available for a wide range of contaminants. Tissue concentration is a "snapshot" of a single animal, dependent on proximity to contamination, age, trophic level, movement, life stage, lipid content, and gender (Niewolny et al. 2014). Unlike water and sediment quality monitoring data, tissue data incorporates bioavailability in the dataset, and can reveal pathways like trophic transfer and maternal transfer to eggs (Meador et al. 2008).

The availability of contaminant data for Puget Sound tissues in reviewed literature is summarized in Table 4.

Table 4. Availability of tissue burden data for Puget Sound biota in reviewed literature

	COPPER	ZINC	MERCURY	PAHS	PCBS	PBDES	PESTICIDES	CECS
PRIMARY PRODUCERS	X	X		X	X	X	X	
BENTHIC BIOTA & PLANKTON	X	X		X	X	X	X	
MUSSELS	X	X	X	X	X	X	X	
DUNGENESS CRAB	X	X	X	X	X	X	X	
SPOT PRAWN			X					
COHO SALMON				X	X		X	
CHINOOK SALMON	X	X		X	X	X	X	X
CHUM & PINK SALMON					X		X	
PACIFIC HERRING				X	X	X	X	
ENGLISH SOLE			X	X		X		X
PACIFIC HAKE					X	X	X	
WALLEYE POLLOCK					X	X	X	
STAGHORN SCULPIN			X		X		X	X
HARBOR SEALS		X	X		X	X	X	
ORCA WHALES					X	X	X	
ROCKFISH, COD, SIXGILL SHARK, BLACKMOUTH			X					

While not as robust as data demonstrating causal or correlative toxicity, contaminant concentrations in fish tissues can be used in many ways, including assessing toxicity mechanisms, analyzing mixture toxicity, estimating risk of toxicity, and developing toxicity criteria (Meador et al. 2008). Toxicant presence in tissue can help rule out chemicals not present in tissue when the mechanism of toxicity is unknown for complex mixtures like stormwater (Meador et al. 2014).

In general, the tissue concentration data below show correlation to adjacent developed land use, implicating stormwater runoff as an important source of the toxics observed. Organic pollutants were generally the most frequently assessed and detected, likely because of bioaccumulation of these compounds. Nonetheless, they serve well as tracers of exposure to the urban environment and are harbingers of the other contaminants likely in the complex mixture.

It is important to note that studies of contaminant accumulation in tissues of wild-caught biota will not capture all of the contaminants present in that organism. Analyzing tissues for the presence of contaminants is expensive. As a result, each study must focus on a limited set of analytes. For example, metals detected in mussels does not preclude the presence of accumulated hydrocarbons. Similarly, hydrocarbons detected in plankton does not preclude the presence of accumulated metals. The studies referenced below merely demonstrate that biota in Puget Sound accumulate a variety of contaminants from their environment, some of which have been explicitly studied.

PRIMARY PRODUCERS

Primary producer tissues in Puget Sound have been shown to accumulate metals, PAHs, PCBs, PBDEs, and DDTs. Contaminants in seagrass are released when they senesce and can be transferred across trophic levels through direct grazing. Contaminants in seagrass tissue can be several times higher those in surrounding sediment and water – in one lab study, metal concentrations in eelgrass tissues were up to 1,850 times greater than initial metal concentrations in water (Lyngby & Brix 1984). It is possible that contaminants in eelgrass affect human health through transfer to seafood (WDNR 2012).

In a study of contaminant concentrations in Puget Sound eelgrass, the metals with the highest average concentrations were iron, zinc, and copper in that order. The highest zinc and copper concentrations were observed at a site down-current from the highly urbanized Seattle waterfront. Copper and zinc concentrations in eelgrass exceeded concentrations found in the WDFW 2014 mussel contamination study (WDNR 2016). Numerous studies show that eelgrasses accumulate metals, often depending on environmental metal availability and outfall proximity. Rhizomes and roots act as a metal sink, while leaves can be a source of metals when they senesce. Cadmium, copper, and zinc generally accumulate in higher concentrations in leaves (Lyngby & Brix 1982), and chromium, iron, and lead accumulate in higher concentrations in roots and rhizomes (WDNR 2012). Zinc has also been shown to accumulate in sea lettuce (Ulva lactuca) upon exposure to tire leachate (Turner & Rice 2010).

In Puget Sound monitoring, concentrations of organic contaminants including PAHs, PCBs, PBDEs, and DDTs were present but low in eelgrasses, likely due to limited uptake and accumulation potential in seagrass. Eelgrass proximate to urbanized areas had elevated PAHs (WDNR 2016). A mesocosm study found that PAH uptake by seagrass matched sediment levels within a 60-day period (WDNR 2012). Green macroalga, live and dead, can rapidly bioaccumulate PCBs from marine sediments (Cheney et al. 2014).

BENTHIC BIOTA & PLANKTON

Benthic communities in Puget Sound have been shown to accumulate metals, and plankton tissues have been shown to accumulate PAHs, PCBs, PBDEs, and DDTs. Benthic monitoring in Indian Creek documented higher concentrations of metals (arsenic, cadmium, copper, iron, lead, zinc) in periphyton downstream of a stormwater outfall than upstream (Ecology 2014b).

In a sound-wide survey of Puget Sound plankton, organic pollutants in plankton tissue were positively correlated with increasing development: concentrations of PCBs, PBDEs, DDTs, and PAHs suggested that urban waters are an important source of these pollutants in the pelagic food web. PAHs were correlated with urbanized areas as well as shoreline land uses like marinas and ferry terminals, even in relatively undeveloped basins. PAHs were detected more frequently and in higher concentrations in marine plankton than the other studied pollutants. PAHs and PCBs were detected in all plankton samples. Hexachlorocyclohexanes, DDTs, and PBDEs were also detected frequently. The *T. spinifera* species of krill had substantially greater pollutant levels than all other krill and phytoplankton samples. In general, this species was larger and had higher lipid concentrations (WDFW 2011b).

MUSSELS

Mussel tissues in Puget Sound have been shown to accumulate metals, PAHs, PCBs, PBDEs, and DDTs. In a Sound-wide mussel monitoring study, lead, copper, zinc, mercury, arsenic, and cadmium were found in mussels from every test site, although at low concentrations (WDFW 2014b). There were weak correlations between impervious surface and lead, copper, and zinc. Concentrations of PAHs in bay mussels (*Mytilus trossulus*) transplanted to nearshore habitats in Puget Sound increased with impervious surface in watersheds adjacent the shoreline (Lanksbury et al. in PSEMP Toxics Work Group 2019). As part of the same study, CECs including pharmaceuticals, were detected in mussels in the nearshore of Puget Sound, some at concentrations of concern (James et al. in PSEMP Toxics Work Group 2019).

Organic contaminants (PAHs and PCBs) were detected in mussels from every test site (WDFW 2014b). Organic contaminants had significant positive correlation to nearshore impervious surface and road area, and other important terrestrial loading sources likely account for variability, including outfalls, marinas, and ferry terminals. The profile of PAH contaminants in mussels indicated that most PAHs were of pyrogenic origin, implicating combustion sources from biomass, fossil fuels, and creosote treated pilings via air deposition and surface runoff. In a few study locations, the PAH profile appeared dominated by petroleum sources – one of these sites has a well-documented history of oil sheens on the water's surface (WDFW 2014b).

Lighter congeners dominated PCB contamination at non-urban sites. PCB congeners with higher molecular weight, which cannot travel as far as lighter congeners, decreased with increasing distance from urban shorelines. Therefore, urban embayments were the most likely source of PCB loading in nonurban areas. The highest concentrations of PCBs, PBDEs, and DDTs were observed in urban embayments (WDFW 2014b).

DUNGENESS CRAB AND SPOT PRAWN

Dungeness crab and spot prawn tissues in Puget Sound have been shown to accumulate metals, PAHs, PCBs, PBDEs, and DDTs. In a study of toxic contaminants in Puget Sound Dungeness crab and spot prawn, the most frequently detected metals were mercury, arsenic, copper, and zinc (WDFW 2014a). Metal concentrations were evenly distributed throughout all sample sites, except for total mercury, which had a strong positive correlation to urban areas. (WDFW 2014a).

The most frequently detected organic pollutants were PCBs. PCB concentrations were highest in urban samples and low in non-urban samples. PCBs were seven times higher in crab muscle than prawn muscle. This difference may be a result of sampling crab from the urban nearshore and prawn samples from deeper waters. PAHs were detected at low concentrations in both species. PBDEs were detected at low concentrations in crab and were rarely detected in prawns. DDTs were detected in most crab muscle samples and in one prawn muscle sample at low concentrations. Contaminant concentrations were up to 36 times higher in crab hepatopancreas and prawn head tissues than corresponding muscle tissues (WDFW 2014a).

COHO SALMON

Coho tissues in Puget Sound have been shown to accumulate mercury as well as organic pollutants including PAHs, PCBs, and pesticides. Salmon with coastal distributions, including coho, have higher organic pollutant contamination that those with oceanic distributions (pink, chum, and sockeye), indicating terrestrial contaminant sources (O'Neill et al. 2006). Mercury has been observed in coho salmon tissue (Niewolny et al. 2014).

In a study of contaminant uptake in outmigrant coho and chinook juveniles, PAHs, PCBs, and DDTs were found in all estuarine tissue samples – contaminants were consistently present in estuarine stomach contents at concentrations significantly correlated with contaminant body burdens, indicating that dietary intake is an important pathway for organic contamination (Johnson et al. 2007). In the heavily industrialized Commencement Bay, coho salmon had body burdens of PCBs and DDTs (Olson et al. 2008). In a study of PCB accumulation in Puget Sound coho, average PCB concentrations were higher in offshore samples than river and nearshore samples, indicating that salmon accumulate most of their PCB body-burden in marine waters (O'Neill, West, & Hoeman 1998). Pesticides were less frequently detected than other organic contaminants in Puget Sound coho (Johnson et al. 2007). Tissue samples from coho salmon that had been exposed to stormwater runoff where compared to a non-target screening of chemical features in stormwater to identify the chemical bioavailability of contaminants in stormwater and narrow down potential CECs causing the adverse effects (Du et al. 2017).

CHINOOK SALMON

Chinook tissues in Puget Sound have been shown to accumulate metals, PAHs, PCBs, PCDD/Fs, PBDEs, pesticides, and CECs.

Most naturally spawning populations of chinook salmon are far below recovery planning targets Only 22 of at least 37 historic Puget Sound Chinook populations survive, and of these, 13 populations have declined and 6 have improved between 2006-2010 and 2011-2013 (PSP & PSEMP 2015). Current populations are at about 10% of historic size, 33% of early 1900s size, with some populations lower than 1% of their historic size. Wild Puget Sound Chinook and some hatchery populations are "threatened" under the Endangered Species Act, and wild populations have been depleted so much that hatchery influence ranges from 40% in the Northern Sound to 98% in the Southern Sound (Duffy & Beauchamp 2011).

Juvenile Chinook out-migrating through Puget Sound accumulated PBDEs at concentrations significantly higher than those of hatchery fish (Sloan et al. 2010). One-third of the 480 chinook sampled in a Puget Sound study had concentrations of PAHs, PCBs, and/or PBDEs associated with adverse effects potentially influencing marine survival – these thresholds are associated with reduced growth, reduced disease resistance, and altered hormone, plasma, lipid, and protein levels (WDFW 2015). Elevated zinc, cadmium, copper, lead, and nickel were detected in 90-100% of chinook tissue samples.

Salmon with coastal distributions, including chinook, had higher organic pollutant contamination than those with oceanic distributions (pink, chum, and sockeye), indicating terrestrial contaminant sources (O'Neill et al. 2006). An estimated 96-99% of the body burden of persistent organic pollutants in Chinook is estimated to be accumulated in marine environments where salmon gain most of their mass (Cullon et al. 2009; O'Neill & West 2009; O'Neill, West, & Hoeman 1998). Juvenile Chinook migrating through a developed watershed accumulated most of their body burden of PBDEs and PCBs in the lower mainstem rather than upper mainstem of distributary channels in the estuary (O'Neill et al. 2020). Additionally, higher PBDE concentrations in natural-origin than hatchery-origin juveniles, correlated with depleted nitrogen stable isotopes, suggested a wastewater influence on PBDE accumulation in natural-origin fish.

A Puget Sound study of 5 rivers and corresponding estuaries and 4 marine basins showed that juvenile chinook salmon residing and feeding in urbanized and industrial rivers and nearshore estuaries had higher tissue concentrations of copper, lead, and persistent organic pollutants than fish in less developed or offshore areas. PAH concentrations in river-caught fish stomachs were all below thresholds for reduced growth, whereas PAH concentrations in estuary-caught fish stomachs were above thresholds for reduced growth in 2 of the 5 estuaries (WDFW 2015). In a Columbia River study, both stomach and bile PAH concentrations in juvenile chinook were directly correlated with land use: salmon from highly urbanized sites had higher PAH concentrations that salmon from rural and moderately urbanized sites (Yanagida et al. 2011).

In a study of tissue contaminant concentration including outmigrant Puget Sound chinook juveniles from 2 estuaries from Puget Sound, PCBs and PAHs were found in all tissue samples from estuarine fish (Johnson et al. 2007). Contaminants were consistently present in estuarine stomach contents at concentrations significantly correlated with contaminant body burdens, indicating that dietary intake is an important pathway for contaminant uptake. Chinook whole body contaminant concentrations were typically 2-5 times higher than coho whole body concentrations from the same sites, possibly because juvenile chinook have a much longer estuarine residency time than coho.

Puget Sound chinook samples had the highest concentrations of PCBs, PCDD/Fs, and DDTs compared to samples from British Columbia straits (Cullon et al. 2009). Of the diverse organochlorine pollutants measured, PCBs were the most abundant in chinook of all life stages from all sites. Among the organochlorine pesticides, DDTs were the most abundant for all smolt samples and 75% of adult samples. Average PCB muscle tissue concentrations in Puget Sound chinook were 3-5 times higher than six other West Coast chinook populations sampled in another study (O'Neill & West 2009). In a Sound-wide study, PCBs were observed in chinook from all sample sites (WDFW 2015). In the Duwamish system, both the river and the estuary were major sources of PBDEs, with bioaccumulation observed in chinook (WDFW 2015). In a different Puget Sound study, DDTs were found in all estuarine samples of outmigrant juvenile chinook (Johnson et al. 2007).

In the heavily industrialized Commencement Bay, chinook stomach contents were contaminated with PAHs, PCBs, and DDTs (Olson et al. 2008). They also had significant body burdens of PCBs and DDTs. Chinook and chum PCB and DDT body burdens were generally higher than those in coho and pink salmon, likely due to chinook and chum salmon's increased estuarine residency and higher trophic diet. Juvenile chinook accumulated PCBs in the lower Duwamish (Meador et al. 2010).

In a Central Sound study, 42 CECs were present in juvenile chinook tissues (Meador et al. 2016). Another Puget Sound study documented a small but significant elevation of estrogen-exposure indicators in juvenile chinook plasma from two urban sites compared to nonurban areas (Peck et al. 2011).

PACIFIC HERRING

Pacific herring tissues in Puget Sound have been shown to accumulate PAHs, PCBs, PBDEs, and DDTs. Pacific herring spawning biomass had declined in all Puget Sound stocks. The largest stock has declined by more than 90% since 1973. The other two stocks have declined less sharply, in some years even exceeding targets. Pacific herring are a critical source of energy for higher-level consumers including larger fish, seabirds, and marine mammals (PSP & PSEMP 2015).

Herring embryos experimentally exposed to roadway runoff from 5-11 days post fertilization accumulated significant concentrations of PAHs, with a profile similar to that of the water, resulting in >10-fold induction cyp1a, an enzyme that detoxifies PAHs (Harding et al. 2020). In a Puget Sound study, Pacific herring embryos accumulated exogenous PAHs from local sources at levels that exceed previously established thresholds for lethal and sublethal effects including yolk sac edema, premature hatching, malformations, genetic damage, reduced size, inhibited swimming, and mortality (West et al. 2014). Herring embryos near 100-year old creosote-treated pilings accumulated PAHs and showed elevated cyp1a induction compared with herring in reference areas without pilings. Embryos showed elevated PAH accumulation and cyp1a induction when incubated near the site where pilings were removed up to a year earlier (West et al. 2019).

PAH accumulation was consistently higher in embayed shorelines than open shorelines, indicating that open shorelines may dilute or disperse pollutants while bays restrict this circulation. PAH accumulation was higher along residential and industrial shorelines than rural shorelines. Embryos sampled in residential and industrial embayments had tissue PAH residues exceeding PAH levels in herring embryos studied in San Francisco Bay's oiled shorelines after the Cosco Busan oil spill. Similarities in PAH patterns between embryo tissues and surrounding sediments indicate that sediment-derived PAHs are available to organisms spawned close to them. Embryonic PAH concentrations increased with development time, strengthening this theory. In many samples, the PAH pattern was consistent with combustion (rather than petroleum), indicating woodstove, fireplace, and vehicle emissions as the primary sources of PAHs. Maternal transfer of PAHs to eggs is an important pathway in low exposure areas – in the location with the lowest PAH levels, maternal transfer appeared to be the leading source.

From 1999 to 2014, there was no significant change in Puget Sound herring PCB concentrations for more developed basins while PCBs declined moderately in herring from two low-development basins. Meanwhile, DDT and PBDE concentrations have declined (West et al. 2017). Whereas 100% of North Sound herring PCB concentrations were below risk thresholds, 86% of Central Sound herring PCBs and 63% of South Sound herring PCBs were above risk thresholds (PSP & PSEMP 2015). In a 2008 study of PCBs, DDTs, and hexachlorobenzene in Pacific herring, Puget Sound herring had 3 to 9 times higher PCB contamination and 1.5 to 2.5 times higher DDT contamination than herring in the Strait of Georgia (West, O'Neill, & Ylitalo 2008).

ENGLISH SOLE

Along with the estrogenic exposures discussed in the toxicity section above, English sole tissues in Puget Sound have been shown to accumulate mercury, PAHs, and PBDEs. Among 10 sites in Puget Sound, PCBs increased in English sole at four and showed no change at six sites between 1999 and 2014. Changes in DDTs and PBDEs across the years showed mixed trends (West et al. 2017). Mercury accumulation in English sole is higher in urban areas compared to nonurban areas (Niewolny et al. 2014). There has been a 65% decrease in PAH levels in English sole from 1999 to 2016 (PSP 2016). PBDE muscle concentrations in Puget Sound English sole were significantly higher at urban sites compared to non-urban sites (WDFW 2014a).

PACIFIC HAKE AND WALLEYE POLLOCK

Pacific hake and walleye pollock tissues in Puget Sound have been shown to accumulate PCBs, PBDEs, and pesticides. In a Sound-wide study, persistent organic pollutant patterns in pacific hake and walleye pollock were consistent with those observed in Pacific herring and salmonids (WDFW 2011c). The results showed greater concentrations and lipid-specific accumulation PCBs PBDEs, and chlordanes, and greater lipid-specific accumulation of dieldrin and DDTs in hake from developed basins compared to less developed basins. Low contaminant concentrations in the oldest female samples were likely due to pollutant transfer to eggs during spawning.

The PCB congener profile was consistent with urbanized point sources, with distillation of heavier and lighter congeners, likely due to changes over 70 years of inputs (WDFW 2011c). PCB concentrations were consistently 25-30% greater than PBDE concentrations. PBDE congener profiles were consistent across Puget Sound, likely due to more recent (20-30 years) inputs. Pesticide concentrations reflected land use patterns, with higher concentrations in basins with high pesticide use. PCBS, PBDEs, and pesticides were all positively correlated with land use, with higher concentrations in samples from developed watersheds. PCBs, PBDEs, and chlordanes exhibited increased bioaccumulation with increasing age, indicating risk to higher trophic predators through biomagnification. DDT loading patterns in hake from developed basins in this study and diverse fish tissues in a 2008 study suggest that newer sources of DDTs exist in developed areas, possibly due to chronic release of historic eroding soil sources and recent unknown urban sources of new product (Olson et al. 2008).

HARBOR SEALS

Harbor seal tissues in Puget Sound have been shown to accumulate metals, PCBs, PBDEs, PCDEs, PCNs, and pesticides.

In Salish Sea harbor seals, concentrations of arsenic, lead, mercury, selenium, and silver were significantly higher in adults than neonate pups, suggesting bioaccumulation. Zinc was significantly higher in pups than adults (Akmajian et al. 2014).

In a Puget Sound study, seal pup tissue samples were taken in four basins: Main Basin, proximate to highly urbanized Seattle; South Sound, proximate to Olympia and Tacoma; and the much less developed Whidbey and Hood Canal basins (WDFW 2011a). Main Basin seal pups had higher mercury concentrations and up to 4 times higher PCB, PBDE, and pesticide concentrations than Hood Canal pups, likely due to increased urbanization. PCB concentrations were 6 times higher than PBDEs, the pollutant with the next highest concentrations. PCB concentrations again showed decline compared to past data. DDTs comprised 92% of total organochlorine pesticides observed in harbor seal tissue (WDFW 2011a).

Concentrations of PCBs, PBDEs, PCDEs, and PCNs are declining in Salish Sea harbor seals (Ross et al. 2013b). From 1984 to 2003, PCBs declined by 81%, PCDEs declined by 71%, and PCNs declined by 98%. PBDE concentrations doubled every 3.1 years from 1984 to 2003 but are now declining. Total contaminant mass in the 53,000 harbor seals in the Salish Sea was estimated at 2.6 kg PCBs and 1.0 kg PBDEs in 2009. PCB contamination is significantly higher in southern Puget Sound seals than Strait seals, though the disparity is less than it was in 1996, suggesting a trend toward more even distribution of legacy contamination.

ORCA WHALES

Orca whales in Puget Sound have been shown to accumulate PAHs, PCBs, PBDEs, and DDTs. The Northeast Pacific is home to three different orca ecotypes: northern residents, on the northern coast of British Columbia; southern residents, in Puget Sound, Strait of San Juan de Fuca, and southern British Columbia; and transients (Ross et al. 2000). Southern resident orca whales consistently have higher PCB (Ross et al. 2000) and PBDE (Rayne et al. 2004) contamination than northern residents, likely due to differences in diet, prey contamination, and habitat contamination. The southern population's daily PCBs intake is estimated to be 4 to 6.6 times higher than the northern population (Cullon et al. 2009).

Several contamination trends have been observed for southern resident orca whales. Toxic burden generally increases with whale age due to bioaccumulation except for females who may lose toxicants through neonatal loss (Lundin et al. 2016; Ross et al. 2000). Juveniles have higher concentrations of PBDEs, HCHs, and HCB than adult males (Krahn et al. 2009). Exceptionally high juvenile contamination suggests high maternal transfer and increased risk for health effects due to high exposure during rapid development. (Krahn et al. 2009). Pollutant transfer from mother to calf during lactation is highest for first-borns and lower for subsequent calves (Lundin et al. 2016). Toxic load decreases in calves by birth order, and mothers with more calves had lower toxic burdens.

Residency is one factor leading to different contaminant body burdens in different populations. Southern residents "spend more time in the more industrialized southern Georgia Basin and in Puget Sound" compared to northern residents along the coast of British Columbia, which contributes to their higher contamination levels (Rayne et al. 2004). One phenomenon that has been observed is a higher ratio of DDTs to PCBs in two southern resident pods compared with the third pod (Krahn et al. 2009). Of the three southern resident pods, the two pods that have been observed feeding off the California coast in winter have higher DDT to PCB rations, likely due to contamination from a coastal California DDT production facility. The third pod remains closer to Puget Sound and Georgia Basin waters and has a lower DDT body burden.

Persistent organic pollutant concentrations were highest, with the greatest potential for toxicity, when prey abundance was lowest (Lundin et al. 2016). Regional body burdens of contaminants in salmon could contribute to the higher levels of contaminants in southern resident killer whales. Differences in population pollutant levels are likely partially attributable to regional dietary differences, even though both populations subsist on Fraser River Chinook around July-September each year (Rayne et al. 2004). Puget Sound chinook is an important winter food source for southern residents, and persistent organic pollutant contamination, including PCBs, PBDEs, and DDTS, are significantly higher in Puget Sound-resident chinook salmon than British Columbia chinook (O'Neill et al. 2006). The lower lipid content of southern salmon may cause southern killer whales to increase their salmon consumption by as much as 50%, further increasing exposure to organic pollutants through chinook, which comprise 70% of their estimated diet (Cullon et al. 2009).

In a study of PAH dietary intake of juvenile chinook, more than 99% of the assimilated PAHs were metabolized, indicating low risk of dietary PAH transfer to orca whales under ambient conditions (Meador et al. 2006). In the event of an oil spill, salmon may not be able to metabolize PAHs quickly enough, in which case PAH contamination risk to orcas is likely. Field sampling of orca whale scat confirms generally low concentrations of PAHs, although concentrations were higher prior to 2011 when new regulations on vessel distance to whales mandated increased distance between whales and vessels (Lundin et al. 2018).

OTHER BIOTA

In Puget Sound, mercury has been documented at or above threshold levels for human consumption in quillback rockfish, brown rockfish, and yelloweye rockfish, as well as in sixgill shark. Mercury has been observed below this threshold in copper rockfish, staghorn sculpin, lingcod, pacific cod, Dungeness crab, English sole, spot prawn, blackmouth, and chinook and coho salmon. Mercury concentrations are correlated with fish age in quillback rockfish and demersal rockfish, and total mercury accumulation over time was much higher in urban areas compared to nonurban areas for demersal rockfish (Niewolny et al. 2014).

In the heavily industrialized Commencement Bay, chum salmon, pink salmon, and staghorn sculpin had significant body burdens of PCBs and DDTs (Olson et al. 2008). Contamination was generally higher in sculpin than salmon.

In a Central Sound study, 42 CECs were present in staghorn sculpin tissues (Meador et al. 2016).

Water & Sediment Quality

Water quality and sediment quality is another important factor determining the health of Puget Sound. The tissue data discussed above often shows correlation with adjacent water and sediment quality, indicating the importance of these datasets to resident biota.

Overall, freshwater quality in Puget Sound streams and rivers has not significantly changed for at least ten years. From 2009-2013, 27% of monitored stations met or exceeded water quality goals. In 2004-2008, 31% of stations met or exceeded goals, a statistically insignificant difference (PSP & PSEMP 2015). Marine water quality has declined overall from 1999 to 2014, with little change observed from 2011 to 2014 (PSP & PSEMP 2015).

Toxic contaminants are regularly observed in water quality monitoring. Detection frequencies in NPDES monitoring of discharges to surface water are: arsenic, copper, lead, magnesium, and zinc (90%); nutrients (90%), PAHs (73%), total petroleum hydrocarbons (73%), phthalates (62%), cadmium (60%), surfactants (60%) (Ecology 2015b).

Contaminants in freshwater can disperse far and wide in the Sound. In spring and summer, northern rivers like the Fraser and Skagit rivers can be the dominant freshwater inputs for huge portions of the Puget Sound basin (Banas et al. 2015). In a study of stormwater river plumes in southern California, plumes moved about 50 cm/sec then slowed to 20-40 km/day depending on their energy and buoyancy. This data indicates that plumes quickly transport contaminants far from their outfalls (Warrick et al. 2007).

Sediment quality in Puget Sound shows mixed results. In a Sound-wide study, 3 of 8 regions and 2 of 6 urban bays did not meet target sediment quality values. In areas that have been sampled for multiple decades, index scores have improved in 3 areas and declined in 8 (mostly due to declining B-IBI scores). All tested regions meet target sediment chemistry scores. Chemistry values have not changed in most areas since the late 1990s, and the number of chemicals in sediment exceeding target thresholds has decreased (PSP & PSEMP 2015).

Diesel, motor oil, copper, and zinc were detected in 100% of sediment samples in a study across Puget Sound (Ecology 2015a). In 1997-2003 many contaminants were detected in Puget Sound sediments: PAHs and metals (92% of samples), PCBs (16%), and other organic compounds including pesticides and PBDEs (<9%). 21% of stations had contaminant concentrations that exceeded state sediment quality standards, representing 11% of the study area: mercury (12.5%), PCBs (5%), phthalates (2.5%), and hexachlorobenzene (1.25%) (Ecology 2013a).

Sediment quality in the Central Sound decreased overall from 1998-2009, mostly due to benthic impairment. Sediment Chemistry Index scores improved over this period, with decreases observed in concentrations of lead, mercury, silver, tin, and some PAHs. However, Sediment Benthic Index scores significantly declined, and toxicity to amphipod survival and sea urchin egg fertilization, as well as the spatial extent of likely impacted sediments, increased significantly (Ecology 2013a)

Sediments can act as a sink and a source for toxic contaminants. For example, a PCB fate model showed that 44% of PCBs entering Lake Washington are buried in sediment while 7% are conserved in lake water (King County 2014b). Larger metal particles are also quickly incorporated in sediment (Pinedo-Gonzalez et al. 2017). However, these contaminants can also be bioavailable. For example, contaminants in sediments can be bioaccumulated by primary producers (Cheney et al. 2014) and fish embryos (West et al. 2014).

In Puget Sound sediments, concentrations of CECs ranged from non-detectable to very low. 14 of 119 tested pharmaceuticals and 3 of 13 tested perfluoroalkyl substances were quantifiable in sediment samples. Concentrations were highest in the Bellingham industrial harbor and near the cities of Seattle and Bremerton (Long et al. 2013). In another Puget Sound sediment study monitoring 134 CECs, 16 were detected (Brandenberger et al. 2014).

In-depth analysis of water and sediment quality data information was not a focus of this report. Valuable resources for this data include the Washington

Department of Ecology's Environmental Information Management, monitoring data from the Department of Ecology's Environmental Assessment Program, and Benthic Index of Biota Integrity data for Puget Sound.

Human Health Impacts

Stormwater is an important indirect pathway for toxics that affect human health (WTRSW 2013). More than half of the documented waterborne disease outbreaks from 1948 to 2003 followed extreme rain events (Gaffield et al. 2003). In a Sound-wide study, a significant number of storm-event samples did not meet water quality/human health standards for copper, lead, zinc, mercury, PCBs, phthalates, PAHs, and pentachlorophenol (Ecology 2011). Many toxic chemicals, including lead, pesticides, and PBDEs, disproportionately affect low income communities and communities of color (Bennett et al. 2016).

Many of the toxic chemicals in the environment that negatively affect human health are conveyed in stormwater:

- Learning and brain development can be impaired by exposure to lead, arsenic, methyl mercury, manganese, PAHs, PCBs, PBDEs, organophosphate pesticides, and phthalates (Bennett et al. 2016; WTRSW 2013).
  - In the last decade, developmental disabilities have increased by 17%. In 2012, 10% of children had ADHD (Bennett et al. 2016). In 2010, 1 in 14 children aged 3 to 21 were receiving special education services in Washington (WTRSW 2013).
  - 900 to 1,000 children are estimated to be diagnosed with autism in Washington every year (WTRSW 2013), and 1 in 68 children were on the autism spectrum in 2010 (Bennett et al. 2016).
  - Experts agree that there is no safe minimum level of fetal or early childhood lead exposure. Every dollar spent to reduce lead exposures in the United States is estimated to produce $17-$221 in benefits (Bennett et al. 2016).
- Birth defects can be impaired by exposure to phthalates and other chemicals. Hypospadias, a birth defect linked to phthalate exposure, affects 1 in 200 boys in Washington every year (WTRSW 2013).
- Cancer can be caused by exposure to carcinogenic chemicals found in stormwater, including arsenic, PAHs (WTRSW 2013), chlordane, pentachlorophenol, and beryllium (Pitt 1998). Cancer is the most common cause of death in children aged 1 to 14 (WTRSW 2013). Carcinogenic PAHs accounted for more than 50% of the total PAHs measured in the Duwamish waterway (Browne et al. 2010).
- Parkinson's disease has been linked to exposure to pesticides, solvents, PCBs, PBDEs, and heavy metals. About 8,500 Washingtonians have Parkinson's disease (WTRSW 2013).
- Insecticide levels occur in stormwater at levels harmful to wildlife and possibly humans (Gaffield et al. 2003).
- Other human health impacts of toxics found in stormwater runoff include respiratory failure, cardiac arrhythmia, neurotoxicity, skeletal changes, and skin, liver, vascular, pulmonary, renal, nervous system, gastrointestinal, and kidney effects (Pitt 1998).
- Several illnesses are associated to human contact with pathogens that originate in fecal bacteria. Pathogen contact typically involves diarrhea, nausea, and vomiting, but can also result in long-term health defects such as liver disease, kidney disease, arthritis, seizures, and Guillan-Barré Syndrome (King County & Seattle Public Health 2019).

Toxic chemicals conveyed in stormwater also affect human wellbeing. Salmon abundance and health are critical to Quinault cultural identity, and stormwater's negative impact on Puget Sound salmon populations has enormous consequences for tribal psychological pride, cultural identity, lifestyle, economic activity, governance, and diet (Biedenweg et al. 2014). Stormwater mainly impacts human health via seafood, recreation, and drinking water.

SEAFOOD

Toxic chemicals and fecal bacteria pollution pose serious threats to seafood harvest and safe consumption in Puget Sound. For example, an 85% reduction in PCB loading in Lake Washington is required to reduce concentrations in fish tissue to the point that the current Department of Health fish consumption advisory could be removed (King County 2014b).

Dungeness crab and spot prawns in urbanized sites in Puget Sound currently have consumption restrictions due to persistent organic pollutant contamination. Crab hepatopancreas and spot prawn head consumption has many more restrictions due to increased concentration of toxics (WDOH 2016). From 1998 to 1999, Dungeness crab and razor clam closures severely impacted revenue for the Quinault and Quileute tribes (Lewitus et al. 2012).

Currently, shellfish harvest and consumption has been the seafood sector most affected by toxic chemicals and fecal pollution. There are about 9,594 acres of commercial shellfish beds in King County, and only about half (4,830 acres) are approved for harvest by the Department of Health (King County 2018). On average, 19% of Puget Sound shellfish beds (36,000 acres) are closed, mostly due to fecal bacteria pollution. There has been an overall increase in net harvestable shellfish area, although progress is below regional targets – about 81% of shellfish beds are currently harvestable (PSP & PSEMP 2015). For people who eat shellfish, seafood may contribute 25% or more of their total dietary PAH exposure (Ecology & WDOH 2012). Stormwater runoff can be contaminated with norovirus (Steele et al. 2018), which can be transmitted to people who eat shellfish. Up to 39 people in King Country came down with the symptoms of norovirus between January and March of 2017, according to the Public Health Department (King County & Seattle Public Health 2019).

Algal blooms are often responsible for shellfish-related illnesses including paralytic shellfish poisoning, diarrhetic shellfish poisoning, and amnesic shellfish poisoning. Algal blooms are primarily caused by natural factors, though nutrient input from stormwater and other sources potentially influences them, especially in enclosed waters like the Strait of San Juan de Fuca and Puget Sound. A 2005 bloom in Penn Cove, Washington was attributed in part to high stream flow and high precipitation. There is concern that bloom frequency is increasing in Puget Sound (Lewitus et al. 2012). Harmful algal blooms are likely to increase with climate change (Moore, Mantua & Salathé 2011).

In 1942, paralytic shellfish poisoning caused 3 Native American fatalities on the Strait of San Juan de Fuca, leading to many shellfish closures. In 1978, ten people reported paralytic shellfish poisoning symptoms, leading to regular closures throughout Puget Sound and creating significant economic losses for Washington tribes (Lewitus et al. 2012).

In 2005, an algal bloom caused amnesic shellfish poisoning in Penn Cove, WA. Amnesic shellfish poisoning from diatom blooms have caused significant fiscal losses due to beach and shellfish harvest closures – fishery closures cost $15-20 million in lost revenue in 1991 (Lewitus et al. 2012).

In 2011, three people contracted diarrhetic shellfish poisoning caused by dinoflagellate blooms after ingesting mussels from Sequim Bay State Park. In 2012, diarrhetic shellfish toxins above guidance concentrations were widespread in mussel tissues throughout Puget Sound, resulting in harvest closures at 38% of sample sites (Trainer et al. 2013).

RECREATIONAL EXPOSURE

Swimming and other recreational exposures to urban stormwater runoff has been linked to numerous illnesses including ear and eye discharges, skin rashes, and gastrointestinal symptoms (Gaffield et al. 2003). Fecal coliform levels have been linked to recreational swimming health impacts for decades, and non-point fecal contamination is one of the most common reasons United States waterbodies are classified as impaired for recreational use (Soller et al. 2015). Swimming in bacteria-contaminated waters has also been linked to gastrointestinal symptoms as well as "respiratory illness, skin rashes, plus eye and ear problems" (Pitt 1998). Additional human health impacts associated with fecal bacteria exposure include diarrhea, nausea, and vomiting, liver disease, kidney disease, arthritis, seizures, and Guillan-Barré Syndrome (King County & Seattle Public Health 2019).

Stormwater runoff is an important pathway for fecal bacteria. Stormwater discharges along San Diego, CA beaches routinely detected human fecal source markers and human viral and bacterial pathogens (Steele et al. 2018). A survey study of Santa Monica Bay swimmers found significantly greater incidence of illnesses (44-127%) in respondents who swam proximate to stormwater outfalls compared to those who swam 400 yards away. The survey results were supported by water quality testing (Pitt 1998). Impervious surfaces generate large bacterial loads: a South Carolina study found correlation between impervious land cover and fecal coliform loads (Gaffield et al. 2003).

In Puget Sound, there has not been an upward or downward trend in swimming beach closures between 2004 and 2014, despite many bacterial source control efforts. The average annual rate for meeting water quality criteria is 83% of swimming beaches (PSP & PSEMP 2015). More recent analysis of long-term trends in bacteria levels in King Country compiled data from Ecology, Department of Health, and King County monitoring sites. Overall trends suggest that the majority of long-term freshwater sites had decreasing levels of bacteria and demonstrated that the majority of freshwater monitoring sites had decreasing levels of bacteria, including four of six marine beach sites (King County & Seattle Public Utilities 2019).

DRINKING WATER

In some Puget Sound communities, stormwater inputs to drinking water sources are a concern. Lake Whatcom supplies drinking water to 86,000 residents in Whatcom County and is threatened by problems with Dieldrin, dissolved oxygen, mercury, PCBs, and phosphorous, due mainly to runoff inputs from surrounding urban development (Visitacion, Booth, & Steinemann 2009). The City of Redmond, concerned about the potential of infiltrating polluted runoff into a shallow drinking water aquifer, conducted a study that found effluent from bioretention cells to exceed groundwater quality standards for nitrate and fecal coliform (Herrera 2014).

Nationwide, approximately 42 million people use private drinking water sources which are predominantly shallow groundwater wells that are possibly contaminated by stormwater runoff and septic systems (Gaffield et al. 2003). Viruses have been detected in shallow groundwater proximate to stormwater recharge basins (Pitt 1998).

HUMAN HEALTH BENEFITS OF STORMWATER MANAGEMENT

In a study of stormwater impacts on human health, the culminating recommendation was that "stormwater management to minimize runoff and associated pollution appears to make sense for protecting public health at the least cost" (Gaffield et al. 2003). Particulates in motor vehicle exhaust are a well-established hazard to human health, increasing adult deaths (Laden et al. 2000) and producing chronic respiratory conditions in children (vanVliet et al. 1997). Source controls of vehicle exhaust such as switching to hydrogen-powered cars is predicted to have a significant positive impact on human health (Jacobson et al. 2005) and would also reduce the pollution of urban stormwater runoff and subsequently Puget Sound and its tributaries.

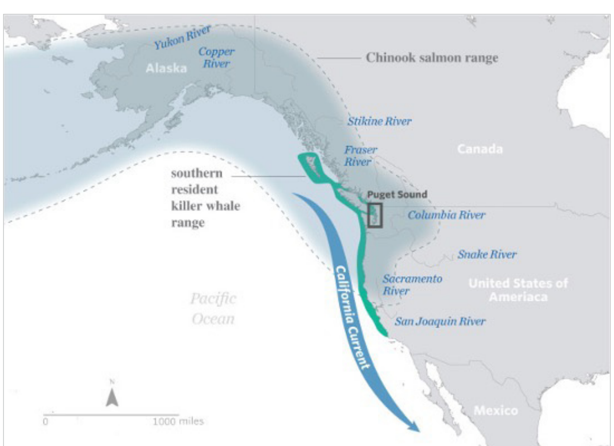
Many of the facilities used to manage stormwater have multiple benefits for urban communities, including the enormous benefits to human health and wellbeing of added green space. Residency in areas with green spaces produces significantly higher wellbeing, reduced stress, fewer crimes, and lower mental distress. Residents are also three times more likely to be physically active, and 40% less likely to be overweight. Nearby nature has been shown to speed up hospitalized recovery time, benefit people with mental illnesses, and possibly enhance immune function. Time spent in green spaces raises standardized test scores, improves concentration in children with ADHD, and increases positive affect in people with major depressive disorder. Childhood interaction with nature has been linked to increased stewardship in adulthood, including behaviors like recycling, voting for green candidates, and pursuing careers in environmental leadership (TNC 2016).

II. How Much and Where

Estimating costs, choosing effective best management practices (BMPs), and prioritizing retrofit sites are all key steps to improving the health of Puget Sound. Control of point-source pollution has decreased fish mortality but has mostly failed to protect migratory fish like salmon. Given the difficulty of determining the precise cause of complex problems like low fish returns and coho prespawn mortality, we should focus on precautionary actions within our control, like toxics load reduction (Ross et al. 2013a). Reduction of toxics loading to Puget Sound will not heal the system over night. For example, instantaneous PCB load reductions in Lake Washington is modeled to produce equilibrium 40 years later (King County 2014b). Despite these delays, answering the question of "how much and where" will empower enormous benefits for life in Puget Sound through cost-effective toxic load reductions with high-performing BMPs and smart prioritization.

How Much: Puget Sound Projections

Despite their limited area relative to the global ocean, coastal zones—the regions where land meets the sea—play a disproportionately important role in generating ecosystem services. Urban stormwater contains complex and unpredictable mixtures of chemicals that result in a multitude of lethal and sublethal impacts on species in coastal systems. Along the western coast of the United States, it is estimated that hundreds of billions of kilograms of suspended solids flow off land surfaces and enter the Northern California Current each year. However, 70% of this pollution could be addressed by treating only 1.35% of the land area. (Levin et al., 2020).



Along the Northern California Current, watersheds feeding into San Francisco Bay contribute the largest amount of stormwater pollution (37% of the total TSS load), followed by the lower Columbia River watersheds (19%) and the Puget Sound watershed (15%) (Levin et al., 2020).

Within Puget Sound, answering the "how much" component of the "how much and where" question is difficult. Determining how to prioritize treatment of stormwater in this region requires a clear articulation of objectives—spatial distribution of appropriate management actions is dependent on the life histories of species, and management schemes optimized for one species may not achieve desired objectives for other species. In particular, we highlight that the scale of stormwater interventions must match the ecological scale relevant to species targeted by management. (Levin et al., 2020).

Most future new development will trigger stormwater controls that improve water quality slowly over time (King County 2016). However, there is concern that permit requirements may fail to sufficiently enforce stormwater BMPs during redevelopment (Futurewise 2016). Even with strict new and redevelopment regulations in Washington State (Ecology 2014c), a net increase in pollution generating surfaces and net decrease in water quality is predicted in King County (King County 2016). Redevelopment has historically occurred at a rate of 1-2 percent per year. A focus on new development and redevelopment, while important, cannot protect or restore the Puget Sound basin, only slow the level of decline (Booth et al. 2008).

Relying only on stormwater mitigation triggered by development requirements would take over 100 years to manage runoff from all developed land (King County 2014a) and fail to protect currently threatened priority areas. Retrofits of existing impervious surface are necessary to prevent important endpoints like coho prespawn mortality and reduce toxic loading to Puget Sound. The answer to the "how much" question is expensive in any scenario: improving water quality for a single contaminant in a single Puget Sound watershed can cost up to $1 million (Visitacion, Booth, & Steinemann 2009). In separate modeling projects, King County and the Puget Sound Partnership estimated costs to retrofit the entire Puget Sound region to meet different thresholds. There have also been cost-benefit analyses performed for the Juanita Creek basin in King County, the City of Seattle, and Commencement Bay in Tacoma.

WHAT WOULD GETTING TO "PERFECT" COST USING EXISTING TECHNOLOGIES?

In order to understand the scale of the stormwater problem created over the past 100 years, King County conducted a comprehensive modeling of needed stormwater retrofits in Water Resources Inventory Area (WRIA) 9. Cost to reach the most aggressive, "near-pre-development conditions" (mimic fully forested land use) in 30 years was estimated, and results were extrapolated to the entire Puget Sound basin based on land use. The cost to reach this threshold was also modeled for a 100-year timeline with strengthened new and redevelopment requirements triggering mitigation on a large portion of developed land, thereby reducing capital costs (Table 5).

Table 5. Cost estimates for WRIA 9 and Puget Sound retrofits to hypothetical "pre-development" hydrology (King County 2014a)

	30-YEAR TIMELINE (ANNUAL COST)	100-YEAR TIMELINE (ANNUAL COST)
PUGET SOUND CAPITAL COST	$4.2-4.4 billion	$650 million
PUGET SOUND OPERATIONS AND MAINTENANCE*	$12-14 billion (peak costs after all facilities are built)	Increasing annually
WRIA 9 CAPITAL COST	$210 million	$46 million
WRIA 9 OPERATIONS AND MAINTENANCE*	$650 million (peak cost after all facilities are built)	$540 million (peak cost after all facilities are built)

**assumes existing technologies for monitoring and inspection of decentralized infrastructure on both public and private property.*

To reach a "pre-development" standard, a King County report recommends strengthening requirements for new and redevelopment and retrofitting pollution generating surfaces by aggressively installing rain gardens, roadside bioretention, cisterns, and detention ponds on all non-forested lands not redeveloped in the next 30 to 100 years. The projected operations and maintenance budget reported in Table 5 includes the costs of maintaining public and regional facilities as well as inspecting private ones (King County 2014a). Monitoring and inspection assumptions were based on existing technologies and represented a notably significant portion of the projected annual operating costs.

Over a thirty-year timeframe, this 2014 King County study proposed it would cost more than $500 billion to get Puget Sound back to a "pre-development" condition. Given that Washington's entire 2017 GDP was just over $524 billion, securing funding in this amount is not feasible. The study elevates the need to answer the following key questions related to Puget Sound recover and develop related workplans:

1. If not perfect, what is the threshold we should be aiming toward? What is good enough?
2. If not everywhere, where are the most important locations to enact pollution reduction measures?
3. What are the specific conservation actions that cost too much implemented at a scale that will have a positive impact on Puget Sound? Where could coordination, innovation, and better supply chain management buy down the cost of recovery?

WHAT WOULD BE THE COST OF A FOCUSED INVESTMENT TO ROLL BACK LEGACY POLLUTION?

Puget Sound Partnership also conducted a Sound-wide study, modeling the cost to reduce TSS in the entire Puget Sound basin based on different ranges of impervious surface treated. This projection was based on data from NPDES Phase I permittees. In 2009, Phase I permittees invested $62.8 million in treatment plus $22.4 million for operations and maintenance, resulting in removal of 233,700 tons of TSS. The model estimated the costs to remove 80% of TSS in urban runoff from various ranges of imperious surface in Puget Sound (Table 6).

Table 6. Cost estimates to retrofit ranges of Puget Sound impervious surface (PSP 2010)

RANGE OF IMPERVIOUS SURFACE MANAGED	80-100%	50-100%	20-100%	0-100%
ACRES OF IMPERVIOUS SURFACE MANAGED	60,206	162,201	282,663	319,409
CAPITAL COSTS IN BILLIONS	$3.01	$8.11	$14.133	$15.645
ANNUAL MAINTENANCE COSTS IN BILLIONS	$0.111	$0.3	$0.523	$0.561

Much of the development that exists in the Puget Sound drainage basin occurred prior to the adoption of Ecology's 1992 Stormwater Management Manual for Western Washington. Therefore, it is likely that greater than 90 percent of the existing developed land in Puget Sound produces stormwater that is never treated. As a result, retrofit of these developed areas to include stormwater filtration systems has been suggested as an important next step towards reducing stormwater impacts to Puget Sound (PSP 2010).

This coarse calculation of potential stormwater benefit highlighted an estimated 223,000 tons of TSS that could be removed annually from the stormwater system with a sharp focus on the densest areas across Puget Sound basin (50 percent and greater imperviousness). There are roughly 8.7 million acres in the Puget Sound drainage. Of that, there are roughly 162,000 acres of impervious land cover in the densest parts of Puget Sound basin that was developed before the mid-1990s when modern-day stormwater permits went into effect. The report recommends these 162,000 acres as the best candidates for retrofitting from public and private lands. Publicly owned roads, buildings and facilities are estimated at 50% of the 162,000 acres. The rest is privately owned (PSP 2010). That leaves an estimated 80,000 acres of private property in need of retrofit.

If we are to make significant progress on the recovery of Puget Sound, accelerating actions to retrofit the existing development may be necessary. Given the other competing interests for public dollars, as well as the significant investment needed to retrofit all pre-1996 development greater than 50% imperviousness, investments will need to be prioritized to the highest need.

WHICH POLLUTION REDUCTION PRACTICES OFFER THE BEST RETURN?

In a retrofit study in the Juanita Creek basin, the cost to meet water quality and flow requirements for salmonids (with the highest performing scenario) was estimated at $1.4 billion in 2012 in the 7 square mile drainage basin. This cost estimate includes land acquisition, construction, and maintenance over a 40-year life cycle. It does not include population growth or redevelopment. Cost estimates for stormwater actions ranged from $30-200 million/mi2. The two highest performing scenarios involved using infiltrative BMPs to treat 80% of the basin's impervious surface. All other scenarios resulted in B-IBI scores of "Poor" (King County 2012).

A cost-benefit analysis of pollution management strategies in Seattle found that roadside rain gardens, industrial runoff treatment, and street sweeping had the greatest cost-benefits (Table 7).

Table 7. Cost-benefit of 3 stormwater management strategies in Seattle (PSP 2015a)

BMP	ROADSIDE RAIN GARDEN RETROFITS	INDUSTRIALIZED RUN-OFF TREATMENT	STREET SWEEPING EX-PANSION
CAPITAL COST	$188,000/acre	$96,000/acre	$350/acre
ANNUAL MAINTE-NANCE	$700/acre	$1,300/acre	$480/acre
COST-BENEFIT COMPARI-SON TO CSO PROJECTS	20 times more TSS removal 10 times more load reduction	60 times more TSS removal 120 times more TSS removal	120 times more TSS removal 70 times more load reduction
POLLUTANTS TREATED	Many types	Fecal, PCBs, dissolved metals, oil/grease	Copper, zinc, PBDEs, PCBs

In a cost-benefit study of four water quality treatment BMPs in Commencement Bay, basin-wide sewer pipe cleaning provided the best bang for the buck (Table 8).

Table 8. Cost-benefit of 4 stormwater management strategies in Tacoma (PSP 2016)

	SEWER PIPE CLEANING	STREET SWEEPING	STORMWATER FILTERS	PERVIOUS PAVEMENT
20-YEAR COST	$677,000	$784,000	$9.9 million	$9.5 million
COST PER UNIT	$3 per linear foot cleaned	$245,000 per sweeper, plus $217,500 in annual O&M	$25,000 - $176,000 per vault installation	$131,000 per acre
PERCENT REDUCTION & (COST PER POLLUTANT)				
PYRENE (a PAH)	67% ($23,000/lb)	23% ($83,000/lb)	49% ($510,000/lb)	16% ($545,000/lb)
PHENANTHRENE (a PAH)	79% ($49,000/lb)	19% ($249,000/lb)	29% ($2.1 million/lb)	15% ($1.48 million/lb)
DEHP (a PHTHALATE)	79% ($1,500/lb)	9% ($19,000/lb)	36% ($53,000/lb)	11% ($62,000/lb)
TSS	33% ($260/ton)	18% ($520/ton)	65% ($1,380/ton)	12% ($6,760/ton)

Basin-wide sewer pipe cleaning quickly reduced large, "legacy" loads of major pollutants based on monitoring before and after cleaning projects conducted by the City of Tacoma. Line cleaning far outperformed the other tested management techniques for removal of all four target pollutants. However, this method removes decades of legacy pollutants in one cleaning, and future cleanings would produce more modest load reduction (PSP 2016).

Reducing stormwater inputs to the Sound is only part of the problem to be tackled. Like the challenge taken on in Tacoma, legacy loads of pollutants that will require treatment exist throughout Puget Sound. The annual cost for all NPDES permittees to remediate legacy loads is estimated at $60-120 million for five years (PSP 2010).

Climate change is likely to affect the requirements of Puget Sound's stormwater system in ways that are not fully understood but may affect the answer to the "how much" question. Climate change models of Puget Sound predict increases in extreme precipitation volume that are likely beyond the sizing capacity of current drainage infrastructure (Rosenberg et al. 2010). Given the uncertainty in how climate change will affect Puget Sound precipitation, the King County WRIA 9 project estimated a necessary increase in stormwater facility sizing by 10% (King County 2014a). A Massachusetts study found reduction of effective impervious surface to be the most important means of reducing runoff, even when modeled with increased precipitation and event intensity due to climate change. Decreasing impervious surface coverage produced significant reductions in TSS and flow in all given precipitation scenarios. Land use and climate change are likely to synergistically increase runoff quantity and quality impacts, and stormwater BMPs need to incorporate climate models in their sizing and design (Pyke et al. 2011).

HOW MUCH HAVE WE SPENT ON OTHER WATER QUALITY PROBLEMS?

The intent of the Clean Water Act is to "...restore and maintain the chemical, physical, and biological integrity of the Nation's waters." Since its adoption in 1972, this Act has driven investments and regulations to improve the quality of water nationwide. In Puget Sound, great strides have been made to retrofit wastewater treatments plants to provide secondary treatment and, consequently, reduce pollutant loading from these sources to Puget Sound. The same success story cannot be told of stormwater for several reasons. First, the federal, state, and local investments made to retrofit wastewater facilities have not been commensurately made to retrofit stormwater facilities. From 1970 to 1995, $61.1 billion in Federal Construction Grant Program funds were made available nationally. From 1988 to 2000, $16.1 billion in State Revolving Loan funds were made available for investments in wastewater quality improvement. While significant state and federal investments have since been made for stormwater controls, the level of investment has not yet reached the scale of historical investment in wastewater (PSP 2010).

How Much: Technique Comparison

The question of "how much" is very dependent on the types of BMPs installed. Given the uncertainty surrounding the mechanism of stormwater toxicity, we should focus on what the biota is telling us in our management approaches. For example, bioretention treatment of road runoff has been shown to prevent coho pre-spawn mortality (Spromberg et al. 2016), acute mortality of juvenile coho and mayfly nymphs (McIntyre et al. 2015) and nearly all developmental toxicity in developing fish embryos (McIntyre et al. 2016a). Coho spawners "appear to be very sensitive ecological indicators, with a response metric that is directly attributable to toxic storm water" (Spromberg et al. 2016). Coho survival and other biological endpoints should be used to measure the effectiveness and inform the implementation of diverse stormwater BMPs to stop toxic sources from releasing pollutants and treat pollutants that have entered the stormwater pathway to Puget Sound. For all BMPs, rigorous pre- and post-monitoring should be conducted to evaluate effectiveness. Traditional BMPs, low impact development, and source control are briefly overviewed in this section.

Traditional BMPs

Both field studies and BMP effectiveness models generally indicate that traditional treatment technologies reduce pollutant loads and improve water quality. The literature shows positive water quality impacts from Austin-style sand filters, wet detention ponds, and biofiltration cells (AWC & Ecology 2013c). Filter vaults, street sweeping, and catch basin cleaning were each determined to have the biggest cost-benefit to water quality in different King County jurisdictions (Futurewise 2016).

Media filtration effectiveness is dependent on the type and composition of the filter media. Studies show that filter drains can remove more than 80% of TSS, more than 50% of total phosphorous, and 50% of dissolved copper and zinc. Filter strips have been shown to significantly remove TSS and metals. Sand filtration, consisting of "a pretreatment system, flow spreaders, a sand bed, and underdrain piping," have been shown to reduce TSS (by 80%), metals, petroleum, and nutrients (City of Seattle 2015). Filter vaults in Tacoma were estimated to provide 49% reduction in the PAH pyrene, 29% in the PAH phenanthrene, 36% in the phthalate DEHP, and 65% in TSS (PSP 2016).

Street sweeping can effectively remove roadway pollutants, especially when performed with high efficiency or regenerative air sweepers. Regenerative air sweepers are 10-30% more effective than mechanical sweepers at pollutant load reduction. A Tacoma study found that street sweeping with regenerative air sweepers at high frequency reduced pyrene by 23%, phenanthrene by 19%, DEHP by 9%, and TSS by 18% (PSP 2016). In a study of street sweeping effectiveness in Korea, sweeping was much more effective at removal of large particles than small particles – there was a higher proportion of smaller TSS in runoff from swept roads compared to unswept roads. Sweeping reduced event mean concentrations of TSS by 78%, copper by 31%, and zinc by 5%. Water quality effectiveness was correlated to lower vehicle speeds, increased loads, and increased particle size. Sweeping twice did not improve load reduction (Kim, Jeong, & Ko 2014). In 2015, street sweeping in Seattle removed 1,046 dry tons of solids, including 235 dry tons of particulate matter with diameters less than 250 microns and 137 tons of fine particulate matter (Futurewise 2016). Street sweeping effectiveness is dependent on the type of vehicle used, sweeping frequency, pavement condition, average traffic, parking restrictions, and season (City of Seattle 2015). The Korean study determined the necessary frequency for maximum efficacy to be once every 4-5 days (Kim, Jeong, & Ko 2014). Some stormwater managers in King County agree that sweeping at least once a week is necessary to protect water quality (Futurewise 2016).

Pipe cleaning has been shown to provide large water quality improvements by reducing legacy pollutant loads. In Tacoma, pipe cleaning was estimated to result in 67% reduction in the PAH pyrene, 79% in the PAH phenanthrene, 79% in the phthalate DEHP, and 33% in TSS (PSP 2016). Wetpool facilities, including wet ponds, wet vaults, and combined detention/wetpond facilities, provide more treatment the bigger the wetpool volume. Wetpools provide runoff treatment for TSS, metals, and nutrients by sedimentation. Oil-water separators can remove water-insoluble hydrocarbons and settleable solids from runoff by trapping floating oil and settling sediment (City of Seattle 2015).

Low Impact Development

Low impact development (LID), also called green stormwater infrastructure, mimics natural hydrologic and biogeochemical processes by encouraging passive treatment and flow control of stormwater runoff. Some of these processes include encouraging stormwater to infiltrate into the ground by slowing down flows and filtering out pollutants. LID practices have been shown to significantly reduce quantity and improve the quality of stormwater runoff (AWC & Ecology 2013a). LID success depends on site-specific information, including infiltration rates, soil type, seasonal groundwater elevation, and interflow potential. LID storage capacity is generally smaller than traditional BMP storage, creating concern about peak flows and larger storms exceeding the sizing of LID facilities basin-wide. There is also the potential for contaminant export, especially nutrients and copper, from LID media, suggesting potential impacts on receiving waters (AWC & Ecology 2013a). Puget Sound is currently pursuing the goal to manage 700 million gallons of stormwater with GSI by 2025 (King County & Seattle Public Utilities 2019).

One of the biggest advantages of LID facilities is their multiple benefits. LID facilities can increase green space in cities, creating enormous benefit for human health and wellbeing. Bringing more nature into cities and towns not only helps us clean our water and the air we breathe but is a key ingredient in growing communities that thrive, healthier people, kids that learn better, and a strong, vibrant economy (summarized in TNC 2016). LID facilities can also reduce flooding and CSOs, provide urban wildlife habitat, improve air quality, and be more cost effective than traditional BMPs like vaults (Futurewise 2016).

For infiltrative LID, significant load removal has been observed for bioretention and swales for dissolved metals, TSS, nutrients, bacteria, oil and grease (reviewed by Ahiablame et al. 2012), as well as PAHs (McIntyre et al. 2014) and PCBs (Jack 2020). Effectiveness is largely dependent on the media mix, layering design, and degree of excavation (e.g., see reviews in AWC & Ecology 2013a; City of Seattle 2015). The 60% sand:40% compost bioretention soil media recommended in Washington state guidance has been found to effectively treat many contaminants in stormwater runoff, but can also export pollutants including copper and nutrients (Chahal et al. 2016). A comparison of alternative media mixes found coconut coir to provide the largest benefit (Herrera 2015). In a 2-year study of bioretention treatment in Seattle, inoculating the mulch layer led to significant reductions in the export of phosphorus and DOC, and significant improvement in removal of copper, lead, zinc over periods of 2-10 months (Taylor et al. 2018; McIntyre et al. 2020).

Infiltration treatment of urban stormwater runoff through bioretention soil media has been shown to prevent lethal and sublethal toxicity, including prespawn mortality, in coho salmon and their prey (Spromberg et al. 2016; McIntyre et al. 2015). Small concentrations of PAHs were found in the bile of juvenile coho after treatment indicating some breakthrough, but this was not associated with an adverse toxic effect (McIntyre et al. 2015). More recent research demonstrates that stormwater exposure impacts lateral line development in zebrafish and coho salmon (Young et al. 2018). Biofiltration rescued the lateral line impacts in zebrafish but not coho salmon, suggesting that coho sensory systems are sensitive to breakthrough contaminants from LID (Young et al. 2018). Bioretention filtration, with and without plants, also protects developing fish embryos from cardiotoxicity caused by road runoff exposure (McIntyre et al. 2016a).

Constructed wetlands provide robust flow control and contaminant treatment. They generally provide similar treatment effectiveness as infiltrative facilities with reduced risk of groundwater quality impacts (City of Seattle 2015). Median removal rates from studies reviewed by City of Seattle are 73% for copper and 79% for zinc. However, these wetlands require large surface area and are uncommon in urbanized areas (City of Seattle 2015). Floating treatment wetlands (FTW) – biomedia planted with wetland plants – are a novel treatment approach that could be added to existing water bodies where infiltration is not feasible. FTW were used to pre-treat roadway runoff for 24 h before exposing juvenile coho salmon. Mortality was reduced by 35% compared to untreated runoff over 24 h with a median time to death of 13 h vs the 3 h in untreated runoff (Seebacher 2020).

Significant load removal has also been observed in field monitoring of permeable pavement for TSS, phosphorous, nitrogen, metals, PAHs, and herbicides, at rates of 50-95% (AWC & Ecology 2013a). A study in the city of Renton study found significant reduction in copper, zinc, and motor oil after permeable pavement treatment (Booth & Leavitt 1999). A Tacoma study found reduction of pyrene (16%), phenanthrene (15%), DEHP (11%), and TSS (12%) (PSP 2016). Export of some chemicals has been observed, like nitrate (AWC & Ecology 2013a) and dissolved copper and zinc (Murphy, Cochrane, & O'Sullivan 2015). In replicated permeable asphalt systems treating stormwater in Puyallup parking lot, removal of Pb, Zn, motor oil and diesel hydrocarbons improved over the 5-year study. Annual maintenance of the pavements with a regenerative air sweeper did not affect treatment of contaminants (Jayakaran et al. 2019).

Green roofs generally reduce runoff volume and treat some pollutants compared to conventional roofs. The loading rate for green roofs is much lower than all other types of LID because the only input is direct rainfall, which generally has good water quality. Healthy roof vegetation can improve water quality through plant uptake. Studies show that green roofs can export phosphorous, nitrogen, and copper in outflow – this export is often tied to fertilizer use and building materials (AWC & Ecology 2013a). Many stormwater managers in King County agree that green roofs are not a cost-effective method of improving water quality in the Puget Sound climate but do provide multiple benefits including urban habitat and regulation of building temperature (Futurewise 2016). Estimated costs per acre from the University of New Hampshire's Stormwater Center for different LID techniques are presented in Table 9.

Table 9. Cost per acre of 5 LID techniques (Trust for Public Land 2016)

LID TECHNIQUE	CAPITAL COST	ANNUAL O & M	ANNUAL STAFF TIME
VEGETATED SWALE	$14,650/acre	$1,023/acre	10 hours/acre
RETENTION BASIN	$16,471/acre	$3,279/acre	28 hours/acre
DETENTION BASIN	$16,471/acre	$2,599/acre	24 hours/acre
BIORETENTION AREA	$25,576/acre	$2,109/acre	21 hours/acre
POROUS ASPHALT	$26,588/acre	$1,781/acre	6 hours/acre

Other non-traditional techniques have the potential to greatly improve water quality, including minimizing impervious surface in new and redevelopment, out-of-the-box propriety systems like Filterra®, disconnecting downspouts, dispersal, and preservation of native trees, vegetation, and soils (Futurewise 2016). More information about the effectiveness of diverse BMPs is available from the Washington Stormwater Center, in the Washington Department of Ecology's 2014 Stormwater Management Manual for Western Washington and the International Stormwater BMP Database. Ongoing research on BMP effectiveness in Puget Sound can be tracked through the Regional Stormwater Monitoring Program.

Source Control

Source control is a critical partner to stormwater BMPs. When release of toxic chemicals is prevented at the source, no treatment is necessary. This section discusses regulatory and structural source control efforts in Washington State.

Regulatory source control is a highly effective way of reducing toxics release and exposure:

- The phase-out of leaded gasoline is likely responsible for the exponential decrease in lead concentrations in road runoff observed on different continents (Kayhanian et al. 2012). In Puget Sound, lead concentrations in harbor seal pup tissue are 4 times lower than they were thirty years ago (Akmajian et al. 2014).
- In 2010, the Better Brakes Law was passed in Washington State, banning the use of asbestos, lead, and several heavy metals and phasing out copper in brake pads. The Department of Ecology estimates that brakes manufactured in 2021 will release about 90% less copper than they do today (Ecology 2013b).
- In 2011, Washington became the first state in the nation to ban coal-tar-based pavement sealants. Coal-tar-based sealants contain known carcinogens and other acute toxicants (Mahler et al. 2014; McIntyre et al. 2016b) and have been consistently shown to significantly pollute receiving waters via stormwater runoff. The human health risk and availability of less toxic asphalt-based sealants were pivotal in passing the Washington State ban (McClure 2011).

Regulatory bans require support from BMPs to prevent exposure from already released toxics. Furthermore, there is evidence of "regrettable substitution," in which manufacturers swap out a banned toxic for similar compounds with similar toxic concerns. After a ban on phthalates in children's products, manufacturers replaced them with structurally similar phthalates. Similarly, a ban of some organophosphate pesticides increased use of neonicotinoid and pyrethroid pesticides (Bennett et al. 2016).

Structural source control, including construction site BMPs, site visits, inspections, and illicit discharge programs, are important tools to improve water quality as well:

- At construction sites, compost blankets, filter socks, permeable check dams, and polyacrylamide BMP treatments are the most effective for controlling sediment and treating erosion. To meet water quality standards for turbidity, source control BMPs generally need to be implemented along with runoff and treatment BMPs (AWC & Ecology 2013b). Studies show significantly greater sediment export at construction sites with no erosion control than from sites with installed erosion control BMPs (City of Seattle 2015). City staff in King County generally report that construction sites comply with source control BMPs, and that effective enforcement options exist to correct noncompliance (Futurewise 2016).
- Stormwater facility site visits can improve stormwater management, especially when agency personnel develop positive relationships with facility operators. One Kitsap County study found improved compliance when visit frequency was increased from every other year to every year (AWC & Ecology 2013b).
- In-person business inspections can improve BMP operation and maintenance. Follow-ups encourage long-term compliance (AWC & Ecology 2013b).

Illicit Discharge Detection Elimination programs are most effective when structured based on a complete understanding of the targeted discharge. NPDES permittees in Western Washington report that effective detection strategies include reporting hotlines and inspections of manholes, catch basins, and outfalls (AWC & Ecology 2013b).

Ample opportunities for source control exist for many Puget Sound toxics. The Ecology & King County 2011 toxics loading study determined pollutants with "large" opportunities for source control to be copper, zinc, PAHs, phthalates, and petroleum. Pollutants with "medium" opportunities for source control were arsenic, cadmium, mercury, PBDEs, and triclopyr. Opportunity for source control was ranked based on toxicity, feasibility of source control, and lack of existing source control (Ecology & King County 2011).

Where: Treatment Priorities

Prioritization of sites needing stormwater retrofits is an incredibly complex task, and many different approaches have been used in Puget Sound. From a salmon recovery standpoint, "protecting habitat that supports larger proportions of the metapopulation's spawners" will have the greatest population-level impact (Spromberg & Scholz, 2011). Mortality risk assessments for coho salmon in the Puget Sound demonstrate increasing risk along an urban gradient (Feist et al. 2017, Peter et al. 2020 *In Prep*). For bioaccumulating toxics, prioritizing loads reduction to eelgrass habitat may decrease the potential for trophic level effects (WDNR 2015). Another approach prioritizes retrofit location as a means of increasing environmental equity. Many toxic chemicals, including lead, pesticides, and PBDEs, disproportionately affect low income communities and communities of color (Bennett et al. 2016). Increasing nature in "park-poor" areas can help correct these inequities, but can also create gentrification that displaces poorer residents (TNC 2016). The "where" component of the "how much and where" question can be answered in many different ways depending on priorities. The following diverse approaches have been proposed or implemented in the siting of Puget Sound retrofits.

The Building Cities in the Rain expert work group developed an in-depth guidance system for prioritizing stormwater retrofit sites. Their guidance emphasized the importance of supplementing region-scale data with local, water-shed specific information, informed by a participatory process including tribes, natural resource agencies, and the general public. They proposed this stepwise use of local data:

1. **Actual and potential fish use**—higher priority given to receiving waters with low to moderate levels of impairment based on % tree canopy, B-IBI, known water quality impairments based on 303(d) listings, total maximum daily loads (TMDLs), local knowledge, and low instream flows
2. **Flow control and treatment opportunities**—using % impervious surface, growth based on zoning, extent age and conditions of existing stormwater facilities, fish passage barriers, and areas with intersection with Salmon Recovery Plans, TMDL plans, Puget Sound Initiative cleanups, Endangered Species Act listings, and critical habitat designations
3. **Environmental justice and social equity as a tie breaker** (Commerce 2016)

To achieve the Puget Sound Partnership's freshwater quality goal of improving 30 basins from "fair" B-IBI scores to "good" B-IBI scores, King County Department of Natural Resources and Parks proposed this stepwise retrofit site prioritization scheme:

1. Landscape analysis of basin characteristics, land cover, geology, and site characteristics
2. Ecoregion
3. Sampling history (greater than 2 samples after 2007 or greater than 4 total samples)
4. Watershed area between 200-3000 acres
5. Puget Sound Watershed Characterization (prioritize all protection areas and restoration areas with high importance)
6. Rank sites by watershed context:
   a. Worst—Urban >30%; Buffer <50% natural
   b. Moderate—Urban >30%; Buffer >50% natural
   c. Good—Urban <30%; Buffer <50% natural
   d. Best—Urban <30%; Buffer >50% natural
7. Rank sites by biotic potential (based on B-IBI score and percentage of watershed urbanization)
8. Cost estimation (King County 2014c)

King County staff recommended a retrofit prioritization approach using B-IBI scores:

1. Identify opportunities with biggest hydrologic impact based on projected B-IBI scores
2. Identify feasible sites based on hydrology, infiltration potential, impervious surface, slope, risk to surrounding landscape, available area, and coordination with utilities, transportation, and other projects
3. Rank projects for benefit, feasibility, and public feedback
4. Conduct field evaluation of top ranked projects
5. Conduct preliminary engineering (Ostergaard, Barker, & Kirschbaum 2014)

The EPA Municipal Separate Storm Sewer System (MS4) permit ranked retrofit locations based on these descending criteria:

1. Feasibility
2. Cost effectiveness
3. Pollutant removal effectiveness
4. Impervious area potentially treated
5. Maintenance requirements
6. Landowner cooperation
7. Neighborhood acceptance
8. Aesthetic qualities
9. Efficacy at addressing concerns
10. Proximity to water bodies (PSP 2010)

The Kitsap County Pollution Identification & Correction Program ranks retrofit locations based on these descending criteria:

1. TMDL listing
2. 303(d) listing for fecal coliform
3. Shellfish harvest impairment determination by the Health Department
4. Marine recovery area listing
5. Health advisory listing
6. Monitoring data (health district or volunteer) violating state water quality standards
7. Mesotrophic/meso-eutrophic/eutrophic/hyper-eutrophic classification
8. Onsite Septic System Area of Concern designation (PSP 2010)

The Puget Sound Ecosystem Monitoring Program recommended this prioritization framework for monitoring CECs:

1. Prioritize components based on data availability
   a. Actual measured environmental concentrations
   b. Predicted environmental concentrations for transport and fate processes
   c. Environmental toxicity data
2. Prioritize compounds with anticipated significant risk
3. Prioritize compounds with predicted no-effect concentrations at less than 0.1 ug/L
4. Consider biological endpoints (PSEMP 2015)

Moving Forward with What We Know

Until we know what components of urban stormwater runoff are responsible for its toxic effects, it will be difficult to focus efforts on source control or sharply targeted mitigation. In the meantime, we must focus on what the biota are telling us about the water rather than what chemicals we are measuring in the water. Developing a performance-based approach and informed action is vital to protect salmon and other biota from stormwater impacts in a changing climate. Action on stressors that we can currently control is vital as new threats continue to emerge (Stormwater Work Group 2010). Given the existing knowledge about urban stormwater runoff and its impacts in Puget Sound, there are many ways we can move forward to buy-down the costs of stormwater action at scale, restore habitat, increase biotic integrity, and improve ecological health, while we are simultaneously filling in scientific gaps:

- Integrate the B-IBI and prespawn mortality datasets Sound-wide to prioritize retrofits
- Install bioretention to reduce toxicity along coho runs and monitor downstream impacts on other biota
- Retrofit an entire basin and rigorously monitor diverse endpoints
- Optimize bioretention media mixes to reduce pollutant export and prevent acute and chronic toxicity to biota
- Focus stormwater mitigation in urban growth and industrial land use areas
- Focus BMP efforts on multiple benefits, including adding urban green space, improving public safety, increasing economic development, and providing habitat
- Monitor new and existing BMPs for downstream biotic impacts
- Adaptively manage stormwater – install stormwater facilities with a measurable hypothesis to be tested, so that performance can improve future action
- Continue and expand biological monitoring programs like Mussel Watch
- Build robust, inclusive, Sound-wide feedback loops for communicating the results of research, monitoring, evaluation, design, and installation
- Include commonly occurring CECs identified in studies like Brandenberger et al. 2014 and Long et al. 2013 to stormwater and toxicity analyses
- Include in stormwater and toxicity analyses some of the 99 polycyclic aromatic compounds proposed in Andersson & Achten 2015
- Explore and test ways to significantly lower costs of monitoring and inspection of distributed, nature-based solutions using new IoT and technological solutions.
- Develop incentives and tools for private landowners to voluntarily go beyond permit requirements or retrofit in targeted areas of strong public and environmental benefit.
- Identify a clear threshold, statement of hypotheses, metrics and monitoring to know what is being accomplished with public and private stormwater investment (performance-based approach)
- Innovative approaches to reducing excess nutrient loading (i.e. nitrogen), elevated temperatures, sediment, toxics

III. What We Don't Know

Sometimes management without sufficient information can be counter-productive. For example, in Lake Ontario native lake trout were extirpated following decades of expensive management including lake stocking, lamprey control, and fishery regulations. Forty-three years later, the primary cause of this extirpation was identified to be PCBs and PCDD/F pollution. The 1980s saw a large source control and remediation effort that eventually improved trout reproduction after water quality was identified as the problem (Ross et al. 2013a). In this case, management with incomplete information resulted in massive expense without improvement in environmental quality.

Given the staggering complexity of stormwater's impact to the biota of Puget, there are many important questions that need to be answered before we can successfully manage stormwater runoff to Puget Sound.

Select Research Questions

- What is the nature and scale of water pollution in Puget Sound? Where should we prioritize green stormwater infrastructure (GSI) for pollution removal and for water flows (floods and water supply)? How much GSI is needed to have a significant impact on water quality and quantity in Puget Sound?
- How can Green Stormwater Infrastructure improve human mental and physical health?
- What is the scale of the solution that will be needed to improve the health of rivers, lakes and marine ecosystems of the Sound? What set of actions will make Puget Sound waters look different in 30 years, and are also economically viable?
- Can we identify the most impactful actions needed and rank them by return of investment?
- What new technologies would enable us to make more impactful change or buy down the cost of needed investments for water quality?
- How do you inspire and engage private businesses and neighbors to act in landscapes, where there are many other competing interests, to consider stormwater investments as part of their approach to business and change behaviors?
- What are the avoided costs in restoring Puget Sound water quality? What are the costs of inaction to the food web, economy and quality of life?
- Which Puget Sound biota are vulnerable to stormwater runoff?
- Are there inexpensive chemical tracers we can use that correlate well with runoff toxicity?
- What are the precise components in stormwater that cause toxicity in target species?
- Can stormwater be diluted to a point that prevents toxicity in target species?
- What are the precise mechanisms of stormwater's toxicity in target species?
- What are the thresholds of individual contaminants and contaminant mixtures that product toxicity in target species?
- Is there a seasonality to pollutant loadings in runoff to Puget Sound?
- How do different types of agriculture affect runoff contamination?
- What is the contribution of untreated sewage from combined sewer overflows to the toxic impact of urban stormwater runoff in Puget Sound?
- How does effluent from wastewater treatment plants contribute to or alter the toxicity of stormwater runoff?
- What are the sources, pathways, loadings, and toxicities of CECs in Puget Sound?
- How is TSS correlated to contaminant concentrations in Puget Sound?
- Are exterior building coatings including caulks, sealants, and flashings important sources of toxic loading to Puget Sound?
- What types and volumes of pesticides do Puget Sound jurisdictions apply?
- Which CECs are high priority?
- Which specific sources are high priority for control/treatment for specific toxicants in stormwater?
- What are the multiple benefits of toxic loading reduction to endpoints like human health, fishery income, etc.?
- How much toxic pollution is addressed with current infrastructure?
- How much toxic pollution will be addressed due to stormwater requirements for new and redevelopment?
- How much toxic pollution do different retrofit BMPs and sizings address?
- Do existing ditches, with and without vegetation, provide infiltration, flow control, or water quality treatment?
- How does catch basin cleaning affect toxics loading to Puget Sound?
- How does the effectiveness of street sweeping compare to the effectiveness of catch basin cleaning?
- Which BMPs effectively treat urban stormwater to prevent toxicity in target species?
- What is the minimum level of treatment (for example, depth of

bioretention soil media) needed to prevent toxicity in target species?

- How long do BMPs function?
- Do BMPs "clog" with pollutants or reach a capacity after which they no longer provide treatment?
- Will soils in infiltrative BMPs require remediation in the future?
- How does treatment performance of BMPs change over time?
- How much do BMPs reduce toxic loads in effluent?
- How do vegetated BMPs like rain gardens function in a variety of management scenarios (dead plants, weeds, mowed grass etc.)?
- Does engineered infiltration recharge aquifers?
- What is the impact of stormwater infiltration on the quality and quantity of groundwater?
- How can stormwater goals like minimizing impervious surface flourish alongside climate change goals like density and growth management?
- How do stormwater BMPs, including LID, perform on a basin-scale?
- Where is interflow likely to occur as a result of stormwater infiltration?
- How can trees be used to manage stormwater runoff?

Conclusion

Reduction of toxic loading through management of stormwater is one of the best hopes for making Puget Sound a healthy home for people and wildlife. Annual loading of some toxics like PCBs and DDTs are low due to decades of source control, yet their negative impacts persist in Puget Sound and continue to harm its residents. Green Stormwater Infrastructure (GSI) cleans an entire cocktail of pollutants from stormwater runoff, so even while the science of chemical specifics is getting more informed, we can advocate for tools that support clean water thru GSI. Effective urban stormwater runoff could well reduce the impact of the next harmful pollutant that we just haven't identified yet. Increased testing of stormwater's toxicity to Puget Sound organisms as well as the continued study and implementation of BMP treatment to prevent toxicity is vital. Effective stormwater management throughout the Puget Sound basin, using GSI techniques like bioretention, has the potential to significantly benefit the waters of our region.

In addition, while local stormwater actions may be meant to solve large-scale issues confronting coastal ecosystems, they will often be inadequate by themselves (Levin et al., 2020). New stormwater-positive approaches, BMPs, products, and technologies can be piloted for performance impact locally. But operationalizing these actions in a way that will move the needle, must be coordinated into broader management systems, culture, policies and institutions at the scale where species themselves live - be they Orca, salmon or people. This type of coastal approach will require cross-scale collaboration, prioritization and visioning to become normal and commonplace.

Appendix – Toxic Impacts by Contaminants

MIXTURE TOXICITY

Given the enormous chemical complexity of urban stormwater runoff, many studies evaluate the toxicity of contaminant mixtures in runoff, especially when the specific contaminant(s) responsible for toxicity are not understood. In a study comparing runoff toxicity in freshwater and marine species, toxic responses were correlated among freshwater species and among marine species, but not between freshwater and marine species, suggesting different toxicants or toxic mechanisms (Kayhanian et al. 2008). In fact, runoff toxicity often results from chemical mixtures rather than single contaminants (Anderson et al. 2007). Runoff toxicity has been observed in coho salmon, chinook salmon, rainbow trout, zebrafish, medaka, inland silverside, fathead minnows, sea urchins, amphibians, and invertebrates.

The prime example of stormwater toxicity is coho prespawn mortality. Coho salmon spawners returning to urban streams display erratic behavior like surface swimming, gaping, fin splaying, and loss of orientation and equilibrium. Affected fish die within hours, and female carcasses retain over 90% of their eggs (Scholz et al. 2011). Salmon that arrive in streams during extended dry periods of a week or more often survive and then become symptomatic and die when it next rains. An eight-year monitoring effort in Puget Sound streams found that coho prespawn mortality occurred at a rate of 0.9% in a rural stream and ranged from 60% to 100% in urban streams (Scholz et al. 2011). Untreated urban road runoff produces 100% mortality in experimentally exposed coho spawners (Spromberg et al. 2016). The City of Bellevue and Muckleshoot Tribe tagged and released coho spawners from the Issaquah Hatchery into two creeks – one with less impervious area (20%; Coal Creek), and one with more impervious area (40%; Kelsey Creek). The Coal Creek transplants had 41% spawning success rate in 2013 and 20% in 2014 whereas the Kelsey Creek transplants had 0.3% spawning success rate in 2013 and 0% in 2014 (City Bellevue 2015).

A model of the effects of coho PSM on populations and metapopulations found that PSM occurring at a rate of 20% is estimated to result in local population extinction in 135 years. The higher the mortality rate, the shorter the time to extinction: PSM at a rate of 60% results in extinction in 22 years, 70% in 16 years, 80% in 12 years, and 90% in 8 years. "Local population extinctions were predicted across the range of PSM rates that have been recently documented in Puget Sound urban streams" (Spromberg & Scholz 2011). Coho populations were projected to persist longer with slower rates of development, as well as increased straying between populations. The more populations experience low levels of PSM, the higher the chance of metapopulation extinction: "for example, a single population experiencing 50% PSM reduced the overall metapopulation abundance by 23%, whereas 2 populations experiencing PSM at half the rate (25%) reduced the metapopulation abundance by 38%" (Spromberg & Scholz 2011). These population estimations reflect the impacts of stormwater on PSM only, and do not account for impacts at other life stages.

Stormwater runoff also causes acute lethal toxicity in juvenile coho salmon. In a 2015 study, highway runoff produced 100% mortality in juvenile coho salmon within 12 hours (McIntyre et al. 2015). Stormwater additionally causes matching behavioral symptoms and blood chemistry dysregulation in juvenile and adult coho salmon (Chow et al. 2019). Juveniles that become symptomatic (surface swimming) do not recover in clean water. The mortality is not associated with methemoglobin production (Blair et al. 2020). Runoff exposure caused some acute mortality in juvenile chinook salmon and steelhead, but none in sockeye (French B, NOAA-NWFSC, unpublished data) or chum (McIntyre et al. 2018).

In a study of Indian Creek, rainbow trout alevin survival was 4% just downstream of a stormwater outfall and 60% just upstream of the outfall, despite no significant differences in Benthic Index of Biotic Integrity (B-IBI) scores. Individually, metal and PAH concentrations did not exceed water quality thresholds, indicating that a chemical mixture was responsible for alevin mortality (Ecology 2014b).

Lethal and sublethal response to stormwater runoff has been observed in other fish species as well. Urban runoff exposure causes a range of symptoms in zebrafish embryos, including delayed hatching, cardiac dysfunction, accumulated blood, cranial hemorrhage, and pericardial edema, even with 95% dilution with clean water (McIntyre et al. 2014). In a San Diego study of runoff toxicity to freshwater medaka and estuarine inland silverside, exposure to urban stormwater runoff produced statistically significant sublethal effects at low concentrations (5-10%) including abnormal swim bladder inflation, spinal curvature, reduced overall size, and abnormal eye size. Exposure to higher concentrations resulted in failure to hatch or mortality. Mortality was most highly correlated with total metal concentrations (Skinner, de Peyster, & Schiff 1999). In another study, stormwater runoff produced 92% mortality in fathead minnows (McQueen et al. 2010).

Sea urchin fertilization has been shown to be highly vulnerable to stormwater runoff, with toxicity observed at runoff concentrations as low as 6% (Greenstein, Tiefenthaler, & Bay 2004; Kayhanian et al. 2008).

Toxic response to runoff has been observed in many other species. Exposure to stormwater sediments has been shown to reduce embryonic survival of gray tree frogs by 50% and accelerated larval development and growth compared to controls. Stormwater contaminants also affect amphibian reproduction (Brand et al. 2010). One study found that runoff exposure causes lethal and sublethal effects in water fleas and mayflies (McIntyre et al. 2015). Samples of runoff from South Carolina parking lots decreased survival in 15% of water fleas and significantly decreased water flea reproduction in over 40% of samples (McQueen et al. 2010).

Chemicals in tire wear debris, which is plentiful in stormwater runoff, can be bioavailable to fish, pelagic filter-feeding organisms, benthic organisms, and plants. Tire wear particles are most chemically similar to toxic stormwater samples, relative to other motor vehicle contaminant sources (Peter et al. 2018). Tire leachate toxicity has been studied many organisms, from bacteria to plants to invertebrates to fish, with most studies observing acute toxicity (Wagner et al. 2018), most likely due to zinc and organic compounds (Wik & Dave 2009). Exposures of tire leachate to coho salmon demonstrate a similar acute mortality and physiological response as to stormwater exposures (McIntyre et al. *In Prep*). Variations in temperature and mechanical stress impacted the toxicity of tire leachate on fathead minnow embryos, where both Zn and PAHs were identified in the samples (Kolomijeca et al. 2020).

In a Sound-wide study, mussel mortality was weakly correlated with both impervious surface and road area, which in turn was correlated with increased PAHs, PCBs, lead, copper, and zinc (WDFW 2014b).

In green and red seaweed, exposure to metal mixtures can cause significant impairment of photosynthetic parameters compared to controls (Jarvis & Bielmyer-Fraser 2015). Toxic responses in growth rates and nitrogen fixation have been observed in eelgrass exposed to metal mixtures (WDNR 2012).

PUTATIVE TOXICS IN STORMWATER RUNOFF

One approach to determining the identity of toxic chemicals in a mixture is the Toxicity Identification Evaluation (TIE) (US EPA 1991). Kayhanian et al. (2008) concluded that toxicity of urban highway runoff in Los Angeles to a variety of organisms was primarily due to copper and zinc in 80% of samples and surfactants in 10% of samples. Similarly, the TIE of stormwater samples from an urban creek feeding Santa Monica Bay in California identified zinc as the primary toxicant to sea urchin fertilization (Bay et al. 2003). In contrast, mixtures of metals (including copper and zinc) at concentrations present in urban road runoff were not sufficient to induce pre-spawn mortality symptoms in coho salmon spawners. Neither were mixtures of metals and low-molecular weight PAHs (Spromberg et al. 2016).

Coho spawner mortality is most closely correlated with the proportion of local roads, impervious surfaces, and commercial property type within a drainage basin, indicating that coho spawners are being killed by “as-yet unidentified toxic chemical contaminants” that reach coho spawning habitat through stormwater runoff (Feist et al. 2011). A risk assessment of prespawn mortality in the Puyallup River watershed found that urbanized regions with high impervious surface posed the greatest risk to coho spawners (Hines and Landis 2014). Similarly, pathogen-associated disease, noninfectious lesions, insecticides, stream temperature, dissolved oxygen, and other conventional water quality indicators do not seem to cause the coho prespawn mortality syndrome (Scholz et al. 2011). Finally, pesticides in stormwater are likely not sufficient to cause coho prespawn mortality (King et al. 2013). Very recently, the primary responsible toxicant was identified as 6PPD-quinone – a transformation product of the anti-ozonant 6PPD in tires (Tian et al. 2021).

Mussel mortality in Puget Sound is weakly correlated with both impervious surface and road area, which was correlated with increased PAHs, PCBs, lead, copper, and zinc (WDFW 2014b).

Tire leachates toxic to daphnids assessed by TIE determined that zinc and non-polar organic compounds were primarily responsible for the observed toxicity (Wik & Dave 2009).

Much more work is needed to confirm the identity of the compound(s) responsible for toxicity in urban stormwater runoff, especially to salmon and nearshore marine species.

COPPER

Copper toxicity has been observed in
Copper toxicity has been observed in
coho salmon, chinook salmon, steelhead salmon, rainbow trout, fathead minnow, Colorado pikeminnow, tilapia, sea

urchin, water fleas, and seaweed. According to data from NPDES Phase I permittees in Puget Sound, dissolved copper exceeded acute aquatic life criteria in 50% of stormwater samples (Ecology 2015). In a study of runoff toxicity in sea urchins, fathead minnows, water fleas, green algae, and luminescent bacteria, copper and zinc were identified as the primary causes of 90% of observed toxicity (Kayhanian et al. 2008).

Copper in freshwater affects juvenile coho salmon olfactory function (Baldwin et al. 2003). By interfering with predator avoidance behavior, copper olfactory toxicity significantly decreases the likelihood of juvenile coho surviving a predator attack (McIntyre et al. 2012). Dissolved copper concentrations lower than frequently found in stormwater runoff can disrupt fish behavior – including critical behaviors like development, reproduction, and predator avoidance – and has the potential to reduce reproductive success at the population level (Hecht et al. 2007). At high enough concentrations, copper can cause acute mortality in coho (Chapman & Stevens 1978). Copper tends to bind strongly to organic matter (Santore et al. 2001, McIntyre et al. 2008), and would not often be bioavailable in stormwater runoff and receiving waters.

Dissolved copper is known to also impair olfaction in chinook salmon, rainbow trout, fathead minnow, Colorado pikeminnow, and tilapia (Sandahl et al. 2007). Copper exposure has been linked to mortality in juvenile chinook and steelhead (Chapman 1978). Dissolved copper can impair olfactory function in hatchery and wild steelhead trout at thresholds similar to those for coho salmon (Baldwin et al. 2011).

Copper at lower concentrations than those measured in Puget Sound has been shown to cause toxicity and affect photosynthetic function in five Australian seagrass species (Prange and Dennison 2000). Eelgrass rapidly accumulates metals from surrounding waters, and growth rates are inhibited by exposure to mercury, copper, cadmium, zinc, chromium, and lead (in order of descending toxicity) (Lyngby & Brix 1984).

Studies show copper exposure can also affect morphology, inhibit photosynthesis, and cause mortality in seagrass (WDNR 2012). Metal exposure results in increased accumulation in green and red seaweed and can cause significant impairment of photosynthetic parameters compared to controls (Jarvis & Bielmyer-Fraser 2015). Copper has also been linked to toxicity in sea urchin embryos (Anderson et al. 2007) and causes mortality to larvae at concentrations found in stormwater runoff (Phillips et al. 2003).

ZINC

Zinc toxicity has been observed in seals, coho salmon, chinook salmon, steelhead salmon, sea urchins, fathead minnows, water fleas, seagrass and algae. According to data from NPDES Phase I permittees in Puget Sound, dissolved zinc exceeded acute aquatic life criteria in 36% of stormwater samples (Ecology 2015). In a study of runoff toxicity in sea urchins, fathead minnows, water fleas, green algae, and luminescent bacteria, zinc and copper were identified as the primary causes of toxicity in 90% of the samples (Kayhanian et al. 2008).

Zinc can compromise seal immune systems: zinc concentrations were much higher in seals infected with canine distemper virus than healthy seals in a mass mortality event in the Caspian Sea. Renal and hepatic zinc concentrations were negatively correlated with blubber thickness (Anan et al. 2002).

Dietary zinc intake has been linked to reduced growth, increased feeding, and decreased gene expression in coho salmon (Bowen, Werner & Johnson 2006). Zinc exposure can cause mortality in adult coho and steelhead salmon, and coho salmon were consistently more vulnerable to metal toxicity than steelhead in one study (Chapman & Stevens 1978). Zinc exposure has also been linked to mortality in juvenile chinook and steelhead salmon (Chapman 1978).

Zinc is partially responsible for tire leachate toxicity has been studied in fish, daphnids, copepods, decapods, bacteria, and algae (Wik & Dave 2009). Sea lettuce exposed to tire leachate was shown to accumulate zinc and have impaired photosynthesis (Turner & Rice 2010). Zinc was determined to be the cause of sea urchin fertilization toxicity in a California study (Bay et al. 2003). Zinc is lethal to sea urchin embryos at concentrations found in stormwater runoff (Phillips et al. 2003). Eelgrass rapidly accumulates metals from surrounding waters, and growth rates are inhibited by exposure to mercury, copper, cadmium, zinc, chromium, and lead (in order of descending toxicity) (Lyngby & Brix 1984). Zinc exposure can reduce seagrass growth (Lyngby & Brix 1984).

PAHs & PETROLEUM RELATED COMPOUNDS

PAHs have been observed to cause toxicity in chinook salmon, pink salmon, rainbow trout, pacific herring, English sole, amphipods, and seagrasses. PAH toxicity is complex: different PAH compounds have different toxic pathways and toxic impacts (Incardona, Linbo, & Scholz 2011). The thresholds for developmental cardiotoxicity in fish are extremely low and may have been significant contributors to fishery collapses like the decline of herring stocks and pink salmon in Prince William Sound after the Exxon Valdez oil spill (Incardona et al. 2015). Tested PAHs in one study did not individually cause prespawn mortality in coho salmon (Spromberg et al. 2016).

Dietary PAH intake by juvenile chinook can alter growth, plasma chemistry, and lipids, and significantly reduce average fish weight at high doses. Reduction in fish size and reduced lipid stores have large ramifications on survival (Meador et al. 2006). Immunity to pathogens is significantly decreased in juvenile chinook after PAH exposure (Arkoosh et al. 2001). Studies also show immune system changes due to PAH exposure in tilapia, spot, medaka, carp, dab, killifish, oyster toadfish, eelpout, and catfish (Reynaud & Deschaux 2006).

Pink salmon embryos exposed to PAHs show delayed growth and 15% lower marine survival (Heintz et al. 2000). Pink salmon embryos exposed to trace levels of crude oil develop permanent heart abnormalities and reduced cardiorespiratory function as juveniles, causing significant survival and population consequences (Incardona et al. 2015).

Rainbow trout fed PAH-contaminated diets show diverse effects. Rainbow trout fed a diet contaminated with PAHs showed lower survival when pathogen challenged and also showed changes in AHR activation and oxidative stress– higher doses increased biomarker response (Bravo et al. 2011). PAH exposure has been linked to immune system changes in rainbow trout (Reynaud & Deschaux 2006).

Pacific herring embryos exposed to crude oil showed pericardial edema, irregular cardiac arrhythmia, and mortality. Impaired cardiac function seriously impacts swimming performance and survival (Incardona et al. 2009). Observed mortality in a study of Puget Sound Pacific herring was highest in areas with the highest PAH concentrations, and two sample sites with long-documented herring embryo mortality were also the sites with the highest PAH concentrations (West et al. 2014).

In Puget Sound English Sole, PAH exposure has been linked to decreased reproductive function and immune response, and increased disease. These responses could impact flatfish populations in Puget Sound, including reduction in sub-population size (Johnson et al. 1998). English sole fed a PAH-contaminated diet showed significantly reduced growth rates, 10-fold lower than control fish growth rates (Rice et al. 2000).

Different PAH compounds have different effects on zebrafish embryos, including abnormally slow heart function, pericardial edema, looping defects, erythrocyte regurgitation, and low genetic response (Incardona, Linbo, & Scholz 2011). Three-ring PAHs caused the characteristic defects of cardiac dysfunction, edema, spinal curvature, and reduction in craniofacial structures in zebrafish as well as other cardiac effects causing later stage consequences for the heart, kidneys, and brain. One four-ring PAH, in contrast, caused anemia, peripheral vascular defects, and neuron death. Toxicity was directly proportional to the concentration of contaminants in the mixture (Incardona, Collier, & Scholz 2004; Incardona et al. 2006).

Amphipod mortality is significantly correlated to PAH exposure (Anderson et al. 2007). PAHs also affect seagrasses, and have been shown to cause reduced growth, leaf senescence, reduced photosynthesis, and mortality (Jacobs 1988). PAHs also reduce nitrogen fixation (Brackup & Capone 1985).

In a study of lugworms exposed to contaminated sediment, PAHs from diesel soot, tire tread materials, and urban particulates were readily bioavailable to marine deposit feeders during digestion. Addition of tire tread to sediment increases solubility of four PAH compounds (Voparil et al. 2004).

PCBs

PCBs have been observed to cause toxicity in chinook, Pacific herring, English sole, harbor seals, and bottlenose dolphins. According to data from NPDES Phase I permittees in Puget Sound, PCBs exceeded chronic aquatic life criteria in 41% of stormwater samples (Ecology 2015). PCBs also affect seagrasses (WDNR 2012).

Juvenile chinook exposed to PCBs show significantly reduced pathogen resistance compared to control fish (Arkoosh et al. 2001). In a Sound-wide study, 10-100% of juvenile chinook sampled from sites with the highest PCB contamination showed adverse effects from PCB exposure. PCB responses included reduced growth and altered hormone and protein levels (WDFW 2015).

Dietary exposure to contaminants including PCBs was shown to increase the acquisition rate of infection by a factor of 2.2 and increase disease-related mortality in outmigrating chinook in the Columbia River Basin (Loge et al. 2005).

In a Sound-wide study, PCB concentrations in 86% of Central Sound herring and 63% of South Sound herring were above toxic risk thresholds (PSP & PSEMP 2015).

In English sole, PCB exposure causes toxic response including decreased reproductive function and immune response, and increased disease. These responses could impact flatfish populations in Puget Sound, including reduction in sub-population size (Johnson et al. 1998).

PCB contamination has been linked to decreased immune function in harbor seals and bottlenose dolphins (WDFW 2011a). PCBs have been linked with "impaired reproduction, skeletal lesions, kidney damage, tumors, premature birth and skin lesions" in marine mammals like harbor seals and killer whales. PCBs are the contaminants that pose the largest health risk to harbor seals in Puget Sound, and observed contaminant concentrations in Puget Sound harbor seal pups affect several seal health indicators: vitamin A, estrogen receptor-alpha, heat shock protein 70, and peroxisome proliferator-activated receptor (WDFW 2011a).

In 2009, all southern resident killer whales except for three recent mothers exceeded health-effects thresholds for total PCBs (Krahn et al. 2009). Four juvenile whales exceeded this threshold by factors of 2-3.6, indicating high maternal transfer and increased risk for health effects due to high exposure during rapid development. In another study, PCB concentrations in Puget Sound killer whales "easily surpassed" toxic thresholds established for harbor seals (Ross et al. 2013b), indicating risk of toxicity (Ross et al. 2000).

PBDEs

Juvenile chinook salmon fed environmentally relevant concentrations of PBDE congeners were more susceptible to infection and mortality during bacterial challenge than control fish (Arkoosh et al. 2010; Arkoosh et al. 2015). In a Sound-wide study, 100% of chinook sampled from the Snohomish River in Everett, the river system with the highest PBDE levels, showed increased disease susceptibility and altered thyroid hormone production (Sloan et al. 2010). 10% of chinook sampled from the Duwamish, Hylebos, and Snohomish systems, the three most PBDE-contaminated estuaries, showed increased disease susceptibility (WDFW 2015).

PBDEs have been linked with "impaired reproduction, skeletal lesions, kidney damage, tumors, premature birth and skin lesions" in marine mammals like harbor seals and killer whales (WDFW 2011a).

PESTICIDES

Pesticide toxicity has been observed in coho salmon, chinook salmon, rainbow trout, striped bass, medaka, fathead minnows, birds, amphipods, and seagrass. Some pesticides are more toxic to euryhaline fish acclimated to hypersaline environments – toxicity to the insecticide phorate was increased 32-fold in marine coho salmon compared to freshwater coho. Previous studies show increased toxicity of these pesticides in higher salinity environments for rainbow trout, striped bass, medaka, and other species (Lavado, Maryoung, & Schlenk 2011).

Coho parr exposed to environmentally realistic concentrations of IPBC fungicide showed altered behavioral and physiological alarm reactions (Tierney et al. 2006). Juvenile coho olfactory function is impaired by low concentrations (<1 µg/L) of the pesticide chlorpyrifos (Sandahl et al. 2004). Similar concentrations of chlorpyrifos also significantly reduce brain and muscle acetylcholinesterase (AChE) activity, reducing activity levels and feeding behavior (Sandahl et al. 2005).

Environmentally realist mixtures of pesticides can produce synergistic effects on the survival (Laetz et al. 2009) and behavior of juvenile coho (Laetz et al. 2013), which are modulated by temperature (Laetz et al. 2014). Several pesticide mixtures are lethal at concentrations that are sublethal for single chemicals (Laetz et al. 2009).

Juvenile chinook show high sensitivity to current-use insecticides – toxic responses include mortality, immune response, inhibited brain and muscle enzyme activity, and changes in liver and muscle gene expression (Eder et al. 2009). Environmentally relevant pesticide exposures may reduce growth and size at ocean entry of juvenile chinook, reducing intrinsic productivity of modeled ocean-type chinook. Juvenile exposure to organophosphate insecticides was modeled to reduce spawner abundance by 73% in 20 years. Exposure to carbamate pesticides produced less severe results due to faster recovery time in chinook (Baldwin et al. 2009).

Inhibition of brain AChE activity from chlorpyrifos (an organophosphate pesticide) exposure in steelhead is similar to that for coho salmon (Sandahl & Jenkins 2002). Toxicity of some pesticides to rainbow trout is higher in high salinity environments (Lavado, Maryoung, & Schlenk 2011).

The acetylcholinesterase (AChE) inhibiting pesticide carbaryl reduced brain and muscle AChE activity in a dose-dependent manner in seawater phase cutthroat trout, which resulted in decreased survival in encounters with predators (Labenia et al. 2007). Trout did not show an avoidance behavior to carbaryl.

In fathead minnows, exposure to the insecticide fipronil, which has been documented in stormwater, produces significant changes in gene expression with neuromuscular and endocrine disrupting effects (Beggel et al. 2012). Fipronil is one of the main chemicals used for ant control in Puget Sound (WSDA, 2014).

Amphipod mortality is significantly correlated to exposure to DDTs and chlordane (Anderson et al. 2007). DDT significantly increases bird mortality by causing thinning in eggshells (Ecology & King County 2011)

Herbicides have been shown to affect photosynthesis and respiration in eelgrass (WDNR 2012). One German study found correlation between herbicide levels and declining seagrass beds (Bester 2000).

CONTAMINANTS OF EMERGING CONCERN

Toxicity data is sparse but increasing for CECs. In one broad study, 65-86% of 459 studied human drug targets were conserved in 12 diverse fish species, and conservation was generally higher in bony fish than jawless fish (Brown et al. 2014).

Observed toxic responses to CECs include benthic microalgal decline, reduced feeding rates, reduced mussel byssus strength, and impacts on immunity and survival (Gaw, Thomas, & Hutchinson 2014). Pharmaceuticals have also been implicated in increased antibiotic resistance in marine bacteria. Pharmaceutical exposure in environmentally relevant concentrations significantly reduced population growth in fathead minnow and medaka but not zebrafish (Brown et al. 2014).

In Puget Sound, a study of English sole detected xenoestrogen exposures at 75% of sites, correlated with proximity to stormwater, industrial, CSO, and wastewater discharges. High estrogen exposure was correlated with later spawning compared to samples with low exposure, which affects gamete survival. Exposure has also been linked to reduced sperm production, sperm quality, and fertilization success (Johnson et al. 2008).

In a study on CECs in Central Sound study, 29 contaminants were detected in wastewater effluent and fish tissue but not in estuarine water, suggesting possible bioaccumulation of these contaminants. Several compounds were detected in both water and fish tissue at concentrations that may cause adverse effects in fish (Meador et al. 2016) and were associated with alterations in metabolism (Meador et al. 2018). Juvenile chinook fed mixtures of CECs showed reduced growth and other evidence of metabolic stress (Meador et al. 2018), as well as mitochondrial dysfunction (Yeh et al. 2017).

Chemicals derived from vehicle tires are increasingly recognized as chemicals of emerging concern. High resolution mass spectrometry shows that chemicals leached from tires are very abundant in receiving waters (Peter et al. 2018). Among these chemicals is the recently discovered 6PPD-quinone – a previously unknown chemical that is the primary responsible toxicant in the acute mortality of coho salmon in runoff-impacted streams throughout the Puget Sound basin (Tian et al. 2021).

SURFACTANTS

Juvenile chinook exposed to sediment contaminated with the surfactant HCBD showed 28% mortality, compared to 16% mortality in the control group (Arkoosh et al. 2001). Surfactants caused toxicity in less than 10% of observed samples in a test of urban stormwater runoff on 5 organisms (Kayhanian et al. 2008).

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washington @TNC.org

74 Wall Street
Seattle, WA 98121

206 343.4344
800 964.0636

AUTHORS

Cailin MacKenzie at Washington State University
Jasmine Prat at Washington State University
Jenifer McIntryre, Ph.D. at Washington State University
Emily Howe, Ph.D. at The Nature Conservancy
Jessie Israel at The Nature Conservancy

RECOMMENDED CITATION

C. Mackenzie, J. Prat, J. McIntyre, E. Howe, and J. Israel. 2021. Stormwater quality in Puget Sound: impacts and solutions in reviewed literature. Seattle, WA: The Nature Conservancy, Washington State Chapter, 42 pp.

ACKNOWLEDGEMENTS

Special thanks for lending assistance and expertise:

Tanyalee Erwin, Washington State University
Leska Fore, Puget Sound Partnership
Anand Jayakaran, Washington State University
Phillip Levin, The Nature Conservancy & University of Washington
Jessica Lundin, NOAA Northwest Fisheries Science Center
Christopher May, Kitsap County
James Meador, NOAA Northwest Fisheries Science Center
Mark Palmer, City of Puyallup
Kit Paulsen, City of Bellevue
Jamie Robertson
Scott Redman, Puget Sound Partnership
Michael Schmidt, Long Live the Kings
Heidi Siegelbaum, Washington State University
John Stark, Washington State University

Photo credits: Front Cover: George Karbus; Conclusion: Alexander Ryckman; Back Cover: Hannah Letinich.

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Updated September 2021