Water Quality Assessment and Monitoring Study: Estimated Present-Day Contaminant Loadings to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal

October 2017

King County

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Alternative Formats Available

Water Quality Assessment and Monitoring Study: Estimated Present-Day Contaminant Loadings to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal

Prepared for:

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Wastewater Treatment Division

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Acknowledgements

The authors would like to thank the following people for their contributions to this report:

- Judy Pickar (project manager), Dean Wilson (science lead), and King County project team members (Bob Bernhard, Mark Buscher, Timothy Clark, Betsy Cooper, Wendy Eash-Loucks, Elizabeth Gaskill, Martin Grassley, Erica Jacobs, Susan Kaufman-Una, Lester, Deborah, Kate Macneale, Chris Magan, Bruce Nairn, Sarah Ogier, Erika Peterson, John Phillips, Jim Simmonds, Jeff Stern, Dave White, Mary Wohleb, and Olivia Wright).
- Kevin Buckley, Shelley Basketfield, and other Seattle Public Utilities staff for their assistance.
- Cathie Scott for the technical editing of this document.
- The project's Science and Technical Review Team members—Virgil Adderley, Mike Brett, Jay Davis, Ken Schiff, and John Stark—for guidance and review of this report.

Citation

King County. 2017. Estimated Present-Day Contaminant Loadings to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal. Prepared by Olivia Wright, Bob Bernhard, and Timothy Clark, Water and Land Resources Division. Seattle, Washington.

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EXECUTIVE SUMMARY

This report documents the approach and results of a study to estimate present-day contaminant loadings to two study areas: Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal. This study is a part of King County's Water Quality Assessment and Monitoring Study, which was undertaken to explore ways to optimize water quality improvements in waterbodies where the County is planning combined sewer overflow control (CSO) projects.

Background

King County updates its CSO control plan about every five years. Before each update, the County reviews its entire CSO Control Program against conditions that have changed since the last update. In September 2012, the King County Council passed Ordinance 17413 approving an amendment to King County's long-term CSO control plan. The plan includes nine projects to control the County's remaining 14 uncontrolled CSO locations by 2030 to meet the Washington State standard of no more than one overflow per year on average. The recommended projects involve construction of underground storage tanks, green stormwater infrastructure, wet weather treatment facilities, or a combination of approaches.

Ordinance 17413 also calls for completion of a Water Quality Assessment and Monitoring Study (referred to as the assessment) to inform the next CSO control plan update due to the Washington State Department of Ecology in 2019. The ordinance specified that the assessment answer the following questions:

1. What are the existing and projected water quality impairments in receiving waters (waterbodies) where King County CSOs discharge?
2. How do county CSOs contribute to the identified impairments?
3. How do other sources contribute to the identified impairments?
4. What activities are planned through 2030 that could affect water quality in the receiving waters?

Three additional questions are being addressed by the County's CSO planning team based partly on the results of the assessment:

5. How can CSO control projects and other planned or potential corrective actions be most effective in addressing the impairments?
6. How do various alternative sequences of CSO control projects integrated with other corrective actions compare in terms of cost, schedule, and effectiveness in addressing impairments?
7. What other possible actions, such as coordinating projects with the City of Seattle and altering the design of planned CSO control projects, could make CSO control projects more effective and/or help reduce the costs to WTD and the region of completing all CSO control projects by 2030?

Study Areas

This study focused on areas where uncontrolled CSOs discharge:

- The Duwamish Estuary/Elliott Bay study area is in the Green-Duwamish watershed. The study area begins at the confluence of the Green and Black rivers, where the Duwamish River starts, and continues downstream to the Duwamish Estuary and then the western boundary of Inner Elliott Bay. The surface area of the waterbodies is approximately 6.2 square miles, representing about 1 percent of the watershed. The study area is located in the City of Seattle, City of Tukwila, and a small area of unincorporated King County. The Duwamish Estuary and Inner Elliott Bay were evaluated together because the freshwater discharge from the Duwamish Estuary influences environmental conditions in Elliott Bay and the flood tides from Elliott Bay affect conditions in the Duwamish Estuary.
- The Lake Union/Ship Canal study area, located in the City of Seattle, forms the mouth of the Cedar-Sammamish watershed. The surface area of the waterbodies in the study area is approximately 1.5 square miles, representing about 0.2 percent of the watershed. The study area begins at the Montlake Cut where Lake Washington's Union Bay drains into Lake Union's Portage Bay. The Hiram H. Chittenden Locks, which separate the salt water of Puget Sound from the fresh water of Lake Union, define the western boundary of the study area.

Study Approach

This study used existing water quality, flow, and other data to estimate the mean annual current (circa 2015) loadings of contaminants entering the study areas from various pathways. Loadings were quantified for 14 contaminants of interest (COIs) from 10 major pathways. (The COIs are shown in Table ES-1.)

Table ES-1. Contaminants of interest.

Category	Contaminant of Interest
Indicator bacteria	Fecal coliform
Nutrients	Total nitrogen Total phosphorus
Solids	Total suspended solids (TSS)
Metals	Total arsenic Total copper Total lead Total mercury Total zinc
Organic compounds	Benzyl butyl phthalate (BBP) Bis(2-ethylhexyl)phthalate (BEHP) Total polycyclic aromatic hydrocarbons (PAHs) Total polybrominated biphenyl ethers (PBDEs) Total polychlorinated biphenyls (PCBs)

This study does not attempt to identify specific pollutant sources. A source is defined as the object or activity that releases a contaminant to the environment and a pathway as a means to transport the contaminant to study area waterbodies. For example, CSOs and stormwater are pathways that carry pollution to waterbodies, but the sources are from human activities.

The pathways examined in this study are as follows:

- Stormwater runoff that directly enters the study areas
- Controlled CSOs
- Uncontrolled CSOs
- Loadings from upstream watersheds into the study areas
- Local tributaries
- Wet weather treatment facility discharges
- Leaching from antifouling vessel paint
- Leaching from creosote-treated pilings
- Atmospheric deposition
- Bridge runoff

Although additional pathways may exist that contribute contaminants to the study areas, the major known pathways with available data were included in this analysis. Antifouling paint and creosote-treated wood pilings could be considered as sources, but the loading analyses included the entire population of vessels and pilings and therefore considered them as pathways.

The study estimated the contributions of contaminants *to* the study areas through water column pathways. It did not assess or predict sediment concentrations from sediment loadings, sediment transport, or sediment resuspension and release of contaminants from sediments, nor did it address declining levels of sediment contamination *within* the study areas from ongoing and planned sediment cleanup activities. Estimates of sediment loadings would require a sophisticated, dynamic sediment transport model that was outside the scope of the study.

Uncertainty in the annual loadings estimates varies by pathway and contaminant. The uncertainties generally result from spatial and temporal limitations in monitoring data or other methodological factors. To provide a first approximation of the possible ranges of estimates (and inherent uncertainty in the estimates), the 95 percent confidence limits around the mean contaminant concentrations and flows were used. For pathways and COIs with insufficient data to estimate these limits, minimum and maximum estimates of contaminant loadings were calculated to estimate an upper and lower bounds.

Study Results

The pathways evaluated had different relative contributions depending on the contaminant analyzed (Tables ES-2 and ES-3):

- Uncontrolled CSOs were the largest contributing pathway of fecal coliform bacteria to both study areas.
- Of the pathways with available data, upstream watersheds and stormwater runoff that directly enters the waterbodies appear to be the largest contributing pathways for total nitrogen, total phosphorus, TSS, total lead, total mercury, total zinc, BBP, BEHP, total PBDEs, and total PCBs.
- Creosote-treated wood pilings was the largest contributing pathway of total PAHs, and antifouling vessel paint was one of the largest contributing pathways of total copper. These pathways carried higher levels of uncertainties in the loading estimates than other pathways.

While human activity likely contributes to the upstream watershed load of each of the COIs, many COIs did not have an upstream watershed loading rate distinguishable from background rates estimated in previous studies conducted in Western Washington. However, the loads of PAHs and PBDEs appear to be substantially influenced by the discharges from the developed areas in the two watersheds. For the Green River watershed, fecal coliform bacteria, total phosphorus, and TSS loadings also appear to be influenced by human contaminant inputs in the upstream watershed.

The results from this loadings analysis are planning-level estimates that could be used to guide discussion of the relative importance of contaminant pathways to the study areas. The identification of specific pollutant sources would require complex analysis that was outside the scope of this study. Mean annual contaminant loads for various pathways were estimated using a range of methods. The reliability of measurements and assumptions inherent to data analysis methods should be considered when evaluating the reliability of the estimates. Measurements and extrapolations for relatively recent periods were used to develop broad estimates of loads for existing conditions. Efforts to estimate loads for other time periods may require different methods and data treatments.

Table E-2. Duwamish Estuary/Elliott Bay: Major contributing pathways of contaminants of interest.

Contaminant of Interest (COI)	Reason for Interest (King County, 2017b & c)	Major Contributing Pathways
Fecal coliform bacteria	Frequent exceedance of peak and geometric mean water quality standards; on 303(d) list for water because of high fecal coliform [a]	King County CSOs (92%)
		Stormwater runoff (2%)[b]
		Upstream watershed (Green River) (4%)
TSS	Suspended solids may carry bound contaminants and also impact habitat	Upstream watershed (Green River) (90%)
		Stormwater runoff (7%) [b]
Total nitrogen	Excess nitrogen (and phosphorus) may cause increased productivity, which may lower dissolved oxygen seasonally	Upstream watershed (Green River) (93%)
Total phosphorus	Excess phosphorus (and nitrogen) may cause increased productivity, which may lower dissolved oxygen seasonally	Upstream watershed (Green River) (87%)
		Stormwater runoff (6%)[b]
		King County CSOs (4%)
Total arsenic	Exceedance of state Sediment Quality Standards (SQS); on 303(d) list for sediment and tissue (inorganic arsenic only)[a]	Upstream watershed (Green River) (94%)
Total copper	Exceedance of state SQS; on 303(d) list for sediment; may pose toxicity to aquatic life in water column[a]	Copper-based antifouling paint (49%)
		Upstream watershed (Green River) (41%)
		Stormwater runoff (6%)[b]
Total lead	Exceedance of state SQS; on 303(d) list for sediment[a]	Upstream watershed (Green River) (67%)
		Stormwater runoff (22%)
		King County CSOs (4%)
Total mercury	Exceedance of SQS; on 303(d) list for tissue and sediment; fish advisory in place[a]	Upstream watershed (Green River) (77%)
		Stormwater runoff (14%)[b]
Total zinc	Exceedance of state SQS; on 303(d) list for sediment; may pose toxicity to aquatic life in water column[a]	Upstream watershed (Green River) (66%)
		Stormwater runoff (21%)[b]
Total PAHs	Exceedance of state SQS; on 303(d) list for tissue and sediment[a]	Creosote-treated wood pilings (97%)
Benzyl butyl phthalate	Exceedance of state SQS; on 303(d) list for sediment[a]	Upstream watershed (Green River) (Not estimated)[b]
		Stormwater runoff (3.8–5.7 g/yr)[b]
		King County CSOs (0.6–4.8 g/yr)[b]
Bis(2-ethylhexyl) phthalate	Exceedance of state SQS; on 303(d) list for tissue and sediment[a]	Upstream watershed (Green River) (Not estimated)[c]
		Stormwater runoff (30–56 g/yr)[b,c]
		King County CSOs (5.1–23 g/yr)[b]
Total PBDEs	May pose toxicity to aquatic life in water column and sediments (no SQS); may bioaccumulate in tissue	Upstream watershed (Green River) (Not estimated)[b]
		Stormwater runoff (300–820 g/yr)[b,c]
		Atmospheric deposition (48–250 g/yr)[b]
		Local tributaries (41–590 g/yr)[c]
		King County CSOs (94–430 g/yr)[c]
Total PCBs	Exceedance of state SQS; on 303(d) list for tissue and sediment[a]	Upstream watershed (Green River) (61%)
		Stormwater runoff (15%)[b]
		Atmospheric deposition (11%)
		King County CSOs (10%)

[a] The 303(d) list includes all impaired waterbodies in Washington State.

[b] Stormwater load reductions associated with current public or private stormwater facilities or operations were not included in the estimates. Thus, the stormwater runoff pathway load is likely overestimated but the magnitude of overestimation is unknown.

[c] Inadequate data for upstream pathway to estimate the percentage of the contribution of current loadings.

Table E-3. Lake Union/Ship Canal: Major contributing pathways of contaminants of interest.

Contaminant of Interest (COI)	Reason for Interest (King County, 2017a)	Major Contributing Pathways
Fecal coliform bacteria	Frequent exceedance of peak and geometric mean water quality standards; on 303(d) list for water because of high fecal coliform [a]	King County CSOs (65%)
		Seattle CSOs (31%)
		Stormwater runoff (4%)[b]
TSS	Suspended solids may carry bound contaminants and impact habitat	Upstream watershed (Lake Washington) (66%)
		Stormwater runoff (30%)[b]
Total nitrogen	Excess nitrogen (and phosphorus) may cause increased productivity, which may seasonally impact dissolved oxygen	Upstream watershed (Lake Washington) (94%)
Total phosphorus	Excess phosphorus (and nitrogen) may cause increased productivity that may seasonally impact dissolved oxygen; on 303(d) list for water [a]	Upstream watershed (Lake Washington) (84%)
		Stormwater runoff (11%) [b]
Total arsenic	Exceedance of State Sediment Quality (SQS) Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (98%)
Total copper	Exceedance of SQS Freshwater Benthic Cleanup Standards; may pose toxicity to aquatic life in water column	Copper-based antifouling paint (74%)
		Upstream watershed (Lake Washington) (22%) [b]
Total lead	Exceedance of SQS Freshwater Benthic Cleanup Standards	Stormwater (60%)[a]
		Upstream watershed (Lake Washington) (27%)
		King County CSOs (4%)
Total mercury	Exceedance of SQS Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (57%)
		Stormwater runoff (36%) [b]
		King County CSOs (3%)
Total zinc	May pose toxicity to aquatic life in water column	Upstream watershed (Lake Washington) (39%)
		Stormwater runoff (48%) [b]
		Atmospheric deposition (8%)
Benzyl butyl phthalate	Exceedance of SQS Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (Not estimated)[b]
		Stormwater runoff (2–3 g/yr)[b,c]
		King County CSOs (0.2–1.2 g/yr)[c]
		Seattle CSOs (0.1–0.5 g/yr)[b]
Bis(2-ethylhexyl) phthalate	Exceedance of SQS Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (99%)
		Stormwater runoff (1%)[b]
Total PAHs	Exceedance of SQS Freshwater Benthic Cleanup Standards	Creosote-treated wood pilings (97%)
Total PBDEs	May pose toxicity to aquatic life in water column and sediments (no SQS); may bioaccumulate in tissue	Upstream watershed (Lake Washington) (75%)
		Stormwater runoff (17%)[b]
Total PCBs	Exceedance of SQS Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (51%)
		Stormwater runoff (24%)[b]
		Atmospheric deposition (10%)
		King County CSOs (10%)
		Seattle CSOs (4%)

[a] The 303(d) list includes all impaired waterbodies in Washington State.

[b] Stormwater load reductions associated with current public or private stormwater facilities or operations were not included in the estimates. Thus, the stormwater runoff pathway load is likely overestimated but the magnitude of overestimation is unknown.

[c] Inadequate data for upstream pathway to estimate the percentage of the contribution of current loadings.

Other Assessment Reports

This report is one of several reports that have been prepared as part of King County's Water Quality Assessment and Monitoring Study. Other reports are as follows:

- Three reports describe existing conditions and long-term trends in the following study areas—Lake Union/Ship Canal, Elliott Bay, and the Duwamish Estuary.
- A report documents the process used to assess identified data gaps for the study areas and select studies to fill prioritized gaps.
- Three reports discuss the methodology and results of selected studies to improve understanding of existing conditions: a study of bacteria in wet and dry weather, a survey of contaminants of emerging concern, and a literature review of potential conservative sewage tracers.
- A future loadings report assesses the potential of planned actions such as CSO control to improve water quality.
- A final report summarizes these analyses and implications.

King County will use the information from the Water Quality Assessment and Monitoring Study to inform the next CSO control plan update, including looking for opportunities to improve water quality outcomes, possibly reduce costs of CSO control projects, establish baseline conditions for post-construction monitoring of CSO control projects, and decide whether to pursue an integrated CSO control plan. The information from the assessment can also be used to inform regional efforts to continue to improve water and sediment quality.

ABBREVIATIONS AND ACRONYMS

BBP	benzyl butyl phthalate
BCa	bias corrected and accelerated
BEHP	bis(2-ethylhexyl)phthalate
BMP	best management practice
COI	contaminant of interest
CFU	colony forming unit
CSO	combined sewer overflow
DAF	Data anomaly form
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management system
EPA	U.S. Environmental Protection Agency
HPAH	high molecular weight polycyclic aromatic hydrocarbon
HSPF	Hydrological Simulation Program–Fortran
I-5	Interstate 5
KCEL	King County Environmental Laboratory
KM	Kaplan-Meier
LCL	lower confidence limit
LDW	Lower Duwamish Waterway
Locks	Hiram H. Chittenden Locks
LPAH	low molecular weight polycyclic aromatic hydrocarbon
MG	million gallons
MS4	municipal separate storm sewer system
NPDES	National Pollutant Discharge Elimination System
PAH	polycyclic aromatic hydrocarbon
PBDE	polybrominated biphenyl ether
PCB	polychlorinated biphenyl
PLM	pollutant load model
QA/QC	quality assurance/quality control
SeaTac	Seattle-Tacoma International Airport
SPU	Seattle Public Utilities
SR	state route
sVGP	Small Vessel General Permit
TBT	tributyltin
TSS	total suspended solids
UCL	upper confidence limit
USGS	U.S. Geological Survey
VFS	vegetative filter strip
VGP	Vessel General Permit

VOC	volatile organic compound
WLRD	Water and Land Resources Division
WRIA	water resource inventory area
WSDOT	Washington State Department of Transportation
WTD	King County Wastewater Treatment Division
WY	water year

1.0 INTRODUCTION

This report presents estimates of current contaminant loadings into the waterbodies in two study areas: Lake Union/Ship Canal and Duwamish Estuary/Elliott Bay. It was prepared as part of King County's Water Quality Assessment and Monitoring Study, which was undertaken to explore ways to optimize water quality improvements in waterbodies where the County is planning combined sewer overflow (CSO) control projects.

The sections in this chapter describe King County's wastewater system and CSO Control Program, the Water Quality Assessment and Monitoring Study, and the scope, limitations, and study areas of this loadings study.

1.1 King County Wastewater System

King County owns and operates a regional wastewater system that serves 1.7 million people in a 420-square-mile area in Washington state. The area covers most of urban King County including Seattle, south Snohomish County, and a small portion of Pierce County (Figure 1-1).

The wastewater system is the largest in the Puget Sound region. It includes over 350 miles of pipelines that collect wastewater from 34 local sewer utilities. The pipelines carry the wastewater to three regional treatment plants—West Point Treatment Plant in the City of Seattle, South Treatment Plant in the City of Renton, and Brightwater Treatment Plant in south Snohomish County—that treat and disinfect the wastewater before discharging it to Puget Sound. The County also owns two local treatment plants in the City of Carnation and on Vashon Island.

Up through the early 20th century, most cities constructed combined sewers to collect both wastewater and stormwater in the same pipes. The combined sewers carried untreated wastewater directly to waterbodies. Today, combined flows are sent to treatment plants for treatment before being discharged to waterbodies. Untreated overflows occur only at designated locations during heavy storms when flows exceed the capacity of sewers and treatment plants. These CSOs serve as constructed relief points in preventing sewer backups into homes and streets.

Combined sewers are located in the Seattle portion of the regional wastewater system. Figure 1-1 shows the combined sewer area. Portions of this area contain separated and partially separated sewers. King County owns and operates 39 CSO locations and the City of Seattle owns and operates about 87 CSO locations in the city limits. The outfall pipes at these locations discharge to Puget Sound, the Duwamish Estuary, Lake Union/Ship Canal, and Lake Washington during large storms.

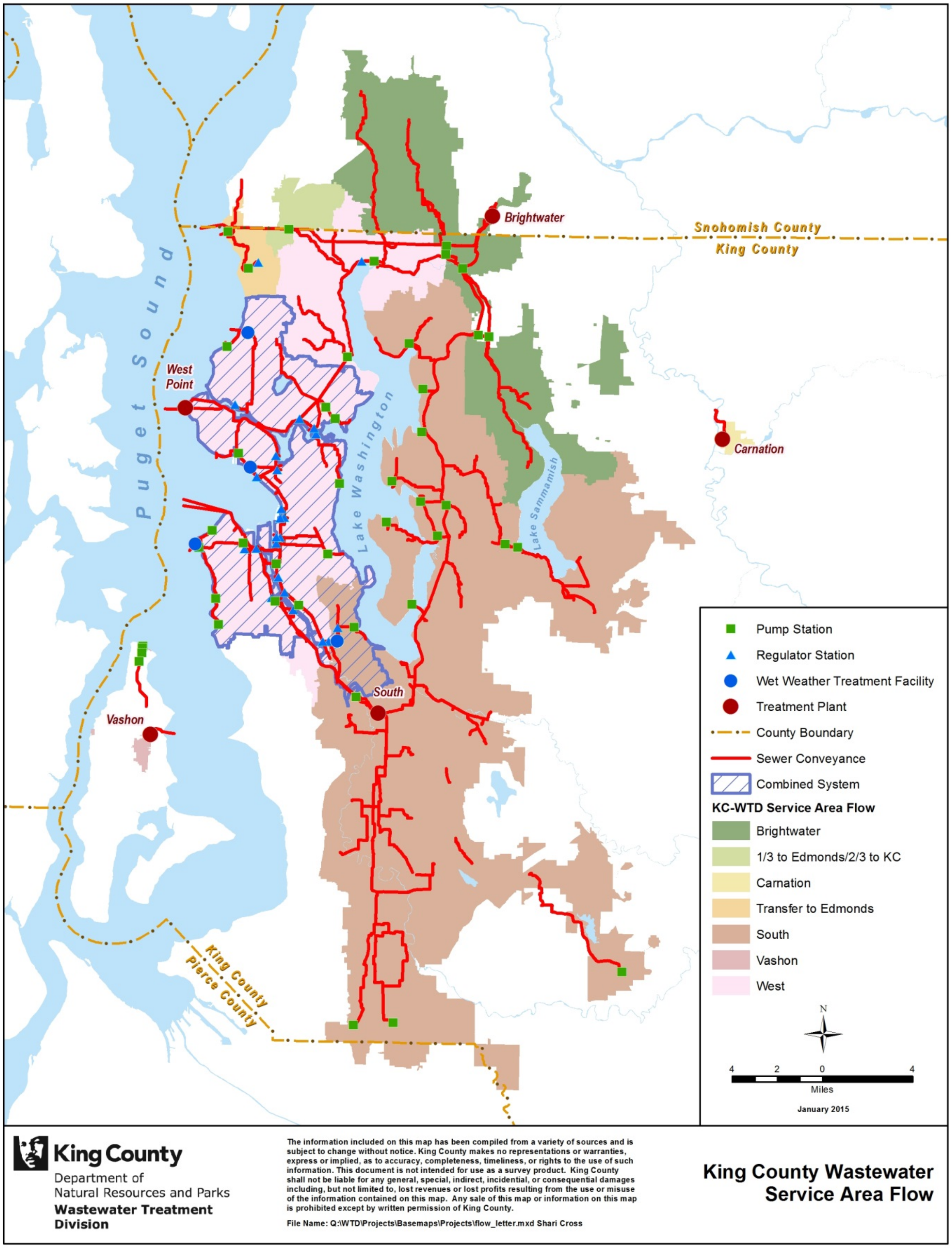

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Figure 1-1. **King County's wastewater treatment system.**

1.2 CSO Control Program

CSO control is required by Washington State and federal law. “Control” means reducing the number of untreated overflows from each location to once per year on a 20-year moving average. Controlling CSOs protects public health and the environment. CSO discharges contain harmful disease-causing organisms and a large number of chemicals.

Since the regional wastewater system began operating in the 1960s, the County and City have reduced the volume of untreated wastewater discharges by around 28 billion gallons a year. Only 14 of the County’s and about half of the City’s CSO locations still require control. The County’s uncontrolled sites are located in the Duwamish Estuary, Elliott Bay, and Lake Union/Ship Canal.

The King County Council approved an amendment in September 2012 to the County’s long-term CSO control plan through Ordinance 17413. The U.S. Environmental Protection Agency (EPA) also approved the plan in 2013, and the plan was incorporated into the consent decree that the County entered into with the U.S. Department of Justice, EPA, and Washington State Department of Ecology (Ecology). The CSO control plan includes nine projects to control the remaining 14 uncontrolled CSOs by 2030. Five projects are in the Duwamish Estuary and Elliott Bay areas, and four are in the Lake Union/Ship Canal area.

The City of Seattle’s Integrated Plan was approved in 2015. The plan includes both CSO control and stormwater treatment/control projects that will be completed by 2030. The City is also under a consent decree to complete its Integrated Plan.

1.3 Water Quality Assessment and Monitoring Study

King County Ordinance 17413, approving the long-term CSO control plan, also calls for completion of a Water Quality Assessment and Monitoring Study to inform the next plan update, which is due to regulators in 2018. In September 2013, the County Council approved the assessment’s scope of work through Motion 13966.

The objective of the assessment is to help ensure that investments in CSO control optimize water quality improvements in CSO sub-basins. It includes a scientific and technical analysis of existing water quality of the receiving waters where uncontrolled county CSOs discharge (Elliott Bay, Lake Union/Ship Canal, and the Duwamish Estuary), identification of water quality impairments, trends in water quality, assessment of sources contributing to impairments, and review of ongoing and planned activities to improve water quality. King County’s Wastewater Treatment Division (WTD) will use the information to prioritize and sequence CSO control projects, establish baseline conditions for post-construction monitoring of CSO control projects, and decide whether to pursue an integrated plan based on EPA guidelines.

An integrated planning process has the potential to identify efficiencies in implementing competing requirements that arise from separate wastewater and stormwater projects, including capital investments and operation and maintenance requirements. This approach can build partnerships among agencies and jurisdictions and can lead to more sustainable and comprehensive solutions, such as green stormwater infrastructure, that improve water quality and support other attributes that enhance the vitality of communities.

The Water Quality Assessment and Monitoring Study set out to generate information that will help answer the following study questions:

1. What are the existing and projected water quality impairments in receiving waters (waterbodies) where King County CSOs discharge?[1]
2. How do county CSOs contribute to the identified impairments?
3. How do other sources contribute to the identified impairments?
4. What activities are planned through 2030 that could affect water quality in the receiving waters?
5. How can CSO control projects and other planned or potential corrective actions be most effective in addressing the impairments?
6. How do various alternative sequences of CSO control projects integrated with other corrective actions compare in terms of cost, schedule, and effectiveness in addressing impairments?
7. What other possible actions, such as coordinating projects with the City of Seattle and altering the design of planned CSO control projects, could make CSO control projects more effective and/or help reduce the costs to WTD and the region of completing all CSO control projects by 2030?

An external Scientific and Technical Review Team has been assembled to review the methodology and results of the assessment. Depending on assessment findings, the King County Council may decide to approve formation of an Executive's Advisory Panel of approximately 10 regional leaders. The panel would develop independent recommendations to the King County Executive on how planned county CSO control projects can best be sequenced and integrated with other projects in order to maximize water quality gains and minimize costs to ratepayers.

Table 1-1 shows elements of the assessment and their associated study questions, deliverables, and estimated timeframes. As shown in the table, 10 studies and reports address Study Questions 1–4; the CSO Control Program will use the information in the reports to address Study Question 5–7 (Figure 1-2). More information on the assessment is available at http://www.kingcounty.gov/environment/wastewater/CSO/WQstudy.aspx.

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[1] The federal Clean Water Act, adopted in 1972, requires that all states restore their waters to be "fishable and swimmable." Washington State's Water Quality Assessment lists the water quality status for waterbodies. The 303(d) list comprises waters that are in the polluted water category, for which beneficial uses– such as drinking, recreation, aquatic habitat, and industrial use – are impaired by pollution (http://www.ecy.wa.gov/programs/wq/303d/index.html).

Table 1-1. Elements of the Water Quality Assessment and Monitoring Study.

Element	Applicable Study Question	Deliverable	Timeframe
Review and analyze existing scientific and technical data on impairments in Lake Union/Ship Canal, Duwamish Estuary, and Elliott Bay.	1	Area reports: • Elliott Bay • Lake Union/Ship Canal • Duwamish Estuary	2013–2016
Identify and prioritize gaps in existing data.	1	Data gap analysis report	2014
Conduct targeted data gathering and monitoring to fill some of the identified gaps in scientific data on water quality in these receiving waters.	2,3	Data gap study reports: • Bacteria • Contaminants of emerging concern • Literature review of conservative sewage tracers	2014–2016
Identify the sources of impairments in the three waterbodies.	2,3	Loadings report	2015–2016
Identify changes in contaminant loadings between 2015 and 2030.	1,2,3,4	Future loadings report	2016
Summarize scientific and technical data collected and reviewed during the assessment and discuss planned and potential corrective actions for identified impairments in the waterbodies.	1,2,3,4	Synthesis report	2016

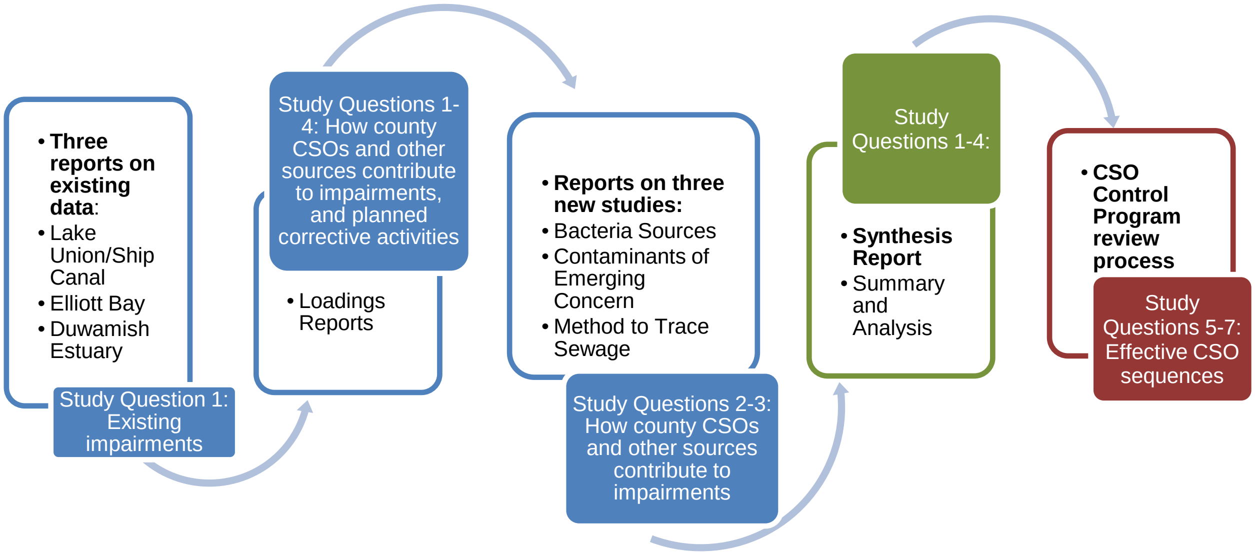

Figure 1-2. Sequence of responses to study questions in the Water Quality Assessment and Monitoring Study.

1.4 Scope and Limitations of this Study

Baseline water quality conditions in the study areas were documented in the area reports for Lake Union/Ship Canal, Elliott Bay, and the Duwamish Estuary (King County, 2017 a, b, and c). The reports include the evaluation of the most recent water and sediment quality data for these waterbodies and fish tissue quality for the Duwamish Estuary and Elliott Bay.

This loadings report documents the evaluation of contaminant contributions from county CSOs and other pathways to the three waterbodies. These baseline current (circa 2015) contaminant mean annual loadings were estimated by using the most recent and reliable data available. The purpose of the report is to present the results of planning-level analyses that will help the region assess and compare the relative magnitude of contaminant loadings from major pathways. The information is organized into two study areas: Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (described below).

The loadings estimates were completed with various degrees of uncertainty depending on data gaps and limitations. The estimates do not attempt to project current or future ambient water concentrations; such a projection would require a sophisticated model beyond the scope and limitations of this assessment. They are estimates of the total mass entering the waterbodies and not the partition of the load that settles to the sediments (the total sediment load).

1.5 Study Areas

Contaminant loads were estimated for the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas (Figure 1-3). Following are brief descriptions of each study area. The three area reports give more detailed descriptions (King County, 2017 a, b, and c).

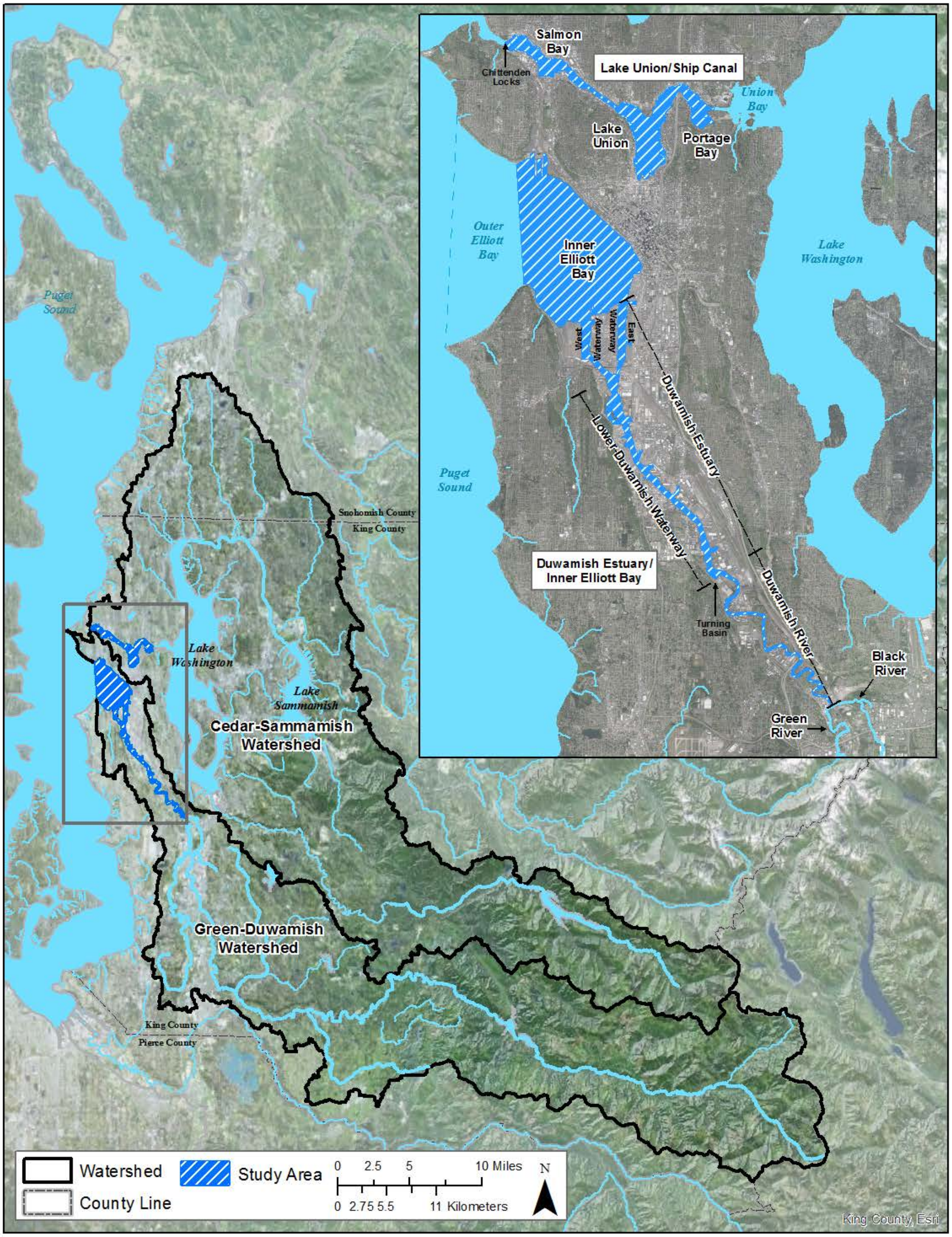

Figure 1-3. **Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas and their watersheds.**

1.1.1 Duwamish Estuary/Elliott Bay

The Duwamish Estuary/Elliott Bay study area is in the Green-Duwamish watershed (WRIA 9). The watershed includes 1,200 km^2 of Puget Lowland and Cascade ecoregions entirely located in King County (King County, 2002). It extends from the crest of the Cascade Mountains at the headwaters of the Green River west into the Duwamish River just downstream of the confluence of the Black and Green rivers to the mouth of the Duwamish Estuary where the East and West waterways empty into Elliott Bay and then Puget Sound.

The Duwamish Estuary and Elliott Bay were evaluated separately in the area reports (King County, 2017 b and c); the two waterbodies were analyzed together for the loadings estimates because of their tidal exchange. The freshwater discharge from the Duwamish Estuary greatly influences environmental conditions in Elliott Bay, and the flood tides from Elliott Bay affect conditions in the Duwamish Estuary.

The Duwamish Estuary/Elliott Bay study area is approximately 28 m^2. The study area begins upstream at the confluence of the Green and Black Rivers, where the Duwamish River starts, and continues downstream to the Duwamish Estuary and then the western boundary of Inner Elliott Bay (Figure 1-3):

- The Duwamish Estuary consists of the Lower Duwamish Waterway and the East and West waterways (divided by Harbor Island). In this report, river mile (RM) designations begin at the southern point of Harbor Island (RM 0) and increase moving upstream.
- Elliott Bay is divided into two sections: (1) Inner Elliott Bay, east of a line drawn between Duwamish Head in West Seattle and Magnolia Bluff near Smith Cove, and (2) Outer Elliott Bay, east of a line drawn between Four Mile Rock and Alki Point. Outer Elliott Bay is not included in the study area. Discharges to Outer Elliott Bay are quickly diluted and transported into Puget Sound.

Approximately 92 percent of the study area is developed: 34 percent high intensity, 29 percent medium intensity, and 21 percent low intensity development and 8 percent developed open space. The majority of the medium and high intensity development is situated along the shoreline of Elliott Bay, south of Elliott Bay around Harbor Island, and along the east side of the Duwamish Estuary. Industrial development is primarily located around the Duwamish Estuary. Stretches of forested lands exist west of the Duwamish Estuary and make up most of the basin’s undeveloped area (6 percent).

The area receives the majority of its flow from the upstream watershed (Green River). The constant interface of fresh water from the Green River and salt water from Elliott Bay sometimes takes the form of a saltwater wedge in the upper half of the Duwamish Estuary (Windward Environmental, 2010). The freshwater lens atop the Duwamish Estuary enters Elliott Bay. The majority of this flow circulates counter-clockwise along Seattle’s waterfront and exits to Puget Sound along the northern half of the bay.

1.1.2 Lake Union/Ship Canal

Lake Union/Ship Canal forms the mouth of the Cedar-Sammamish watershed (Water Resource Inventory Area [WRIA] 8). The total area of the watershed is 1,525 square kilometers (km^2), located in both King and Snohomish counties. It contains two major rivers that drain to Lake Washington (Edmondson, 1977; King County, 2003):

- The Sammamish River, which drains Lake Sammamish and tributaries, enters Lake Washington from the north and provides about 30 percent of the inflow to the lake.
- The Cedar River enters the south end of Lake Washington and contributes about 50 percent of the total inflow.

The Lake Union/Ship Canal study area is approximately 24 m^2, all in the City of Seattle. The area is divided into three sections: Portage Bay, Lake Union, and Salmon Bay (Figure 1-3). It begins at the Montlake Cut where Lake Washington's Union Bay drains into Lake Union's Portage Bay. The Hiram M. Chittenden Locks (Locks), which separate the salt water of Puget Sound from the fresh water of Lake Union, define the western boundary of the study area.

The contribution of water from the immediate Lake Union/Ship Canal watershed (the area of the Cedar-Sammamish watershed that does not drain to Lake Washington) is small relative to the inflow from Lake Washington; the water from this local watershed generally enters as surface runoff and through stormwater and CSO outfalls (Tomlinson et al., 1977). A system of pipes maintains the surface elevation of Green Lake, an urban lake in north Seattle, by transporting overspill from Green Lake and stormwater runoff from the Densmore basin and from Interstate-5 (I-5) to Lake Union/Ship Canal.

Approximately 92 percent of the Lake Union/Ship Canal study area basin is developed: 21 percent high intensity, 43 percent medium intensity, and 24 percent low intensity development and 4 percent developed open space. The medium intensity development is spread throughout the basin; areas of high intensity development are located along the southern end of Lake Union, the northern end of Salmon Bay, and at the northern end of the basin along State Route 99 (SR 99) (Homer et al., 2015).

Circulation patterns in the study are variable and are determined by several factors: volume of salt water entering the system via the Locks, wind, strength of stratification (Seattle, 1994), and inflow from the upstream watershed (Lake Washington) (Figure 1-3). Seasonal circulation patterns are as follows:

- During the winter and spring months, circulation is likely dominated by inflow from Lake Washington. Water passes from Lake Washington through the Montlake Cut into Portage Bay, through northern Lake Union, out into Salmon Bay, and finally into Puget Sound through the Locks. Water stagnation in southern Lake Union may occur during periods of dominant north-to-south movement or minimal circulation (low wind and sustained low precipitation).
- During the summer when flow from Lake Washington and the immediate watershed is at a minimum and use of the Locks is at maximum, large volumes of salt water

entering from lock operations may overwhelm the capacity of the saltwater barrier and drain at the Locks, causing a saltwater wedge to accumulate east of the Locks. Without mixing by strong winds, the cold and dense salt water may move through the Ship Canal to Lake Union, Portage Bay, and even Lake Washington. This phenomenon is termed “saltwater intrusion.”

2.0 STUDY METHODOLOGY

This study used existing water quality data, flow data, and other data sets as appropriate to estimate the mean annual load of contaminants entering the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas from major pathways. Similar approaches have been used to estimate loadings in the greater Lake Washington watershed (King County, 2013a), San Francisco Bay (Davis et al., 2000), and Puget Sound tributaries (Herrera, 2011). The approach described in this chapter is appropriate for assessing and comparing the relative magnitude of loadings from major pathways to the study areas.

The following sections present an overview of the study methodology and specific methods used for calculating summary statistics, validating data, summing data, and assessing uncertainties. Chapter 3 describes the pathways in more detail, including the data and methods used to estimate loadings for each pathway.

2.1 Overview of Methodology

Quantitative estimates of loadings in the study areas were estimated in terms of 14 contaminants of interest (COIs) and 10 pathways through which the COIs are likely to be introduced into the study areas. COIs were chosen because they were either on the 303d list of impairments, were shown to be a concern from other studies, and enough data were available to calculate loadings. Pathways were chosen because they represented the largest volumes of water flowing into the study areas, or were associated with an important COI, and enough data were available to calculate loadings. All pathways with enough data were estimated to provide a relative basis for comparison of loadings by pathway.

Study methods and limitations were as follows:

- Identifying sources that contribute contaminants to the pathways was beyond the scope of this study.[2]
- The study estimated the contributions of contaminants *to* the study areas through water column pathways. It did not assess or predict sediment concentrations from sediment loadings, sediment transport, or sediment resuspension and release of contaminants from sediments, nor did it address declining levels of sediment contamination *within* the study areas from ongoing and planned sediment cleanup activities. Estimates of sediment loadings would require a sophisticated, dynamic sediment transport model that was outside the scope of the study.

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[2] *Pathways* are the routes by which a contaminant is transported from its source or other intermediate media (air, surface water, groundwater, or soil) to the study areas. A *source* is the object from which a contaminant may be initially released to environmental media or released in a form that can be mobilized and transported in an environmental pathway. Examples of sources include industrial byproducts, creosote-treated wood pilings, pesticides, combustion of fossil fuels, brake pad abrasion, vessel antifouling paint, and human and animal feces.

- Loading estimates used contaminant concentration data collected by King County and others that were part of efforts to characterize the spatial and temporal variation in concentrations of contaminants associated with different loading pathways.
- Loading estimates used the most recent flow or discharge data to estimate mean annual hydrological conditions representing existing flow conditions.
- The study did not differentiate between naturally occurring background contaminant loading and loading from anthropogenic activities.
- To provide a first approximation of the possible ranges of estimates (and inherent uncertainty in those estimates), the 95 percent upper and lower confidence limits (UCLs and LCLs) of the contaminant concentration and flow data were used. For pathways and COIs with insufficient data to estimate these statistics, a range of contaminant loadings was estimated to represent upper and lower bounds of potential loadings.

Appendix B and Appendix C present summaries of the water quality and flow data statistics, respectively; Appendix E presents a summary of the contaminant data available for each pathway, including the number of samples available and the contaminants detected.

2.1.1 Contaminants of Interest

The COIs are shown in Table 2-1. They were identified based on impairments documented in the three area reports prepared for Elliott Bay, Lake Union/Ship Canal, and Duwamish Estuary and from available water quality data (King County, 2017 a, b, and c). Although dioxins/furans have been identified as a contaminant of concern in the Lower Duwamish Waterway (Windward Environmental, 2010), they are not addressed in this study because of limitations in available data.

Table 2-1. Contaminants of interest.

Category	Contaminants of Interest
Indicator bacteria	Fecal coliform
Nutrients	Total nitrogen Total phosphorus
Solids	Total suspended solids
Metals	Total arsenic Total copper Total lead Total mercury Total zinc
Organic compounds	Benzyl butyl phthalate (BBP) Bis(2-ethylhexyl)phthalate (BEHP) Total polycyclic aromatic hydrocarbons (PAHs) Total polybrominated biphenyl ethers (PBDEs) Total polychlorinated biphenyls (PCBs)

2.1.2 Pathways

Fifteen contaminant pathways were initially identified for evaluation. Loadings were estimated for 10 of the pathways. A literature review was completed for the other five pathways because of data limitations. The 10 pathways included in the loadings estimates are as follows:

- Upstream watersheds (includes stormwater discharges upstream of the study areas such as municipal stormwater discharges from Kent, Auburn, Mercer Island, or Issaquah)
- Local tributaries
- Stormwater discharged directly into the study areas
- Bridge runoff
- Uncontrolled CSOs
- Controlled CSOs
- Wet weather treatment facilities
- Atmospheric deposition
- Antifouling paint on boat bottoms
- Creosote-treated wood pilings

A literature review was completed for the following five pathways:

- Vessel discharge
- Sacrificial anodes on boats
- Groundwater
- Shoreline erosion
- Puget Sound

Although additional pathways may exist that contribute additional contaminants to the study areas, the pathways that incorporate the largest volumes of water entering the study area with available data were included in this analysis. Antifouling paint and creosote-treated wood pilings could be considered as sources, but the loading analyses included the entire population of vessels and pilings and therefore considered them as pathways.

2.2 Statistical Methods

The statistics were calculated separately for the compiled water quality and flow data. The water quality data available for each pathway, the suite of analytes measured, the analytical methods, and the sample sizes were incongruent. Likewise, the type of flow data (monitored or modeled) and the years with data available varied between the pathways.

For some analytes such as metals and organic compounds, concentrations below the laboratory method detection limit (MDL) were observed with regularity. The Kaplan-Meier

(KM) estimation method was used to calculate means for analytes in the presence of non-detects (concentrations below the MDL). Non-detect values are considered censored and the KM estimation method, also known as the product limit estimation method, is based on a distribution function estimate adjusted for censorship. For the purposes of this report, the KM method is used to estimate the population mean for left-censored data sets. This method was selected because it does not require an assumption of the distribution of the analyte (it is nonparametric) and can handle multiple detection limits (Singh et al., 2006; Helsel, 2012). KM was performed on a data set only if there were three or more detections. Data sets with more than 80 percent non-detects are considered highly uncertain and are noted in the results.

In cases where no non-detects were present in the contaminant concentration data, the mean was simply calculated arithmetically. The mean annual flow was also calculated arithmetically using annual flow data.

The upper and lower confidence limits of the mean were calculated at the 95 percent level of confidence using bootstrap resampling. Bootstrapping was used because it allows for confidence interval estimates that do not require an assumption of the distribution of the mean. For bootstrapping, *n* samples are drawn with replacement from a given set of observations of length *n*. The process is repeated many times (999), and each time an estimate of the mean is computed arithmetically or, if necessary, through KM estimation. From these estimates of the mean, the bias corrected and accelerated (BCa) method developed by Efron (1987), which adjusts for bias and skewness, was applied to determine the 95 percent confidence limit.

When analytes were measured more than once for a single sample (duplicates) or when multiple samples were taken over the course of a single storm event, the mean concentration of the analyte for that sample or event was calculated prior to calculating summary statistics. This procedure prevents bias toward events where many samples were taken, which occurred for some CSO and stormwater characterization studies.

All statistical analyses were completed using R 3.2.2 (R Core Team, 2015). The *NADA* package was used for KM analysis, and the *boot* package was used for bootstrap analysis (Davision and Hinkley, 1997; Helsel, 2012; Lee, 2013; Canty and Ripley, 2015). These analyses assume that samples are random (independent and unbiased).

2.3 Data Validation

The following data validation methods were used:

- In cases where raw data from the King County Environmental Laboratory (KCEL) were analyzed (CSO effluent, Lake Washington outlet, Green River outlet, and Black River outlet data), the data were validated for usability. To validate the data, sample holding times, quality control samples, and data anomaly forms (DAFs) were reviewed.

- Review of the chemistry data was conducted in accordance with the quality assurance/quality control (QA/QC) requirements, technical specifications of the methods, and national functional guidelines for organic and inorganic data review (EPA, 2014a and b).
- Data downloaded from Ecology's Environmental Information Management (EIM) system were validated prior to their entry to the database; further QC measures were not necessary.
- Data received from other agencies were previously examined for quality by the distributing agency and were only superficially reviewed.

During data validation, results below the MDL (KCEL flag "< MDL") were reported at the MDL value and given a "U" flag indicating non-detects. Results below the reporting detection limit (KCEL flag "< RDL") were reported with a "J" flag indicating estimated values. All "J" flags were included in the analysis. Samples analyzed past holding times were removed from the analysis. All data with "R" (rejected) flags were also removed.

Method blank samples provide an indication of potential chemical contamination associated with laboratory equipment. They can help detect false positives or results that may have a high bias by identifying if chemical contamination is associated with laboratory equipment. The criteria presented in Table 3-2 were used for qualifying samples with blank contamination.

Table 2-2. Data reporting and qualification in presence of blank contamination.

Blank Result	Sample Result	Action
< MDL	< MDL	Report at MDL and qualify as non-detect ("U")
	≥ MDL and < RDL	Report at detected value and qualify as estimated value ("J")
	≥ RDL	Report at detected value
≥ MDL and < RDL	< MDL	Report at MDL and qualify as non-detect ("U")
	≥ MDL and < blank concentration OR ≥ MDL and < RDL	Report at RDL and qualify as non-detect ("U")
	≥ MDL and >RDL, ≥ blank concentration, and < 5x blank concentration	Report at detected value and qualify as non-detect ("U")
	≥ MDL and ≥ 5x blank concentration	Report at detected and qualify as estimated value ("J")
≥ RDL	< MDL	Report at MDL and qualify as non-detect ("U")
	≥ MDL and < RDL	Report at RDL and qualify as non-detect ("U")
	≥ RDL and < 5x blank concentration	Report at detected value and qualify as non-detect ("U")
	≥ 5x blank concentration	Report at detected value and qualify as estimated value ("J")

MDL = method detection limit.
RDL = reporting detection limit.
U = non-detect.
J = estimated value.

2.4 Summation for PAHs and for PCB and PBDE Congeners

Total PAHs were calculated as the sum of the individual detected 16 EPA priority PAHs (acenaphthene, acenaphthylene, anthracene, fluorene, naphthalene, phenanthrene, benzo(a)anthracene, benzo(g,h,i)perylene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene chrysene, dibenzo(a,h)anthracene, fluoranthene, indeno(1,2,3-cd)perylene, and pyrene). If no PAHs were detected, the reported MDL for these totals is the highest MDL reported of the individual PAHs.

PCB and PBDE data are presented as total PCB and PBDE concentrations, respectively, and were calculated as the sum of congeners. All compiled PCB data were analyzed for PCB congeners using EPA Method 1668, and PBDE data were analyzed for PBDE congeners using EPA Method 1614 (Windward Environmental, 2010; Herrera, 2011; King County, 2013b; King County, 2014).[3]

2.5 Uncertainty Assessment

Understanding uncertainty in measured hydrologic and contaminant data is critical to water quality assessment, management, and modeling (Harmel et al., 2009). Harmel et al. (2006) identified four procedural sources of uncertainty: flow measurement, sample collection, sample preservation/storage, and laboratory analysis. Herrera (2011) identified a slightly more expansive list of sources of uncertainty that include flow measurement, laboratory error, and extrapolation of sampling results. Uncertainty from extrapolation includes extrapolation from instantaneous loads based on measured flow and concentration to longer periods (months to years) and extrapolation of loads estimated for a monitored location to unmonitored locations (Webb et al., 1997).

A quantitative uncertainty analysis of all sources of error is beyond the scope of this study. In general, the contaminant loadings approach provides a planning-level estimate for relative comparison of the magnitude of loadings from major pathways in the study areas. The 95 percent confidence limits were estimated for the water quality and flow data to provide an estimate of the uncertainty around the mean and to reflect the interannual variability of the data. For pathways and COIs with insufficient data to estimate these statistics, a range of contaminant loadings was estimated to represent upper and lower bounds of potential loadings.

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[3] Potential equipment contamination issues for three PCB coelution groups have been identified for samples collected via autosampler during the 2011–2012 Green River PCB study (King County, 2014; C. Greyell, pers. comm., May 12, 2016). These coelution groups were removed before summing total PCBs for samples collected via autosampler, and therefore the estimates may be biased low (C. Greyell, pers. comm.). The grab samples collected for the Green River at Fort Dent and in Lake Union/Ship Canal would not be affected by the equipment contamination because autosamplers were not used.

Because each pathway is unique and the available data are variable, contaminant loadings for the pathways were estimated using different methods. Some estimates had larger uncertainties than others, often reflecting the location of the monitored data in relation to the study areas (within the study area or extrapolated from regional/national studies) and the robustness of the sample sizes for the different parameters and pathways. The level of uncertainty varies by pathway and parameter.

The following subsections describe key components of the data and methods that contributed to the uncertainty in the loading estimates. Additional uncertainties specific to the results are presented in Chapter 5.

2.5.1 Contaminant Concentrations and Flow/Discharge Volumes

The following factors contributed to uncertainties in estimates of contaminant concentration and of flow and discharge volumes:

- Contaminant concentrations are variable in space and in time. The limited monitoring data available for the pathways, including the number of samples from a monitoring location or the lack of complete monitoring of a pathway across the study area, introduced uncertainty as to the representativeness of the contaminant concentrations.
- Multiplying the mean and 95 percent confidence limits of the contaminant concentration data by the mean and 95 percent confidence limits of flow, respectively, does not account for the potential impact that the correlation between contaminant concentrations and flow conditions (baseflow or storm event) has on annual contaminant loadings. Of the major pathways, the Green River was the only pathway with enough data to perform this analysis. The analysis for the Green River found a significant correlation between most of the contaminants and flow. For these contaminants, annual loadings estimated using the regression equations identified in the correlation analysis were within the same ranges as the annual loadings estimated by multiplying the mean and 95 percent confidence limits of the flow times the mean and 95 percent confidence limits of the contaminant concentrations, respectively. It is uncertain whether the correlations between flow and contaminant concentrations for the other pathways have a small or large impact on the annual loading estimates.
- The frequent occurrence of contaminant concentrations below the MDL and the small data sets for parameters representing different pathways introduced a large amount of uncertainty in the mean contaminant concentrations in each loading pathway and also introduced associated extrapolation errors. Appendix B reports the number of data points available, minimum and maximum MDLs for non-detects, and percent detection frequency for contaminant concentrations used in the loadings estimates.
- The years with annual flow data available varied by pathway in the number of the years with data available, timeframe, and mean annual rainfall occurring during each period of record (Table 2-3). The annual rainfall for each of the years used in

the flow estimates is presented in Table 2-4 (2000–2014); the average rainfall was 38.7 inches. Rainfall was recorded at Seattle-Tacoma International Airport (SeaTac).

- The water years (WY) with flow data available for the upstream watersheds (WY 2000–2011) had the lowest mean annual rainfall (less than 40 in/yr).
- Stormwater, King County uncontrolled and controlled CSOs, wet weather treatment facilities, and bridges used flow data from the most recent 10 years (WY 2005–2014) and had a mean annual rainfall of approximately 40 in/yr.
- City of Seattle uncontrolled and controlled CSOs used flow data from the most recent six years (WY 2009–2014) and had a mean annual rainfall greater than 40 in/yr.
- Local tributaries had the shortest period of record used, with the a mean annual rainfall of 38.8 in/yr for areal loadings estimated with data collected in WY 2002–2003 and 45.0 in/yr for fecal coliform bacteria loading estimated with data collected in WY 2010.

Table 2-3. Years of annual monitored or modeled flow data used in the loading estimates for the major pathways and corresponding average rainfall at SeaTac.

Major Pathway	Water Years of Available Flow Data	Mean Annual Rainfall at SeaTac for Period of Flow Record (in/yr)
Green River	2000–2009	36.5
Black River	2000–2009	36.5
Lake Washington	2002–2011	38.7
Local tributaries	2002–2003; 2010	38.8; 45.0
Stormwater	2005–2014	40.3
Highway bridges	2005–2014	40.3
King County uncontrolled CSOs	2005–2014	40.3
King County controlled CSOs	2005–2014	40.3
Seattle uncontrolled CSOs	2009–2014	42.0
Seattle controlled CSOs	2009–2014	42.0
Wet weather treatment facilities	Elliott West: 2006–2014; Henderson/MLK: 2007–2014	41.3; 41.8

Table 2-4. Annual rainfall at SeaTac for years used for flow estimates (2000–2014).

Year	Annual Rainfall (inches)
2000	37.5
2001	28.2
2002	37.0
2003	40.6
2004	34.2
2005	30.6
2006	37.9
2007	49.1
2008	32.9
2009	37.4

Year	Annual Rainfall (inches)
2010	45.0
2011	42.7
2012	40.5
2013	42.2
2014	44.3

2.5.2 Upstream Watersheds

The following factors affect the certainty of loadings estimates for the upstream watersheds pathway:

- Highest flows in the mainstem of the Green River do not necessarily correspond to the greatest rainfall events because of water releases from the Howard A. Hanson Dam. Samples may characterize flow conditions upstream of the dam or runoff during a storm event.
- Lake Washington flow into Lake Union was estimated by solving for the water balance equation. Only a portion of the tributaries discharging to Lake Washington have monitored data. Therefore, flows monitored at May Creek were extrapolated to unmonitored basins to estimate incoming flows to solve the water balance equation. This method assumes that all tributaries discharging to Lake Washington have hydrologic behavior similar to that of May Creek.

2.5.3 Stormwater

Because of the lack of monitored data from stormwater drainage basins, annual runoff volume from stormwater basins was estimated using Seattle Public Utilities' (SPU's) pollutant load model (PLM) (SPU, 2015a). The model estimates runoff based on annual rainfall, amount of impervious surfaces, and runoff coefficients. It does not model existing stormwater treatment and flow control infrastructure, nor does it model baseflow. The contaminant concentrations used in PLM assume that the stormwater outfalls sampled during National Pollutant Discharge Elimination System (NPDES) monitoring represent the conditions in the study areas (Ecology, 2015).

2.5.4 Local Tributaries

Areal loading rates from regional studies were used for local tributaries. Use of these data introduced additional uncertainty by ignoring site-specific details and differences that may directly impact the contaminant load in the study areas.

2.5.5 Antifouling Paint

The following factors affect the certainty of loadings estimates for the antifouling paint pathway:

- No local data or information was available for contaminant loading from antifouling paint. Leaching rates used in the loadings estimates were taken from studies done outside of Washington (Schiff et al., 2004; Valkirs et al., 2003; CRWQCB, 2005). The rates may not reflect local conditions or changes in antifouling paint formulations.

- The surface area of vessels that could contribute contaminant loads through leaching from antifouling paint were based on an estimate of length, width, and bow coefficients of hypothetical recreational and commercial vessels.
- Only limited information was available on all vessels in the study areas. The numbers of vessels were based on a combination of marina specifications, July 2013 King County orthoimagery, and a Port of Seattle 2014 vessel log. It is expected that the commercial vessel count in Lake Union/Ship Canal was underestimated because many of the vessels would be out of port in July.

2.5.6 Creosote-Treated Wood Pilings

The following factors affect the certainty of loadings estimates for the creosote-treated pilings pathway:

- No local data or information was available on contaminant loading from creosote-treated wood pilings. Leaching rates used in the loading estimates were from previous laboratory and in situ studies in San Diego Bay.
- In order to compare total PAH loadings from creosote-treated wood pilings to loadings from other pathways, the analysis included only the EPA 16 priority PAHs. Because this fraction of total PAHs is highly variable, ranging from 20 to 100 percent of the total PAHs (Brooks, 1997), it was assumed that 20 percent of leached PAHs from creosote were priority PAHs (Valle et al., 2007).
- The leaching of PAHs from creosote depends on water temperature and salinity. This analysis did not factor in variable water temperatures or salinity. Leaching rates in the salt water of Elliott Bay and the Duwamish Estuary were assumed to be half those of the fresh water in Lake Union/Ship Canal. All three waterbodies have salinity across depth because of the presence of a saltwater wedge and freshwater lens.

3.0 PATHWAY-SPECIFIC DESCRIPTIONS AND LOAD ESTIMATING METHODS

This chapter describes the pathways and the methods used to estimate contaminant loadings from each pathway. The section for each pathway includes the sources and availability of contaminant concentration and flow data used to estimate the loadings.

3.1 Upstream Watersheds

Two watersheds contribute flow and contaminants to the study areas: The Green River watershed drains to the Duwamish Estuary/Elliott Bay study area and the Lake Washington watershed drains to Lake Union/Ship Canal.

Loadings from upstream watersheds are influenced by watershed land use (Figure 3-1) and by atmospheric deposition and natural background concentrations of contaminants. Developed areas may discharge stormwater into surface waters upstream, which are covered under NPDES permits issued by Ecology. These municipal separate storm sewer systems (MS4s) are shown in Figure 3-2.

The following sections describe each study area's upstream watershed, including land cover and major tributaries, water quality and flow data, and methods used to estimate loadings from the two watersheds.

3.1.1 Green River Watershed

The Green River watershed (1,200 km^2) discharges into the Duwamish River just downstream of the confluence of the Black and Green rivers (Figure 3-1). Many MS4s discharge stormwater to surface waters in the watershed (Figure 3-2). The watershed is divided into three sub-watersheds: Lower (170 km^2), Middle (440 km^2), and Upper Green River (580 km^2):

- The Lower Green River sub-watershed begins at RM 11 and includes two major tributaries: Mill (in Auburn) and Springbrook/Mill creeks (in Renton and Kent). Springbrook/Mill Creek becomes the Black River. Of the three sub-watersheds, the Lower Green River is the most developed and has the greatest potential to contribute contaminants to Duwamish Estuary/Elliott Bay via stormwater runoff. Approximately 83 percent of the sub-watershed is developed, 4 percent is agricultural, and 12 percent is undeveloped (Homer et al., 2015). The higher intensity development runs north-south through the center of the sub-watershed, parallel to the Green River and its tributaries.

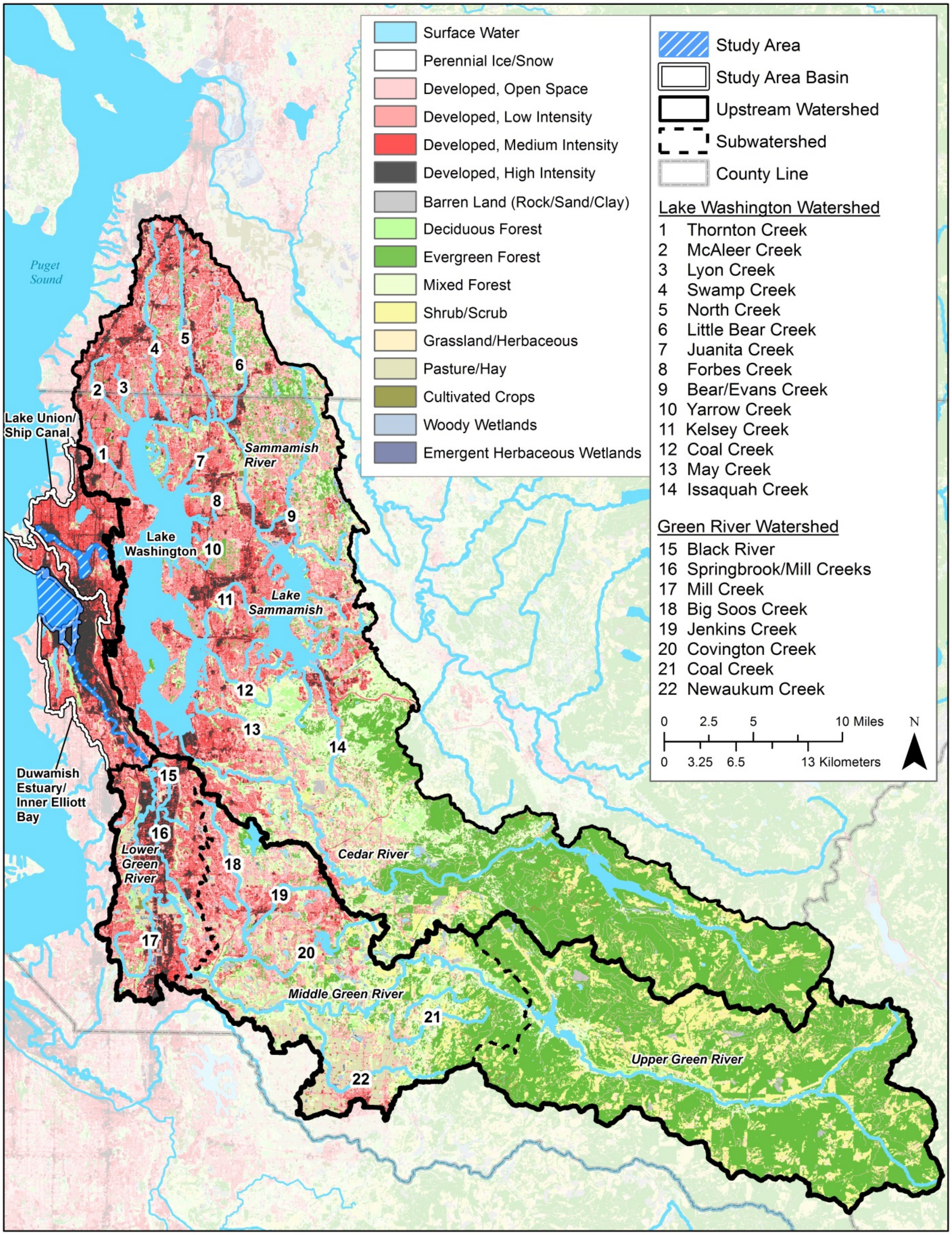

Figure 3-1. **Land cover in the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas.**

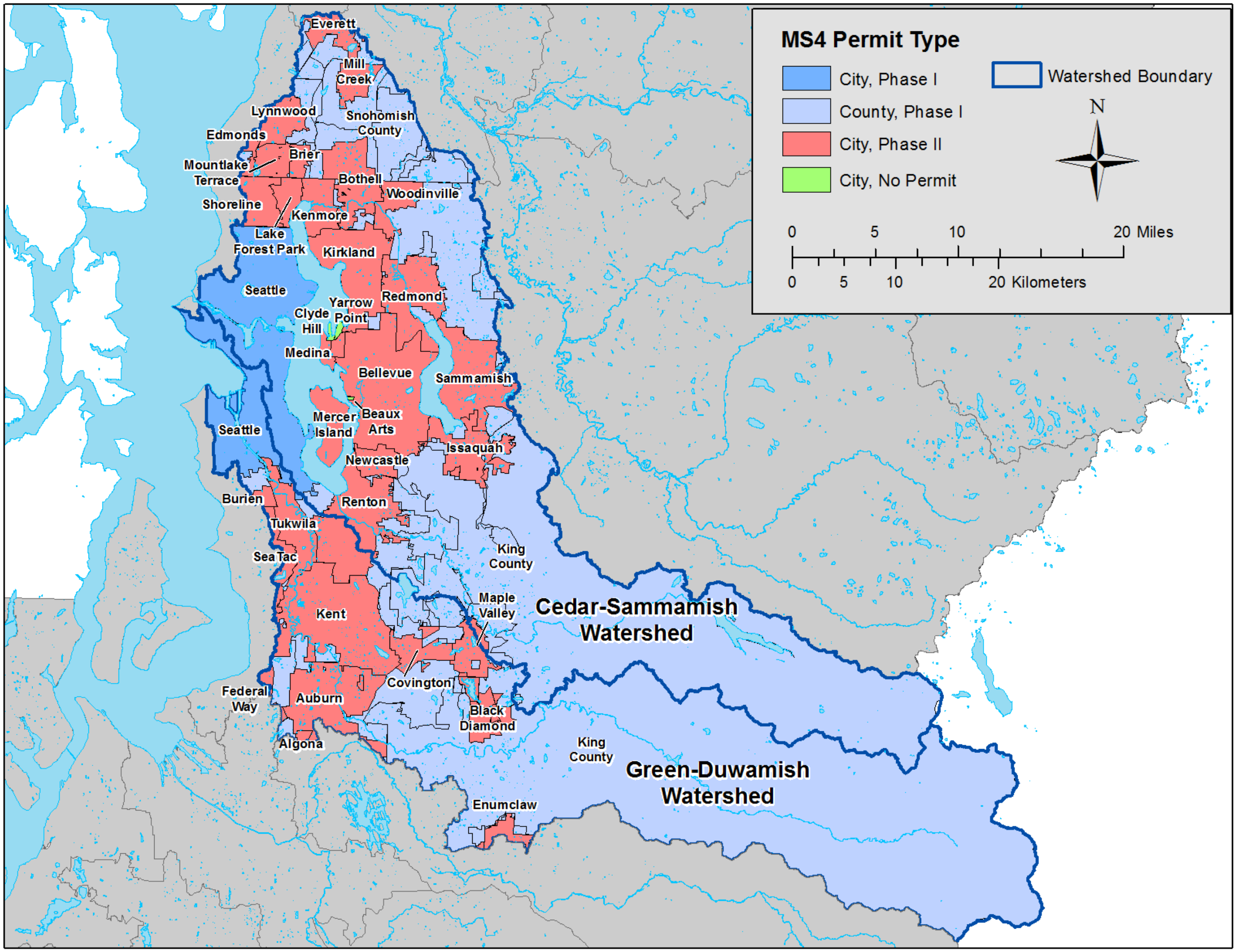

Figure 3-2. Municipal separate storm sewer system (MS4) jurisdictions in the Green-Duwamish and Cedar-Samammish watersheds.

- The Middle Green River sub-watershed begins at RM 32, terminates at the Howard A. Hanson Dam (RM 64.5), and includes four major tributaries: Covington, Jenkins, Newaukum, and Soos creeks. This sub-watershed is approximately 33 percent developed, 10 percent agricultural, and 56 percent undeveloped (Homer et al., 2015). The majority of the development in the Middle Green River sub-watershed is located within the Soos and Jenkins creek basins, with a pocket of development in Enumclaw along Newaukum Creek.
- The Upper Green River sub-watershed stretches 30 miles east from the Howard A. Hanson Dam to the crest of the Cascade Mountains and represents the headwaters of the Green-Duwamish watershed. It is the least developed sub-watershed. Approximately 4 percent of the land is developed; the remaining land, approximately 95 percent, is undeveloped. This sub-watershed serves as the municipal water supply for the City of Tacoma.

Water Quality Data

Water quality data for the COIs were compiled from King County's long-term monitoring program at locations that represent conditions in the Green River watershed prior to discharging to the Duwamish Estuary. The most downstream Green River monitoring location that is minimally affected by tidal exchange is located near Fort Dent at RM 11.1 (Station 3106/A310) (Figure 3-3). This station is just upstream of the confluence of the Green and Black rivers. Data were compiled for the following COIs and periods:

- BBP, BEHP, and total PAHs: 2002–2003 and 2008–2010
- Total arsenic, total copper, total lead, total mercury, and total zinc: 2000–2010
- Total suspended solids (TSS), fecal coliform, total nitrogen, and total phosphorus: 2004–2013
- Total PCBs, based on PCB congener data collected from the Green River at Fort Dent in 2005 and 2007–2008 (Windward Environmental, 2010)

Because the sample locations on the Green River at Fort Dent are upstream of the confluence of the Green and Black rivers, it was necessary to compile water quality data from the Black River to estimate contaminant loadings. Data were compiled from King County's most downstream ambient monitoring location near the mouth of the Black River at Station 0317 prior to discharge to the Green River. COIs and sampling periods were as follows:

- BBP, BEHP, and total PAHs: 2009–2010
- Total arsenic, total copper, total lead, total mercury, and total zinc: 2001–2010
- TSS, fecal coliform, total nitrogen, and total phosphorus: 2001–2013
- Total PCBs, based on PCB congener data collected 2011–2012 at the Black River Pump Station (King County, 2014)

Appendix B presents contaminant concentration summary statistics for the Green River and Black River water quality data.

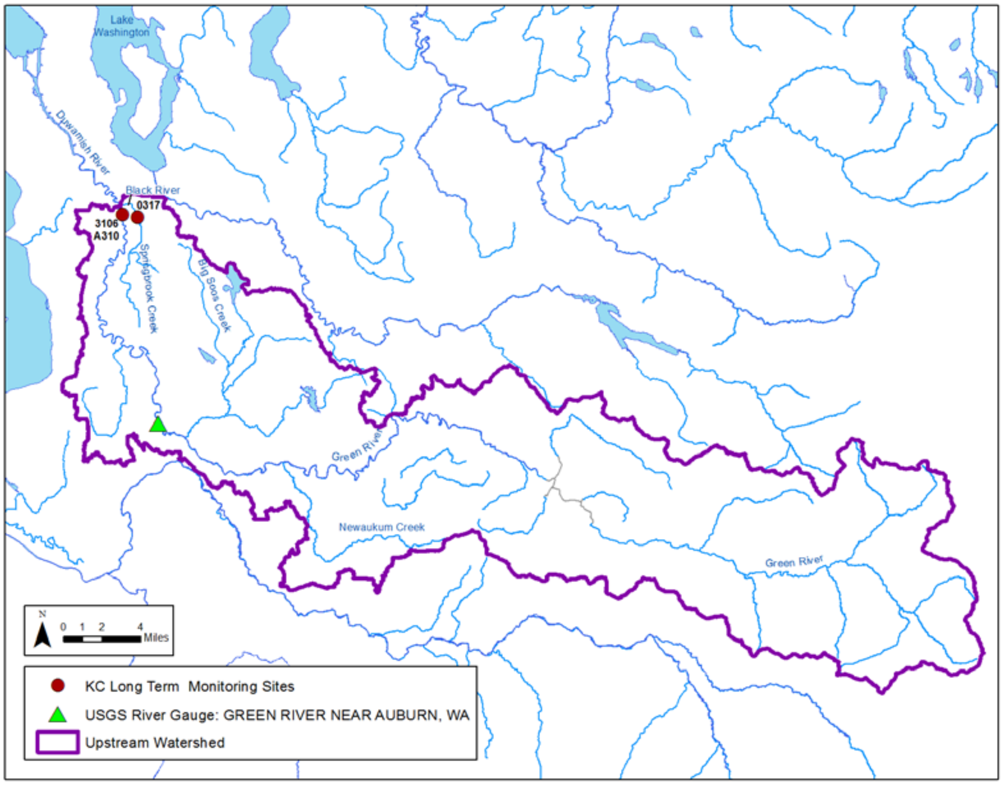

Figure 3-3. **The Green River watershed and King County long-term water quality monitoring locations.**

Hydrologic Data and Flow Estimates

The flow volume of the Green River was estimated using a combination of existing gauged streamflow data and simulated model data. A U.S. Geological Survey (USGS) stream gauge, located on the Green River at RM 32 near Auburn (USGS Auburn Gauge 12113000) provides annual streamflow data for the portion of the watershed upstream of the gauge (Figure 3-3). Flows from the watersheds downstream of the gauge (Black River/Springbrook Creek, Mill Creek, Olsen Creek, and two unnamed tributaries [model names: Green LCL4 and Green LCL5]) were estimated using simulated flow from the Hydrologic Simulation Program-FORTRAN (HSPF) model because there are no streamflow gauges downstream on the Green River that are not affected by tidal exchange.

King County has routinely used the HSPF model as a stormwater management and basin planning tool since the late 1980s. The County's WRIA 9 stormwater retrofit watershed modeling effort provided long-term (WY 1949–2009) hydrologic output for all stream reaches flowing to the Lower and Middle Green River downstream of the Howard A. Hanson Dam to characterize present-day hydrologic conditions of the drainage basins (King County, 2013c). The models incorporate site-specific land use, slope, precipitation, soil, geology, and stream channel data.

The Mill Creek HSPF-modeled annual flow was aggregated with the annual flow measured at the upstream USGS Auburn Gauge over the same period to calculate the annual flow of the Green River upstream of its confluence with the Black River.

To estimate the loadings from the Black River before it enters the Green River, flow from the Black River watershed was kept separate because the Green River long-term ambient monitoring site is upstream of the confluence with the Black River. The Black River/Springbrook Creek HSPF model output was used to estimate annual flows from the Black River. Modeling the behavior of the Black River Pump Station would not have a significant impact on the mean annual flow because of the annual timescale of this analysis and flow, therefore, was modeled as if no pump station existed.

The HSPF models for Mill Creek and Black River/Springbrook Creek were calibrated to observed streamflow and TSS data (King County, 2013c). Quantitative thresholds were identified to evaluate model calibration accuracy for flow rate and TSS metrics. The calibration assessment assigned categories (poor, fair, good, excellent) to reflect how well model output fit observations. The Mill Creek HSPF model calibration was categorized as good to excellent for flow metrics and fair for TSS (King County, 2013c).The Black River/Springbrook Creek HSPF model calibration was categorized as fair to good for flow metrics and poor for TSS.

The mean annual flow volumes and 95 percent UCL and LCL for the Green and Black rivers were estimated using the most recent 10 years of available simulated flow (WY 2000–2009). The estimated flows are presented in Appendix C.

Loading Estimates

Because the Green River water quality monitoring location is upstream of the confluence with the Black River, contaminant loadings from the Green and the Black rivers were calculated separately. For both rivers, the mean and 95 percent UCL and LCL concentrations of each COI were multiplied by the mean and 95 percent UCL and LCL flow, respectively. The contaminant loads from the Green and Black rivers were aggregated to represent total loading from the Green River watershed at RM 10.5 where it drains to the Duwamish Estuary/Elliott Bay study area.

Correlation of Contaminant Concentration and Flow

It was assumed that the correlation between contaminant concentration loading and different storm events would have minimal impact on annual loads. To test this assumption, the correlation between contaminant concentrations used for the Green River and daily flow from the USGS Auburn Gauge was explored. If a statistically significant relationship between concentration of a COI and flow was found, annual contaminant loadings from the Green River were estimated based on a regression equation using daily flow data from the USGS Auburn Gauge.

A significant relationship was found between flow and the following COIs: fecal coliform bacteria, TSS, total arsenic, total copper, total lead, total mercury, total zinc, and total PAHs.

For all these contaminants except fecal coliform bacteria, the annual loadings calculated using daily loadings based on the regression equations were within the range of the results. The fecal coliform load estimated was approximately an order of magnitude lower than the load estimated using annualized means. The annual loadings for fecal coliform of the Green River provided in this report may therefore be biased high but will not likely affect other contaminant loading estimates.

Appendix D describes the methods and results of this correlation analysis in more detail.

3.1.2 Lake Washington Watershed

The Lake Washington watershed (1,525 km^2) drains into Portage Bay at the Montlake Cut, which is the easternmost segment of the Lake Union/Ship Canal study area. Lake Washington is fed by two major rivers: the Sammamish River and the Cedar River (Figure 3-1), which make up 80 percent of the inputs to Lake Washington (50 percent from the Cedar River and 30 percent from the Sammamish River) (Edmondson, 1977; King County, 2003; Cerco et al., 2004; King County, 2013a). Lake Sammamish and four tributaries (Swamp, North, Little Bear, and Bear/Evans creeks) drain to the Sammamish River, which subsequently drains to Lake Washington from the north along with Thornton, McAleer, and Lyon creeks. The Cedar River enters at the south end of Lake Washington. Juanita, Forbes, Yarrow, Kelsey, Coal, and May creeks discharge into Lake Washington from the east.

The Lake Washington watershed has equal parts developed and undeveloped lands. Approximately 1 percent of agricultural land cover is located north of the confluence of Bear and Evans creeks along the Sammamish River and between Issaquah Creek and the Cedar River (Homer et al., 2015). Most development is found along the periphery of Lakes Washington and Sammamish; additional development occurs along the northern tributaries discharging to the Sammamish River. Many MS4s discharge stormwater to surface waters in the watershed (Figure 3-2). The headwaters of the Cedar River are relatively undeveloped forested areas and serve as one of the primary municipal water supplies for the greater Seattle area.

Water Quality Data

Water quality data were compiled from King County's long-term monitoring at the Montlake Cut Station to represent the quality of waters entering Lake Union from the Lake Washington drainage basin. The Montlake Cut station (Station 0540) is located approximately 40 m west of the Montlake Bridge in the Montlake Cut between Portage Bay and Lake Washington's Union Bay (Figure 3-4). Data were compiled from this ambient monitoring location for the following COIs and periods:

- BBP, BEHP, and total PAHs: 2000–2003
- Total arsenic, total copper, total lead, total mercury, and total zinc: 2000–2008
- TSS, fecal coliform, total nitrogen, and total phosphorus: 2009–2013.
- Total PCBs and PBDEs, from data collected from the Montlake Cut in 2011–2012 (King County, 2013a)

Appendix B presents the contaminant concentration summary statistics for Lake Washington at the Montlake Cut Station.

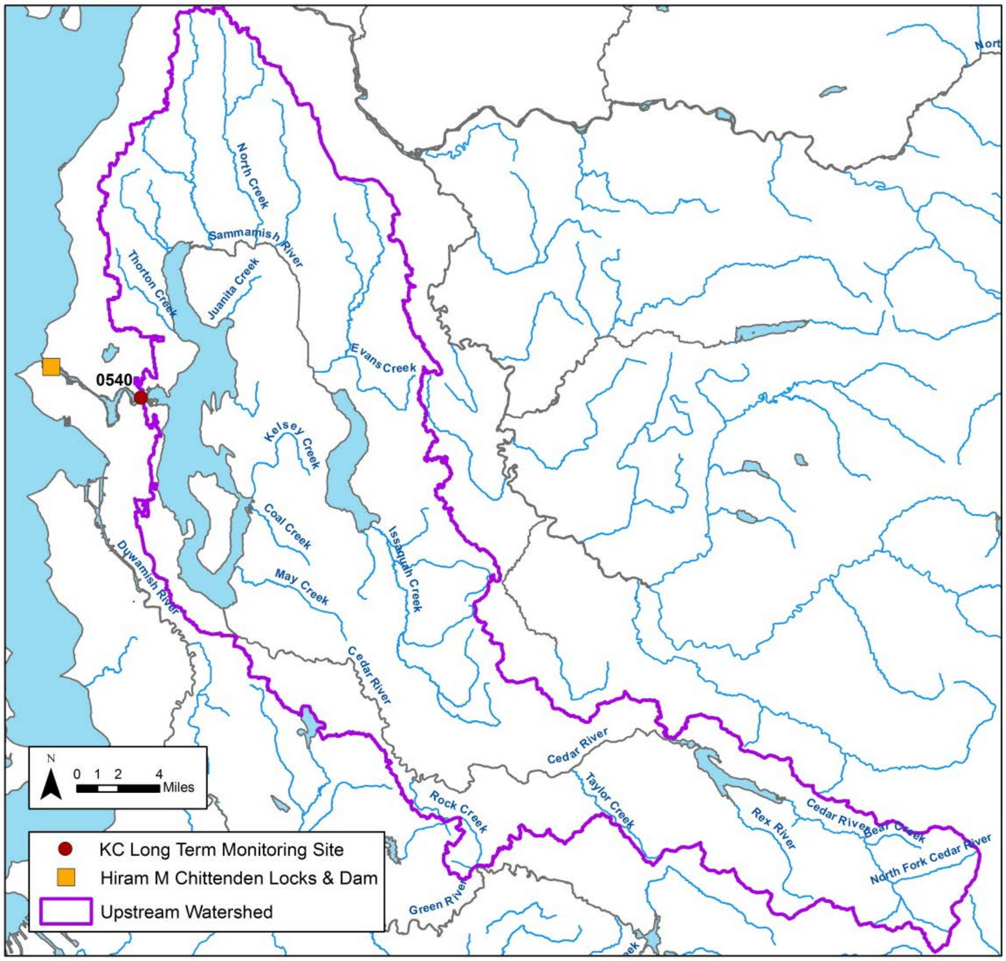

Figure 3-4. **Lake Washington watershed and King County long-term water quality monitoring location.**

Hydrologic Data and Flow Estimates

Discharge from Lake Washington to Lake Union is not directly measured because of the complexity of the lock and dam system at the outlet of the Lake Washington watershed. This study followed the method used by King County (2013a) to estimate discharge from Lake Washington to the Lake Union/Ship Canal study area. The method used precipitation data in conjunction with daily flow, lake elevation, and evaporation estimates to develop a lake water budget. This approach has been used in previous flow modeling of the lake (Edmondson and Lehman, 1981; Cerco et al., 2014).

The daily water balance equation solved for the system outflow is as follows:

$$Q_{out} = \left(Q_{in} + Q_{prec}\right) - \left(Q_{\Delta S} + Q_{evap}\right) \tag{1}$$

Where:

$Q_{out} = total\ outflow\ to\ Puget\ Sound\ (cubic\ feet\ per\ second\ [cfs])$

$Q_{in} = watershed\ inflows\ (cfs)$

$Q_{prec} = precipitation\ on\ water\ body\ (cfs)$

$Q_{\Delta S} = storage\ (cfs)$

$Q_{evap} = evaporation\ from\ the\ water\ body\ surface\ (cfs)$

The following data were input to the daily water balance:

- Watershed inflows were based on the sum of gauged river and tributary inflows and estimated ungauged tributary inflows between October 2002 and September 2011. Ungauged tributary flows were estimated by scaling daily flow from gauged tributaries in the Lake Washington watershed. The daily flow records for Juanita and May creeks were used as the basis for extrapolation (King County, 2013a).
- Precipitation was based on the average of daily precipitation measured at the Renton Airport and at the Sand Point Station near Magnuson Park close to the Lake Washington shoreline (WY 2002–2011).
- Daily evaporation data were obtained from Washington State University's Experimental Station in Puyallup (WY 2002–2011).
- Storage changes in the lake were based on daily changes in lake level reported by the Seattle District of the U.S. Army Corps of Engineers (WY 2002–2011) and the surface area of Lakes Washington and Union.

All inputs were converted to daily flow by multiplying the depth of rainfall, evaporation, or lake level change by the area of Lake Washington (89 km^2 [34.4 mi^2]). The mean annual flow was estimated by averaging annual flow volumes in 2002–2011.

Estimated flows are presented in Appendix C.

Loading Estimates

Annual contaminant loading from Lake Washington at the Montlake Cut Station was estimated by multiplying the mean and 95 percent UCL and LCL of the flow calculated from Lake Washington by the mean and 95 percent UCL and LCL concentrations for each COI.

3.2 Stormwater Runoff

Stormwater and other overland flows from sources such as excess landscape irrigation result in surface runoff and sheet flow that drain to surface waterbodies. As surface runoff travels overland, contaminants may become entrained in the flow. Rainfall can also transport atmospheric pollutants to the ground. The quantity and quality of overland flow that reaches surface waters is greatly influenced by the landscape through which it flows.

Pervious surfaces (undeveloped land such as forests) allow most overland flows to infiltrate into the ground. The remaining flow is directed to surface waters through a stormwater conveyance system. As the amount of impervious surface increases (streets, parking lots, rooftops), the amount of infiltration decreases and the volume of stormwater runoff increases.

In both study areas, stormwater is directed to either a combined, separated, or partially separated sewer system. In a combined sewer system, stormwater and wastewater are collected and conveyed to a wastewater treatment plant. In a separated sewer system, stormwater is collected in stormwater conveyance systems and discharged directly to surface waters, receiving no treatment. In partially separated sewer systems, rooftop drains are connected to the wastewater conveyance system, while other impervious surfaces, such as roads and highways, are connected to the stormwater conveyance system that discharges directly to surface waters. Stormwater can also be discharged directly to a surface waterbody from adjacent lands or structures as overland flow (referred to as direct discharge areas in this study).

Separated and partially separated stormwater conveyance systems and direct discharge areas can contribute contaminant loading to the study area and were included in the stormwater drainage basin pathway. Overall, seven entities operate MS4s adjacent to the study areas: Seattle, Tukwila, Burien, King County, Port of Seattle, University of Washington, and Washington State Department of Transportation (WSDOT).

Figure 3-5 shows the stormwater drainage basins that discharge to study area waterbodies. The basins were compiled using delineated drainage basins from the Cities of Seattle, Tukwila, and Burien, and unincorporated King County updated with recent MS4 data.

3.2.1 Water Quality Data

The compiled data from *Western Washington NPDES Phase I Stormwater Permit Final S8.D Data Characterization 2009–2013* were used to represent the contaminant concentrations in surface runoff in the separated and partially separated stormwater basins draining to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal. The report summarizes the stormwater discharge data collected by NPDES Phase I Municipal Stormwater permittees from 2009 to 2013 (Ecology, 2015). The Phase I permittees included four counties (Clark, King, Pierce, and Snohomish), two cities (Seattle and Tacoma), and two ports (Seattle and Tacoma). Each permittee collected stormwater discharge data from a commercial, industrial, and residential basin in its jurisdiction.

For commercial and industrial land uses, summary statistics were calculated using the data collected from all permittees. For residential land use, only data from Seattle and Tacoma were used because the residential land use of these cities is more similar to the stormwater basins discharging to the study areas than are the residential areas sampled in the counties.

Data were available for fecal coliform, total nitrogen, total phosphorus, TSS, total copper, total lead, total mercury, total zinc, BBP, BEHP, total PAHs, and total PCBs (Ecology, 2015).

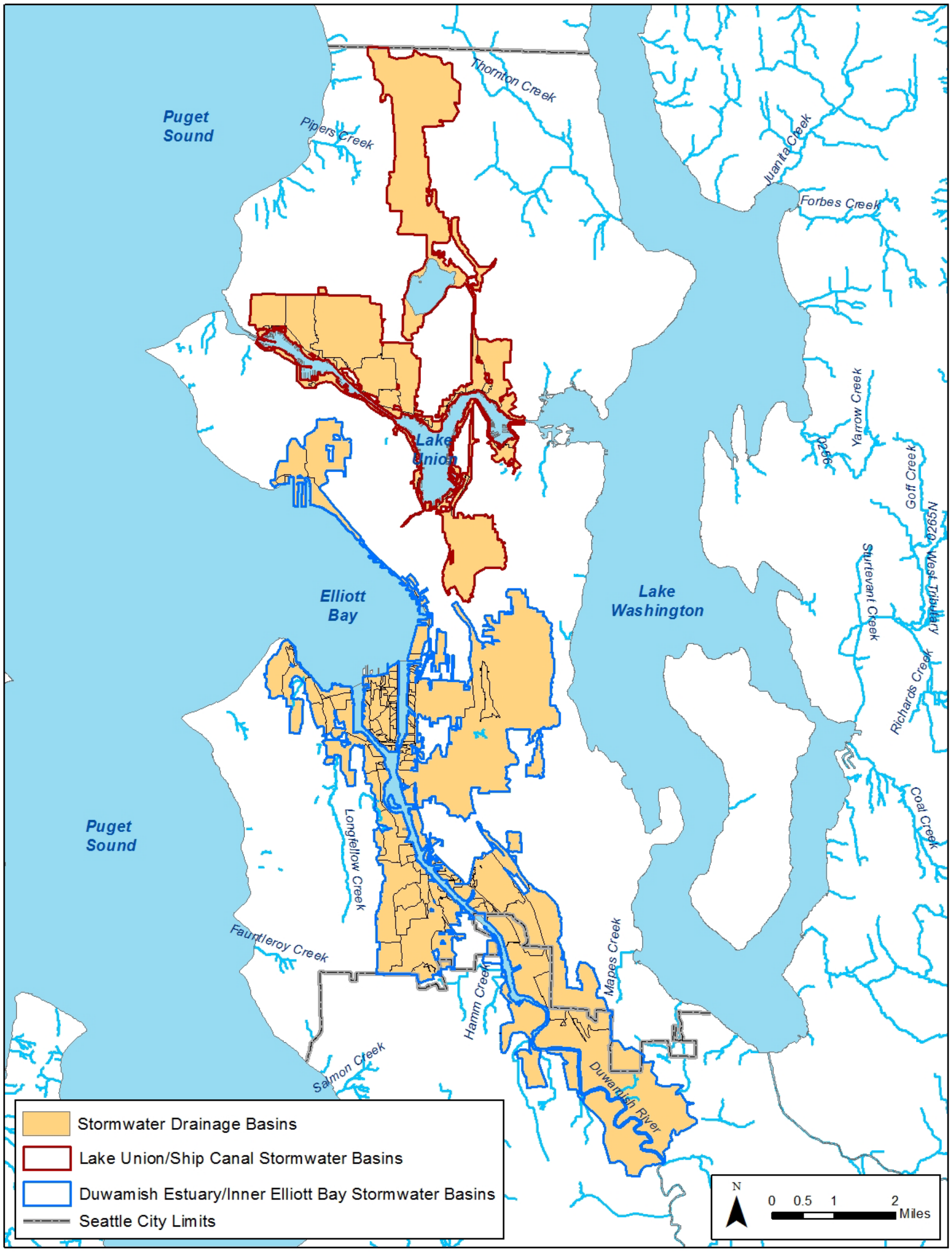

Figure 3-5. **Stormwater drainage basins that discharge to the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas.**

Additional total PCB and total PBDE data collected from stormwater basins in 2011–2012 were used (King County, 2013a). Because no stormwater total arsenic data were available for Washington, total arsenic data, collected in Oregon (EPA rain zone 7) in 1991–1996, were obtained from the National Stormwater Quality Database (version 4.02) (http://www.bmpdatabase.org/nsqd.html). The mean and 95 percent confidence limits were calculated for the contaminants.

Appendix B presents the stormwater contaminant concentrations used to estimate pollutant loadings from stormwater drainage basins.

3.2.2 Loading Estimates

Stormwater runoff loads were estimated using SPU's' PLM, which SPU used to estimate the pollutant load reduction of candidate stormwater projects in its Integrated Plan (SPU, 2014). For this study, SPU reran the PLM for the stormwater basins in Seattle, Port of Seattle, Tukwila, Burien, and unincorporated King County that drain into the study areas downstream from the Green River and Lake Washington watersheds. The mean annual precipitation and 95 percent confidence limits were calculated using the most recent 10 years (WY 2005–2014) of observations at the SeaTac rain gauge (mean = 40.26 in/yr; 95 percent UCL = 43.31 in/yr; 95 percent LCL = 36.73 in/yr). Basin boundaries were compiled from field-verified delineated drainage basins from the Cities of Seattle, Tukwila, and Burien, and unincorporated King County updated with recent MS4 data (Figure 3-5).

The PLM uses the Simple Method to estimate pollutant load and runoff volume in urban areas with basin-specific information, including drainage area, ratio of impervious cover to pervious cover, runoff pollutant concentrations, and annual precipitation (Schueller, 1987). The method provides a general planning estimate of likely stormwater pollutant export from select areas and is most appropriate for assessing and comparing the relative stormflow pollutant load of different land uses and sub-basins. Documentation for PLM methods can be found in SPU (2015a).

The PLM estimates annual average runoff volume (AARV [m^3/yr]), using the following equation:

$$AARV = P * P_j * R_v * A \tag{2}$$

Where:

$P = mean\ annual\ rainfall\ (m/yr)$

$P_j = fraction\ of\ mean\ annual\ rainfall\ that\ produces\ runoff\ (0.9)$

$R_v = runoff\ coefficient\ (impervious\ surfaces = 0.95, pervious\ surface = 0.05)$

$A = pollutant\ generating\ area\ (m^2)$

The pollutant-generating area is the effective area of a basin, which is the area that generates runoff that is routed to the storm sewer system and then discharged at the outlet of the basin. The mean annual load (Load [kg/yr]) is calculated as follows:

$$Load = AARV * RC \tag{3}$$

Where:

$RC = runoff\ contaminant\ concentration\ of\ a\ specific\ land\ use\ (ex. \frac{kg}{m^3})$

Land uses of the stormwater basins were categorized into commercial, industrial, residential, open space, and vacant regardless of the surface type (road, driveway, rooftop, parking lot, pervious area). The contaminant concentrations for the commercial, residential, and industrial land uses were used as the RC in the PLM model. Open space areas were assumed to generate the same contaminant concentrations as residential areas; vacant lands were assumed to generate the same contaminant concentrations as commercial areas (SPU, 2015a).

Contaminant loads were estimated by multiplying the mean and 95 percent UCL and LCL contaminant concentrations by the annual runoff estimated using the mean 95 percent UCL and LCL rainfall, respectively. The mean and 95 percent UCL and LCL annual runoff for each land use and study area are presented in Appendix C.

The PLM estimates pollutant loads generated during storm events only; it does not consider pollutants associated with baseflow volume that may be discharging from the storm sewer system. Although baseflow could be introduced to the storm sewer system through infiltration and inflow from groundwater or through illicit connections, baseflow in stormwater basins was assumed to be small to negligible. Additionally, the PLM does not consider existing facilities that may intercept generated runoff before it enters the storm system.

3.3 Local Tributaries

No local tributaries discharge to the Lake Union/Ship Canal study area.

Seven local tributaries flow into the Duwamish Estuary/Elliott Bay study area: Fairmont Creek (0.2 km^2 basin), Hamm Creek (5.9 km^2 basin), Longfellow Creek (6.1 km^2 basin), Puget Creek (1.3 km^2 basin), Riverton Creek (1.8 km^2 basin), Southgate Creek (2.3 km^2 basin), and an unnamed tributary (2.7 km^2 basin) (Figure 3-6). Portions of the local tributary catchment basins are in the combined sewer system; the remainder of the drainage areas are served by partially or fully separated sewer systems that contribute to local tributary flow that directly discharges to the study area. The total drainage area of the tributaries is 20 km^2, including 13.5 km^2 that drains to the separated sewer system, 4.6 km^2 to the partially separated system, and 2 km^2 to the combined sewer system.

The methods for estimating contaminant loadings from local tributaries differ from those used for stormwater drainage basin estimates because the baseflow component of local tributary flow is known.

Figure 3-6. **Local tributaries that flow into the Duwamish Estuary/Elliott Bay study area.**

3.3.1 Areal Loading Rates

To estimate contaminant loadings from local tributaries, areal loading rates (mass/area/year) estimated from monitored tributaries in the Puget Sound watershed were extrapolated to the local tributary drainage basins (Herrera, 2007a; Herrera, 2011).

Herrera (2011) monitored water quality and flow data from tributaries representing major land uses (residential, commercial/industrial, agricultural, and forest/field/other) in the Snohomish and Puyallup watersheds between October 2009 and July 2010. Water quality and flow data were available to estimate areal contaminant loadings for total phosphorus, TSS, total arsenic, total copper, total lead, total mercury, total zinc, BEHP, total PAHs, total PBDEs, and total PCBs.

Similarly, the local tributaries that discharge to the Duwamish Estuary/Elliott Bay study area represent a combination of high, medium, and low intensity development. Therefore, areal loading rates and flow data used for extrapolation were estimated by compiling the commercial/industrial and residential water quality data collected from Herrera (2011) into one data set and then calculated. Contaminant areal loading rates were estimated using the following steps:

1. Annual baseflow and stormflow were converted from cfs to L/yr for each monitored commercial/industrial and residential drainage basin.
2. Annual areal flow rates for stormflow and baseflow were estimated by dividing the annual baseflow and stormflow for each drainage basin by its respective drainage area to calculate L/yr/km^2.
3. The contaminant concentrations for each baseflow or stormflow sampling event were multiplied by the baseflow or stormflow areal flow rate, respectively, to calculate the contaminant load per year per area (for example, mg/yr/km^2).
4. The mean, 95 percent UCL, and 95 percent LCL were calculated separately for the pooled baseflow events and for the pooled stormflow events.
5. Total contaminant areal loading was calculated by summing the mean, 95 percent UCL, and 95 percent LCL stormwater contaminant areal loadings with the respective mean, 95 percent UCL, and 95 percent LCL baseflow contaminant areal loading. These contaminant areal loading rates can be found in Appendix B.

Additionally, fecal coliform bacteria areal loading rates from monitored tributaries in the Green River watershed (Herrera, 2007a) were available to estimate fecal coliform loading from the local tributaries. (Fecal coliform data were not available from Herrera, 2011.) Herrera (2007a) calculated average annual flow-weighted areal loading rates based on sampling from November 2001 to November 2003 from tributaries representing four major land uses (low-to-medium density development, high density development, agricultural, and forested). The flow-weighted areal loading rates were estimated using a different method than that used by Herrera 2011, and calculating the 95 percent confidence limits were not possible. Therefore, the fecal coliform areal loading rate used for extrapolation was calculated by taking the minimum, mean, and maximum average annual loading rates from low, medium, and high density development tributaries in the watershed (Herrera, 2007a).

The areal loading rates for the Green River tributaries are presented in Appendix B.

3.3.2 Loading Estimates

The contaminant loadings from local tributaries that discharge to Duwamish Estuary/Elliott Bay were estimated by multiplying the mean and 95 percent UCL and LCL contaminant areal loading rates by the total separated and partially separated areas of the local tributaries (18 km^2). The areal loading rates were not applied to the combined sewer system area (2 km^2) because flow is primarily routed to the wastewater conveyance system and any discharges that may occur from CSOs are accounted for in the CSO loading estimates.

The combined, partially separated, and fully separated sewer areas of the local tributaries were obtained from the SPU PLM (SPU, 2014). Table 3-1 presents the total area of the local tributary basins and the associated combined, partially separated, and separated sewer basin areas.

Table 3-1. Total area of local tributary basins and associated combined, partially separated, and fully separated sewer areas that drain to the Duwamish Estuary/Elliott Bay study area (km^2).

Local Tributary	Combined Area	Partially Separated Area	Separated Area	Total Basin Area
Hamm Creek	0.03	0.1	5.6	5.7
Fairmount Creek	0.02	0.1	0	0.2
Longfellow Creek	1.6	3.4	1.1	6.1
Puget Creek	0.4	1.0	0	1.3
Riverton Creek	0	0	1.8	1.8
Southgate Creek	0	0	2.3	2.3
Unnamed tributary	0	0	2.7	2.7

3.4 Bridges

Motor vehicle bridges generate stormwater runoff that may be discharged directly to underlying surface water. Types and amounts of contaminants found in the runoff depend on factors such as vehicle traffic, vehicle types (commercial and non-commercial), bridge construction (asphalt, grated), frequency of sweeping, and whether it is a drawbridge.

There are 18 bridge crossings in the two study areas: 11 across Duwamish Estuary/Elliott Bay and 7 across Lake Union/Ship Canal. The bridges include highways and arterial roads. Bridge crossings were not included in the SPU PLM model and therefore were estimated separately. Runoff from inland highways and arterial roads were included in the loading estimates for the CSO, stormwater runoff, local tributaries, and upstream watershed drainage areas.

3.4.1 Water Quality Data

Runoff generated from highway bridges crossing Lake Union/Ship Canal is untreated. A portion of the stormwater runoff from highways crossing the Duwamish Estuary/Elliott Bay is managed with stormwater best management practices (BMPs) that treat stormwater runoff or control its flow. BMPs in the Duwamish Estuary/Elliott Bay study area include bioswales, wet ponds, and wetlands (Table 3-2). Water quality data were available for untreated and treated highway runoff and were used to represent the water quality of runoff from the highway and arterial road bridges crossing the study areas. The arterial bridges crossing the study area were assumed to be untreated.

Table 3-2. Contributing areas and treatment status of stormwater runoff from bridge crossings directly discharging to the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas.

Type	Bridge	Receiving Waterbody	Treatment	Area (m^2)
Duwamish Estuary/Elliott Bay				
Highways	SR 99/1st Ave S	Duwamish Estuary	Biofiltration swale	2,565
	SR 99/1st Ave S	Duwamish Estuary	Wet pond to wetland mitigation	4,619
	SR 99/1st Ave S grated bridge deck	Duwamish Estuary	None	1,682
	I-5 Duwamish River	Duwamish Estuary	Biofiltration swale	2,307
Arterial roads	West Seattle Bridge	Duwamish Estuary	None	9,326
	SW Spokane St	Duwamish Estuary	None	5,021
	South Park/16th Ave	Duwamish Estuary	None	2,437
	S 98th St	Duwamish Estuary	None	866
	S 102nd St	Duwamish Estuary	None	725
	Tukwila International Blvd	Duwamish Estuary	None	1,234
	E Marginal Way S	Duwamish Estuary	None	905
	42nd Ave S	Duwamish Estuary	None	549
	56th Ave S	Duwamish Estuary	None	359
Lake Union/Ship Canal				
Highways	I-5 Ship Canal Bridge	Lake Union/Ship Canal	None	5,583
	SR 520 Portage Bay	Lake Union/Ship Canal	None	12,065
	SR 99 Lake Union	Lake Union/Ship Canal	None	4,622
Arterial roads	Montlake Blvd NE	Lake Union/Ship Canal	None	838
	Eastlake Ave NE	Lake Union/Ship Canal	None	4,912
	Fremont Ave N	Lake Union/Ship Canal	None	1,543
	Ballard Bridge/15th Ave NW	Lake Union/Ship Canal	None	9,211

Herrera (2007b) characterized pollutants from untreated highway bridge runoff in Western Washington based on data compiled from 11 studies and 35 monitoring locations. These data were used in this loadings analysis to estimate loadings generated from untreated highway runoff in the two study areas. Most of the monitoring locations were in the Seattle vicinity, with two locations in Vancouver and one location near Snoqualmie Pass. Water quality data were available for fecal coliform bacteria, total nitrogen, total phosphorus, TSS, total arsenic, total copper, total lead, total mercury, total zinc, BBP, and BEHP. Total PCB and PBDE data collected from the Montlake Cut in 2011 and 2012 were also used (King County, 2013a). Appendix B presents the untreated highway contaminant concentration summary statistics used to estimate contaminant loadings from untreated highway bridge runoff.

Data from WSDOT were used to estimate contaminant concentrations of highway bridge runoff managed through BMPs. As part of the NPDES Municipal Stormwater Permit BMP Effectiveness Monitoring Program, WSDOT monitored the effluent water quality from highway vegetative filter strips (VFS), compost-amended VFS, and modified VFS (WSDOT, 2014). The different VFS types were installed along roadside embankments adjacent to the northbound and southbound lanes of I-5 near Pilchuck Creek and Everett, both in Snohomish County. Water quality of the BMP effluent was monitored 2 m and 4 m downslope from the pavement edge. Data were available for total copper, total zinc, total nitrogen, total phosphorus, and TSS from 2012 and 2013. The data from each BMP and from both sampling locations were compiled to summarize contaminant concentrations for treated highway runoff. Although, these VFS systems are different from the highway runoff treatment in the Duwamish Estuary/Elliott Bay study area, highway runoff water quality data from VFS facilities were the only data available from WSDOT and were used to provide a first-level approximation to meet the planning-level needs of this study. Appendix B presents the treated highway contaminant concentration summary statistics used to estimate contaminant loadings from treated runoff discharging from bridges.

3.4.2 Loading Estimates

Annual runoff volumes generated from bridges and directly discharged to the study areas were calculated by multiplying the untreated and treated surface areas of the bridges (Table 3-2) by the mean and 95 percent UCL and LCL annual precipitation depth recorded at the SeaTac rain gauge (WY 2005–2014). It was assumed that there were no evaporative losses during runoff events. The annual runoff volumes are presented in Appendix C.

Estimated annual untreated and treated bridge runoff volumes were summed for each study area and multiplied by the corresponding untreated and treated contaminant concentrations (mean; 95 percent UCL and LCL) to estimate the mean and 95 percent UCL and LCL annual contaminant loads to the two study areas. The loading estimates were not adjusted for potential reduction in runoff volume from increased infiltration provided by treatment facilities prior to discharging into the study areas.

3.5 Combined Sewer Overflows

There are 58 CSO outfalls in the two study areas: 27 outfalls discharge to Duwamish Estuary/Elliott Bay, and 31 outfalls discharge to Lake Union/Ship Canal. The numbers of King County and City of Seattle uncontrolled or controlled CSOs are shown in Table 3-3; the locations of the CSO outfalls are shown in Figure 3-7. For more information on CSO status and receiving waterbodies, see Appendix A.

Table 3-3. Control status of combined sewer overflow outfalls in the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas.

Study Area	Owner	Controlled CSOs	Uncontrolled CSOs
Duwamish Estuary/Elliott Bay	King County	7[a]	10
	Seattle	5	5
Lake Union/Ship Canal	King County	3[b]	4
	Seattle	17	7

[a] Includes Denny Way and Harbor Ave CSOs, which are currently attaining control under supplemental compliance.

[b] Includes the Dexter Ave CSO, which is currently attaining control under supplemental compliance.

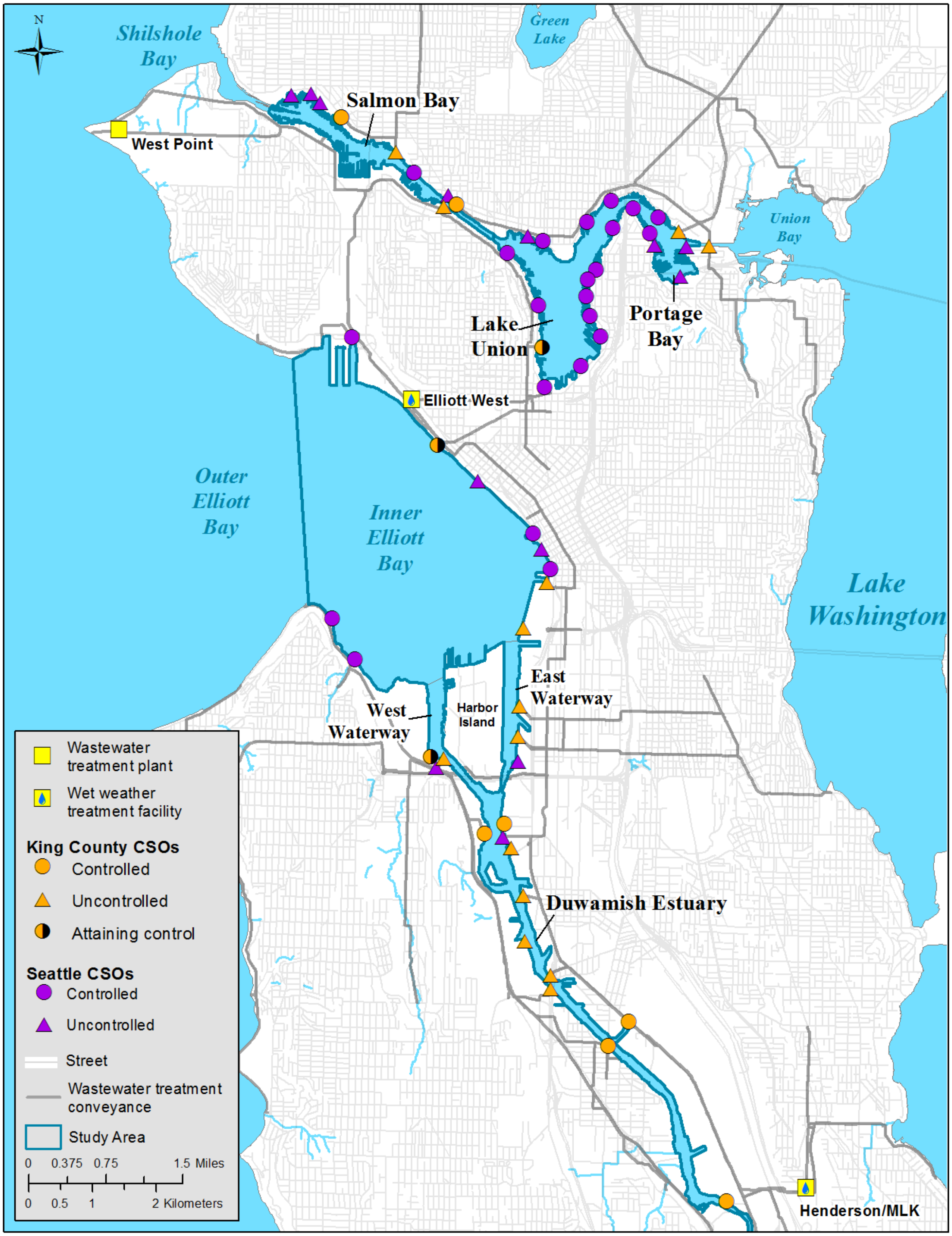

Figure 3-7. **Combined sewer overflow outfalls and treatment facilities that discharge to the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas.**

3.5.1 Uncontrolled CSOs

A total of 26 uncontrolled CSOs discharge to the study areas: 10 King County and 5 Seattle uncontrolled CSOs discharge to Duwamish Estuary/Elliott Bay; 4 King County and 7 Seattle uncontrolled CSOs discharge to Lake Union/Ship Canal. The following water quality and flow data were used to estimate loadings from these uncontrolled CSOs.

Water Quality Data

Water quality data collected from King County CSO discharges (King County, 2009; King County, 2011; King County, 2013b) were compiled to represent the water quality of CSO discharges from King County and Seattle uncontrolled CSOs in the study areas. Data were available for the following COIs and periods:

- BBPs, BEHPs, total PAHs, total arsenic, total copper, total lead, total mercury, total zinc, and TSS: 1996–2015
- Total nitrogen: 2007-2010
- Total phosphorus: 2007–2014
- Fecal coliform bacteria: 1996–2004
- Total PBDEs: 2011–2012
- Total PCBs: 2007–2012

The mean contaminant concentrations and 95 percent confidence limits were calculated for the loading estimates. Summary statistics for the contaminant concentrations can be found in Appendix B.

Hydrologic Data

Discharge volumes for King County and Seattle uncontrolled CSOs were compiled from annual reports (for example, King County, 2015a; SPU, 2015b). For county uncontrolled CSOs, the most recent 10 years of flow data were used (WY 2005–2014). For Seattle uncontrolled CSOs, flow data were available for six years (WY 2009–2014). The mean annual discharge volume and 95 percent confidence limits calculated for all uncontrolled CSOs are presented in Appendix C.

Loading Estimates

The mean and 95 percent UCL and LCL annual King County and Seattle uncontrolled CSO discharge volumes to the study areas were multiplied by the mean and 95 percent UCL and LCL CSO effluent contaminant concentrations, respectively, to estimate the contaminant loadings from uncontrolled CSOs.

3.5.2 Controlled CSOs

A total of 32 controlled CSOs discharge to the study areas: 7 King County and 5 Seattle controlled CSOs discharge to Duwamish Estuary/Elliott Bay; 3 King County and 17 Seattle controlled CSOs discharge to Lake Union/Ship Canal.

Since King County signed the consent decree with EPA in 2013, actions have been taken to attain full control of four CSO locations where control facilities were constructed (EPA, 2013). The control of the Ballard CSO was confirmed in 2014. The Dexter Ave, Denny Way, and Harbor Ave CSOs are currently undergoing adjustments under supplemental compliance to achieve full control.[4]

The following subsections describe the water quality and flow data used to estimate loadings from these controlled CSOs.

Water Quality Data

Water quality data from King County discharges from uncontrolled CSOs were used to represent the water quality of CSO discharges from King County and Seattle controlled CSOs in the study areas. The mean contaminant concentrations and 95 percent confidence limits were calculated for the loading estimates. Summary statistics for the contaminant concentrations can be found in Appendix B.

Hydrologic Data

A combination of monitored and modeled CSO discharge data was used to estimate annual discharge volumes from controlled CSOs discharging to the two study areas. Similarly to uncontrolled CSOs, annual discharge volumes for controlled King County and Seattle CSOs were compiled from annual reports (for example, King County, 2015a; SPU, 2015b). For county CSOs, the most recent 10 years of flow data were used (WY 2005–2014). For Seattle CSOs, flow data were available for six years (WY 2009–2014).

Average annual discharge volumes from King County CSOs that were recently controlled and those under supplemental compliance were estimated using modeled CSO discharge data because long-term monitoring data were not available (King County, 2013d; King County, 2013e; King County, 2013f). King County uses models that simulate the long-term hydrologic and hydraulic responses of the County's controlled CSO outfalls. The modeled data for controlled CSOs reflect the long-term behavior of the system once a CSO is controlled. The model results do not include changes in CSO control over time, but rather represent the performance of the system once controlled. The models have been run with historical rainfall data to determine the system response to a variety of storm conditions and to establish long-term overflow statistics and control requirements for the long-term CSO control plan (King County, 2012).

Average annual CSO volumes were estimated using the 31 water years (WY 1979–2009) of available modeled CSO discharge data. The mean annual discharge volume and 95 percent confidence limits calculated for all controlled CSOs are presented in Appendix C.

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[4] Post-control project facilities require further adjustment to achieve full control status.

Loading Estimates

The mean and 95 percent UCL and LCL annual King County and Seattle controlled CSO discharge volumes were multiplied by the mean and 95 percent UCL and LCL CSO contaminant concentrations, respectively, to estimate contaminant loadings from controlled CSOs.

3.6 Wet Weather Treatment Facilities

Combined sewer flows are diverted to a wet weather treatment facility for primary treatment during large storm events when the instantaneous flow rate to the wastewater treatment plant exceeds secondary treatment capacity. Primary treatment at a wet weather treatment facility removes solids through settling. The effluent is disinfected with chlorine and then dechlorinated prior to discharge.

Two wet weather treatment facilities are located in the Duwamish Estuary/Elliott Bay study area: the Elliott West treatment facility discharges to Inner Elliott Bay near Myrtle Edwards Park, and the Henderson/MLK treatment facility discharges to the Duwamish Estuary at around RM 5.0 (Figure 3-7).

3.6.1 Water Quality Data

King County–monitored water quality data for wet weather treatment facilities were available for the Elliott West, Henderson/MLK, Alki, and Carkeek wet weather treatment facilities. The Alki and Carkeek facilities discharge to Puget Sound outside of the study areas. Data from Elliott West were compiled to characterize the contaminant concentration of the facility’s effluent discharging to Inner Elliott Bay. Because of the differences between the Elliott West and Henderson/MLK treatment facilities and the low sample size for Henderson/MLK facility discharges, data from Henderson/MLK, Alki, and Carkeek treatment facilities were compiled to represent the contaminant concentration of Henderson/MLK effluent discharging to the Duwamish Estuary.

The following water quality data were available:

- Total phosphorus, total arsenic, total copper, total lead, total mercury, total zinc, BBP, and BEHP: 2007–2015
- PCB Aroclors, with no detections; no available data for PCB congeners for comparison with the other pathways
- Total PAH data from the Elliott West wet weather treatment facility

Total PAH data from Henderson/MLK, Alki, and Carkeek treatment facilities were mostly below the detection limit and not included in this analysis. Summary statistics were calculated for the compiled water quality data. Appendix B presents the contaminant concentration summary statistics used to estimate pollutant loadings from Elliott West and Henderson/MLK.

Additionally, fecal coliform bacteria and TSS were monitored for each discharge event from the treatment facilities as required by the NPDES permit (for example, King County 2015a). Data were available for the Henderson/MLK treatment facility for WY 2006–2014. An Elliott West chlorination-dechlorination system improvement project was completed in November 2011. Much lower fecal coliform values were measured after project completion. To represent current conditions of fecal coliform loading, only data collected from discharge events in WY 2012–2014 were used in the Elliott West fecal coliform loading estimates. TSS data were compiled from 2006–2014 data because the improvement project did not appear to affect TSS concentrations.

3.6.2 Hydrologic Data

Average annual flow discharge volumes from the wet weather treatment facilities were estimated by compiling the most recent discharge volumes monitored by King County (for example, King County, 2015a). Discharge event volumes were available for Henderson/MLK from WY 2007–2014 and for Elliott West from WY 2006–2014. It was assumed that the chlorination-dechlorination system improvement project did not have an impact on the Elliott West discharge volumes and therefore the full extent of available discharge data was used. The mean annual flow and 95 percent confidence limits were estimated to represent the volumes discharging from the facilities and are presented in Appendix C.

Fecal coliform bacteria and TSS loadings were estimated from observed water quality data from discharge events and therefore monitoring occurred during the same timeframe as the flow monitoring used to estimate volumes. However, flow data prior to WY 2012 were not included in the fecal coliform loading estimates for the Elliott facility because of the effects of the chlorination-dechlorination system improvement project. Timeframes were as follows: Henderson/MLK (WY 2007–2014 for TSS and fecal coliform), and Elliott West (WY 2006–2014 for TSS and WY 2012–1014 for fecal coliform).

3.6.3 Loading Estimates

For most of the COIs, annual wet weather treatment facility contaminant loadings to Duwamish Estuary/Elliott Bay were estimated by multiplying the mean and 95 percent UCL and LCL annual discharge volumes by the mean and 95 percent UCL and LCL effluent contaminant concentrations, respectively. Fecal coliform and TSS loadings were estimated using the mean of the calculated loads for the years with observed TSS and fecal coliform.

3.7 Atmospheric Deposition

Atmospheric deposition of contaminants onto the surfaces of the study area waterbodies is the result of two factors: the emission of pollutants into the atmosphere and the atmospheric conditions that transport and deposit airborne pollutants (Environment Canada, 2004). The emissions of pollutants originate from two types of sources—natural and anthropogenic:

- Vegetation (such as deciduous and coniferous trees) is the largest source of natural emissions of volatile organic compounds (VOCs), which are greatest during clear skies and warm temperatures (Morgan and Makar, 2001). Marine areas are also important local sources of natural emissions of VOCs (such as methane).
- Anthropogenic sources of emissions are more concentrated in developed areas than in less developed rural areas. Petroleum industries, manufacturing plants, harbor facilities, dry cleaners, and auto body shops are examples of sources of industrial and commercial emissions. Rural activities such as agriculture (such as dust from tillage and animal waste) and forestry practices (such as prescribed burning) are also sources of anthropogenic emissions. Home heating and outdoor burning are types of localized sources found in both rural and urban locations.

The atmospheric conditions that transport and deposit airborne pollutants are largely determined by weather patterns that circulate the air and are, in turn, affected by the topography of the region (for example, Chehalis Gap and Cascade Mountains) (Environment Canada, 2004). During times of air stagnation, the lack of wind flow tends to accumulate localized air pollutants in the airshed between the Olympic and Cascade mountain ranges (Environment Canada, 2004). Airborne pollutants in the airshed do not always originate from localized sources. For example, pollutants enter the region in the spring from the Pacific Ocean, likely from Eurasia (Environment Canada, 2004).

3.7.1 Atmospheric Deposition Data

Atmospheric deposition rates were obtained from previous King County studies in the Green-Duwamish and Lake Washington watersheds in order to characterize atmospheric deposition of pollutants associated with different land use types and degree of urbanization (King County, 2013a; King County, 2013g; King County, 2015b). The data from these previous studies were combined and used for both study areas. Atmospheric deposition rate, or flux, refers to the flow rate of particles and rainfall from the air to the land surface; it is the mass of a chemical deposited on 1 m^2 of land surface per day.

King County (2013a; 2013g; 2015b) used a sampling system modified from the system used by Pacific Northwest National Laboratories (Brandenberger et al., 2010). The sampler consisted of a wood frame supporting four collection funnels designed to collect both rainwater and dry particulates. Each funnel drained directly into a sample bottle. Collection funnels sat approximately 6 feet above the group or roof, depending on the station. Each sampling system had two organics samplers: a metals sampler and a mercury sampler. Collection occurred during the dry and wet seasons.

Figure 3-8 shows atmospheric deposition monitoring locations:

- Bulk atmospheric deposition data (wet and dry deposition) were collected for total arsenic, total copper, total lead, total mercury, total zinc, total PAHs, and total PCBs from four stations in the Green-Duwamish watershed: three along the Lower Duwamish Waterway (LDW) (Duwamish, South Park, and Georgetown stations) and one in Beacon Hill (Beacon Hill Station) (King County, 2013f; King County, 2015b). The LDW stations were centrally located in the LDW corridor and represent a mix of commercial, industrial, and residential land uses in an urban area. The Beacon Hill Station represents urban residential land use.

- King County (2013a) collected atmospheric deposition data for total PCBs and total PBDEs in the Lake Washington watershed from the Sand Point Station located near Magnuson Park close to the Lake Washington shoreline.
- Atmospheric deposition rates were available for the following dates: 2011–2013 for total PCBs, total arsenic, total copper, total lead, total mercury, and total zinc, and 2011–2012 for total PAHs and total PBDEs.

Data from the five stations were combined to represent the range of potential atmospheric deposition loading onto the surface of the Duwamish Estuary, Inner Elliot Bay, and Lake Union/Ship Canal. The data were combined because of the limited number and distribution of sample locations, uncertainty associated with the deposition patterns in the study area airsheds, and lack of local information that may influence atmospheric deposition.

Summary statistics for atmospheric deposition rates can be found Appendix B.

3.7.2 Loading Estimates

Annual direct atmospheric loadings to the two study areas were estimated by calculating the mean and 95percent UCL and LCL contaminant deposition rates and multiplying them by the surface area of each study area waterbody. Atmospheric deposition occurring at other locations in the watersheds that discharge to the study areas is included in the loading estimates for the upstream watersheds, local tributaries, stormwater runoff, and CSO pathways.

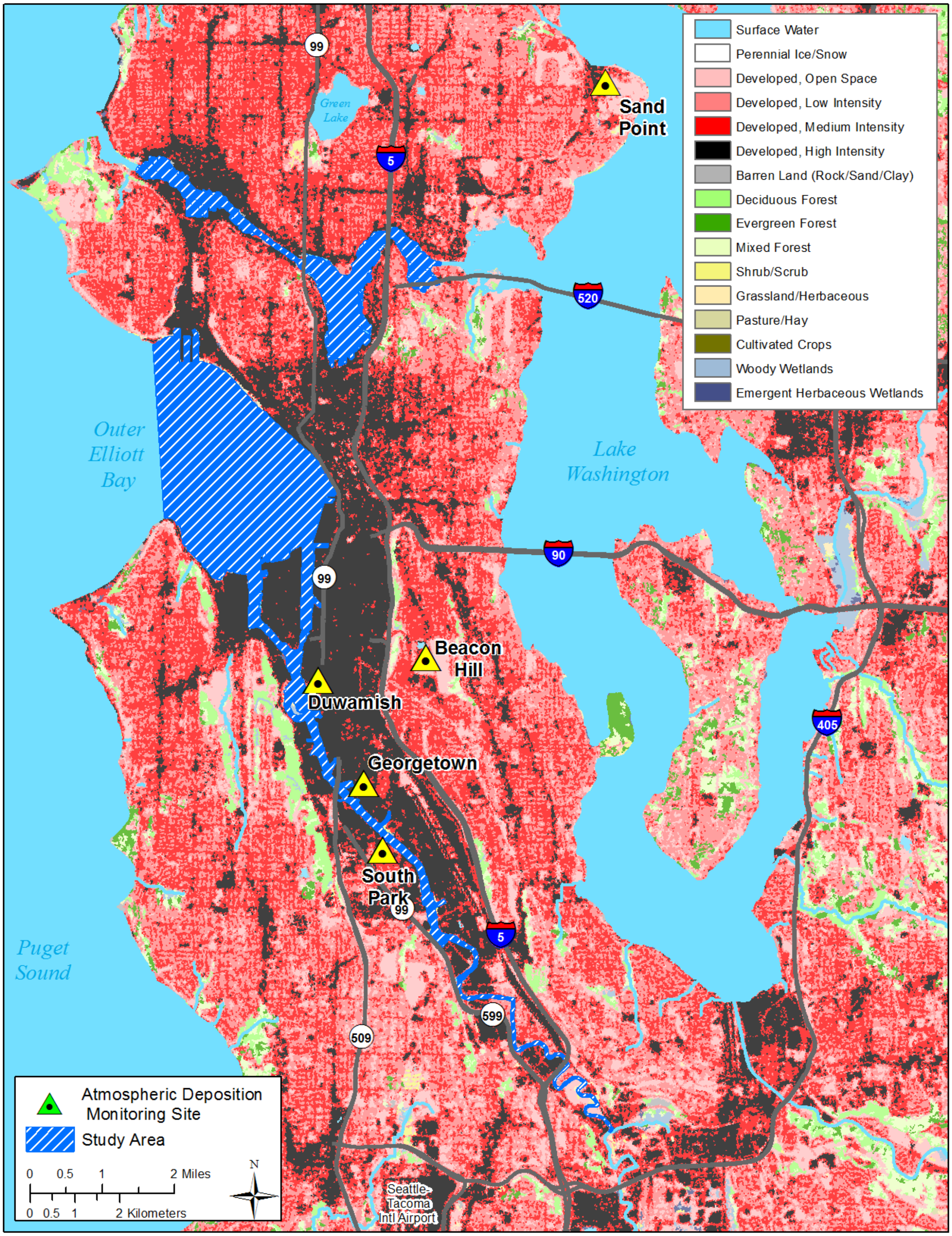

Figure 3-8. **Atmosheric deposition monitoring locations in the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas.**

3.8 Antifouling Paint

Total copper was the only COI loading estimated from antifouling paint because of its intended release into the environment and percent composition in antifouling paint (20–70 percent). The loading from antifouling paint is estimated separately from other discharges originating from vessels.

Copper-based antifouling paints are applied to a vessel's hull to impede buildup of fouling organisms (such as barnacles, mussels, algae, and wood-boring worms) that could damage the vessel and decrease fuel efficiency. The paint is designed to slowly leach copper at the hull surface. In addition to harming the fouling organisms, the leached copper may be toxic to a wide range of aquatic organisms including salmon species important to local fisheries (Hansen et al., 1999; Sandahl et al., 2006). Ecology (2011) identified antifouling paint as a major source of copper release to the Puget Sound basin, along with pesticides, plumbing fixtures, brake pads, and roofing materials.

Antifouling paint is recommended for marine and freshwater vessels that remain in water for long periods. Freshwater use may be less common than saltwater use because of the lower severity of fouling in fresh water (King, pers. comm., 2016), but antifouling paint use on freshwater vessels is still common (Gonzales, pers. comm., 2016).[5,6] Vessels with antifouling paint that spend long periods in salt water but have a home moorage in fresh water may be a pathway of copper into fresh water. For example, the many commercial vessels in Lake Union/Ship Canal's Fishermen's Terminal spend multiple months in the marine environment but moor in fresh water.

In August 2006 and March 2007, Ecology measured dissolved copper concentrations in surface waters in and near two Puget Sound marinas to examine the potential impacts of antifouling paint (Ecology, 2007). The two marinas were Cap Sante Boat Haven (1,050 slips) and Skyline Marina (over 500 marina and private slips), both in the Anacortes area. The study found that acute and chronic marine aquatic life criteria for copper were exceeded, mainly in the inner parts of the marinas. Dissolved copper concentrations at the entrance of the marinas were greater during ebbtide than floodtide but generally met the chronic criteria during ebbtide and always met the criteria during floodtide. This finding suggests that although marina activities were causing a significant increase in dissolved copper and exceedances of criteria, the concentrations did not appear high enough to cause toxicity in adjacent waters.

Prior to the use of copper (before the 1980s) as the active ingredient in antifouling paint, tributyltin (TBT) was commonly used as the active ingredient. In 1990, the Marine Environment Protection Committee proposed to eliminate the use of TBT on vessels less than 25 m (82 feet) long because of the impacts the compound can have on ecologically and

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[5] King, Jason. Fisheries Supply. Seattle, WA.

[6] Gonzales, Frank. Clean Boating Foundation. Seattle, WA.

economically important marine organisms (MEPC, 1990). In 2012, the United States banned the use of TBT (United States Code Title 33, Chapter 51 [Clean Hull]) with some exceptions (warships, scientific equipment, and floating platforms or storage units constructed prior to 2003). Because TBT is no longer allowed, it was not included as a COI.

3.8.1 Leaching Rates

No studies have been conducted to estimate the leaching rate of copper from boat bottom antifouling paint in the study areas. The leaching rate in salt water was estimated from three studies (Schiff et al., 2004; Valkirs et al., 2003; CRWQCB, 2005):

- Schiff et al. (2004) measured the leaching rates of copper from fiberglass panels painted with epoxy and hard vinyl paints. The rates were 4.3 μg/cm^2/day and 3.7 μg/cm^2/day, respectively, with a mean of 4.0 μg/cm^2/day.
- The U.S. Navy measured leaching rates from seven recreational vessels painted with epoxy paints (Valkirs et al., 2003). The reported mean value was 8.2 μg/cm^2/day.
- The California Regional Water Quality Control Board (CRWQB) modeled copper loading for a dissolved copper total maximum daily load (CRWQCB, 2005). CRWQB used data from Schiff et al. (2004) and Valkirs et al. (2003) to estimate mean leaching rates of copper from epoxy paints (7.1 μg/cm^2/day) and hard vinyl paints (5.9 μg/cm^2/day). Using the results of a survey of boatyards in the San Diego area (Johnson and Miller, 2002), CRWQCB assumed that half of the vessels used epoxy paint and the other half used hard vinyl paint and estimated a mean copper leaching rate of 6.5 μg/cm^2/day.

The leaching rates of 4.0 μg/cm^2/day, 6.5 μg/cm^2/day, and 8.2 μg/cm^2/day were used for the purposes of this study to calculate the lower bound, mean, and upper bounds of copper loading from antifouling paint, respectively. The leaching rate in fresh water was assumed to be the same as in salt water. No literature was found that examined leaching rates of copper from antifouling paint in fresh water. It is likely that the leaching rate would be affected by the difference in salinity.

3.8.2 Vessel Population and Dimensions

Antifouling paint is used on the wetted hull surface of a vessel. A bow coefficient (b), which accounts for the tapering of the bow, and the vessel width and length were used to estimate the wetted hull surface area (Equation 4). The bow coefficient was 0.85 for most vessels, 0.75 for container and passenger (cruise) ships, and 1 for barges.

$$A_v = (l_v)(w_v)(b) \tag{4}$$

Where:

$A_v = wetted\ hull\ surface\ area\ (cm^2)$

$l_v = length\ of\ vessel\ (cm)$

$w_v = width\ of\ vessel\ (cm)\ (\frac{l_v}{3}\ for\ recreational\ vessels;\ \frac{l_v}{6}\ for\ commercial\ vessels)$

$b = bow\ coefficient$[7]

The dimensions of the vessels populating the study areas vary based on the type of vessel. Four categories of vessels use the study areas: commercial, recreational, tugboats, and barges. The following was done to account for differences in these categories for vessels in Duwamish Estuary/Elliott Bay:

- Commercial vessels were divided into two subcategories: those logged by the Port of Seattle and those not logged by the Port of Seattle.
- Recreational vessels were divided into two subcategories: those in the Elliott Bay Marina and those outside the Elliott Bay Marina.

Different methods were used for each of the categories to determine the number of vessels in the study areas, the wetted hull surface area (length, width, bow coefficient), and the length of time in the study areas. The methods for each vessel category are summarized in Table 3-4 and discussed in the sections that follow.

Table 3-4. Methods used to estimate contaminant loadings from antifouling paint for each vessel category in the Duwamish Estuary/Elliott Bay and Lake/Union Ship Canal study areas.

Study Area	Vessel Category	Number of Vessels (n)	Length (l_v)	Width[a] (w_v)	Bow Coefficient (b_v)	Time in Study Area (t)
Duwamish Estuary/ Elliott Bay	Recreational (Elliott Bay Marina)	D	D	l_v/3	0.85	365 days
	Commercial (Port of Seattle)	E	F	F	0.75 (container ships only); 0.85 (all other vessels)	E
	Recreational (outside Elliott Bay Marina)	A	B	l_v/3	0.85	365 days
	Commercial (non-Port tugboats)	G	F	F	0.85	365 days
	Commercial (non-Port barges)	H	H	H	1.00	365 days
Lake Union/Ship Canal	Recreational	A	B	l_v/3	0.85	365 days
	Commercial	A	C	l_v/6	0.85	365 days

[a] Width was derived from a desktop analysis of the ratio of a vessel's length to width.
A = Counts were determined from Google maps satellite imagery viewed on 7/30/2015.
B = Average length of a recreational vessel was derived from 2011 registered vessels in King County. It was assumed that vessels < 610 cm (20 ft) were stored either on trailers or dry-dock. The average length of on-the-water vessels was calculated from a population of vessel lengths consisting of 89% 910 cm, 5.5% 1,525 cm, and 5.5% 1,830 cm.
C = The average length of a commercial vessel (3,350 cm) was estimated from lengths measured on Google maps satellite imagery viewed on 7/30/2015.
D = The number and length of boat slips at the Elliott Bay Marina were used to determine the number of vessels and length of vessels (http://www.elliottbaymarina.co/wp-content/uploads/2012/12/68748-EBM_Map-v2-1.pdf).
E = The number of commercial vessels at call at Port of Seattle and the length of stay (days) were obtained from the 2014 Port vessel log.
F = The length and width of a vessel were obtained from www.marinetraffic.com using the vessel's name.
G = The number of tugboats in a study area was estimated from Live Map on www.marinetraffic.com, accessed on several occasions to determine the average number of vessels.
H = The number, length, and width of barges were determined from King County 2013 aerial photos in ArcGIS.

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[7] Calculation of wetted hull surface area and the use of a bow coefficient were derived from Interlux (2013).

Lake Union/Ship Canal Vessels

It was assumed that recreational and commercial vessel populations in the Lake Union/Ship Canal study area spend the majority of the year in the study area (365 days).

The loads from the recreational and commercial vessels were summed to calculate the total load of copper into the study area from antifouling paint. The methods for estimating the number and dimensions of the recreational and commercial vessel populations in the Lake Union/Ship Canal are detailed below.

Recreational Vessels

The number of vessels in the Lake Union/Ship Canal study area was estimated from King County orthoimagery taken July 1, 2013. A total of 3,650 recreational vessels were counted. Vessels in transit or on dry-dock were excluded because their homeports could not be confirmed. Boat slips under a covered marina were assumed to be occupied with a recreational vessel.

The average length of a recreational vessel was estimated from Washington State's 2011 registered vessels residing in King County. Vessels less than 20 ft (610 cm) long were not included in the calculation of the average length of a recreational vessel. It was assumed that these vessels would either be stored in dry dock or kept on a trailer and, thus, would not be leaching copper into the study area the entire year. Registered vessels kept on the water were divided into three classes: 20–40 ft (average of 30 ft; 89 percent), 40–60 ft (average 50 ft; 5.5 percent), and greater than 60 ft (average 65 ft; 5.5 percent).

Using Equation 4, the average wetted hull surface area of a recreational vessel in the Lake Union/Ship Canal study area was estimated to be 330 ft^2 (3.08×10^5 cm^2).

Commercial Vessels

A total of 400 commercial vessels were counted in the Lake Union/Ship Canal study area using July 2013 orthoimagery. Because July is the peak month for commercial fishing, the number of commercial vessels counted is likely an underestimate of the year-round population. Vessels in transit or on dry dock were not counted because their homeports could not be confirmed. The average length of a commercial vessel, 110 ft (3,350 cm) was calculated by averaging the measurements of the approximate length of all the commercial vessels counted in the study area.

Using Equation 4, the average wetted hull surface area of a commercial vessel in the Lake Union/Ship Canal study area was estimated to be 1,700 ft^2 (1.59×10^6 cm^2).

Duwamish Estuary/Elliott Bay Vessels

The annual loading of copper from antifouling paint was estimated for the Duwamish Estuary/Elliott Bay study area using data derived from King County July 2013 orthoimagery, a map of the Elliott Bay Marina, the 2014 Port of Seattle vessel log, the website www.marinetraffic.com, and the 2013 King County aerial layer in ArcGIS.

It was assumed that all vessels, except barges and vessels at call in the Port of Seattle, spend the majority of time in the study area and therefore a time of 365 days was used to calculate the loadings into Duwamish Estuary/Elliott Bay. The length of time a vessel was at call in the Port varied from less than one day to nine days. Barges often travel outside of the study area, so the range of days in the area was estimated to be from 25 percent of the year (92 days) to a full year (365 days).

The loads from the vessel categories were added together to calculate the total load of copper into the Duwamish Estuary/Elliott Bay study area from antifouling paint. The methods for the estimating the numbers and dimensions of the recreational, commercial, tugboat, and barge vessels in the Duwamish Estuary/Elliott Bay are described below.

Elliott Bay Marina – Recreational Vessels

Unlike for other recreational vessels in the two study areas, location-specific data were available to calculate the wetted hull surface area for the vessels located in the Elliott Bay Marina. The data from the Elliott Bay Marina map were used to determine the number and the average length of vessels at the marina (http://www.elliottbaymarina.co/wp-content/uploads/2012/12/68748-EBM_Map-v2-1.pdf). The marina has 1,202 boat slips; the average slip length is 42 ft (1,300 cm).

Using Equation 4, the average wetted hull surface area of a recreational vessel at the Elliott Bay Marina is approximately 500 ft^2 (4.65×10^5 cm^2). This is 50 percent more surface area than that calculated for recreational vessels in the Lake Union/Ship Canal study area.

Recreational Vessels in Other Parts of the Study Area

In addition to the vessels in the Elliott Bay Marina, 350 recreational vessels were counted along the Duwamish Estuary using July 2013 orthoimagery; no other recreational vessels were counted in Elliott Bay. Vessels in transit or on dry dock were not counted because their homeports could not be confirmed. Boat slips under a covered marina were assumed to be occupied with a recreational vessel.

The average wetted hull surface area of a recreational vessel in the Duwamish Estuary/Elliott Bay study area (other than vessels in the Elliott Bay Marina) was estimated to be 330 ft^2 (3.08×10^5 cm^2).

Port of Seattle Vessels – Commercial Vessels

The loading of copper from antifouling paint on commercial vessels at call in the Port Seattle was estimated for each vessel and then summed for a cumulative load. The wetted hull surface area of each vessel was determined by using the name of the vessel listed in the 2014 Port vessel log and obtaining the vessel's dimensions (length and width) from www.marinetraffic.com. A vessel's date of departure (reported to the minute) was subtracted from the vessel's date of arrival (reported to the minute) to determine the number of days at call. In 2014, 739 commercial vessels were at call: 479 container, 180 passenger, 79 bulk carrier, and 1 roll on-roll off (ro-ro) cargo vessel.[8] Table 3-6 shows the number of days at call in the Port and wetted hull surface areas for the four vessel types from the 2014 Port of Seattle vessel log.

Table 3-5. 2014 Port of Seattle vessel log summary for commercial vessels at call in the Duwamish Estuary/Elliott Bay study area.

Vessel Type	Number of vessels (n)	Time at Call in Port (days)			Wetted Hull Vessel Surface Area (cm^2)		
		Minimum	Maximum	Average	Minimum	Maximum	Average
Bulk carrier	79	0.4	9.1	3.5	3.9×10^7	9.3×10^7	6.0×10^7
Container	479	0.2	8.4	1.4	8.9×10^6	1.2×10^8	8.5×10^7
Passenger	180	0.4	4.0	0.4	3.5×10^7	8.9×10^7	7.4×10^7
Roll on-roll off cargo	1	0.4	0.4	0.4	4.2×10^7	4.2×10^7	4.2×10^7

Tugboats

The website www.marinetraffic.com was referenced to estimate the average number of tugboats in the Duwamish Estuary/Elliott Bay study area and to calculate the average wetted hull surface area. On average, six tugboats were present in the website's Live Map view of the study area (randomly viewed on weekdays, 8 am – 4 pm Pacific Daylight Time, July through September). The vessel dimensions ranged from 20–30 m long and 6–10 m wide. Because tugboats operate year round, the vessels were assumed to be in the study area for 365 days. The average length and width of 25 m and 8 m, respectively, were used to calculate the load of copper leached from antifouling paint on tugboats.

Barges

Copper loading from antifouling paint on barges in the Duwamish Estuary/Elliott Bay study area was estimated using data obtained from July 2013 orthoimagery. A total of 73 barges were counted, with an average wetted hull surface area of 1.0×10^7 cm^2 (minimum = 1.3×10^6 cm^2; maximum = 3.7×10^7 cm^2). A bow coefficient was not used when calculating the wetted hull surface area because the barges are rectangular. Because barges are transitory and seasonal, a range of the number of barges (n) (25 percent to 100 percent) was included in the range of copper loadings from barges:

- Lower bound using a leaching rate of 4.0 μg/cm^2/day; $n = (0.25)*(73$ vessels)
- Mean using a leaching rate of 6.5 μg/cm^2/day; $n = (0.5)*(73$ vessels)
- Upper bound using a leaching rate of 8.2 μg/cm^2/day; $n = (1.0)*(73$ vessels)

The length of time in the study area was 365 days, assuming that at any time in the year there will be n amount of barges present.

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[8] Roll on–roll off vessels are designed to carry wheeled cargo.

3.8.3 Loading Estimates

Equation 5 was used to calculate total copper loading estimates. The loading estimates were the product of the copper leaching rate, number of vessels, vessel wetted hull surface area, and length of time in the study area. The load was calculated for each vessel category separately and then summed for the total copper loading of the boat bottom antifouling paint pathway:

$$Load = \sum(l_{AFP})(n_v)(A_v)(t)(\frac{1\,x\,10^{-9}\,kg}{1\,ug})\,) \tag{5}$$

Where:

$l_{AFP} = leaching\ rate\ of\ copper\ from\ antifouling\ paint\ (4.0, 6.5, or\ 8.2\ \mu g/cm^2/day)$
$n_v = number\ of\ vessels\ in\ the\ study\ area\ with\ applied\ antifouling\ paint$
$A_v = vessels'\ wetted\ hull\ surface\ area\ (cm^2)$
$t = length\ of\ time\ within\ study\ area\ (days)$

The estimated total copper loading rate is 0.74 kg/vessel/year, which is slightly lower than the loading rate of 0.85 kg/vessel/year estimated in the CRWQCB (2005) study. Both loading rates were based on the 6.5-µg/cm^2/day total copper leaching rate from CRWQCB (2005). The annual load of total copper in CRWQCB (2005) (from antifouling paint in yacht basins) was determined using an equation similar to Equation 5, assuming that the vessels were present throughout the year (t = 365 days) and that the number of vessels was equal to the number of vessel slips. CRWQCB calculated the average recreational vessel surface area with Equation 4, which resulted in a vessel surface area of approximately 35 m^2. In contrast, the estimated average recreational vessel surface area in Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas was 31 m^2. This difference in vessel surface areas explains the difference in total loadings rates.

3.9 Creosote-Treated Wood Pilings

Chemical preservatives are often applied to wood used in outdoor applications to slow decay by preventing growth on or in the wood. Creosote, a coal-tar based distillate, is extensively used as a long-term wood preservative for marine and freshwater pilings (support structures), utility poles, and railway ties. The primary effective components in creosote are PAHs, which account for 75 to 90 percent of the composition. Because of the effectiveness of creosote to protect wood from decay, with an estimated longevity as high as 75–100 years in colder environments (Smith, 2007; Cooper, 1991), creosote-treated pilings are the most commonly used marine piling. Metals-based preservatives such as chromated copper arsenate and ammoniacal copper zinc arsenate are also used to treat wood. These preservatives are not as common as creosote for in-water applications and are not included in this study.

The preservatives in treated wood used in water applications (such as pilings) can leach from the wood and mix with the water column. Some can adsorb to sediments. The leaching rate is affected by factors such as current speed, salinity, temperature, type of preservative, and age and method of the treatment process (EVS, 1994). Pilings in colder, slower moving waters typically leach less than those in warmer waters with faster currents. In locations where currents are slow and contact from vessels abrade the pilings, such as the end of a boat slip, PAHs tend to accumulate in sediments closer to the pilings (within 2 m) and in higher concentrations. As currents increase, the PAHs are more evenly dispersed from the pilings and accumulate in lower concentrations (Stratus, 2006; Evans et al., 2009). The PAHs that accumulate in sediment are typically the high molecular weight PAHs (HPAHs), some of which are carcinogenic; the more water-soluble low molecular weight PAHs (LPAHs) are more readily transported away with the currents and degrade.

In 2004, Washington State's Department of Natural Resources began a program to identify and remove creosote-treated debris and nearshore structures that no longer serve a function in the Puget Sound area. The City of Seattle banned the use of creosote for in-water marine and freshwater applications beginning in January 2013 (Seattle Municipal Code 23.60A.187(c)(15) and (e)(5)). However, the existing creosote-treated pilings will continue to leach PAHs into the environment for many decades.

In aquatic environments, creosote-treated wood products may account for a substantial fraction of the total mass loading of PAHs (Katz, 1998; Ecology, 2012). Approximately 20 percent of creosote by weight is EPA 16 priority PAHs. Concentrations vary depending on the distillation process (Valle et al., 2007).

The leaching rate of PAHs from creosote-treated pilings was estimated from available literature because no studies have been done to estimate leaching rates in the study areas.

3.9.1 Piling Counts and Surface Area

The total surface area of creosote-treated pilings that leach to the water column (SA) was calculated by estimating the number and average length of pilings by subarea in the waterbodies (Equation 6). Piling diameters can vary from less than 8 inches to greater than 18 inches, depending on the application (Collin Group, 2002). For support of large structures, such as docks and piers, larger diameter pilings are used. To allow for uncertainty in these estimates, three diameters were used to create low, mid, and high estimates.

$$SA_{TOT} = \sum(\pi * d) * l_i * n \tag{6}$$

Where:
$SA_{TOT} = surface\ area\ of\ pilings\ leaching\ to\ the\ water\ column\ (cm^2)$
$d = diameter\ of\ piling\ (cm)$
$l_i = length\ of\ piling\ exposed\ to\ water\ column\ in\ subarea\ "i"\ (cm)$
$n_i = number\ of\ pilings\ in\ subarea\ "i"$

The number of pilings in a study area was estimated by assuming a piling density (number of pilings per unit area) for three overwater structure categories:

- Low density docks and piers (such as finger piers): 0.15 piling/m^2

- High density docks and piers (such as Pier 48 along the downtown Seattle waterfront): 0.25 piling/m^2
- Covered docks: 0.035 piling/m^2

These densities were estimated by sub-sampling and counting individual pilings. Structures with creosote-treated pilings were identified in the Bird's Eye feature in Bing Maps by panning across the nearshore landscape. Polygons for identified structures were created in ArcGIS 10.1. Floating docks are typically supported by pilings constructed of materials other than creosote-treated wood (concrete or aluminum); these pilings were not counted. Also not counted were dolphins (clusters of creosote-treated pilings) and isolated pilings that are not associated with a structure. An estimated 24,000 pilings are located in Lake Union/Ship Canal; 39,000 are located in Duwamish Estuary/Elliott Bay (Table 3-6).

The lengths of the pilings exposed to the water column were estimated using the nearshore depth from bathymetry maps (http://www.charts.noaa.gov).[9] Because the bathymetry is not constant, the study areas were subdivided into sections where depths were assumed to be similar throughout (Table 3-6). For each section, Equation 6 was used to calculate the total surface area of pilings present and then the total surface area was summed by study area. The piling lengths exposed to water (*l*) in each section are given in Table 3-6. To account for the large amount of uncertainty in the piling counts and lengths, the estimated counts were multiplied by factors of 0.5, 1.0, and 1.5 to expand the range of the estimates.

Table 3-6. Average lengths of exposed piling and estimated number of pilings in the Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal study areas.

	Lake Union/Ship Canal Sections			Duwamish Estuary/Elliott Bay Sections			
	Portage Bay	Lake Union	Salmon Bay	Elliott Bay	West Waterway	East Waterway	Lower Duwamish Waterway
Length of piling exposed to water (*l*) (m)	4.6	9.1	5.3	9.1	12	11	6.1
Number of pilings (*n*)	6,000	7,700	10,700	18,800	4,800	2,400	13,300

3.9.2 Piling Concentrations and Leaching Rate

Several studies have shown that the majority of the leaching of creosote from marine pilings occurs in the first few days to months of service (Bramhall and Cooper, 1972; Cooper, 1991). In fresh water, Kang et al. (2005) found that leaching of PAHs from recently treated wood was greatest immediately after immersion and then decreased, reaching a steady state after one week of approximately 1.7 mg/cm^2/yr of the EPA 16 priority PAHs from the treated wood's surface area. Because no new creosote-treated pilings are being

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[9] Data from the National Oceanographic and Atmospheric Administration's Office of Coast Survey website: Chart 18447, 30th edition (9/12), for Lake Washington Ship Canal and Chart 18450, 19th edition (11/12), for Seattle Harbor, Elliott Bay, and Duwamish Waterway

installed in the study areas, only the estimated leaching rates of older pilings were used in this loadings analysis.

A 1995 study in the brackish water of San Diego Bay calculated the leaching rate of total PAHs from creosote-treated pilings based on in situ measurements (Katz et al., 1995). The estimated range of total PAH leaching from the aged pilings was 2.2 mg/cm^2/yr to 3.3 mg/cm^2/yr. Assuming that one-quarter of the PAHs are priority PAHs, the range of priority PAH leaching is estimated to be 0.55 mg/cm^2/yr to 0.825 mg/cm^2/yr.

Ingram et al. (1982) found that the leaching rate of the PAHs in salt water is approximately 50 percent less than that in fresh water. Thus, the saltwater leaching rate estimates from Katz et al. (1995) translate to a range of 1.1 mg/cm^2/yr to 1.65 mg/cm^2/yr, similar to that estimated for fresh water by Kang et al. (2005).

Flow velocity and temperature are positively correlated with PAH leaching rates (Ingram et al., 1982; Kang et al., 2005). However, the influence of flow and temperature were not included in loading estimates from pilings. The flow velocity in San Diego Bay may be similar to that of Elliott Bay and Lake Union/Ship Canal, but the water temperatures in San Diego are typically warmer than those of Seattle.

3.9.3 Loading Estimates

The annual loading of total PAHs from creosote-treated pilings was estimated for the study areas using six assumed leaching rates (three for salt water and three for fresh water), three assumed piling diameters (0.30 m, 0.36 m, and 0.41 m), and three piling count uncertainty factors (0.5, 1.0, and 1.5) to calculate the lower, mid, and upper loading limits, respectively (Table 3-7). The estimated annual PAH loading rate per piling for Lake Union/Ship Canal was 0.08 kg/piling/yr to 0.15 kg/piling/yr, and the estimated rate for Duwamish Estuary/Elliott Bay was 0.04 kg/piling/yr to 0.09 kg/piling/yr.

Table 3-7. Factors used in estimating PAH loading rate per creosote-treated piling.

Loading Limit	Freshwater Leaching Rate (mg/cm^2/year)	Saltwater Leaching Rate (mg/cm^2/year)	*d* - Piling Diameter (m)	Piling Count Uncertainty Factor
Lower	1.1	0.55	0.41	0.5
Mid	1.4	0.70	0.36	1.0
Upper	1.7	0.85	0.3	1.5

In a PAH chemical action plan, Ecology (2012) estimated an annual PAH loading rate of 0.482 kg/piling/yr into Puget Sound from creosote-treated pilings, which was derived from release rates in Valle et al. (2007). Anchor QEA (2015) estimated a PAH leaching rate from pilings over a 25-year lifetime in the Duwamish Estuary using an equation developed by Brooks (1997), which considers salinity and temperature. Using salinity and temperature data from 2006–2011, Anchor QEA (2015) calculated a mean leaching rate of 0.23 kg/piling/yr that includes the initial year when the leaching rate is elevated. An aged piling in the Duwamish Estuary is estimated to release approximately 0.06 kg/yr, based on the Brooks (1997) model. Ecology (2012) and Anchor QEA (2015) calculated total PAH loadings using the total PAH concentration in creosote and did not consider the fraction of priority PAHs present, and Ecology (2012) did not consider that the majority of the loss occurs in the initial year.

Katz et al. (1995) estimated that 13,600 creosote-treated pilings in the 49-km^2 brackish San Diego Bay leached 3,100 to 4,600 kg of PAHs per year, or 0.22 to 0.37 kg/piling/yr. This load corresponds to the mass of all PAHs, not just the priority PAHs. Assuming that priority PAHs represent 25 percent of the total mass of PAHs, the estimated loading rate is 0.06 kg/piling/yr to 0.08 kg/piling/yr, similar to that of this study.

3.10 Pathways Not Quantified

Loadings from vessel discharges, sacrificial anodes, groundwater, shoreline erosion, and Puget Sound were not estimated because of limited or insufficient data. Each of these pathways may be contributing contaminant loadings to the study areas. A literature review was done to gauge the impact they may have on the study areas, as described below.

3.10.1 Vessel Discharges

During a vessel's operation and maintenance, numerous discharges occur that may affect surface water quality. The quantity and quality of vessel discharges vary by operation. Common contaminants include metals (such as arsenic, mercury, and zinc), nutrients, oils and greases, PAHs, and VOCs (EPA, 2010).

Beginning in 2008, discharges from non-military, non-fishing commercial vessels greater than 79 ft are being regulated by EPA through an NPDES Vessel General Permit (VGP). Discharges from non-military, non-recreational vessels less than 79 ft and all commercial fishing vessels are regulated through a small VGP (sVGP). Shortly after issuance of the regulation, a moratorium was imposed that allows vessels subject to the sVGP to operate without the permit. In December 2014, a law was signed extending the moratorium to the end of 2017. In response to the initial moratorium, EPA (2010) produced a report estimating contaminant loads discharged from vessels subject to sVGP coverage.

The EPA (2010) study estimated vessel discharge loading rates from hypothetical fishing, metropolitan, and recreational harbors. The objective of the study was to characterize the nature, type, composition, and average volumes discharged for each vessel class studied (such as fishing, tour, water taxi, research). Vessel discharges included bilgewater, deck washdown and runoff, propulsion and generator engine effluents, firemain systems, fish hold and fish hold cleaning effluents, graywater (bathing, dish washing, laundry), and shaft packing gland effluent. Blackwater (sewage) or ballast discharges were not included in the study. Loading rates were based on vessels sampled across the country. The three hypothetical harbor scenarios were modeled using total vessel populations from the top 20 homeports in the United States (Table 3-8):

- Fishing harbor (70 percent fishing vessels; 30 percent non-fishing vessels) assuming a population of 175 vessels

- Recreational harbor (45 percent fishing vessels; 55 percent non-fishing vessels) assuming a population of 175 vessels
- Metropolitan harbor (32 percent fishing vessels; 68 percent non-fishing vessels) assuming a population of 300 vessels

The estimated contaminant loading rates from these harbors are presented in Table 3-9.

Table 3-8. Vessel populations for hypothetical fishing, metropolitan, and recreational harbors modeled from the top 20 homeports in the United States (EPA, 2010).

Vessel Class	Vessel Subclass	Fishing Harbor		Metropolitan Harbor		Recreational Harbor	
		No. of Vessels	%	No. of Vessels	%	No. of Vessels	%
Fire boat	NA	1	0.6	5	1.7	1	0.6
Fishing	Gillnetter	12	6.9	10	3.3	9	5.1
Fishing	Lobster boat	12	6.9	10	3.3	9	5.1
Fishing	Longliner	24	13.7	16	5.3	15	8.6
Fishing	Purse seiner	12	6.9	10	3.3	9	5.1
Fishing	Shrimper	10	5.7	8	2.7	5	2.9
Fishing	Tender Vessel	20	11.4	10	3.3	9	5.1
Fishing	Trawler	20	11.4	16	5.3	13	7.4
Fishing	Troller	12	6.9	10	3.3	9	5.1
Research	NA	2	1.1	10	3.3	8	4.6
Supply boat	NA	12	6.9	55	18.3	10	5.7
Tour boat	NA	10	5.7	20	6.7	24	13.7
Tow/ salvage	NA	6	3.4	40	13.3	20	11.4
Tugboat	NA	12	6.9	60	20.0	10	5.7
Water taxi	NA	10	5.7	20	6.7	24	13.7
Total vessels		175		300		175	

Table 3-9. Estimated daily contaminant loading rates from fishing, metropolitan, and recreational harbors (EPA, 2010) (kg/day, unless noted).

Analyte	Fishing Harbor (175 vessels)	Metropolitan Harbor (300 vessels)	Recreational Harbor (175 vessels)
Fecal coliform (CFU/day)	2.75×10^{10}	8.15×10^{10}	2.03×10^{10}
Total suspended solids	104	93	84
Total nitrogen (TKN + nitrate/nitrite)	44.1	30.9	26.6
Total phosphorus	6.21	4.01	3.48
Total arsenic	0.0126	0.0162	0.0142
Total copper	0.071	0.081	0.074
Total lead	0.0049	0.0069	0.0064
Total zinc	0.341	0.276	0.232
BEHP	0.0007	0.0016	0.0016

CFU = colony forming unit.
TKN = total Kjeldahl nitrogen.

The hypothetical harbors in the EPA (2010) study are not comparable to the harbors in Duwamish Estuary/Elliott Bay and the Lake Union/Ship Canal because of the differences in the boat composition of the harbors, behavior of the vessel populations, and uncertainty of vessel discharges occurring in the study areas.

The vessel populations in the study areas were determined through desktop analysis using satellite imagery available from Google maps on July 30, 2015. Only in-water vessels at docks or piers were counted; vessels under way or in dry-dock were not included:

- The Lake Union/Ship Canal study area vessel population was estimated to include approximately 400 commercial fishing vessels and non-recreational vessels less than 79 feet and approximately 3,650 recreational vessels.
- The vessel population in the Duwamish Estuary/Elliott Bay study area consists primarily of non-fishing commercial vessels greater than 79 feet and includes an estimated 1,550 recreational vessels.

The EPA (2010) hypothetical harbors did not include recreational vessels or non-fishing commercial vessels greater than 79 ft (such as cruise ships, ferries, and tankers). The loading rates from the EPA study cannot be extrapolated to these vessels because their design, construction, and operation differ considerably from those included in the study.

EPA has designated Seattle as a fishing harbor because the vessel composition is 69 percent fishing and 31 percent non-fishing. Although many commercial fishing vessels have a homeport in Seattle, most do not undertake activities locally that would generate discharges associated with fishing vessels (fish hold and fish hold cleaning effluents). Most of Seattle's fishing vessels travel north to the Bering Sea and Gulf of Alaska and offload their catch at ports in Alaska and Canada. It is uncertain as to how much fish hold effluent is discharged in the study areas since a common practice is to discharge while under way.

It is illegal to discharge blackwater and contaminated bilge water into the waters of Washington state. Many of the marinas in the study areas require BMPs for vessel discharges. The Port of Seattle requires BMPs for commercial vessels in Fishermen's Terminal and Maritime Industrial Center located in the Lake Union/Ship Canal study area. The BMPs prohibit the discharge of laundry water from a vessel and require that graywater be discharged to a pump-out station. Clean water under pressure can be used to clean boat decks, but any turbidity, oil sheen, or discoloration to the receiving water is prohibited.[10] Additionally, some marinas in the study areas, such as the Elliott Bay Marina, Fremont Boat Company, Fishermen's Terminal, Harbor Island Marina, Shilshole Bay Marina, and Seattle Yacht Club, are certified Clean Marinas in Washington state and require BMPs to reduce pollution entering the waterbodies.[11] These BMPs prohibit the discharge of oil, fuel, antifreeze, contaminated bilge water, and sewage; minimize detergent usage and food

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[10] Port of Seattle commercial vessel BMPs: https://www.portseattle.org/Commercial-Marine/Maritime-Industrial-Center/Documents/FTBMP_2008.pdf.

[11] For a complete list of certified Washington Clean Marinas, see http://www.cleanmarinawashington.org/certifiedmarinas.asp.

waste in onboard sinks and showers; minimize use of cleaners; and specify that cleaners be phosphate-free.[12]

3.10.2 Sacrificial Anodes

Sacrificial anodes are used to prevent galvanic corrosion on metal vessel hulls exposed to water. These anodes may be zinc, magnesium, or magnesium or aluminum alloys. The anode is preferentially corroded or "sacrificed" to produce a flow of electrons to the cathode that reduces or eliminates corrosion at the cathode. Sacrificial anodes continually corrode when immersed and require routine replacement to maintain sufficient mass and surface area for cathodic protection.

Zinc anodes are the most commonly used to the degree that anodes are colloquially referred to as "zincs." Recently, boating publications have recommended using different metals based on salinity of the waters (Falvey, 2013). Aluminum or zinc anodes are recommended for salt or brackish water, and aluminum or magnesium anodes are recommended for fresh water. Despite these recommendations, zinc anodes remain the most popular anode for both saltwater and freshwater use, but aluminum anodes are increasingly used (F. Gonzales, pers. comm., 2016). Zinc anodes also contain small amounts of cadmium.

Zinc is one of the COIs in this loadings analysis. However, the annual zinc loading from sacrificial anodes was not estimated for this loadings analysis because there is uncertainty regarding the recommended zinc anode rate for each vessel in the waterbody, whether vessel owners follow the recommended zinc anode rate, how frequently owners replace anodes, and what percentage of vessels use zinc anodes (opposed to the alternatives).

Based on the available, albeit limited, data, it appears that zinc anodes may be a substantial pathway of zinc to Duwamish Estuary/Elliott Bay. The following paragraphs discuss the findings from a literature review and provide a "worst-case" estimate of zinc loadings.

In fresh waters, zinc anodes do not have the current output to fully protect against corrosion (Harbor Island Supply, 2016). According to the industry professionals at Harbor Island Supply, zinc anodes are not "sacrificed" at a meaningful or useful rate in fresh water. Therefore, it is not likely that zinc anodes are a substantial pathway of zinc in Lake Union/Ship Canal. In the brackish and saltwater Duwamish Estuary and Elliott Bay, zinc anodes can provide adequate protection and thus can be a substantial pathway of zinc.

A 1999 EPA nature of discharge report for cathodic protection examined the loading of zinc from vessels of the armed forces (EPA, 1999). The report estimated average at-dock and underway zinc leaching rates into salt water of 1.3×10^{-6} wetted surface/hr and 5.1×10^{-6} lb/ft^2 wetted surface/hr, respectively (0.63 μg/cm^2/hr and 2.49 μg/cm^2/hr). The mass of

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[12] Certified Washington Clean Marina BMPs can be found at http://www.cleanmarinawashington.org/CleanMarinaBMPs.pdf.

anodes applied to the vessels was estimated at 23 lb/115 ft^2 (98 mg/cm^2) of total wetted area for large vessels (with more than 3,000 ft^2 of wetted area) and 23 lb/400 ft^2 (28 mg/cm^2) of total wetted area for smaller vessels, boats, and craft.

The American Boat & Yacht Council's marine corrosion guide recommends using a total weight of sacrificial anodes based on the following formula (ABYC, 2008):

$$\frac{Anode\ Weight\ (lbs)}{Wetted\ Surface\ Area\ (ft^2)} = \frac{Current\ Density\ (mA/ft^2) * Immersion\ Time\ (hrs)}{Energy\ Content\ (Amp - hrs\ per\ lb) * 1000\ mA/Amp}$$

Where:
368 amp-hrs/lb = energy content of a zinc anode
Immersion time = number of hours in water per replacement interval
Current density = function of flow rate and the quality of the hull's protective paint coating (can range from 1.5 mA/ft^2 to 100 mA/ft^2 in high velocity water with an uncoated hull)

Assuming an annual replacement rate of 8,766 hours (immersed) and a current density of 1.5 mA/ft^2 to 30 mA/ft^2, the required zinc anode density is between 0.036 lb/ft^2 and 0.71 lb/ft^2 (17 mg/cm^2 and 350 mg/cm^2). Therefore, for a hypothetical vessel with a 100-ft^2 wetted surface, between 3.6 lb and 71 lb (1.6 kg and 32 kg) of zinc anodes are applied and depleted each year.

For the antifouling paint pathway, it was estimated that the wetted surface area of vessels in Duwamish Estuary/Elliott Bay is approximately 1.6 x 10^9 cm^2 (1.7 x 10^6 ft^2). Assuming that all vessels in the study area use zinc anodes, replace them annually, use the recommended density of anodes, and have an application rate between 17 mg/cm^2 and 350 mg/cm^2, the possible upper bound for zinc loading from sacrificial anodes could be 27,000 kg/yr to 560,000 kg/yr.

3.10.3 Groundwater

Groundwater is the water that collects and flows beneath the Earth's surface. It is formed from the infiltration of rainfall, snowmelt, and surface waters. Groundwater can seep into surface waters and often comprises the baseflow for rivers and streams. The seepage or discharge rate of nearshore groundwater into surface waters can be affected by both precipitation and tide. Rainfall infiltration results in an increased water table elevation and increased groundwater discharge to rivers and streams. Tides have a similar effect on nearshore groundwater. During flood tides, surface water moves into groundwater; as tidal waters retreat during ebbtide, groundwater inflow to surface waters increases as a result of the elevated nearshore water table (Winter et al., 1998). In the intertidal zone, the less dense groundwater inflow will enter the surface waters above the more dense surface water.

Leaching, which is the dissolution of soluble constituents (such as metals and VOCs) into water, can introduce contaminants into groundwater and surface water. The pH, reduction-oxidation state, dissolved organic matter concentration, and conductivity of the groundwater or surface water are some of the factors that can affect the rate at which leaching occurs. Contaminants may be transported via groundwater into and from surface waters. Sources of groundwater contamination can include infiltration from contaminated sites, brownfields, dumped or spilled pollutants, leaking underground storage tanks, landfill leachate, failing septic systems, and leaking sanitary and storm sewer systems.

The complexity of groundwater movement makes it difficult to estimate loadings of contaminants to the study areas. Unlike pathways such as sewer systems where drainage basins are defined and where monitored water quality and flow data are available, the flow of groundwater and the contaminants in the groundwater are not as well studied for the study areas. Sources of contamination from soils can greatly affect the chemistry of the groundwater, and the topography, pedology of the soils, and salinity gradient between the groundwater and surface waters can affect the conveyance of groundwater to nearby surface waters.

3.10.4 Shoreline Erosion

Natural processes such as wind, surface water movement, and overland flow can erode shorelines, introducing soils and contaminants into surface waters. Vessel operations can contribute to erosion (propeller wash and boat wakes). Shoreline stabilization or armoring can reduce erosion.

Limited data and information are available to estimate contaminant loadings from shoreline erosion in the study areas. Below are possible areas of contamination that could be impacted by erosion processes.

Duwamish Estuary/Elliott Bay

During the industrial development of the Lower Duwamish Waterway in the early to mid-1900s, fill material was placed behind bulkheads and riprap (AECOM, 2012). The quality of the fill material is mostly unknown. Hart Crowser (2012) sampled the shoreline at nine locations along the waterway to assess the potential of sediment contamination. The sites were at or above the mean high water line and included sandy beaches with creosote-treated wood pilings, armored riprap, fill material of unknown origin, and suspected slag piles from industrial operations. Six of the locations exceeded at least one of the remedial action levels for the Lower Duwamish Waterway risk drivers (arsenic, carcinogenic PAHs, total PCBs, and dioxins/furans); other contaminants detected included chlorinated hydrocarbons, metals (mercury, zinc), phenols, phthalates, and pesticides.

While the majority of the shoreline in the Duwamish Estuary/Elliott Bay study area is stabilized with bulkheads, riprap, or vegetation, approximately 3.5 miles of exposed shoreline has a potential for erosion (Ecology and Leidos, 2014). Over 70 percent (2.6 miles) of the exposed shoreline has been identified as contaminated (greater than the apparent effects threshold [AET] criteria) under an Ecology or EPA order and/or Ecology study (Ecology and Leidos, 2014). Approximately 1.8 miles of this contaminated area is in the process of being cleaned up or stabilized; the remaining 0.8 mile requires attention

(Ecology and Leidos, 2014). Until the contamination status of the remaining 0.8 mile is known, erosion of the shoreline may be a potential pathway of contamination to the Duwamish Estuary.

Lake Union/Ship Canal

Lake Union/Ship Canal has over 20 miles of shoreline between Montlake Cut and the Locks. Most of this shoreline is stabilized. Approximately 1.3 miles of shoreline are not stabilized: 0.6 mile along the south side of Portage Bay, 0.4 mile along the south side of Lake Union, and 0.3 mile on the south side of Gas Works Park. While there is potential for shoreline erosion along the south ends of both Portage Bay and Lake Union, the likelihood is minimal because of the low velocity of surface waters and the relative absence of vessel wake. The shoreline along Gas Works Park has the greatest potential for erosion because of its proximity to wake-producing vessel traffic. Wind-driven waves may also erode the exposed shoreline along Gas Works Park.

From the early 1900s to the 1960s, various gas production plants operated along the north shore of Lake Union, the current site of Gas Works Park. A tar refinery operated west of the gas plants from the early 1900s to the mid-1950s, with storage operations present until the mid-1960s (GeoEngineers, 2013). The over half-century of industrial activity has taken its toll on the area. Soil and groundwater investigations from the 1970s to 2010s detected benzene, naphthalene, benzo(a)pyrene, arsenic, and non-aqueous phase liquid (NAPL), which is a liquid that does not dissolve readily in water (for example, oils and gasoline).

Because of the proximity of the contaminants to Lake Union, erosion or leaching processes that may occur along the shoreline could be a pathway for contaminant loading. A supplemental investigation and cleanup feasibility study is being conducted by Puget Sound Energy. A cleanup action plan is scheduled for completion in 2018.

3.10.5 Puget Sound

Water passing through Puget Sound's Central Basin just west of Elliott Bay and Shilshole Bay, consists of a density-driven two-layer flow (NOAA, 1983; Ebbesmeyer et al., 1998). The net movement of the upper layer (approximately 0–50 m) travels north toward Admiralty Inlet and exits to the Pacific Ocean through the Strait of Juan de Fuca. The net lower layer movement (approximately 50–180 m) is south from Admiralty Inlet toward the Tacoma Narrows. A small portion of the flow travels south through the Narrows at approximately 50 m and enters the South Sound between Tacoma and Olympia; the remaining flow upwells toward the surface where it travels north through either the Colvos or East passages. Contaminants from the Pacific Ocean, Salish Sea, and surrounding Puget Sound may enter the study areas with the incoming marine waters.

Surface flow entering Elliott Bay from the Central Basin flows clockwise or counter-clockwise depending on tidal condition (Jiing-Yih, 1991). During ebbtides, water enters Elliott Bay from the Duwamish Estuary and flows counter-clockwise, hugging the Seattle waterfront. During flood tides, a clockwise flow enters central Elliott Bay and travels from

Inner Elliott Bay into the Duwamish Estuary, pushing the saltwater wedge upstream, while flow from Outer Elliott Bay heads south toward Duwamish Head and travels along the shoreline to join the Central Basin flow (Jiing-Yih, 1991).

At depth, Central Basin tidal currents in Elliott Bay travel primarily along the bay floor. Bottom waters from the north end of the bay travel south and upwell near the West Waterway. The upwelled water mixes with ebb waters exiting the Duwamish Estuary forming less saline surface water compared to the bottom waters.

The entrance of marine waters into Lake Union/Ship Canal is limited by the Locks. The operation of the Locks allows marine water to enter Salmon Bay, where it is diluted with fresh water. A saltwater drain upstream of the Locks is designed to drain marine water that passes through the Locks during operation. In the summer during peak lockages and low freshwater flow, marine water may overwhelm the capacity of the saltwater drain and travel through the Ship Canal.

Flood tides entering Duwamish Estuary/Elliott Bay and marine waters entering Lake Union/Ship Canal through the Locks are pathways for COIs to enter the study areas from Puget Sound. Surface water contaminant levels in Puget Sound differ from those in waterbodies in major urban areas such as Seattle. It is expected that the dilution from and transport to the Pacific Ocean and the fewer contaminant sources from Puget Sound's lesser developed shorelines contribute to lower contaminant levels in Puget Sound. However, a thorough comparison of water quality data, both at depth (waters coming from the Pacific Ocean) and near the surface (waters going to the Pacific Ocean), is required to confirm this assumption.

Ambient water quality data are collected near the mouths of the two study areas for conventional parameters such as nutrients, salinity, temperature, and dissolved oxygen, but few data for organics such as PCBs, PAHs, and phthalates exist. Long-term datasets throughout Puget Sound have demonstrated that Puget Sound is a pathway for high nutrient, low dissolved oxygen water during upwelling events on the coast. This pattern is cyclical and seasonal. There is limited information to estimate the volumes entering Inner Elliott Bay from Puget Sound. A more robust data set throughout Puget Sound could help enhance the understanding of the importance of the Sound as a contaminant pathway.

4.0 ESTIMATED ANNUAL LOADINGS

This chapter presents estimated annual loadings for the major pathways for each COI and study area. The differences in methods used and the associated uncertainties for each method should be considered when comparing the loading estimates across pathways. Appendix E summarizes contaminant data for each pathway, including the number of samples available and the contaminants detected, and compares the contaminant concentrations in the pathways to the monitoring data available for the two study areas.

4.1 Summary of Loadings Estimates

Tables 4-1 and 4-2 present a summary of the estimated annual loadings for each COI by the major pathways that contribute these loads to the study areas.

Table 4-1. Summary of estimated annual loadings for contaminants of interest and major contributing pathways to Duwamish Estuary/Elliott Bay (kg/yr, unless noted).

Contaminant of Interest	Major Contributing Pathways	Estimated Present-Day (2015) Load[a]
Fecal coliform bacteria	Uncontrolled King County CSOs	16,000 to 130,000 trillion colony forming units (CFU)/yr
	Upstream watershed (Green River)	950 to 5,000 trillion CFU/yr
	Stormwater runoff	380 to 3,700 trillion CFUyr
TSS	Upstream watershed (Green River)	11 to 32 million
	Stormwater runoff	0.96 to 1.8 million
Total nitrogen	Upstream watershed (Green River)	590,000 to 870,000
Total phosphorus	Upstream watershed (Green River)	47,000 to 73,000
Total arsenic	Upstream watershed (Green River)	740 to 1,200
Total copper	Copper-based antifouling paint	1,600 to 4,900
	Upstream watershed (Green River)	1,700 to 4,600
	Upstream watershed (Green River)	610 to 1,400
	Stormwater runoff	240 to 410
Total mercury	Upstream watershed (Green River)	2.2 to 5.1
Total zinc	Upstream watershed (Green River)	4,700 to 10,000
	Stormwater runoff	1,800 to 2,800
	Sacrificial anodes	Not estimated (insufficient data)[b]
Benzyl butyl phthalate	Upstream watershed (Green River)	Not estimated (insufficient data)[c]
	Stormwater runoff	3.8 to 5.7
	Uncontrolled King County CSOs	0.62 to 4.8
	Wet weather treatment facilities	0.28 to 0.97
Bis(2-ethylhexyl) phthalate	Upstream watershed (Green River)	Not estimated (insufficient data)[c]
	Stormwater runoff	30 to 56
	Uncontrolled King County CSOs	5.1 to 23

Contaminant of Interest	Major Contributing Pathways	Estimated Present-Day (2015) Load[a]
	Wet weather treatment facilities	2.1 to 7.1
	Local tributaries	1.5 to 5.0
Total PAHs	Creosote-treated wood pilings	870 to 5,500
Total PBDEs	Upstream watershed (Green River)	Not estimated (insufficient data)[c]
	Stormwater runoff	300 to 820 g/yr
	Uncontrolled King County CSOs	94 to 430 g/yr
	Local tributaries	41 to 590 g/yr
	Atmospheric deposition	48 to 250 g/yr
Total PCBs	Upstream watershed (Green River)	240 to 1,400 g/yr
	Stormwater runoff	50 to 430 g/yr
	Atmospheric deposition	73 to 190 g/yr
	Uncontrolled King County CSOs	49 to 230 g/yr
	Local tributaries	16 to 120 g/yr

[a] 95 percent confidence limits of load estimate provided.

[b] Zinc loadings from sacrificial anodes were not quantified but are expected to be meaningful based on the literature.

[c] The Green River was assumed to be a major contributing pathway of BBP, BEHP, and PBDEs based on findings for Lake Washington.

Table 4-2. Summary of estimated annual loadings for contaminants of interest and major contributing pathways to Lake Union/Ship Canal (kg/yr, unless noted).

Contaminant of Interest	Major Contributing Pathways	Estimated Present-Day (2015) Load[a]
Fecal coliform bacteria	Uncontrolled King County CSOs	3,700 to 32,000 trillion colony forming units (CFU)/yr
	Uncontrolled Seattle CSOs	1,500 to 14,000 trillion CFU/year
	Stormwater runoff	220 to 1,800 trillion CFU/yr
TSS	Upstream watershed (Lake Washington)	1.1 to 1.9 million
	Stormwater runoff	0.5 to 0.9 million
Total nitrogen	Upstream watershed (Lake Washington)	280,000 to 390,000
Total phosphorus	Upstream watershed (Lake Washington)	12,000 to 18,000
Total arsenic	Upstream watershed (Lake Washington)	780 to 1,100
Total copper	Copper-based antifouling paint	2,600 to 5,300
	Upstream watershed (Lake Washington)	1,100 to 1,400
Total lead	Stormwater runoff	240 to 410
	Upstream watershed (Lake Washington)	60 to 120
	Uncontrolled King County CSOs	7.0 to 29
Total mercury	Upstream watershed (Lake Washington)	0.41 to 0.79
	Stormwater runoff	0.07 to 0.58
	King County CSOs	0.015 to 0.064
Total zinc	Upstream watershed (Lake Washington)	610 to 1,000
	Stormwater runoff	770 to 1,200
	Atmospheric deposition	130 to 170
	Sacrificial anodes	Not estimated (insufficient data)[b]

Contaminant of Interest	Major Contributing Pathways	Estimated Present-Day (2015) Load[a]
Benzyl butyl phthalate	Upstream watershed (Lake Washington)	Not estimated (insufficient data)[c]
	Stormwater runoff	2.0 to 3.0
	Uncontrolled King County CSOs	0.1 to 1.2
	Uncontrolled Seattle CSOs	0.1 to 0.5
Bis(2-ethylhexyl) phthalate	Upstream watershed (Lake Washington)	90 to 7,000
	Stormwater runoff	16 to 30
Total PAHs	Creosote-treated wood pilings	890 to 5,600
	Upstream watershed (Lake Washington)	50 to 100
Total PBDEs	Upstream watershed (Lake Washington)	670 to 1,500 g/yr
	Stormwater runoff	160 to 430 g/yr
	Uncontrolled King County CSOs	20 to 110 g/yr
	Atmospheric deposition	10 to 60 g/yr
	Uncontrolled Seattle CSOs	10 to 50 g/yr
Total PCBs	Upstream watershed (Lake Washington)	110 to 230 g/yr
	Stormwater runoff	80 to 200 g/yr
	Atmospheric deposition	20 to 40 g/yr
	Uncontrolled King County CSOs	10 to 60 g/yr
	Uncontrolled Seattle CSOs	30 to 50 g/yr

[a.] 95 percent confidence limits of load estimate provided.
[b.] Zinc loadings from sacrificial anodes were not quantified but are expected to be meaningful based on the literature.
[C] Lake Washington was assumed to be a major contributing pathway of BBP based on data for BEHP.

4.2 Explanation of Bar Charts

The flow volume and loadings estimates in this chapter are displayed in bar plots. In each bar chart, the mean annual loading is represented by the top of the solid colored bar. The vertical black line represents the uncertainty around the mean, which considers interannual variability and potential range of annual loadings:

- The upper and lower limits of the black line represent the 95 percent UCL and LCL, respectively, for the following pathways: Green River, Lake Washington, stormwater runoff, local tributaries, King County uncontrolled and controlled CSOs, Seattle uncontrolled and controlled CSOs, wet weather treatment facilities, highway bridges, and atmospheric deposition.
- The upper and lower extents of the vertical black line represent the potential upper and lower range of loadings for the antifouling paint and creosote-treated wood pilings pathways.

If a pathway does not have a plot, it does not necessarily mean that there are no loads from the pathway. Instead, it could reflect a lack of available data for making an acceptable estimate. These pathways are labeled either as NA or NE:

- NA (not applicable) indicates the pathway would likely not contribute loading of a specific contaminant.

- NE (not estimated) indicates that not enough data or information is available to estimate the loadings of a specific contaminant discharging from the pathway.

4.3 Flow Volumes

The amount of annual water volume discharge (flow) of a pathway can be a driver of the total load and should be considered when comparing contaminant loadings across pathways. Flow estimates from the major pathways are presented in Figure 4-1 for Duwamish Estuary/Elliott Bay and Figure 4-2 for Lake Union/Ship Canal. The estimates are also given in Table 4-3. In both study areas, flow discharged from upstream watersheds represents the largest flow volume of the pathways by at least an order of magnitude and flow discharged from stormwater runoff represents the second greatest flow volume. The large contributions of loadings from upstream watersheds were a reflection of these high flow volumes; the contaminant concentrations were relatively low.

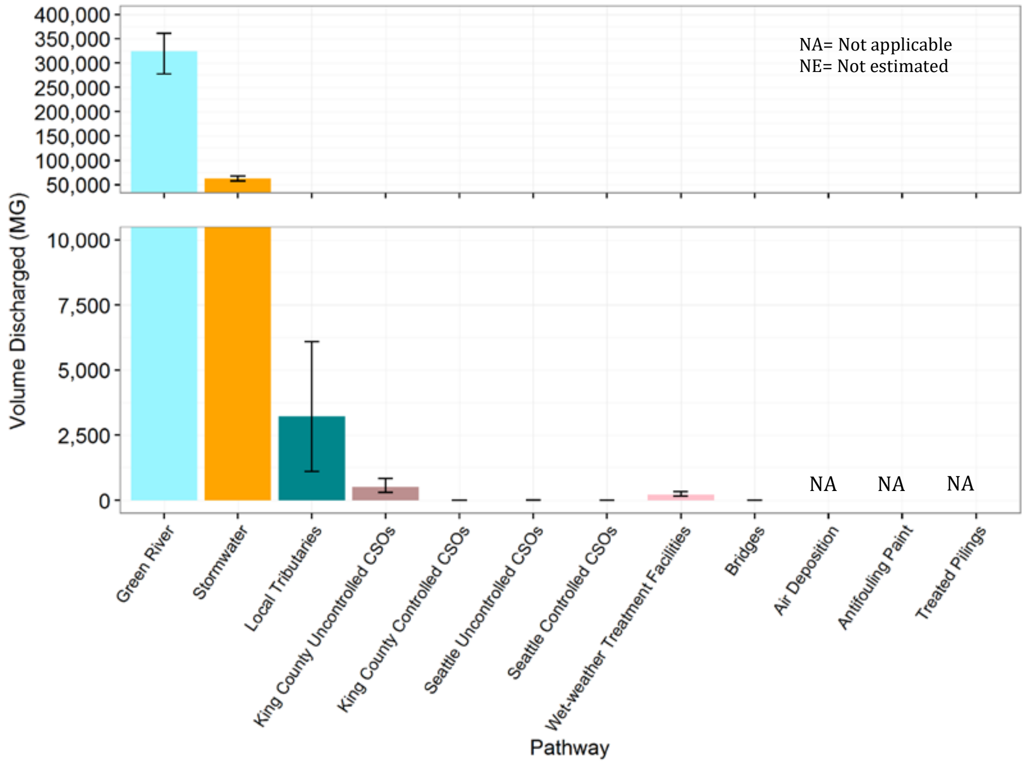

Figure 4-1. Estimated annual flow volume from major pathways to Duwamish Estuary/Elliott Bay.

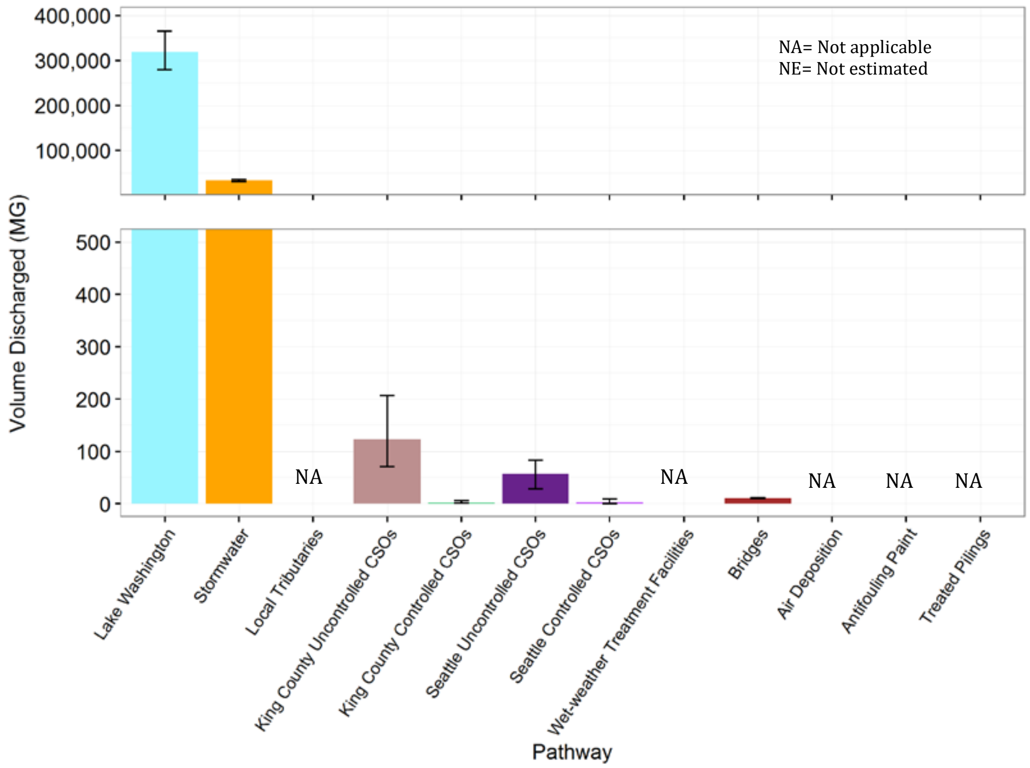

Figure 4-2. **Estimated annual flow volume from major pathways to the Lake Union/Ship Canal.**

Table 4-3. Estimated annual volume discharged from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (MG/year).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	280,000	320,000	360,000
	Stormwater runoff	57,000	63,000	68,000
	Local tributaries	1,100	3,200	6,100
	Uncontrolled CSOs - King County	300	520	840
	Uncontrolled CSOs - Seattle	1.7	5.7	13.3
	Controlled CSOs - King County	0.91	2.87	8.79
	Controlled CSOs - Seattle	0.075	0.89	2.34
	Wet weather treatment facilities	160	227	335
	Bridges	8.03	8.80	9.49
Lake Union/Ship Canal	Lake Washington	280,000	320,000	360,000
	Stormwater runoff	30,000	33,000	36,000
	Uncontrolled CSOs - King County	70	123	210
	Uncontrolled CSOs - Seattle	29	57	83
	Controlled CSOs - King County	0.61	1.84	5.83
	Controlled CSOs - Seattle	0.00028	2.46	9.26
	Bridges	9.56	10.5	11.3

4.4 Estimated Contaminant Loadings and Contributing Pathways

4.4.1 Fecal Coliform Bacteria

Annual fecal coliform bacteria loading estimates from the major pathways are presented in Figure 4-3 for Duwamish Estuary/Elliott Bay and Figure 4-4 for Lake Union/Ship Canal. The estimates are also given in Table 4-4. Findings are as follows:

- **Duwamish Estuary/Elliott Bay.** King County uncontrolled CSOs were the largest pathway of fecal coliform. Loadings from the Green River, stormwater runoff, local tributaries, King County controlled CSOs, and Seattle uncontrolled and controlled CSOs are at least one magnitude lower and with overlapping 95 percent UCL and LCL loadings.
- **Lake Union/Ship Canal.** King County and Seattle uncontrolled CSOs are the largest contributing pathways of fecal coliform loading, with similar magnitudes of loading. Although there is some overlap in the 95 percent UCL loadings from stormwater runoff and from Seattle uncontrolled CSOs, a larger overlapping range exists between stormwater runoff and King County and Seattle controlled CSOs. The volumes discharging from Seattle and King County uncontrolled CSOs to Duwamish Estuary/Elliott Bay are not as comparable because the King County uncontrolled CSOs discharge larger volumes than Seattle uncontrolled CSOs.

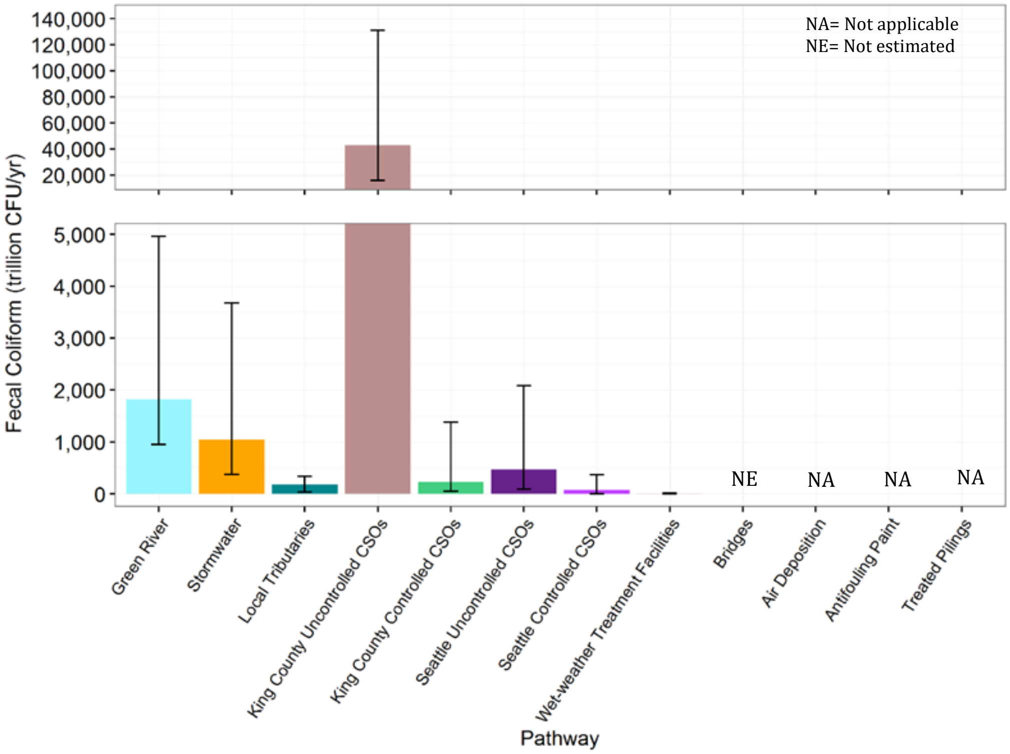

Figure 4-3. Estimated annual fecal coliform bacteria loads from major pathways to Duwamish Estuary/Elliott Bay.

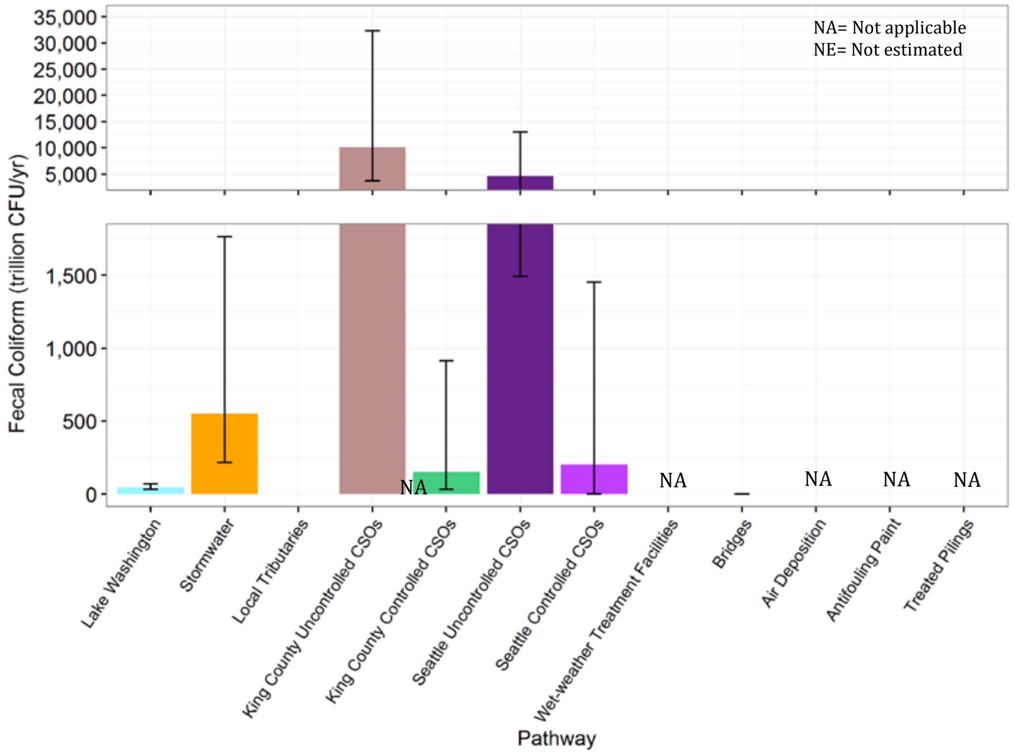

Figure 4-4. **Estimated annual fecal coliform bacteria loads from major pathways to Lake Union/Ship Canal.**

Table 4-4. **Estimated annual fecal coliform bacteria loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (trillion CFU/yr).**

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit	Min.	Max.
Duwamish Estuary/Elliott Bay	Green River	950	1,800	5,000	--	--
	Stormwater runoff	380	1,000	3,700	--	--
	Local tributaries	--	180	--	37	340
	Uncontrolled CSOs - King County	16,000	43,000	130,000	--	--
	Uncontrolled CSOs - Seattle	88	470	2,100	--	--
	Controlled CSOs - King County	48	240	1,400	--	--
	Controlled CSOs - Seattle	3.9	73	370	--	--
	Wet weather treatment facilities	1.7	6.9	19.4	--	--
Lake Union/Ship Canal	Lake Washington	33	46	67	--	--
	Stormwater runoff	220	550	1,800	--	--
	Uncontrolled CSOs - King County	3,700	10,000	32,000	--	--
	Uncontrolled CSOs - Seattle	1,500	4,700	13,000	--	--
	Controlled CSOs - King County	32	150	910	--	--
	Controlled CSOs - Seattle	0.014	200	1,500	--	--
	Bridges	0.13	0.70	1.40	--	--

-- = not estimated; CFU = colony forming unit.

4.4.2 Total Nitrogen

Annual total nitrogen loading estimates from the major pathways are presented in Figure 4-5 for Duwamish Estuary/Elliott Bay and Figure 4-6 for Lake Union/Ship Canal. The estimates are also given in Table 4-5. In both study areas, upstream watersheds are the largest contributing pathways of total nitrogen by an order of magnitude.

- In Duwamish Estuary/Elliott Bay, stormwater runoff, King County uncontrolled CSOs, and wet weather treatment facilities are the second largest contributing pathways and have overlapping 95 percent UCL and LCL loadings.
- In Lake Union/Ship Canal, stormwater runoff is the second largest contributing pathway, followed by King County and Seattle uncontrolled CSOs.

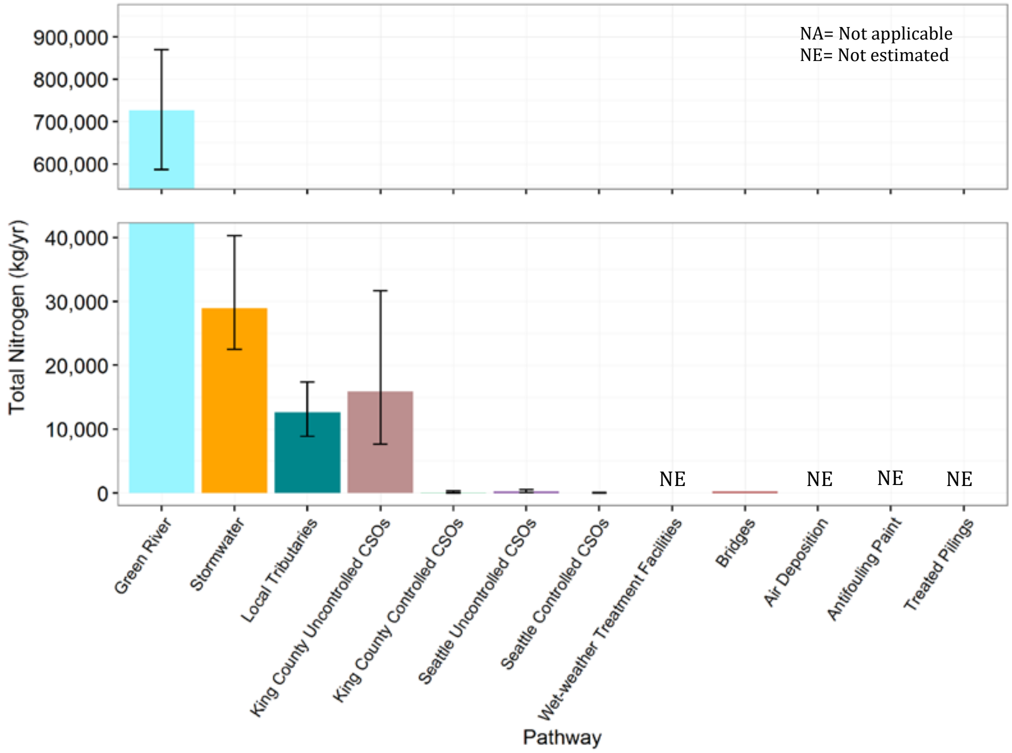

Figure 4-5. **Estimated annual total nitrogen loads from major pathways to Duwamish Estuary/Elliott Bay.**

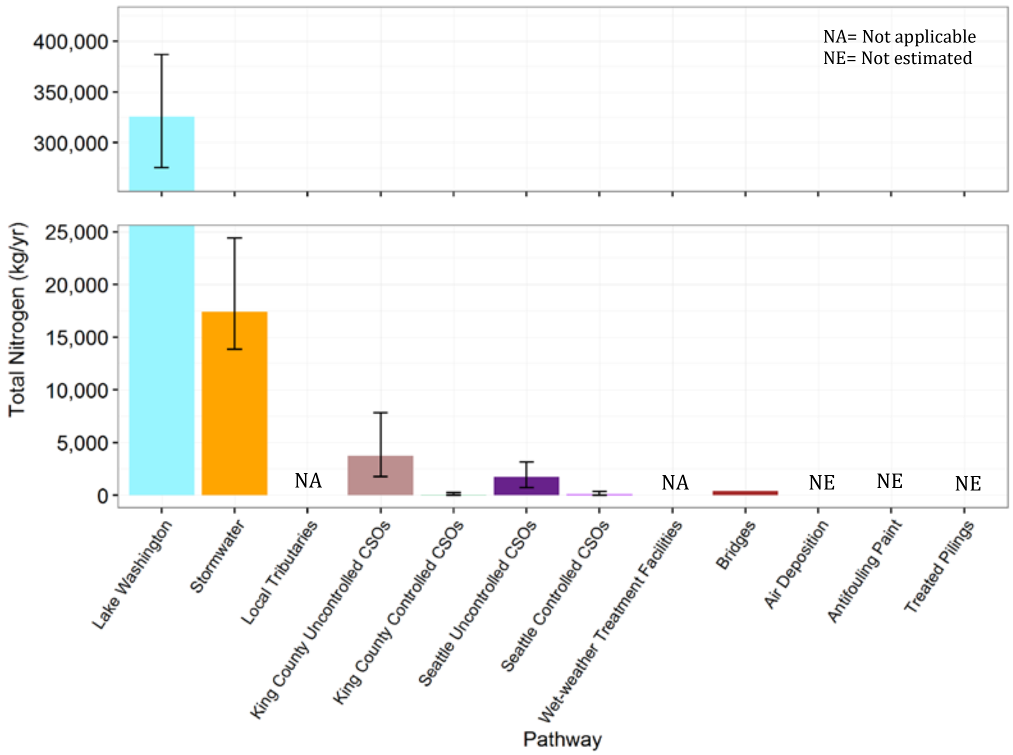

Figure 4-6. **Estimated annual total nitrogen loads from major pathways to Lake Union/Ship Canal.**

Table 4-5. **Estimated annual total nitrogen loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).**

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	590,000	730,000	870,000
	Stormwater runoff	23,000	29,000	40,000
	Local tributaries	8,900	13,000	17,000
	Uncontrolled CSOs - King County	7,700	16,000	32,000
	Uncontrolled CSOs - Seattle	42	170	500
	Controlled CSOs - King County	23	87	330
	Controlled CSOs - Seattle	1.9	27	89
	Bridges	–53	230	560
Lake Union/Ship Canal	Lake Washington	280,000	330,000	390,000
	Stormwater runoff	14,000	17,000	24,000
	Uncontrolled CSOs - King County	1,800	3,700	7,800
	Uncontrolled CSOs - Seattle	720	1,700	3,100
	Controlled CSOs - King County	15	56	220
	Controlled CSOs - Seattle	0.0069	75	350
	Bridges	–93	380	940

4.4.3 Total Phosphorus

Annual total phosphorus loading estimates from the major pathways are presented in Figures 4-7 and 4-8 for Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal, respectively. The results are also given in Table 4-6. In both study areas, upstream watersheds are the largest contributing pathways of total phosphorus.

- In Duwamish Estuary/Elliott Bay, stormwater runoff and King County uncontrolled CSOs are the second largest contributing pathways.
- In Lake Union/Ship Canal, stormwater runoff is the second largest contributing pathway followed by King County and Seattle uncontrolled CSOs.

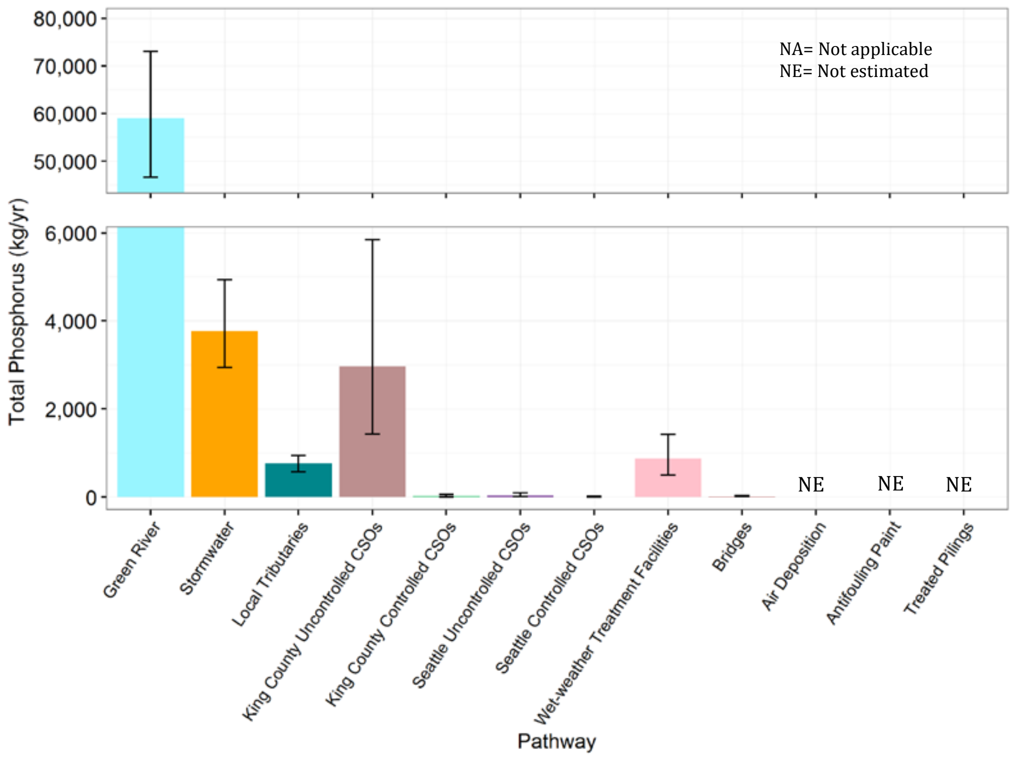

Figure 4-7. **Estimated annual total phosphorus loads from major pathways to Duwamish Estuary/Elliott Bay.**

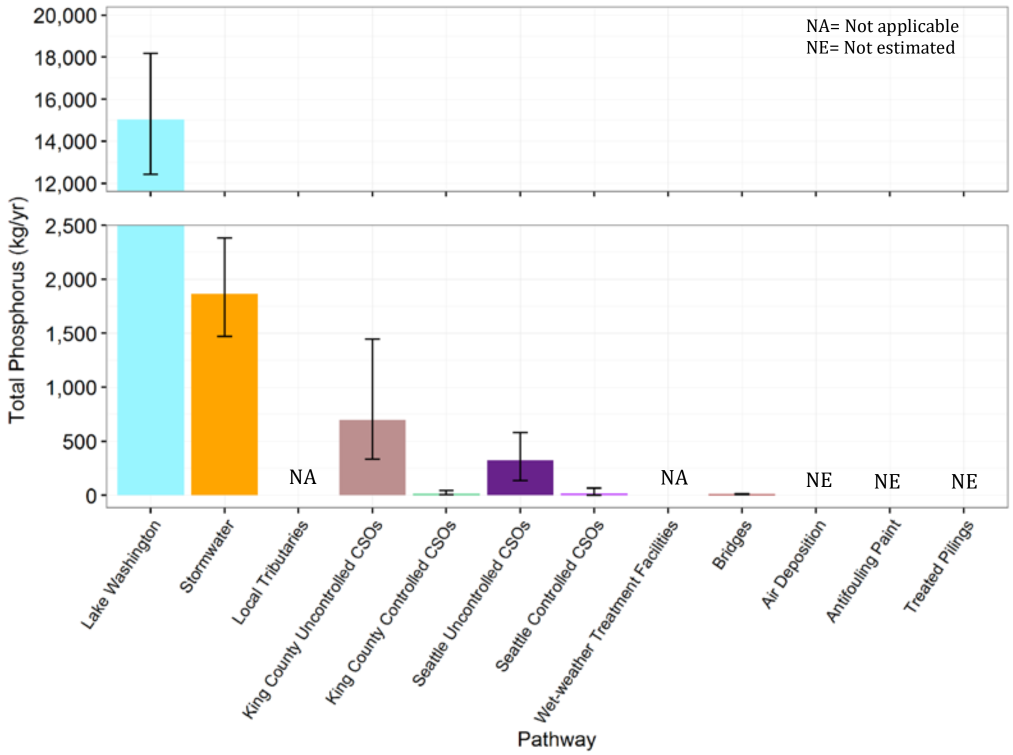

Figure 4-8. **Estimated annual total phosphorus loads from major pathways to Lake Union/Ship Canal.**

Table 4-6. **Estimated annual total phosphorus loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).**

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	47,000	59,000	73,000
	Stormwater runoff	2,900	3,800	4,900
	Local tributaries	570	770	940
	Uncontrolled CSOs - King County	1,400	3,000	5,800
	Uncontrolled CSOs - Seattle	7.9	32	93
	Controlled CSOs - King County	4.3	16	62
	Controlled CSOs - Seattle	0.35	5.1	16
	Wet weather treatment facilities	500	870	1,400
	Bridges	8.0	14	28
Lake Union/Ship Canal	Lake Washington	12,000	15,000	18,000
	Stormwater runoff	1,500	1,900	2,400
	Uncontrolled CSOs - King County	330	700	1,400
	Uncontrolled CSOs - Seattle	130	320	580
	Controlled CSOs - King County	2.9	10	41
	Controlled CSOs - Seattle	0.0013	14	65
	Bridges	5.8	8.7	12

4.4.4 Total Suspended Solids

Annual TSS loading estimates from the major pathways are presented in Figure 4-9 for Duwamish Estuary/Elliott Bay and Figure 4-10 for Lake Union/Ship Canal. The estimates are also given in Table 4-7. In both study areas, upstream watersheds and stormwater runoff are the largest contributing pathways of TSS by one to two orders of magnitude.

- In Duwamish Estuary/Elliott Bay, local tributaries, King County uncontrolled CSOs, and wet weather treatment facilities contribute the third largest loadings with similar magnitudes.
- In Lake Union/Ship Canal, King County and Seattle uncontrolled CSOs contribute the third largest loadings.

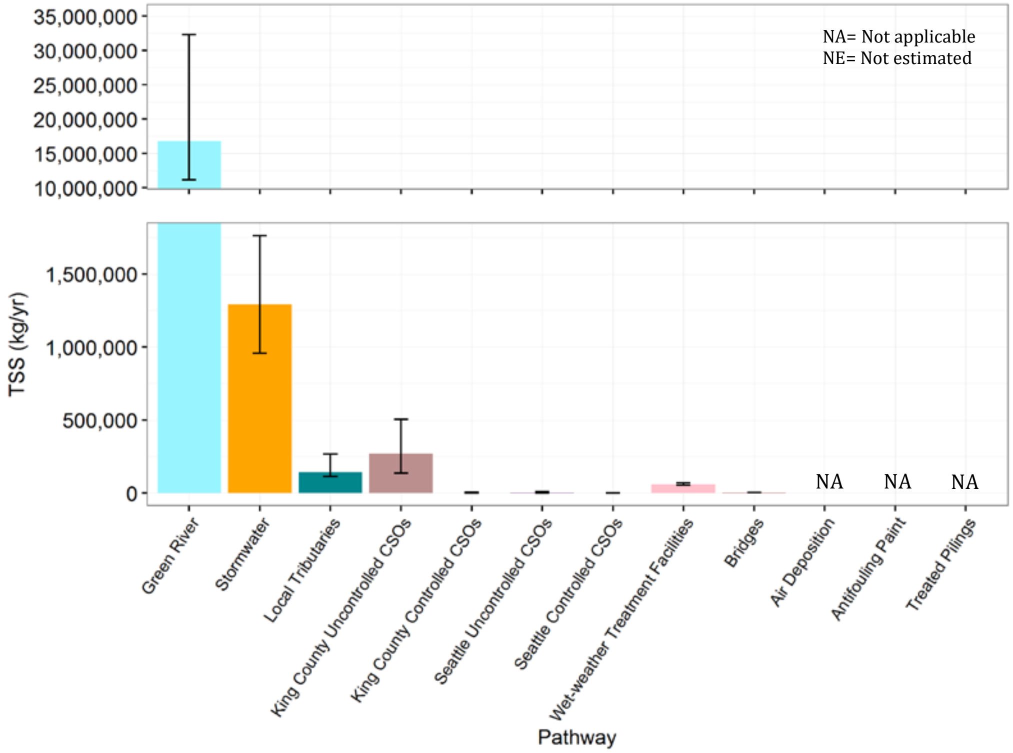

Figure 4-9. Estimated annual TSS loads from major pathways to Duwamish Estuary/Elliott Bay.

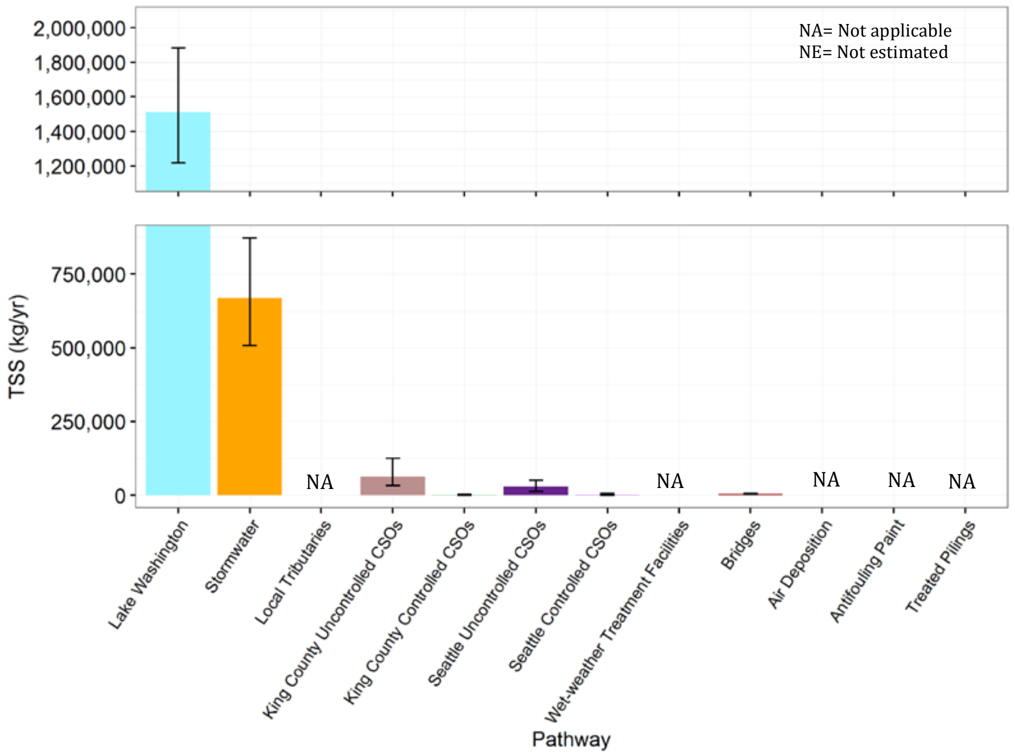

Figure 4-10. Estimated annual TSS loads from major pathways to Lake Union/Ship Canal.

Table 4-7. Estimated annual TSS loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	11,000,000	17,000,000	32,000,000
	Stormwater runoff	960,000	1,300,000	1,800,000
	Local tributaries	110,000	140,000	270,000
	Uncontrolled CSOs - King County	140,000	270,000	500,000
	Uncontrolled CSOs - Seattle	760	2,900	8,000
	Controlled CSOs - King County	410	1,500	5,300
	Controlled CSOs - Seattle	34	460	1,400
	Wet weather treatment facilities	51,000	69,000	110,000
	Bridges	2,000	3,000	4,200
Lake Union/Ship Canal	Lake Washington	1,200,000	1,500,000	1,900,000
	Stormwater runoff	510,000	670,000	870,000
	Uncontrolled CSOs - King County	32,000	63,000	120,000
	Uncontrolled CSOs – Seattle	13,000	29,000	50,000
	Controlled CSOs - King County	280	940	3,500
	Controlled CSOs – Seattle	0.13	1,300	5,600
	Bridges	3,200	4,700	6,400

4.4.5 Total Arsenic

Annual total arsenic loading estimates from the major pathways are presented in Figure 4-11 for Duwamish Estuary/Elliott Bay and Figure 4-12 for Lake Union/Ship Canal. The estimates are also given in Table 4-8. Because total arsenic data were not available for local stormwater, the load was estimated using regional data from the National Stormwater Quality Database. In both study areas, upstream watersheds are the greatest contributing pathway for total arsenic.

- In Duwamish Estuary/Elliott Bay, local tributaries are the second largest contributors.
- In Lake Union/Ship Canal, King County and Seattle uncontrolled CSOs and atmospheric deposition contribute arsenic loading within the sample magnitude and are the second largest contributing pathways.

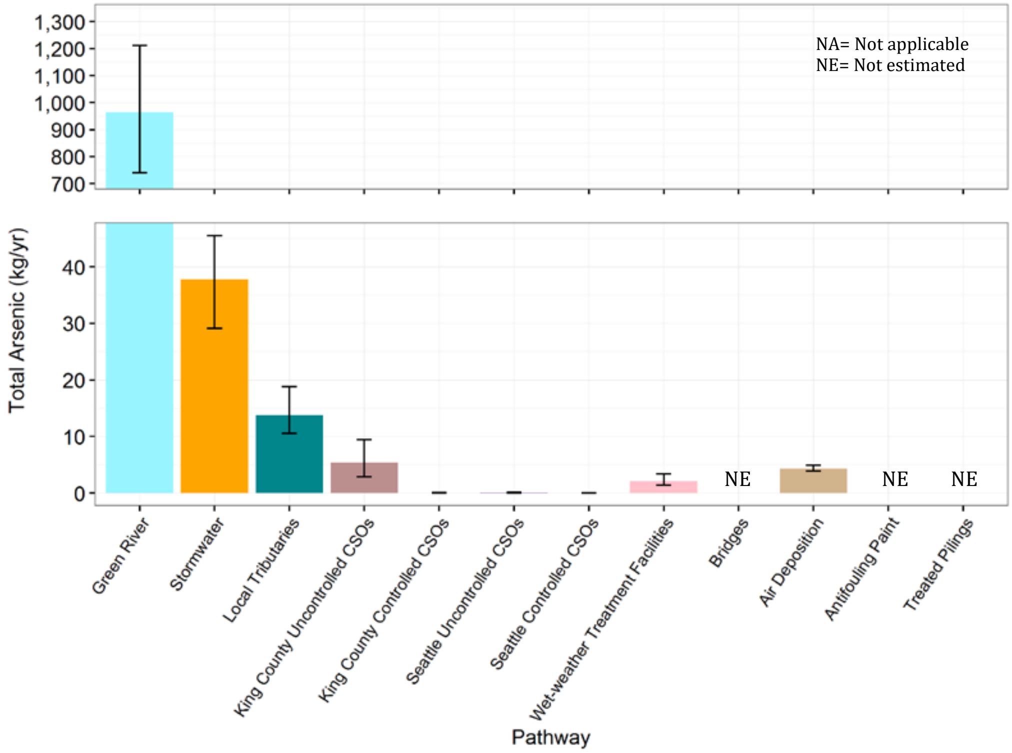

Figure 4-11. **Estimated annual total arsenic loads from major pathways to Duwamish Estuary/Elliott Bay.**

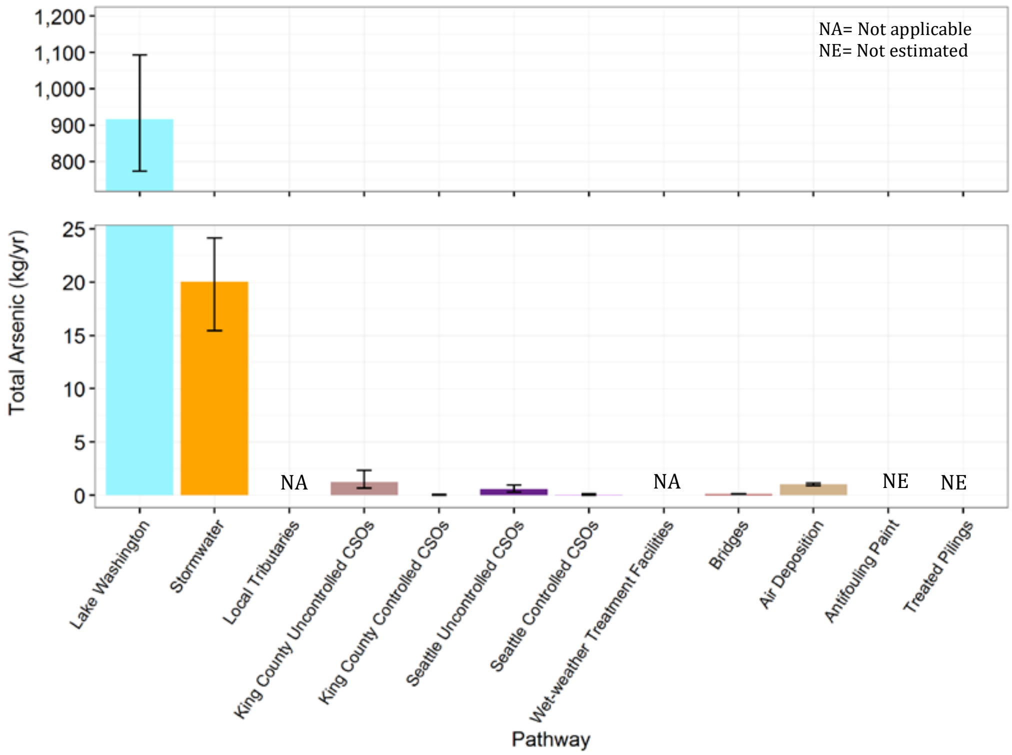

Figure 4-12. **Estimated annual total arsenic loads from major pathways to Lake Union/Ship Canal.**

Table 4-8. **Estimated annual total arsenic loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).**

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	740	960	1,200
	Stormwater runoff	29	38	46
	Local tributaries	11	14	19
	Uncontrolled CSOs - King County	2.9	5.3	9.4
	Uncontrolled CSOs - Seattle	0.016	0.058	0.15
	Controlled CSOs - King County	0.0086	0.029	0.099
	Controlled CSOs - Seattle	0.00071	0.0090	0.026
	Wet weather treatment facilities	1.4	2.1	3.4
	Atmospheric deposition	3.9	4.3	4.9
Lake Union/Ship Canal	Lake Washington	770	920	1,100
	Stormwater runoff	15	20	24
	Uncontrolled CSOs - King County	0.66	1.2	2.3
	Uncontrolled CSOs - Seattle	0.27	0.58	0.93
	Controlled CSOs - King County	0.0057	0.019	0.066
	Controlled CSOs - Seattle	0.0000026	0.025	0.10
	Bridges	0.073	0.094	0.12
	Atmospheric deposition	0.90	1.0	1.1

4.4.6 Total Copper

Annual total copper loading estimates from the major pathways are presented in Figure 4-13 for Duwamish Estuary/Elliott Bay and Figure 4-14 for Lake Union/Ship Canal. The estimates are also given in Table 4-9. Upstream watersheds and antifouling paint are the greatest contributing pathways of total copper in both study areas. Stormwater runoff is the next largest contributing pathway.

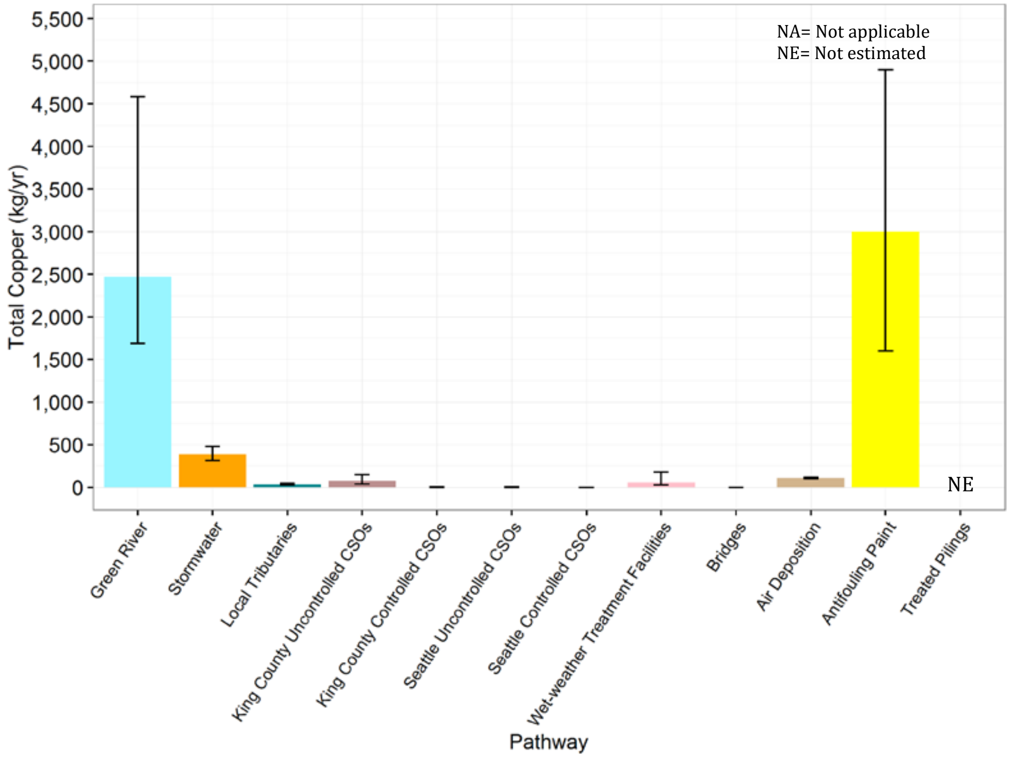

Figure 4-13. **Estimated annual total copper loads from major pathways to Duwamish Estuary/Elliott Bay.**

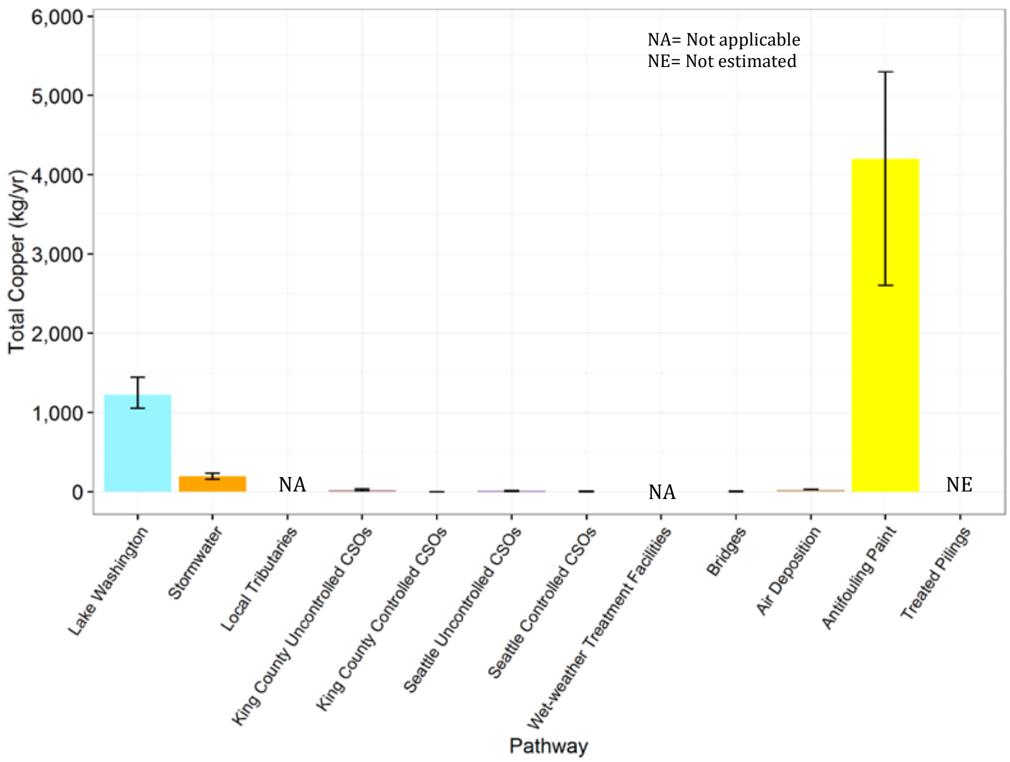

Figure 4-14. Estimated annual total copper loads from major pathways to Lake Union/Ship Canal.

Table 4-9. Estimated annual total copper loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit	4.0 ug/cm^2 leaching rate	6.5 ug/cm^2 leaching rate	8.2 ug/cm^2 leaching rate
Duwamish Estuary/Elliott Bay	Green River	1,700	2,500	4,600	--	--	--
	Stormwater runoff	310	390	480	--	--	--
	Local tributaries	29	31	45	--	--	--
	Uncontrolled CSOs - King County	39	77	150	--	--	--
	Uncontrolled CSOs - Seattle	0.22	0.84	2.4	--	--	--
	Controlled CSOs - King County	0.12	0.42	1.6	--	--	--
	Controlled CSOs - Seattle	0.0097	0.13	0.42	--	--	--
	Wet weather treatment facilities	27	59	180	--	--	--
	Bridges	0.52	0.74	0.98	--	--	--
	Atmospheric deposition	99	110	120	--	--	--
	Antifouling paint	--	--	--	1,600	3,000	4,900

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit	4.0 ug/cm^2 leaching rate	6.5 ug/cm^2 leaching rate	8.2 ug/cm^2 leaching rate
Lake Union/Ship Canal	Lake Washington	1,100	1,200	1,400	--	--	--
	Stormwater runoff	160	190	230	--	--	--
	Uncontrolled CSOs - King County	9.1	18	37	--	--	--
	Uncontrolled CSOs - Seattle	3.7	8.3	15	--	--	--
	Controlled CSOs - King County	0.078	0.27	1	--	--	--
	Controlled CSOs - Seattle	0.000036	0.36	1.7	--	--	--
	Bridges	0.80	1.1	1.5	--	--	--
	Atmospheric deposition	23	25	28	--	--	--
	Antifouling paint	--	--	--	2,600	4,200	5,300

-- = no data available; not estimated.

4.4.7 Total Lead

Annual total lead loading estimates from the major pathways are presented in Figure 4-15 for Duwamish Estuary/Elliott Bay and Figure 4-16 for Lake Union/Ship Canal. The estimates are also given in Table 4-10. Upstream watersheds and stormwater runoff are the greatest contributing pathways of total lead for both study areas.

- In the Duwamish Estuary/Elliott Bay, the Green River contributes more total lead loading than stormwater runoff.
- In Lake Union/Ship Canal, the opposite is true: stormwater runoff has a larger contribution than Lake Washington.

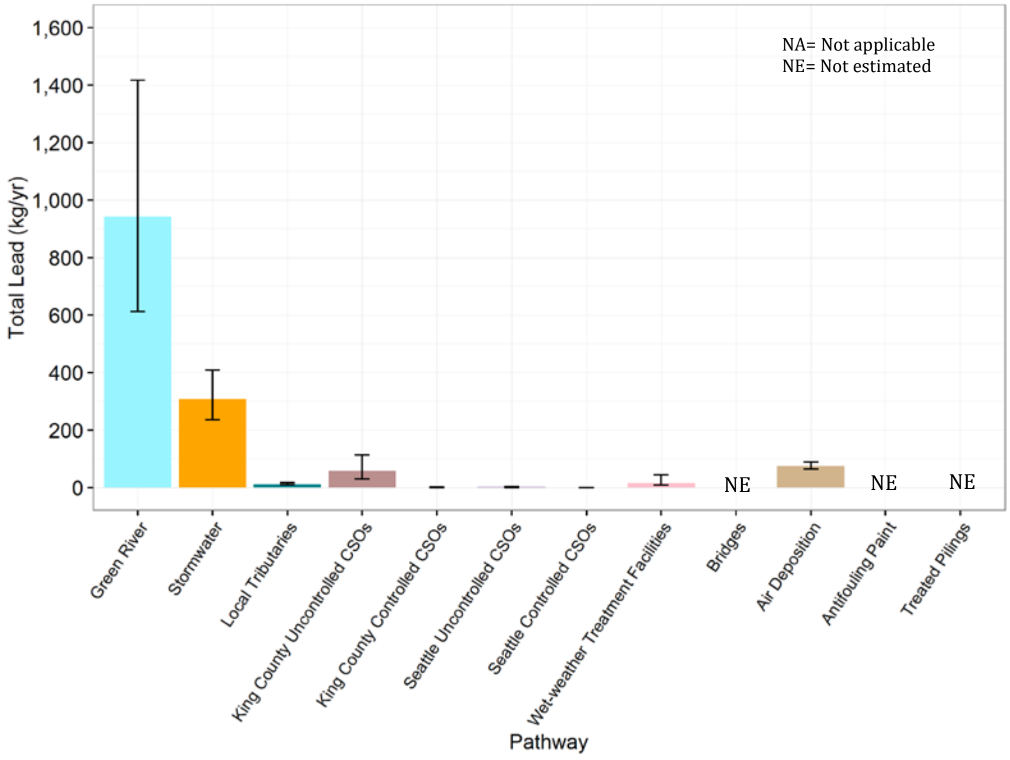

Figure 4-15. Estimated annual total lead loads from major pathways to Duwamish Estuary/Elliott Bay.

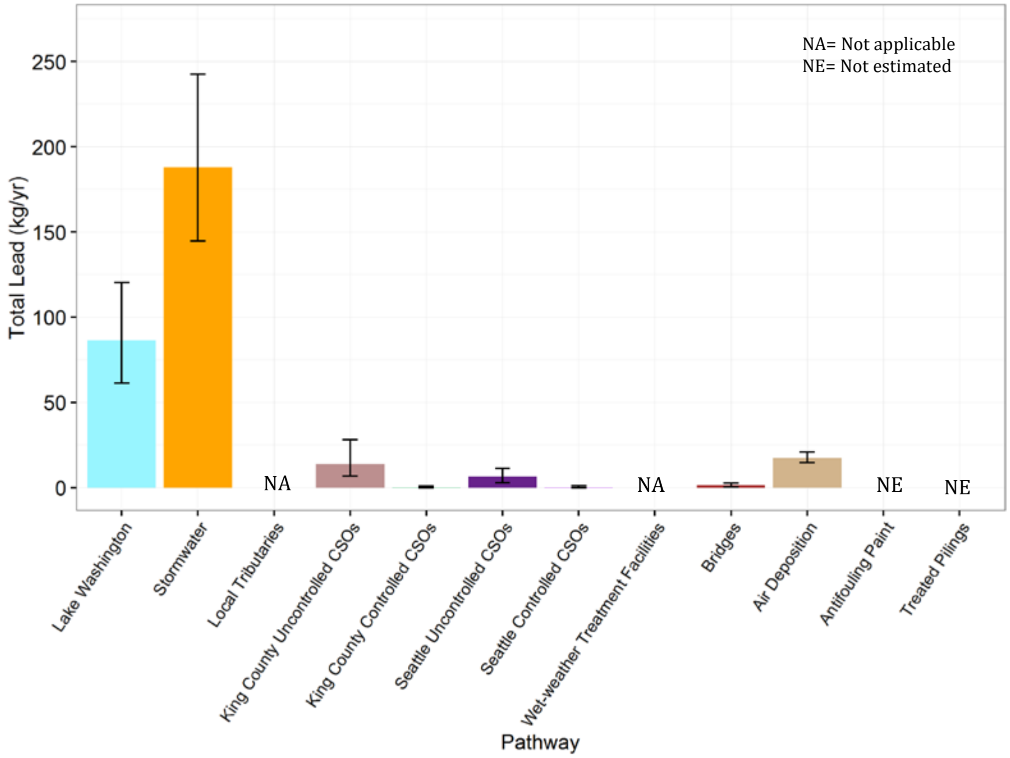

Figure 4-16. Estimated annual total lead loads from major pathways to Lake Union/Ship Canal.

Table 4-10. Estimated annual total lead loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	610	940	1,400
	Stormwater runoff	240	310	410
	Local tributaries	9.5	10	16
	Uncontrolled CSOs - King County	29	59	110
	Uncontrolled CSOs - Seattle	0.16	0.64	1.8
	Controlled CSOs - King County	0.088	0.32	1.2
	Controlled CSOs - Seattle	0.0072	0.10	0.32
	Wet weather treatment facilities	8.5	16	45
	Atmospheric deposition	64	75	89
Lake Union/Ship Canal	Lake Washington	61	86	120
	Stormwater runoff	140	190	240
	Uncontrolled CSOs - King County	6.8	14	28
	Uncontrolled CSOs - Seattle	2.8	6.4	11
	Controlled CSOs - King County	0.059	0.21	0.79
	Controlled CSOs - Seattle	0.000027	0.28	1.3
	Bridges	0.52	1.5	2.6
	Atmospheric deposition	15	17	21

4.4.8 Total Mercury

Annual total mercury loading estimates from the major pathways are presented in Figure 4-17 for Duwamish Estuary/Elliott Bay and Figure 4-18 for Lake Union/Ship Canal. The estimates are also given in Table 4-11.

- In the Duwamish Estuary/Elliott Bay, the Green River is the greatest contributing pathway followed by stormwater runoff.
- In the Lake Union /Ship Canal, Lake Washington and stormwater runoff are the greatest contributing pathways with overlapping 95 percent UCL and LCL.

Total mercury loading from stormwater runoff in both study areas had substantial uncertainty because mercury was detected in only 26 percent of the samples, in part because of high detection limits (95 out of 365 samples).

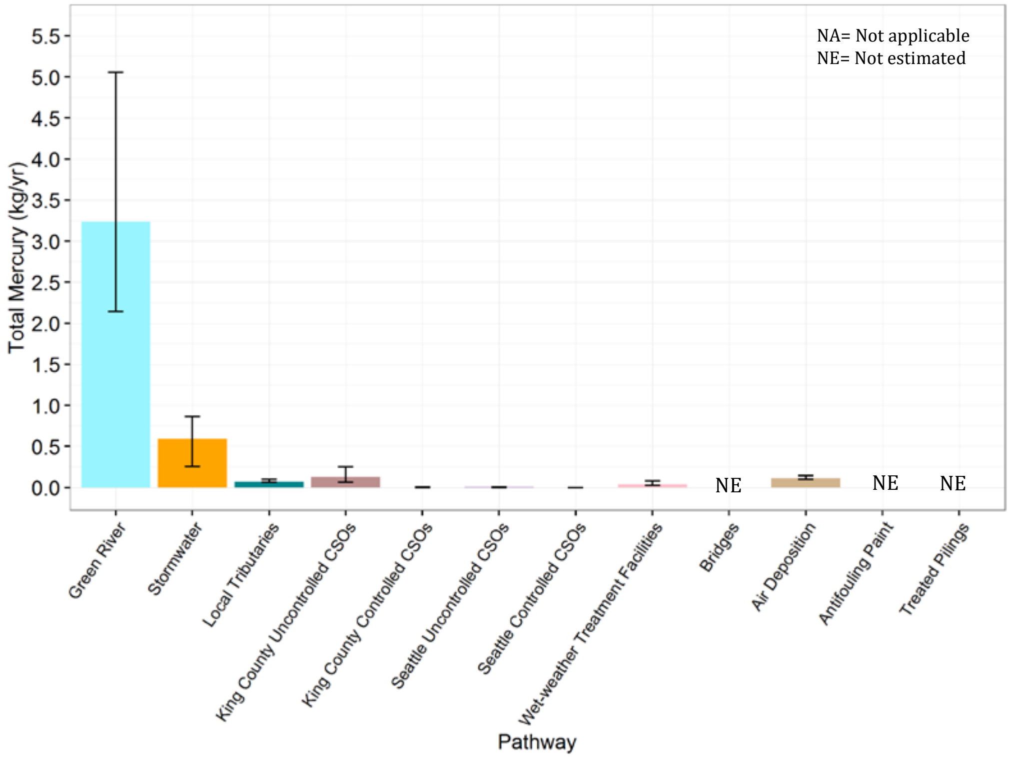

Figure 4-17. Estimated annual total mercury loads from major pathways to Duwamish Estuary/Elliott Bay.

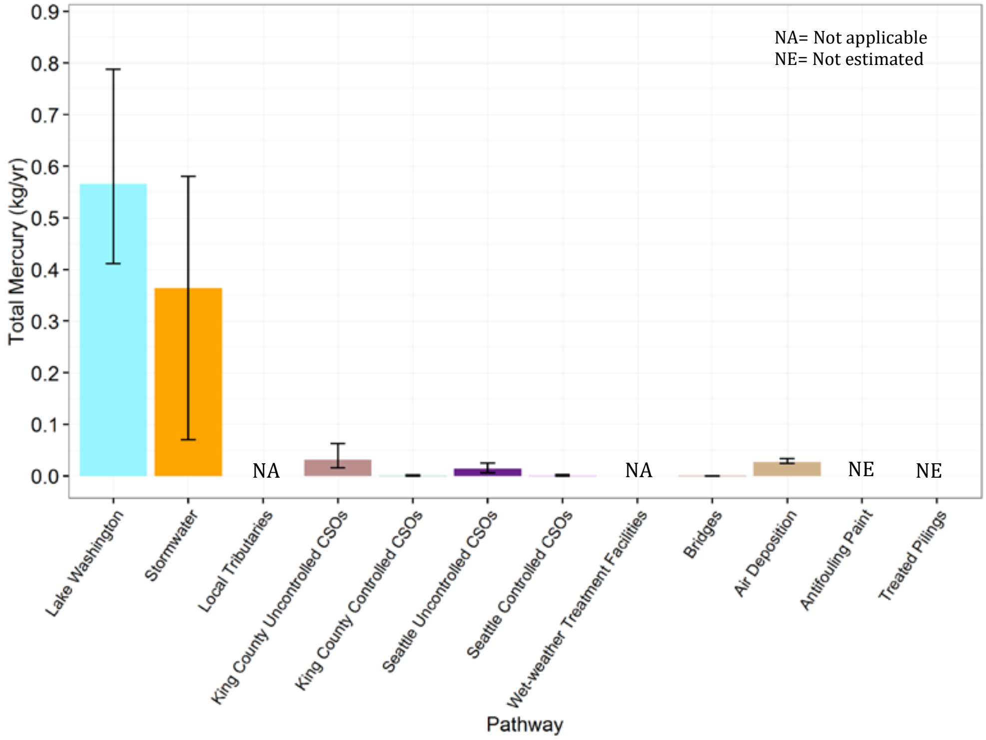

Figure 4-18. Estimated annual total mercury loads from major pathways to Lake Union/Ship Canal.

Table 4-11. Estimated annual total mercury loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	2.2	3.2	5.1
	Stormwater runoff	0.26	0.59	0.86
	Local tributaries	0.062	0.070	0.10
	Uncontrolled CSOs - King County	0.065	0.13	0.25
	Uncontrolled CSOs - Seattle	0.00036	0.0014	0.0040
	Controlled CSOs - King County	0.00020	0.00072	0.0027
	Controlled CSOs - Seattle	0.000016	0.00022	0.00071
	Wet weather treatment facilities	0.023	0.041	0.082
	Atmospheric deposition	0.10	0.12	.14
Lake Union/Ship Canal	Lake Washington	0.41	0.57	0.79
	Stormwater runoff	0.070	0.36	0.58
	Uncontrolled CSOs - King County	0.015	0.031	0.062
	Uncontrolled CSOs - Seattle	0.0061	0.014	0.025
	Controlled CSOs - King County	0.00013	0.00046	0.0018
	Controlled CSOs - Seattle	5.9 x 10^{-8}	6.2 x 10^{-4}	2.8 x 10^{-3}
	Bridges	0.00079	0.00079	0.00079
	Atmospheric deposition	0.024	0.027	0.034

4.4.9 Total Zinc

Annual total zinc loading estimates from the major pathways are presented in Figure 4-19 for Duwamish Estuary/Elliott Bay and Figure 4-20 for Lake Union/Ship Canal. The estimates are also given in Table 4-12.

- In Duwamish Estuary/Elliott Bay, the Green River is the greatest contributing pathway of total zinc, followed by stormwater runoff.
- In Lake Union/Ship Canal, Lake Washington and stormwater runoff are the greatest contributing pathways.

It appears from the limited data available that zinc anodes may be a substantial pathway of zinc to Duwamish Estuary/Elliott Bay. However, the annual zinc loading from sacrificial anodes was not estimated because of uncertainty regarding the recommended zinc anode rate for each vessel in the waterbody, whether vessel owners follow the recommended zinc anode rate, how frequently owners replace anodes, and what percentage of vessels use zinc anodes (opposed to the alternatives).

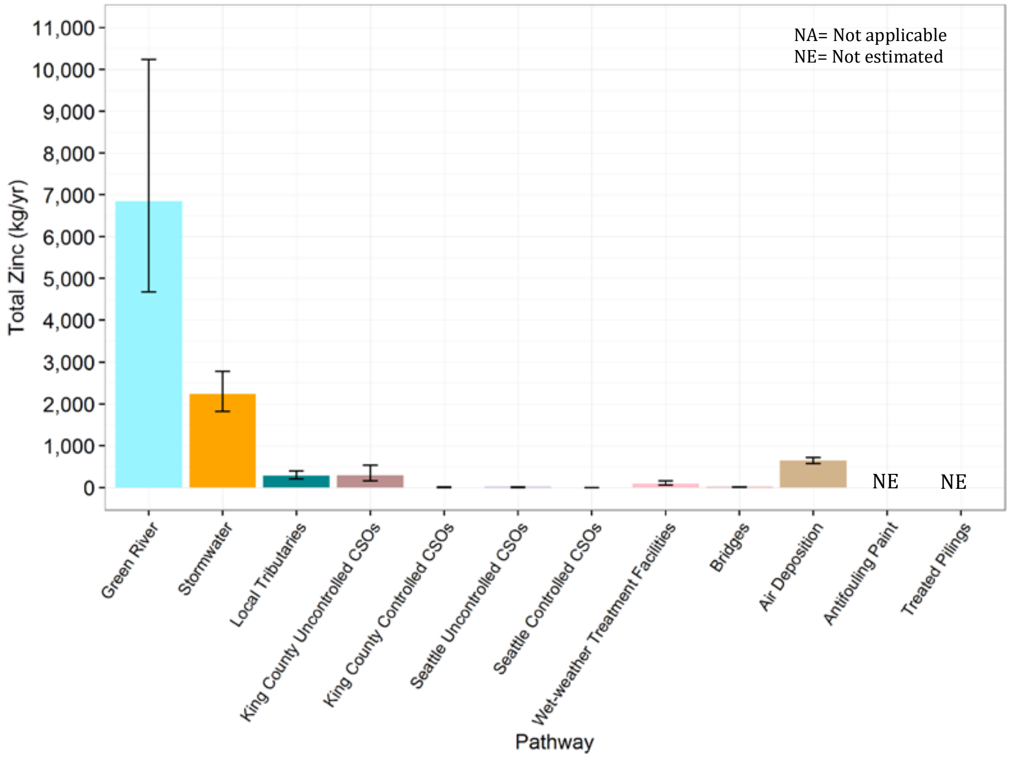

Figure 4-19. Estimated annual total zinc loads from major pathways to Duwamish Estuary/Elliott Bay.

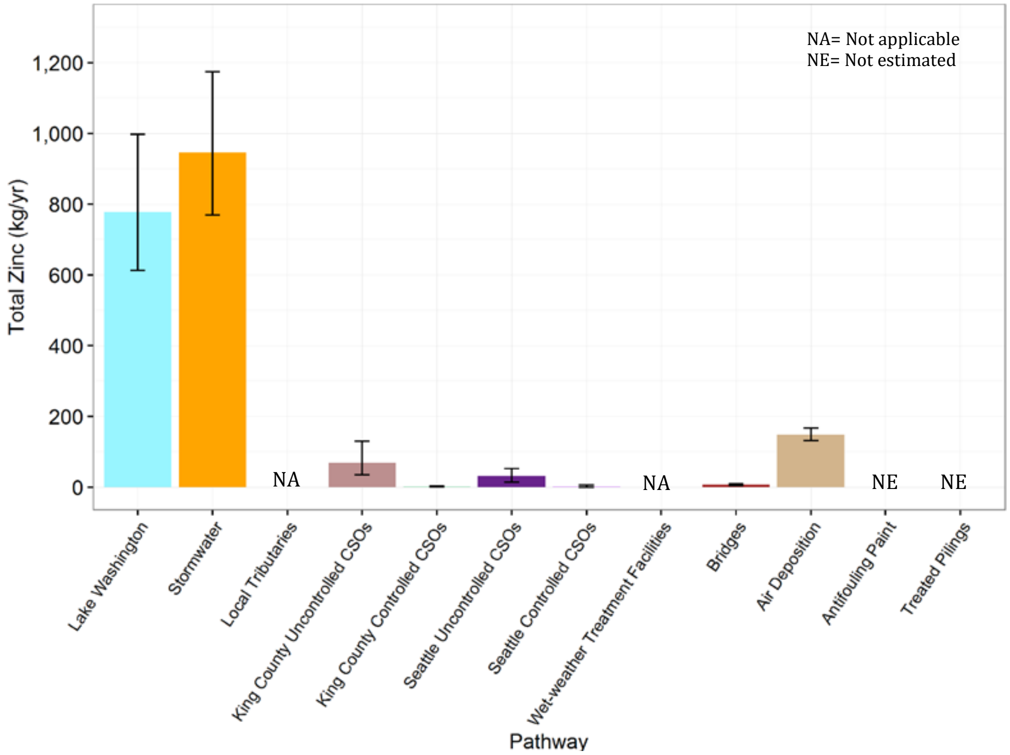

Figure 4-20. Estimated annual total zinc loads from major pathways to Lake Union/Ship Canal.

Table 4-12. Estimated annual total zinc loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).

Study Area	Pathway	95% Local Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	4,700	6,800	10,000
	Stormwater runoff	1,800	2,200	2,800
	Local tributaries	210	290	390
	Uncontrolled CSOs - King County	150	290	530
	Uncontrolled CSOs - Seattle	0.84	3.2	8.4
	Controlled CSOs - King County	0.45	1.6	5.5
	Controlled CSOs - Seattle	0.037	0.50	1.5
	Wet weather treatment facilities	60	92	150
	Bridges	2.9	4.2	5.9
	Atmospheric deposition	570	640	720
Lake Union/Ship Canal	Lake Washington	610	780	1,000
	Stormwater runoff	770	950	1,200
	Uncontrolled CSOs - King County	35	68	130
	Uncontrolled CSOs - Seattle	14	32	52
	Controlled CSOs - King County	0.30	1.0	3.7
	Controlled CSOs - Seattle	0.00014	1.4	5.8
	Bridges	4.4	6.4	8.7
	Atmospheric deposition	130	150	170

4.4.10 Benzyl Butyl Phthalate

Annual BBP loading estimates from the major pathways are presented in Figure 4-21 for Duwamish Estuary/Elliott Bay and Figure 4-22 for Lake Union/Ship Canal. The estimates are also given in Table 4-13. Study area findings are as follows:

- **Duwamish Estuary/Elliott Bay.** Stormwater runoff and King County uncontrolled CSOs were the largest contributing pathways. Stormwater runoff has a high amount of uncertainty, with detection in only 22 percent of the samples (87 out of 395). There were not enough data to estimate loadings from the Green River (3 detections out of 20 samples).
- **Lake Union/Ship Canal.** Stormwater runoff is the largest contributing pathway, followed by King County and Seattle uncontrolled CSOs. There were not enough data to estimate BBP loading from Lake Washington (30 samples; no detections).

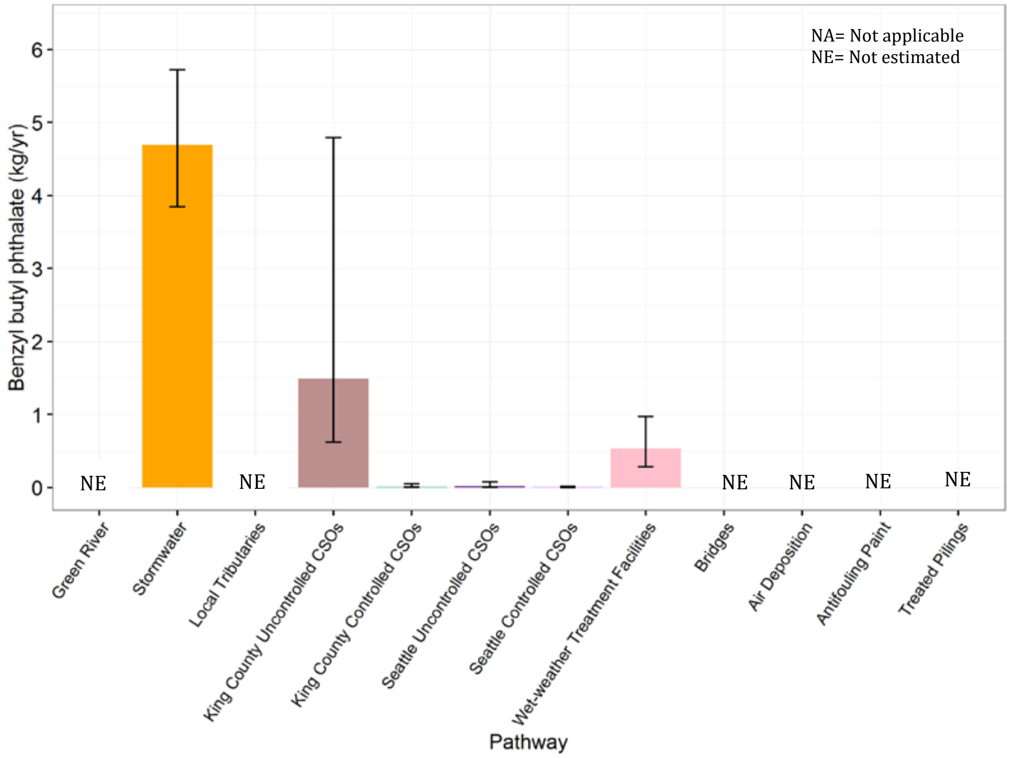

Figure 4-21. Estimated annual BBP loads from major pathways to Duwamish Estuary/Elliott Bay.

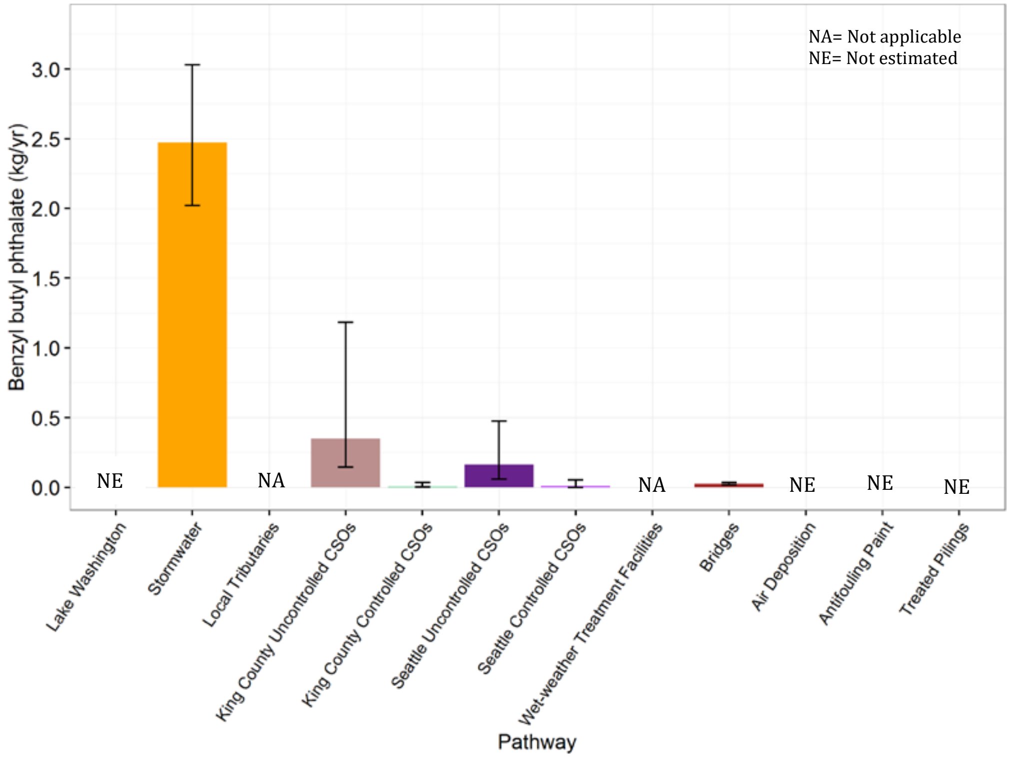

Figure 4-22. Estimated annual BBP loads from major pathways to Lake Union/Ship Canal.

Table 4-13. (Estimated annual BBP loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	--	--	--
	Stormwater runoff	3.8	4.7	5.7
	Uncontrolled CSOs - King County	0.62	1.5	4.8
	Uncontrolled CSOs - Seattle	0.0035	0.016	0.076
	Controlled CSOs - King County	0.0019	0.0082	0.050
	Controlled CSOs - Seattle	0.00015	0.0025	0.013
	Wet weather treatment facilities	0.28	0.54	0.97
Lake Union/Ship Canal	Lake Washington	--	--	--
	Stormwater runoff	2.0	2.5	3.0
	Uncontrolled CSOs - King County	0.14	0.35	1.2
	Uncontrolled CSOs - Seattle	0.058	0.16	0.48
	Controlled CSOs - King County	0.0012	0.0052	0.033
	Controlled CSOs - Seattle	0.00000057	0.0070	0.053
	Bridges	0.016	0.025	0.035

-- = no data available; not estimated.

4.4.11 Bis(2-ethylhexyl) Phthalate

Annual BEHP loading estimates from the major pathways are presented in Figure 4-23 for Duwamish Estuary/Elliott Bay and Figure 4-24 for Lake Union/Ship Canal. The estimates are also given in Table 4-14. Study area findings are as follows:

- **Duwamish Estuary/Elliott Bay:**
  - There were not enough data to estimate loadings from the Green River. Only 10 percent of the Green River samples (2 out of 20) had detections, and 25 percent of the Black River samples (2 out of 8) had detections.
  - Stormwater is the greatest contributing pathway, followed by King County uncontrolled CSOs.
  - Because BEHP was not detected during baseflow conditions in local tributaries, BEHP loadings from local tributaries are a conservative estimate and were calculated with concentrations detected during storm events only. Assuming that the maximum detection limit for BEHP in baseflow samples represents the baseflow concentration in local tributaries, the maximum areal baseflow loading would be 0.035 kg/km^2/yr and baseflow BEHP loadings would be minimal, contributing up to an additional 0.6 kg/yr.
- **Lake Union/Ship Canal.** Lake Washington is the largest contributing pathway of BEHP loads but also has the greatest amount of uncertainty, with a 95 percent UCL and LCL ranging from 0 kg/yr to 7,000 kg/yr. Only 33 percent of the samples (4 out of 12) had detections. Stormwater is the second largest contributing pathway.

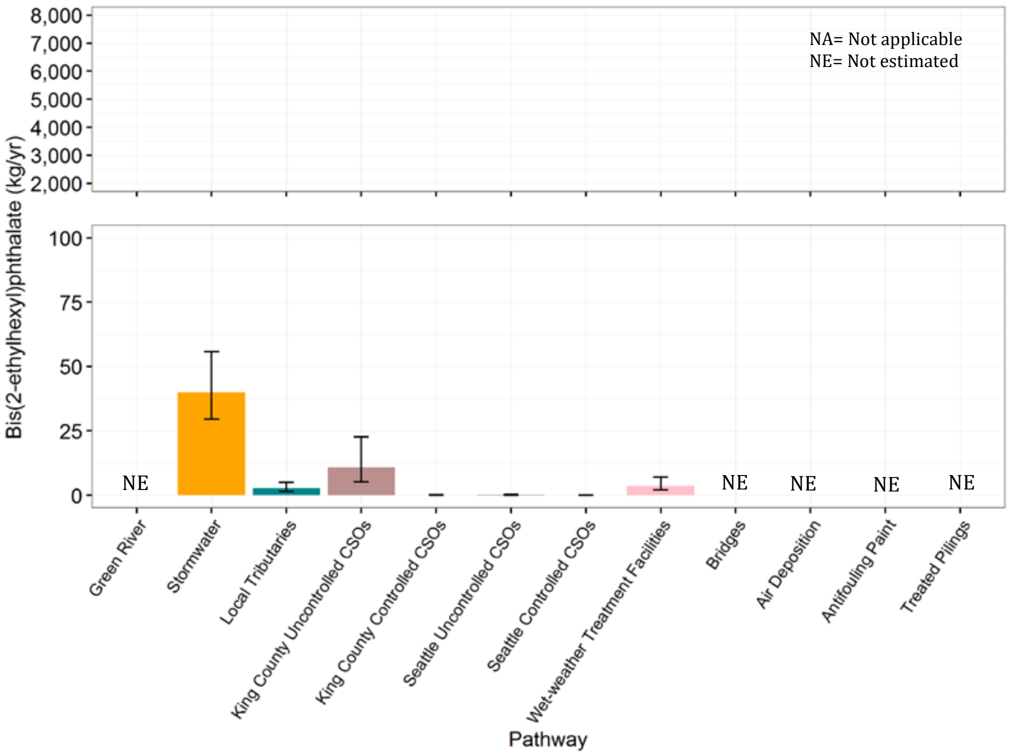

Figure 4-23. Estimated annual BEHP loads from major pathways to Duwamish Estuary/Elliott Bay.

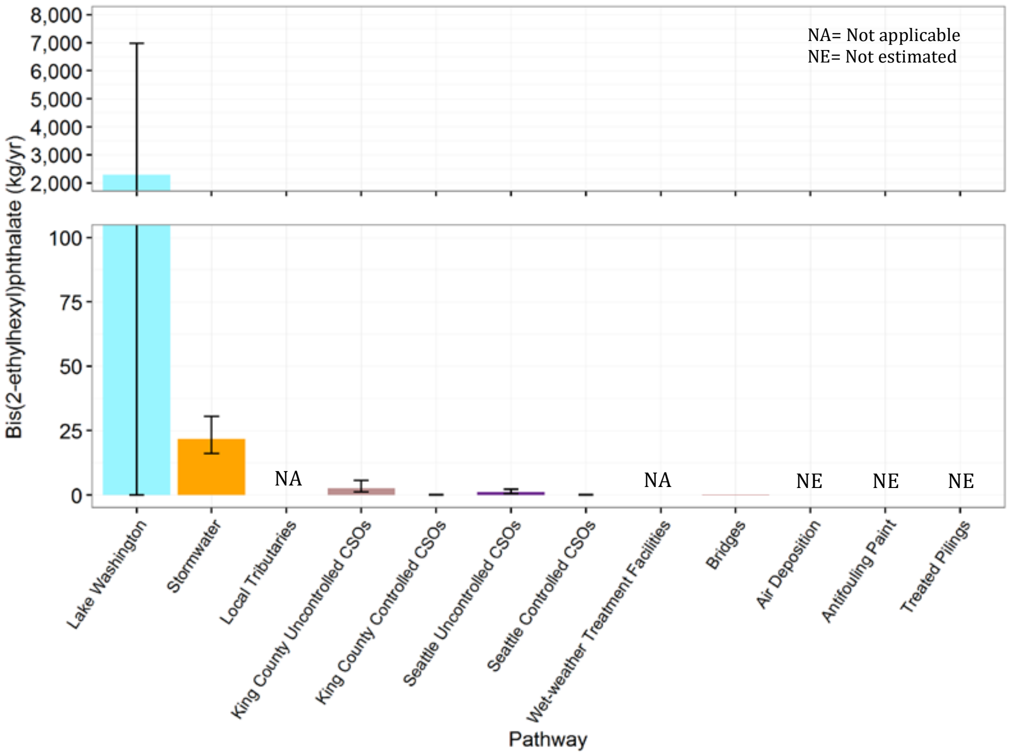

Figure 4-24. Estimated annual BEHP loads from major pathways to Lake Union/Ship Canal.

Table 4-14. Estimated annual BEHP loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	--	--	--
	Stormwater runoff	30	40	56
	Local tributaries	1.5	2.8	5.0
	Uncontrolled CSOs - King County	5.1	11	23
	Uncontrolled CSOs - Seattle	0.028	0.12	0.36
	Controlled CSOs - King County	0.015	0.059	0.24
	Controlled CSOs - Seattle	0.0013	0.018	0.063
	Wet weather treatment facilities	2.1	3.6	7.1
Lake Union/Ship Canal	Lake Washington	0	2,300	7,000
	Stormwater runoff	16	22	30
	Uncontrolled CSOs - King County	1.2	2.5	5.6
	Uncontrolled CSOs – Seattle	0.48	1.2	2.2
	Controlled CSOs - King County	0.010	0.038	0.16
	Controlled CSOs – Seattle	0.0000046	0.051	0.25
	Bridges	0.19	0.19	0.19

-- = no data available; not estimated.

4.4.12 Total Polycyclic Aromatic Hydrocarbons

Annual total PAH loading estimates from the major pathways are presented in Figures 4-25 for the Duwamish Estuary/Elliott Bay and Figure 4-26 for Lake Union/Ship Canal. The estimates are also given in Table 4-15. Creosote-treated wood pilings is the largest contributing pathway of total PAH loadings into both study areas by an order of magnitude two to three times larger than the other pathways. Loading estimates from creosote-treated pilings have a large amount of uncertainty because of the many factors that affect the leaching rate of total PAHs, including the age and size of pilings and the amount of the EPA-priority PAHs in the creosote.

Study area findings are as follows:

- **Duwamish Estuary/Elliott Bay:**
    - Total PAH loadings range from 1,100 kg/yr to 14,000 kg/yr.
    - The Green River and stormwater runoff are the second largest contributing pathways.
    - PAHs were not detected above MDLs in baseflow samples from local tributaries. Therefore, total PAH loadings from local tributaries were a conservative estimate and were calculated with stormflow concentrations only. Assuming that the maximum detection limit represents the total PAH concentration in local tributaries during baseflow conditions, the maximum areal baseflow loading would be 0.004 kg/km^2/yr and total baseflow PAH loadings could contribute up to an additional 0.07 kg/yr.

- **Lake Union/Ship Canal.** Total PAH loadings range from 420 kg/yr to 5,400 kg/yr. Lake Washington is the second largest contributing pathway, followed by stormwater runoff. Inflow from Lake Washington has a high amount of uncertainty, with a 95 percent UCL and LCL ranging from 49 kg/yr to 99 kg/yr. The uncertainty is largely because only 31 percent of samples (4 out of 13) had PAH detections.

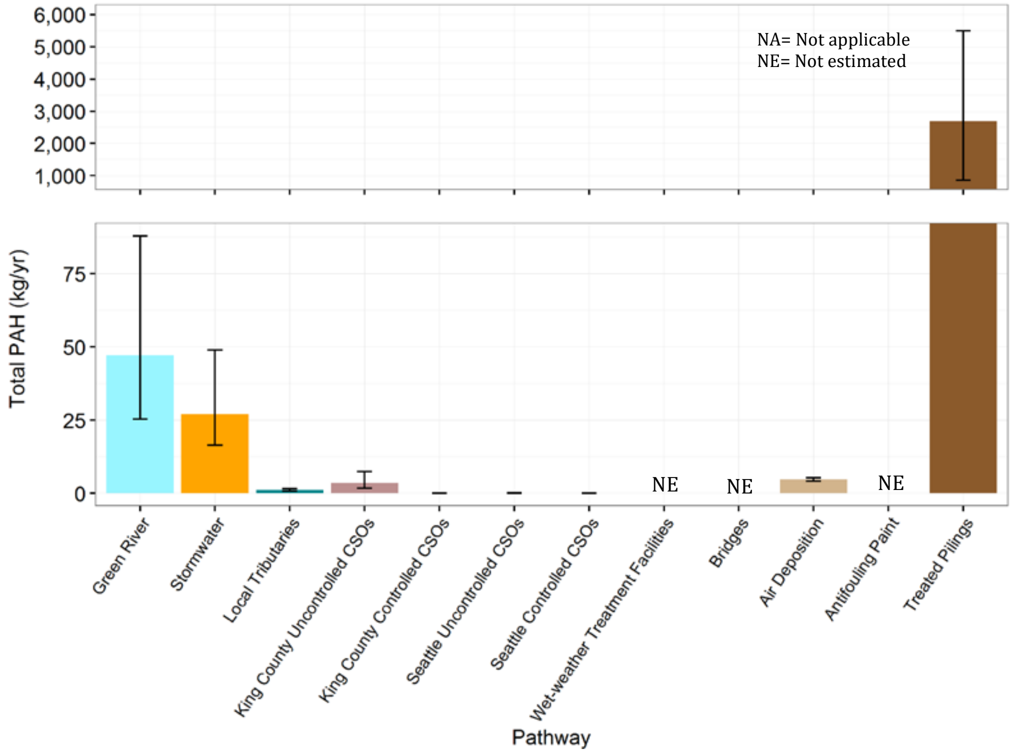

Figure 4-25. **Estimated annual total PAH loads from major pathways to Duwamish Estuary/Elliott Bay.**

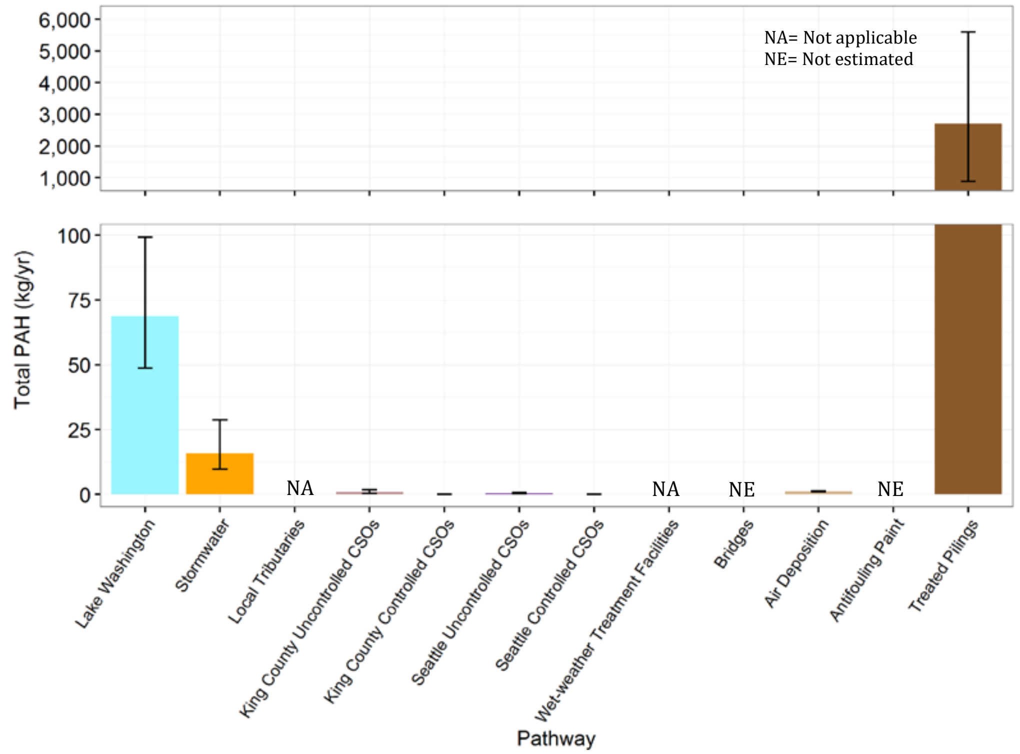

Figure 4-26. **Estimated annual total PAH loads from major pathways to Lake Union/Ship Canal.**

Table 4-15. **Estimated annual total PAH loads from the major pathways for Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (kg/yr).**

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit	Low Estimate	Mid Estimate	High Estimate
Duwamish Estuary/Elliott Bay	Green River	25	47	88	--	--	--
	Stormwater runoff	16	27	49	--	--	--
	Local tributaries	0.76	1.1	1.6	--	--	--
	Uncontrolled CSOs - King County	1.7	3.5	7.3	--	--	--
	Uncontrolled CSOs - Seattle	0.0093	0.039	0.12	--	--	--
	Controlled CSOs - King County	0.0050	0.020	0.077	--	--	--
	Controlled CSO - Seattle	0.00042	0.0061	0.021	--	--	--
	Atmospheric deposition	4.1	4.6	5.3	--	--	--
	Creosote-treated wood pilings	--	--	--	870	2,700	5,500
Lake Union/ Ship Canal	Lake Washington	49	69	99	--	--	--
	Stormwater runoff	10	16	29	--	--	--
	Uncontrolled CSOs - King County	0.39	0.83	1.8	--	--	--

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit	Low Estimate	Mid Estimate	High Estimate
	Uncontrolled CSOs - Seattle	0.16	0.38	0.72	--	--	--
	Controlled CSOs - King County	0.0034	0.013	0.051	--	--	--
	Controlled CSOs - Seattle	0.0000015	0.017	0.081	--	--	--
	Atmospheric deposition	0.96	1.1	1.2	--	--	--
	Creosote-treated wood pilings	--	--	--	890	2,700	5,600

-- = no data available; not estimated.

4.4.13 Total Polybrominated Diphenyl Ethers

Annual total PBDE loading estimates from the major pathways are presented in Figure 4-27 for Duwamish Estuary/Elliott Bay and Figure 4-28 for Lake Union/Ship Canal. The estimates are also given in Table 4-16. The amount of total PBDE data available for the major pathways was limited. There were no data available to estimate total PBDE loadings from the Green River to Duwamish Estuary/Elliott Bay. Further, only 6 samples of Lake Washington outflow, 25 samples of stormwater runoff in both study areas, and 8 samples of CSO effluent in both study areas had been analyzed for PBDEs.

Considering the limited data and sample sizes, stormwater runoff, local tributaries, King County uncontrolled CSOs, and atmospheric deposition are the greatest contributing pathways for total PBDE loading to Duwamish Estuary/Elliott Bay, with overlapping UCLs and LCLs. Lake Washington is the largest contributing pathway to Lake Union/Ship Canal, followed by stormwater runoff.

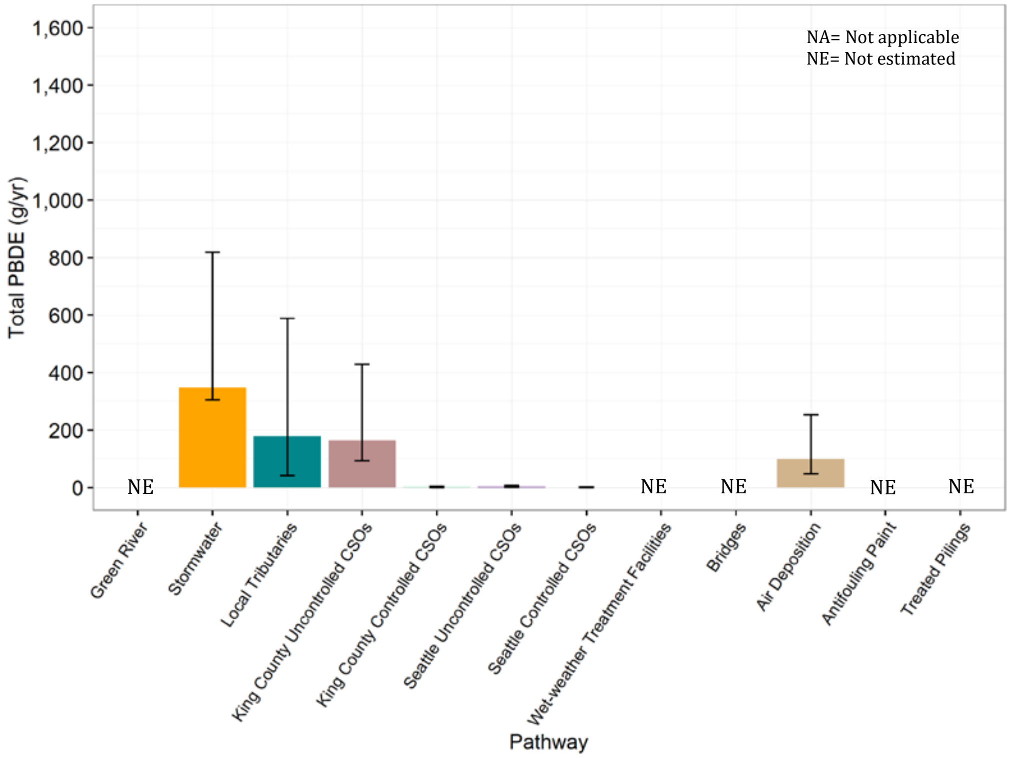

Figure 4-27. **Estimated annual total PBDE loads from major pathways to Duwamish Estuary/Elliott Bay.**

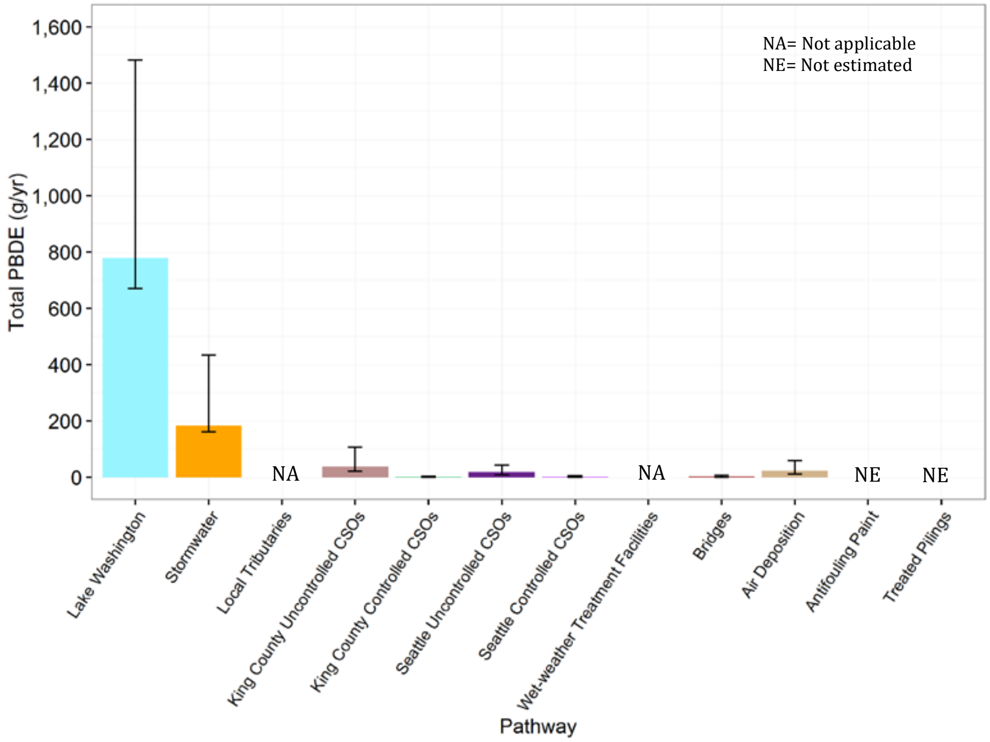

Figure 4-28. **Estimated annual total PBDE loads from major pathways to Lake Union/Ship Canal.**

Table 4-16. Estimated annual total PBDE loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (g/yr).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Stormwater runoff	300	350	820
	Local tributaries	41	180	590
	Uncontrolled CSOs - King County	94	160	430
	Uncontrolled CSOs - Seattle	0.52	1.8	6.8
	Controlled CSOs - King County	0.28	0.9	4.5
	Controlled CSOs - Seattle	0.023	0.28	1.2
	Atmospheric deposition	48	99	250
Lake Union/Ship Canal	Lake Washington	680	780	1,500
	Stormwater runoff	160	180	430
	Uncontrolled CSOs - King County	22	39	110
	Uncontrolled CSOs - Seattle	8.8	18	42
	Controlled CSOs - King County	0.19	0.58	3
	Controlled CSOs - Seattle	0.000085	0.77	4.7
	Bridges	0.13	2.4	7.3
	Atmospheric deposition	11	23	59

4.4.14 Total Polychlorinated Biphenyls

Annual total PCB loading estimates from the major pathways are presented in Figure 4-29 for Duwamish Estuary/Elliott Bay and Figure 4-30 for Lake Union/Ship Canal. The estimates are also given in Table 4-17. The amount of total PCB data available for the upstream watersheds was limited. There were only 15 samples available for the Green River, 10 samples available for the Black River, and 20 samples available for Lake Washington.

Considering the limited data available for upstream watersheds, the Green River, Lake Washington, and stormwater runoff are the largest contributing pathways to total PCBs in both study areas.

- In Duwamish Estuary/Elliott Bay, local tributaries, King County uncontrolled CSOs, wet weather treatment facilities and atmospheric deposition are the second largest contributing pathways.
- In Lake Union/Ship Canal, King County and Seattle uncontrolled CSOs and atmospheric deposition are the second largest contributing pathways.

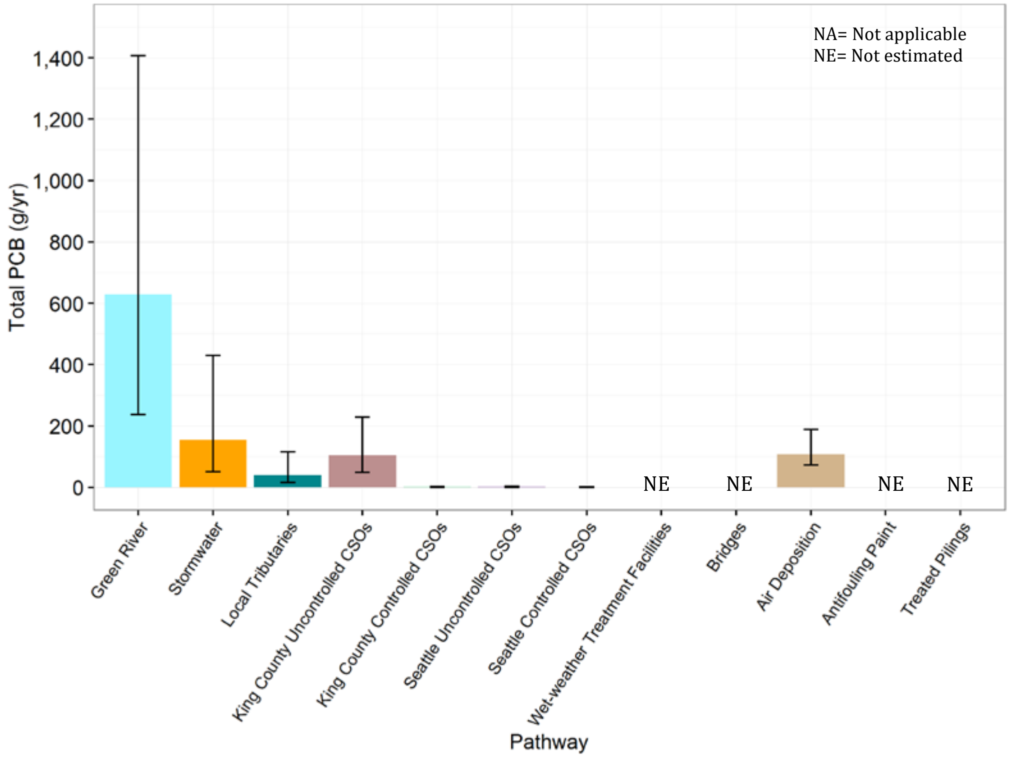

Figure 4-29. Estimated annual total PCB loads from major pathways to Duwamish Estuary/Elliott Bay.

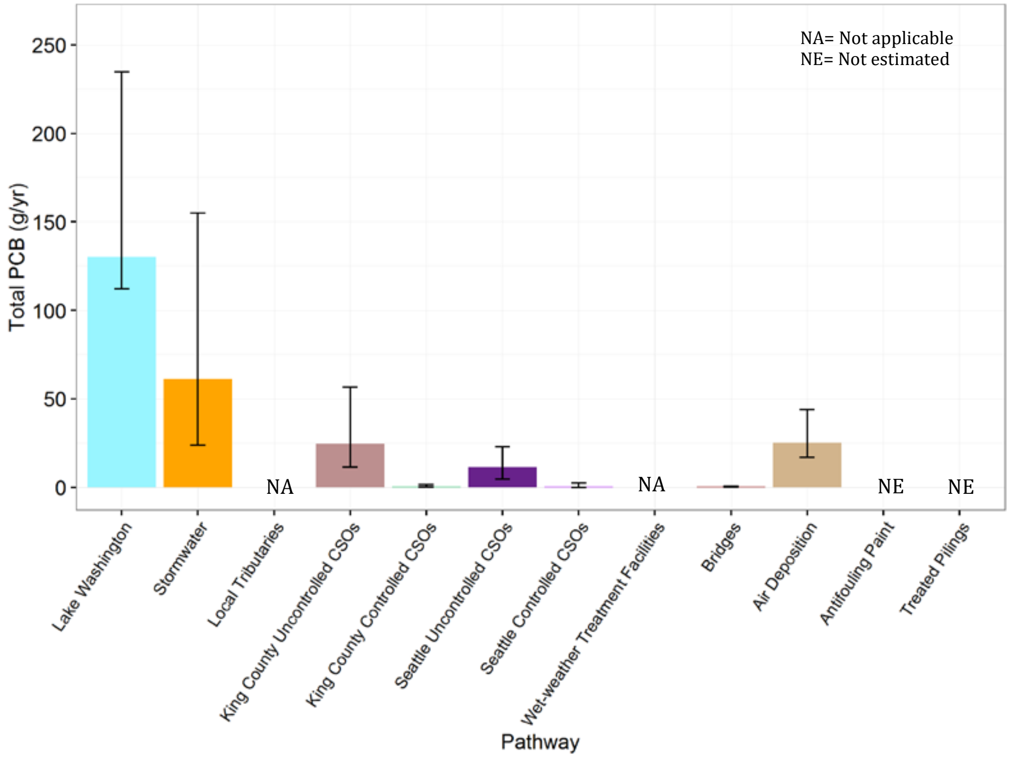

Figure 4-30. Estimated annual total PCB loads from major pathways to Lake Union/Ship Canal.

Table 4-17. Estimated annual total PCB loads from major pathways to Duwamish Estuary/Elliott Bay and Lake Union/Ship Canal (g/yr).

Study Area	Pathway	95% Lower Confidence Limit	Mean	95% Upper Confidence Limit
Duwamish Estuary/Elliott Bay	Green River	240	630	1400
	Stormwater runoff	50	155	430
	Local tributaries	16	40	120
	Uncontrolled CSOs - King County	49	100	230
	Uncontrolled CSOs - Seattle	0.27	1.1	3.6
	Controlled CSOs - King County	0.15	0.58	2.4
	Controlled CSOs - Seattle	0.015	0.18	0.64
	Atmospheric deposition	73	110	190
Lake Union/Ship Canal	Lake Washington	110	130	240
	Stormwater runoff	23	61	150
	Uncontrolled CSOs - King County	11	25	57
	Uncontrolled CSOs - Seattle	4.6	11	23
	Controlled CSOs - King County	0.098	0.37	1.6
	Controlled CSOs - Seattle	0.000044	0.49	2.5
	Bridges	0.15	0.37	0.60
	Atmospheric deposition	17	25	44

5.0 DISCUSSION AND CONCLUSIONS

This chapter discusses the major contributing pathways of contaminant loading, compares upstream watershed and background loading rates, and relates findings to key uncertainties and data gaps limiting the loadings analysis.

The purpose of this study was to provide planning-level estimates of the mean annual loading of selected contaminants from major pathways in the study areas using data from previous studies and monitoring. Another study as part of this Water Quality Assessment and Monitoring Study evaluates the impact that planned activities between 2015 and 2030 will have on the estimated annual contaminant loadings.

5.1 Pathway Load Contributions

The pathways evaluated had different relative contributions of loadings depending on the contaminant analyzed (Tables 5-1 and 5-2). In both study areas, upstream watersheds and local stormwater runoff were the two largest contributing pathways of loadings for about half of the COIs evaluated, specifically for total nitrogen, total phosphorus, TSS, total lead, total mercury, and total zinc. Additionally, upstream watersheds and stormwater runoff were the largest contributing pathways for BBP in Duwamish Estuary/Elliott Bay and for BEHP and total PBDEs in Lake Union/Ship Canal. The large contributions of loadings from upstream watersheds were a reflection of high flow volumes; the contaminant concentrations were relatively low. It is likely that upstream stormwater runoff contributes substantially to the upstream watershed load for some contaminants, but these discharges were not quantitatively evaluated as part of this study. There were not enough data to estimate BBP loadings from Lake Washington to Lake Union/Ship Canal and BEHP or total PBDEs from the Green River to Duwamish Estuary/Elliott Bay.

A different pattern was seen among the pathways for fecal coliform, total copper, and total PAH loadings to the study areas:

- Uncontrolled CSOs were the largest contributing pathway of fecal coliform bacteria to both study areas.
- Creosote-treated wood pilings were the largest contributing pathway of total PAHs, followed by upstream watersheds and stormwater runoff.
- Antifouling paint was the largest contributing pathway of total copper loads to both study areas. The Green River was the second largest contributing pathway of total copper loading into Duwamish Estuary/Elliott Bay, followed by stormwater runoff. Lake Washington and stormwater runoff were the second largest contributing pathways of total copper into Lake Union/Ship Canal.

Table 5-1. Duwamish Estuary/Elliott Bay: Major contributing pathways of contaminants of interest.

Contaminant of Interest (COI)	Reason for Interest (King County, 2017b & c)	Major Contributing Pathways
Fecal coliform bacteria	Frequent exceedance of peak and geometric mean water quality standards; on 303(d) list for water because of high fecal coliform	King County CSOs (92%)
		Stormwater runoff (2%)[b]
		Upstream watershed (Green River) (4%)
TSS	Suspended solids may carry bound contaminants and also impact habitat	Upstream watershed (Green River) (90%)
		Stormwater runoff (7%) [b]
Total nitrogen	Excess nitrogen (and phosphorus) may cause increased productivity, which may lower dissolved oxygen seasonally	Upstream watershed (Green River) (93%)
Total phosphorus	Excess phosphorus (and nitrogen) may cause increased productivity, which may lower dissolved oxygen seasonally	Upstream watershed (Green River) (87%)
		Stormwater runoff (6%)[b]
		King County CSOs (4%)
Total arsenic	Exceedance of state Sediment Quality Standards (SQS); on 303(d) list for sediment and tissue (inorganic arsenic only)[a]	Upstream watershed (Green River) (94%)
Total copper	Exceedance of state SQS; on 303(d) list for sediment; may pose toxicity to aquatic life in water column	Copper-based antifouling paint (49%)
		Upstream watershed (Green River) (41%)
		Stormwater runoff (6%)[b]
Total lead	Exceedance of state SQS; on 303(d) list for sediment [a]	Upstream watershed (Green River) (67%)
		Stormwater runoff (22%)[b]
		King County CSOs (4%)
Total mercury	Exceedance of SQS; on 303(d) list for tissue and sediment; fish advisory in place	Upstream watershed (Green River) (77%)
		Stormwater runoff (14%) [b]
Total zinc	Exceedance of state SQS; on 303(d) list for sediment; may pose toxicity to aquatic life in water column [a]	Upstream watershed (Green River) (66%)
		Stormwater runoff (21%)[b]
Total PAHs	Exceedance of state SQS; on 303(d) list for tissue and sediment [a]	Creosote-treated wood pilings (97%)
Benzyl butyl phthalate	Exceedance of state SQS; on 303(d) list for sediment [a]	Upstream watershed (Green River) (Not estimated)[c]
		Stormwater runoff (3.8–5.7 g/yr)[c]
		King County CSOs (0.6–4.8 g/yr)[c]
Bis(2-ethylhexyl) phthalate	Exceedance of state SQS; on 303(d) list for tissue and sediment [a]	Upstream watershed (Green River) (Not estimated)[c]
		Stormwater runoff (30–56 g/yr)[b,c]
		King County CSOs (5.1–23 g/yr)[b]
Total PBDEs	May pose toxicity to aquatic life in water column and sediments (no SQS); may bioaccumulate in tissue	Upstream watershed (Green River) (Not estimated)[c]
		Stormwater runoff (300–820 g/yr)[b,c]
		Atmospheric deposition (48–250 g/yr[c]
		Local tributaries (41–590 g/yr)[c]
		King County CSOs (94–430 g/yr)[c]
Total PCBs	Exceedance of state SQS; on 303(d) list for tissue and sediment [a]	Upstream watershed (Green River) (61%)
		Stormwater runoff (15%) [b]
		Atmospheric deposition (11%)
		King County CSOs (10%)

[a] The 303(d) list includes all impaired waterbodies in Washington State.

[b] Stormwater load reductions associated with current public or private stormwater facilities or operations were not included in the estimates. Thus, the stormwater runoff pathway load is likely overestimated but the magnitude of overestimation is unknown.

[c] Inadequate data for upstream pathway to estimate the percentage of the contribution of current loadings.

Table 5-2. Lake Union/Ship Canal: Major contributing pathways of contaminants of interest.

Contaminant of Interest (COI)	Reason for Interest (King County, 2017a)	Major Contributing Pathways
Fecal coliform bacteria	Frequent exceedance of peak and geometric mean water quality standards; on 303(d) list for water because of high fecal coliform[a]	King County CSOs (65%)
		Seattle CSOs (31%)
		Stormwater runoff (4%)[b]
TSS	Suspended solids may carry bound contaminants and impact habitat	Upstream watershed (Lake Washington) (66%)
		Stormwater runoff (30%)[b]
Total nitrogen	Excess nitrogen (and phosphorus) may cause increased productivity, which may seasonally impact dissolved oxygen	Upstream watershed (Lake Washington) (94%)
Total phosphorus	Excess phosphorus (and nitrogen) may cause increased productivity that may seasonally impact dissolved oxygen; on 303(d) list for water[a]	Upstream watershed (Lake Washington) (84%)
		Stormwater runoff (11%)[b]
Total arsenic	Exceedance of State Sediment Quality (SQS) Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (98%)
Total copper	Exceedance of SQS Freshwater Benthic Cleanup Standards; may pose toxicity to aquatic life in water column	Copper-based antifouling paint (74%)
		Upstream watershed (Lake Washington) (22%)[b]
Total lead	Exceedance of SQS Freshwater Benthic Cleanup Standards	Stormwater (60%)[b]
		Upstream watershed (Lake Washington) (27%)
		King County CSOs (4%)
Total mercury	Exceedance of SQS Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (57%)
		Stormwater runoff (36%)[b]
		King County CSOs (3%)
Total zinc	May pose toxicity to aquatic life in water column	Upstream watershed (Lake Washington) (39%)
		Stormwater runoff (48%)[b]
		Atmospheric deposition (8%)
Benzyl butyl phthalate	Exceedance of SQS Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (Not estimated)[c]
		Stormwater runoff (2–3 g/yr)[b,c]
		King County CSOs (0.2–1.2 g/yr)[c]
		Seattle CSOs (0.1–0.5 g/yr)[c]
Bis(2-ethylhexyl) phthalate	Exceedance of SQS Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (99%)
		Stormwater runoff (1%)[b]
Total PAHs	Exceedance of SQS Freshwater Benthic Cleanup Standards	Creosote-treated wood pilings (97%)
Total PBDEs	May pose toxicity to aquatic life in water column and sediments (no SQS); may bioaccumulate in tissue	Upstream watershed (Lake Washington) (75%)
		Stormwater runoff (17%)[b]
Total PCBs	Exceedance of SQS Freshwater Benthic Cleanup Standards	Upstream watershed (Lake Washington) (51%)
		Stormwater runoff (24%)[b]
		Atmospheric deposition (10%)
		King County CSOs (10%)
		Seattle CSOs (4%)

[a] The 303(d) list includes all impaired waterbodies in Washington State.

[b] Stormwater load reductions associated with current public or private stormwater facilities or operations were not included in the estimates. Thus, the stormwater runoff pathway load is likely overestimated but the magnitude of overestimation is unknown.

[c] Inadequate data for upstream pathway to estimate the percentage of the contribution of current loadings.

The importance of the pathway depends on the COI and the scale of analysis. Often the smallest loadings were from pathways, such as bridges, with a small drainage area contributing to flow. To eliminate flow or drainage area as a key element in estimating the loadings from the different pathways, area-weighted loading results for the major pathways were calculated that identified the greatest loading per area. For the atmospheric deposition, antifouling paint, and creosote-treated pilings pathways, the loads were divided by the surface area of the waterbody. When standardized to drainage area, stormwater runoff typically contributed the greatest area-weighted load of contaminants, followed by CSOs, local tributaries, upstream watersheds, and, sometimes, atmospheric deposition. The area-weighted loading estimates for the major pathways and COIs are presented in Appendix F.

5.2 Comparison to 2015 USGS Green River Instantaneous Load Study

Appendix G compares the loading estimates from this study to the results of a USGS study conducted between 2013 and 2015 (Conn et al., 2015). The USGS study collected representative samples of water, suspended sediment, and bed sediment from a continuous stream gauging station during 28 periods of differing flow conditions. From these discrete data combined with the continuous streamflow record, estimates of instantaneous sediment and chemical loads from the Green River to the Lower Duwamish Waterway were calculated.

Generally, the loading estimates in this report are similar in magnitude to the baseflow and stormflow loads in the USGS study. The instantaneous loads associated with the releases from Howard A. Hanson dam for metals were about an order of magnitude greater than this study's upper bound estimates. Exceptions are for total PCBs and total PAHs where the USGS study's estimated median instantaneous loads for dam release flows are within this loading report's 95 percent confidence limit range for loading from the Green River to the Duwamish Estuary/Elliott Bay study area. This may be because concentrations of metals were typically higher during dam release than during baseflow or stormflow, but the concentrations of PAHs and PCBs (as well as dioxins/furans) were not.

5.3 Comparison of Upstream Watershed Loading Rates to Background Loading Rates

For many of the COIs, the upstream watersheds contributed a substantial proportion of the overall load to the study areas. Two important questions arise from this finding:

- How much of the upstream load represents natural background chemical levels?
- How much of the upstream load represents inputs from anthropogenic sources and pathways, such as stormwater runoff and agriculture?

To approximate the portion of the upstream load that represents predevelopment background loading, area-normalized loading rates from this study were compared to those of previous studies. Three previous studies estimated areal loadings from a variety of land uses, including undeveloped lands (such as forests and non-agricultural fields) in Western Washington (Herrera, 2007a; EnviroVision et al., 2008; Herrera, 2011).

The comparison assumed that the undeveloped loading rates from the previous studies are representative of the background loading rates for the two watersheds. However, differences in basin geology, historical land use/activity, atmospheric circulation, and topographic features could affect the background loading rate for specific COIs. Additionally, the previous studies were based on separately calculated baseflow and stormflow contaminant concentrations. This study did not calculate these flows separately for the upstream watersheds pathway, which may have biased the loading estimates low.

Generally, the upstream areal loading rates estimated in this study are similar to those observed in undeveloped basins (Table 5-3). Some differences were as follows:

- The area-normalized loadings of fecal coliform, total phosphorus, TSS, and total PAHs estimated in this study for the upstream Green River watershed were greater than that of the undeveloped basins.
- The Lake Washington watershed area-normalized loadings of total PAHs and total PBDEs were greater than that of the undeveloped basins.
- The area-normalized lead, mercury, and zinc loads from undeveloped basins were greater than those from the Lake Washington watershed and similar or greater to those from the Green River watershed.

Insufficient data were available to compare BBP and BEHP for both upstream watersheds and total PBDEs for the Green River watershed.

While human activity likely contributes to the upstream load of each of the COIs, many COIs did not have an overall loading rate distinguishable from estimated background rates. For example, copper and zinc loading estimates from this study were not greater than loading rates from undeveloped basins despite the expected high loadings from brake pad wear and roofing materials from the developed regions of the watershed. This unexpected result may be due to methodological differences between this and the previous studies.

The total loads of PAHs and PBDEs entering the study areas appear to be substantially influenced by the discharges and activities from the developed areas in the two watersheds. Fecal coliform, total phosphorus, and TSS loadings to the Duwamish Estuary/ Elliott Bay study area also appear to be substantially influenced by upstream anthropogenic contaminant inputs.

Table 5-3. Area-normalized loadings rates for upstream watersheds compared to loading rates estimated for undeveloped areas (kg/km^2/year, unless noted).

Contaminant	**Areal Loading Rates Estimated in this Study**		**Loading Rate Estimates for Undeveloped Areas from Other Studies**		
	Lake Washington Watershed	**Green River Watershed**	**Green-Duwamish Pollutant Loading[a]**	**Puget Toxics Phase II[b]**	**Puget Toxics Phase III[c]**
Fecal coliform (trillion CFU/km^2/year)	*0.021–0.044*	**0.8–4.1**	0.6	NE	NE
Total nitrogen	180–250	490–720	NE	NE	220–620
Total phosphorus	*8.2–11.9*	**39–61**	31	NE	14–40
Total suspended solids	*800–1,240*	**9,000–27,000**	11,000	NE	2,900–6,400
Total arsenic	0.51–0.72	0.62–1.0	NE	0.67–2.6	0.39–0.60
Total copper	0.69–0.95	1.4–3.8	0.83	0.58–2.9	0.75–1.8
Total lead	0.040–0.079	0.51–1.2	NE	0.18–2.4	0.065–0.18[d]
Total mercury (g/km^2/yr)	*0.27–0.52*	1.8–4.2	3.1	2.4–18	2.6–7.1
Total zinc	*0.40–0.65*	3.9–8.5	1.4	1.2–5.9	3.3[d]
Benzyl butyl phthalate	NE	NE	NE	NE	NE
Bis(2-ethylhexyl) phthalate	0.10–4.6	NE	NE	0.024–0.71	< 0.17
Total PAHs	**0.032–0.065**	**0.021–0.073**	NE	0.0088–0.013	< 0.020
Total PBDEs (g/km^2/yr)	**0.44–0.97**	NE	NE	0.0027–0.040	0.16–0.21[d]
Total PCBs (g/km^2/yr)	0.074–0.154	0.20–1.2	NE	0.24–7.1	0.074–0.44

Bolded values indicate estimated loadings greater than the observed loading from undeveloped areas. *Italicized values* indicate estimates less than background.

CFU = colony forming unit

NE = not estimated.

[a] Herrera, 2007a.

[b] Interquartile range (EnviroVision et al., 2008).

[c] interquartile range (Herrera, 2011).

[d] Estimated value; considered to be low accuracy (Herrera, 2011).

5.4 Study Limitations and Uncertainties

An upper and lower bound to the loading estimates were calculated using the 95 percent confidence limits of the water quality and flow data available or using alternative data to estimate a range of loadings. While the loadings estimates were calculated based on highly simplified representations of a heterogeneous and dynamic ecosystem, the results allow for a comparison of the relative magnitude of contaminant loadings from major pathways. Importantly, this assessment did not estimate loads coming from within the study areas (internal loading). Sediment resuspension and contaminant release from the sediments were not assessed.

Limitations in the availability of representative data sets and monitoring locations both temporally and spatially contribute to the uncertainty of the annual pollutant loading estimates for the pathways. The pollutant loadings for the various pathways evaluated were estimated using different methods reflective of the available data, and each has its own set of uncertainties. These factors should be considered when comparing the relative magnitude of pollutant loads.

The study included the following pathway- and contaminant-specific data gaps and limitations:

- There were not enough data to estimate BBP loadings from Lake Washington to Lake Union/Ship Canal and to estimate BEHP and total PBDEs from the Green River to Duwamish Estuary/Elliott Bay. Data available for the upstream watersheds for BBP, BEHP, and total PBDEs were very limited in sample numbers, and the available BBP and BEHP data had very low detection rates. Use of these data may have introduced additional uncertainty by ignoring site-specific details or differences that may directly impact the contaminant load in the study areas.
- The loadings estimates assume that water quality data for local tributaries, bridges, antifouling paint, and creosote-treated wood pilings collected elsewhere in the region or nation are representative of major pathways in the study areas. The results show that total PAH and total copper loadings from creosote-treated wood pilings and antifouling paint, respectively, could be considerable.
- Vessel discharges, sacrificial anodes, groundwater, shoreline erosion, and inflow from Puget Sound were identified as pathways that may contribute contaminant loadings to the study areas, but there was not enough information to quantify loadings for any contaminants.
- Insufficient water quality or flow data precluded an analysis of the relationship of water quality concentrations to different storm events or flow conditions for CSOs, stormwater runoff, local tributaries, bridges, and Lake Washington outflow. For the Green River, the relationship between water quality and flow at the Auburn USGS gauge was investigated, and it was determined that the load estimate using annual flow and average COI concentrations was adequately comparable to the load estimated using daily flow and interpolated COI concentrations. The results presented in this study do not account for the potential correlation between water quality concentrations and flow conditions.
- Although some of the COIs exceeded water quality criteria in the study areas, this study did not evaluate the impacts of the estimated loadings on ambient water quality conditions.

If a finer scale analysis is desired, continued and more spatially explicit monitoring of water quality and flow from pathways of interest are recommended. Field counts of the number of creosote-treated wood pilings and vessels and monitoring of the behavior of vessels and the type and amount of sacrificial anodes within the study areas would improve the estimates for creosote-treated wood pilings, antifouling paint, vessel discharges, and sacrificial anodes. To evaluate the impact of loadings from pathways on the ambient water quality of the study areas, a three-dimensional fate and transport model is needed.

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Appendix A: Control Status of King County and City of Seattle CSOs

List of King County and Seattle CSO control status.

Operator	CSO	NPDES Discharge Serial Number	Waterbody	Status
King County	8th Ave	40	Duwamish Estuary	Controlled
King County	Denny Way	027a	Inner Elliott Bay	Controlled
King County	E. Duwamish	34	Duwamish Estuary	Controlled
King County	E. Marginal	43	Duwamish Estuary	Controlled
King County	Harbor	37	Duwamish Estuary	Controlled
King County	Norfolk	044a	Duwamish Estuary	Controlled
King County	W. Duwamish	35	Duwamish Estuary	Controlled
King County	Brandon	41	Duwamish Estuary	Uncontrolled
King County	Chelan	36	Duwamish Estuary	Uncontrolled
King County	Hanford #1	31	Duwamish Estuary	Uncontrolled
King County	Hanford #2	32	Duwamish Estuary	Uncontrolled
King County	King	28	Inner Elliott Bay	Uncontrolled
King County	Kingdome	29	Inner Elliott Bay	Uncontrolled
King County	Lander	30	Duwamish Estuary	Uncontrolled
King County	Michigan	39	Duwamish Estuary	Uncontrolled
King County	Terminal 115	38	Duwamish Estuary	Uncontrolled
King County	W. Michigan	42	Duwamish Estuary	Uncontrolled
King County	Ballard	3	Lake Union/Ship Canal	Controlled
King County	Canal Street	7	Lake Union/Ship Canal	Controlled
King County	Dexter	9	Lake Union/Ship Canal	Controlled
King County	11th Ave	4	Lake Union/Ship Canal	Uncontrolled
King County	3rd Ave	8	Lake Union/Ship Canal	Uncontrolled
King County	Montlake	14	Lake Union/Ship Canal	Uncontrolled
King County	University	15	Lake Union/Ship Canal	Uncontrolled
Seattle	68	68	Inner Elliott Bay	Controlled
Seattle	69	69	Inner Elliott Bay	Uncontrolled
Seattle	70	70	Inner Elliott Bay	Controlled
Seattle	71	71	Inner Elliott Bay	Uncontrolled
Seattle	72	72	Inner Elliott Bay	Controlled
Seattle	78	78	Inner Elliott Bay	Controlled
Seattle	80	80	Inner Elliott Bay	Controlled
Seattle	99	99	Duwamish Estuary	Uncontrolled
Seattle	107	107	Duwamish Estuary	Uncontrolled
Seattle	111	111	Duwamish Estuary	Uncontrolled
Seattle	120	120	Lake Union/Ship Canal	Controlled
Seattle	121	121	Lake Union/Ship Canal	Controlled
Seattle	124	124	Lake Union/Ship Canal	Controlled
Seattle	127	127	Lake Union/Ship Canal	Controlled
Seattle	129	129	Lake Union/Ship Canal	Controlled

Operator	CSO	NPDES Discharge Serial Number	Waterbody	Status
Seattle	130	130	Lake Union/Ship Canal	Controlled
Seattle	131	131	Lake Union/Ship Canal	Controlled
Seattle	132	132	Lake Union/Ship Canal	Controlled
Seattle	134	134	Lake Union/Ship Canal	Controlled
Seattle	135	135	Lake Union/Ship Canal	Controlled
Seattle	136	136	Lake Union/Ship Canal	Controlled
Seattle	138	138	Lake Union/Ship Canal	Uncontrolled
Seattle	139	139	Lake Union/Ship Canal	Uncontrolled
Seattle	140	140	Lake Union/Ship Canal	Uncontrolled
Seattle	141	141	Lake Union/Ship Canal	Controlled
Seattle	144	144	Lake Union/Ship Canal	Controlled
Seattle	145	145	Lake Union/Ship Canal	Controlled
Seattle	146	146	Lake Union/Ship Canal	Controlled
Seattle	147	147	Lake Union/Ship Canal	Uncontrolled
Seattle	148	148	Lake Union/Ship Canal	Controlled
Seattle	152	152	Lake Union/Ship Canal	Uncontrolled
Seattle	174	174	Lake Union/Ship Canal	Uncontrolled
Seattle	175	175	Lake Union/Ship Canal	Controlled
Seattle	150/151	150/151	Lake Union/Ship Canal	Uncontrolled

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Appendix B: Water Quality Contamiant Summary Statistics for Pathways

Upstream Watersheds

Table B-1 Green River Contaminant Concentration Summary.

Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Fecal Coliform*	CFU/ 100ml	136	100%	1	1	82.03	135.01	333.81
Total Nitrogen*	mg/L	137	100%	0.05	0.05	0.55	0.58	0.62
Total Phosphorus*	mg/L	136	100%	0.005	0.005	0.04	0.05	0.05
Total Suspended Solids*	mg/L	150	100%	0.5	5	10.69	13.82	23.82
Total Arsenic*	µg/L	17	100%	0.1	0.5	0.69	0.77	0.86
Total Copper*	µg/L	58	98%	0.1	0.4	1.55	1.95	3.28
Total Lead*	µg/L	58	81%	0.025	0.2	0.56	0.74	0.99
Total Mercury*	ng/L	58	38%	0.1	200	2.04	2.64	3.68
Total Zinc*	µg/L	58	100%	0.15	0.5	4.03	5.08	6.86
Benzyl Butyl Phthalate*	µg/L	20	15%	0.0255	0.296	0	0.13	0.20
Bis(2-Ethylhexyl) Phthalate*	µg/L	20	10%	0.024	2.25	NA	NA	NA
Total PAHs*	µg/L	29	66%	0.01196	0.467	0.02	0.04	0.06
Total PCBs**	ng/L	15	100%	--	--	0.22	0.50	1.00

*Data from King County long-term ambient monitoring location sites 3106 and A310.
**Data from Windward (2010).
NA – not applicable.
Total PBDE data were not available.

Table B-2 Black River Contaminant Concentration Summary.

Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Fecal Coliform*	CFU/ 100ml	174	100%	1	1	434	685	1,454
Total Nitrogen*	mg/L	176	100%	0.05	0.05	0.99	1.02	1.05
Total Phosphorus*	mg/L	175	100%	0.005	0.01	0.13	0.13	0.14
Total Suspended Solids*	mg/L	176	100%	0.5	5	7.95	9.27	11.18
Total Arsenic*	µg/L	36	100%	0.01	0.5	1.40	1.60	1.93
Total Copper*	µg/L	36	100%	0.1	0.4	3.91	4.77	5.65
Total Lead*	µg/L	36	100%	0.025	0.2	1.58	2.09	2.80
Total Mercury*	ng/L	35	60%	0.2	200	1.92	2.67	3.78
Total Zinc*	µg/L	36	100%	0.5	0.5	21.59	25.94	30.91
Benzyl Butyl Phthalate*	µg/L	8	38%	0.047	0.332	0.00	0.09	0.18
Bis(2-Ethylhexyl) Phthalate*	µg/L	8	25%	0.024	2.28	NA	NA	NA

Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Total PAHs*	µg/L	8	63%	0.165	0.168	0.04	0.09	0.17
Total PCBs**	ng/L	9	100%	--	--	0.43	0.71	1.27

*Data from King County long-term ambient monitoring location sites 317.
**Data from King County (2014) – the PCB congeners coeluting with 44, 45, and 68 removed.
NA – not applicable.
Total PBDE data were not available.

Table B-3 Lake Washington Contaminant Concentration Summary.

Parameter	Units	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Fecal Coliform*	CFU/ 100ml	100	84%	1	1	3.09	3.78	4.88
Total Nitrogen*	mg/L	101	100%	0.05	0.05	0.26	0.27	0.28
Total Phosphorus*	mg/L	99	98%	0.005	0.005	0.01	0.01	0.01
Total Suspended Solids*	mg/L	106	94%	0.5	1	1.15	1.25	1.36
Total Arsenic*	µg/L	21	100%	0.01	0.1	0.73	0.76	0.79
Total Copper*	µg/L	21	100%	0.1	0.1	1.00	1.02	1.04
Total Lead*	µg/L	21	100%	0.025	0.025	0.06	0.07	0.09
Total Mercury*	ng/L	21	95%	0.1	0.2	0.39	0.47	0.57
Total Zinc*	µg/L	21	81%	0.15	0.5	0.58	0.65	0.72
Benzyl Butyl Phthalate*	µg/L	13	0%	0.012	0.0622	NA	NA	NA
Bis(2-Ethylhexyl) Phthalate*	µg/L	12	33%	0.0048	1.66	0.00	1.90	5.05
Total PAHs*	µg/L	13	31%	0.164	0.552	0.05	0.06	0.07
Total PBDEs**	ng/L	6	100%	--	--	0.63	0.65	1.07
Total PCBs**	ng/L	6	100%	--	--	0.11	0.11	0.17

*Data from King County long-term ambient monitoring location site 0540.
**Data from King County (2013a).
NA – not applicable.

Stormwater Runoff

Table B-4 Stormwater Runoff Annual Contaminant Concentration Summary.

Parameter	Land Use	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Fecal coliform*	COM	CFU/ 100mL	187	97%	1	10	2,674	8,757	32,850
	IND	CFU/ 100mL	41	100%	--	--	1,722	4,461	15,475
	RES	CFU/ 100mL	42	100%	--	--	2,131	3,545	6,805

Parameter	Land Use	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Total Nitrogen*	COM	mg/L	266	88%	0	0.679	1.49	1.80	2.93
	IND	mg/L	65	80%	0	0	0.92	1.11	1.28
	RES	mg/L	70	91%	0	0	1.49	1.66	1.88
Total Phosphorus*	COM	mg/L	237	96%	0.005	0.04	0.15	0.17	0.18
	IND	mg/L	51	98%	0.107	0.107	0.18	0.21	0.27
	RES	mg/L	63	97%	0.016	0.1275	0.15	0.18	0.22
Total Suspended Solids*	COM	mg/L	250	100%	NA	--	62.91	72.47	84.37
	IND	mg/L	62	100%	--	--	50.38	65.12	89.42
	RES	mg/L	68	100%	--	--	48.21	58.79	71.77
Total Arsenic	All	µg/L	140	79%	1	5	1.61	1.90	2.29
Total Copper*	COM	µg/L	261	100%	--	--	23.85	26.69	29.98
	IND	µg/L	66	100%	--	--	17.06	19.45	22.83
	RES	µg/L	68	100%	--	--	12.13	13.74	15.47
Total Lead*	COM	µg/L	264	100%	--	--	22.14	26.05	31.06
	IND	µg/L	66	100%	--	--	8.08	9.71	13.17
	RES	µg/L	69	100%	--	--	12.46	14.75	17.64
Total Mercury*	COM	ng/L	263	31%	20	200	17.45	20.94	26.87
	IND	ng/L	66	12%	20	50	22.33	25.61	29.57
	RES	ng/L	36	14%	50	50	0.00	42.74	66.81
Total Zinc*	COM	µg/L	260	100%	--	--	132.18	146.8	170.3
	IND	µg/L	65	100%	--	--	119	133.9	155.1
	RES	µg/L	69	100%	--	--	48.32	54.63	62.52
Butyl benzyl phthalate*	COM	µg/L	262	26%	0.047	2.1	0.28	0.32	0.37
	IND	µg/L	64	16%	0.17	2	0.2	0.22	0.24
	RES	µg/L	69	12%	0.17	3	0.18	0.19	0.22
Bis(2-ethylhexyl) phthalate*	COM	µg/L	253	78%	0.642	7.42	2.87	3.36	4.19
	IND	µg/L	63	63%	0.407	2.36	1.26	1.58	2.11
	RES	µg/L	69	62%	0.407	3	1.13	1.47	2.01
Total PAH*	COM	µg/L	263	84%	0.1	1	2.93	4.38	7.47
	IND	µg/L	64	84%	0.1	0.2	0.27	0.41	0.69
	RES	µg/L	69	74%	0.1	2.2	0.14	0.19	0.26
Total PBDE**	All	ng/L	25	100%	--	--	16.83	17.50	38.33
Total PCB***	COM /IND	ng/L	6	100%	--	--	3.11	9.92	27.0
	RES	ng/L	15	100%	--	--	2.05	3.14	5.00

*Data from Ecology (2015).

**Data from the King County (2013a).

***Data from the Ecology (2015) and King County (2013a) – the PCB congeners coeluting with 44, 45, and 68 removed.

Total arsenic data were not available.

Local Tributaries

Table B-5 Combined Areal Loading Rates for Commercial and Residential Tributaries in Snohomish Puyallup River Watersheds.

Flow	Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Baseflow	Total Nitrogen	kg/km^2/yr	14	100%	--	--	197	275	525
	Total Phosphorus	kg/km^2/yr	14	100%	--	--	9	14	20
	Total Suspended Solids	kg/km^2/yr	14	71%	204	204	349	594	953
	Total Arsenic	g/km^2/yr	14	100%	--	--	205	352	472
	Total Copper	g/km^2/yr	14	100%	--	--	182	266	384
	Total Lead	g/km^2/yr	14	86%	20	20	29	45	63
	Total Mercury	g/km^2/yr	14	93%	0	0	0.5	0.7	1.0
	Total Zinc	g/km^2/yr	14	57%	1,021	1,021	1,111	1,716	2,660
	Bis(2-Ethylhexyl) Phthalate	g/km^2/yr	14	7%	31	35	NA	NA	NA
	Benzyl Butyl Phthalate	g/km^2/yr	14	0%	63	67	NA	NA	NA
	Total PAH	g/km^2/yr	14	14%	2	4	NA	NA	NA
	Total PBDE	mg/km^2/yr	14	64%	51	125	32	249	1,531
	Total PCB	mg/km^2/yr	14	64%	34	167	29	80	189
Stormflow	Total Nitrogen	kg/km^2/yr	48	100%	--	--	295	426	441
	Total Phosphorus	kg/km^2/yr	48	100%	--	--	23	29	32
	Total Suspended Solids	kg/km^2/yr	48	100%	--	--	5,986	7,236	13,812
	Total Arsenic	g/km^2/yr	48	100%	--	--	381	412	574
	Total Copper	g/km^2/yr	48	100%	--	--	1,405	1,446	2,110
	Total Lead	g/km^2/yr	48	100%	--	--	499	537	844
	Total Mercury	g/km^2/yr	48	100%	--	--	3.0	3.1	4.6
	Total Zinc	g/km^2/yr	48	83%	2,083	2,083	10,468	14,215	19,010
	Bis(2-Ethylhexyl) Phthalate	g/km^2/yr	48	35%	62	212	85	154	278
	Benzyl Butyl Phthalate	g/km^2/yr	48	6%	125	142	NA	NA	NA
	Total PAH	g/km^2/yr	48	69%	4	14	42	61	90
	Total PBDE	mg/km^2/yr	32	78%	104	367	2,265	9,684	31,123

Flow	Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
	Total PCB	mg/km²/yr	24	92%	40	79	851	2,135	6,241
Total flow	Total Nitrogen	kg/km²/yr	--	--	--	--	492	701	966
	Total Phosphorus	kg/km²/yr	--	--	--	--	32	43	52
	Total Suspended Solids	kg/km²/yr	--	--	--	--	6,335	7,830	14,765
	Total Arsenic	g/km²/yr	--	--	--	--	586	764	1,045
	Total Copper	g/km²/yr	--	--	--	--	1,588	1,712	2,494
	Total Lead	g/km²/yr	--	--	--	--	529	582	906
	Total Mercury	g/km²/yr	--	--	--	--	3	4	6
	Total Zinc	g/km²/yr	--	--	--	--	11,579	15,931	21,670
	Bis(2-Ethylhexyl) Phthalate	g/km²/yr	--	--	--	--	85	154	278
	Benzyl Butyl Phthalate	g/km²/yr	--	--	--	--	NA	NA	NA
	Total PAH	g/km²/yr	--	--	--	--	42	61	90
	Total PBDE	mg/km²/yr	--	--	--	--	2,297	9,932	32,654
	Total PCB	mg/km²/yr	--	--	--	--	881	2,215	6,431

Data from Herrera (2011).
Total nitrogen data were not available.

Table B-6 Averaged areal loading rates for low to medium and high density developed tributaries in the Green Duwamish Watershed (2001-2003).

Flow	Parameter	Unit	Min	Mean	Max
Baseflow	Fecal Coliform	billion CFU/km²/yr	148	1,500	5,370
Stormflow	Fecal Coliform	billion CFU/km²/yr	1,900	8,230	13,340
Total Flow	Fecal Coliform	billion CFU/km²/yr	2,048	9,730	18,710

Data from Herrera (2007a).

Highway Bridges

Table B-7 Untreated Highway Runoff Contaminant Concentrations.

Parameter	Unit	# of Sites With Data	Average Percent Detected*	95% LCL	Mean	95% UCL
Fecal Coliform	CFU/ 100mL	16	100%	367.02	1,763	3,158.98
Total Nitrogen	mg/L	3	100%	-2.56	9.66	21.88
Total Phosphorus	mg/L	24	98.60%	0.16	0.22	0.28
Total Suspended Solids	mg/L	27	99.50%	87.78	118.9	150.02
Total Arsenic	µg/L	2	100%	2.03	2.39	2.75

Parameter	Unit	# of Sites With Data	Average Percent Detected*	95% LCL	Mean	95% UCL
Total Copper	µg/L	29	98.30%	22.07	28	33.93
Total Lead	µg/L	3	–	14.32	37.4	60.48
Total Mercury	ng/L	1	100%	20.0	20.0	20.0
Total Zinc	µg/L	29	–	121.60	162	202.40
Benzyl Butyl Phthalate	µg/L	2	100%	0.45	0.63	0.81
Bis(2-Ethylhexyl) Phthalate	µg/L	1	100%	4.68	4.68	4.68

*Average Percent Detected refers to the percentage of time the measured parameter was detected averaged over all sites reporting data.
Data from Herrera (2007b).
Total PAH data were not available.

Table B-8 Total PCB and total PBDE contaminant concentration from untreated highway runoff.

Parameter	Unit	n	Percent Detected	95% LCL	Mean	95% UCL
Total PBDE	ng/L	4	100%	14.1	72.8	178.2
Total PCB	ng/L	4	100%	4.2	9.4	13.0

Data from King County (2013a).

Table B-9 Treated Highway Runoff Contaminant Concentration Summary from vegetation filter strips.

Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Total Nitrogen	mg/L	30	97%	0.01	0.01	0.24	0.33	0.44
Total Phosphorus	mg/L	31	94%	0.01	0.01	0.51	0.93	2.0
Total Suspended Solids	mg/L	30	90%	1	1	14.6	21.7	35.6
Total Copper	µg/L	23	100%	--	--	5.6	7.7	10.6
Total Zinc	µg/L	23	87%	5	5	26.5	41.4	73.1

Data from WSDOT (2014).
Fecal coliform, total arsenic, total lead, total mercury, benzyl butyl phthalate, bis(2-ethylhexyl) phthalate, total PAH, total PBDE, and total PCB data were not available.

Combined Sewer Overflows

Table B-10 CSO contaminant concentration summary from King County monitored CSO effluent.

Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Fecal Coliform	CFU/ 100ml	85	100%	1	1	1,378,957	2,169,626	4,145,072
Total Nitrogen	mg/L	39	100%	0.05	1.5	6.64	8.02	10.02

Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Total Phosphorus	mg/L	44	100%	0.005	0.15	1.24	1.50	1.85
Total Suspended Solids	mg/L	131	100%	0.5	25	119.38	135.67	159.38
Total Arsenic	µg/L	160	94%	0.1	50	2.48	2.68	2.98
Total Copper	µg/L	156	100%	0.4	5	33.90	38.80	47.49
Total Lead	µg/L	156	95%	0.075	30	25.45	29.69	36.01
Total Mercury	µg/L	162	50%	0.0001	0.2	0.06	0.07	0.08
Total Zinc	µg/L	156	100%	0.5	5	131.65	146.71	166.61
Benzyl Butyl Phthalate	µg/L	132	70%	0.025	2.4	0.54	0.75	1.52
Bis(2-Ethylhexyl) Phthalate	µg/L	130	76%	0.024	5.09	4.41	5.46	7.17
Total PAH	µg/L	126	82%	0.08	14.32	1.46	1.79	2.31
Total PBDE	µg/L	8	100%	--	--	0.08	0.08	0.14
Total PCB	µg/L	49	100%	--	--	0.047	0.062	0.096

Wet Weather Treatment Facilities

Table B-11 Mercer/Elliott West effluent contaminant concentration summary (includes water quality data sampled at Mercer/Elliott West treatment facility only).

Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Total Phosphorus	mg/L	5	100%	--	--	0.82	1.03	1.13
Total Arsenic	ug/L	29	100%	--	--	2.33	2.47	2.66
Total Copper	ug/L	29	100%	--	--	45.84	70.79	145.12
Total Lead	ug/L	29	100%	--	--	14.12	19.18	36.67
Total Mercury	ug/L	28	50%	0.05	0.05	0.04	0.05	0.07
Total Zinc	ug/L	29	100%	--	--	99.22	109.09	122.33
Benzyl Butyl Phthalate	ug/L	27	74%	0.28	0.57	0.47	0.63	0.76
Bis (2-Ethylhexyl) Phthalate	ug/L	27	67%	2.42	12.8	3.57	4.24	5.75
Total PAH	ug/L	24	13%	0.2	1.6	0.00	0.91	1.72

Table B-12 Henderson/MLK effluent contaminant concentration summary (includes water quality data sampled at Henderson/MLK, Alki, and Carkeek treatment facilities).

Parameter	Unit	n	Percent Detected	Min MDL	Max MDL	95% LCL	Mean	95% UCL
Total Phosphorus	mg/L	10	100%	--	--	0.66	0.82	0.96
Total Arsenic	ug/L	34	100%	--	--	2.18	2.36	2.61
Total Copper	ug/L	34	100%	--	--	12.55	13.68	15.51
Total Lead	ug/L	34	100%	--	--	4.40	5.09	5.95
Total Mercury	ug/L	33	55%	0.05	1.7	0.027	0.035	0.046
Total Zinc	ug/L	34	100%	--	--	45.56	49.87	55.79
Benzyl Butyl Phthalate	ug/L	33	42%	0.075	1.5	0.23	0.39	0.85
Bis(2-Ethylhexyl) Phthalate	ug/L	18	89%	0.5	1.04	1.40	2.20	3.37

Atmospheric Deposition

Table B-13 Annual contaminant atmospheric deposition flux data used for loading estimates.

Parameter	Unit	n	95% LCL	Mean	95% UCL
Total Arsenic	µg/m^2/day	108	0.65	0.73	0.83
Total Copper	µg/m^2/day	108	16.71	18.34	20.15
Total Lead	µg/m^2/day	108	10.79	12.63	15.07
Total Mercury	µg/m^2/day	108	0.017	0.020	0.024
Total Zinc	µg/m^2/day	108	95.92	107.76	121.5
Total PAH	µg/m^2/day	110	0.70	0.78	0.893
Total PBDE	ng/m^2/day	14	8.07	16.69	42.79
Total PCB	ng/m^2/day	54	12.34	18.25	31.82

Data from King County (2013g, 2015b).

Total Nitrogen, total phosphorus, benzyl butyl phthalate, and bis(2-ethylhexyl) phalate data were not available.

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Appendix C: Flow Summary Statistics

Table C-1 Upstream watershed annual flow volume.

Categories	Major Pathways	Study Area	Water Years	Annual Flow (MG/yr)		
				95% LCL	Mean	95% UCL
Upstream Watershed	Green River	Duwamish Estuary/Elliott Bay	2000-2009	271,190	316,246	351,948
	Black River*	Duwamish Estuary/Elliott Bay	2000-2009	6,602	7,771	9,039
	Lake Washington	Lake Union/Ship Canal	2002-2011	279,647	318,301	364,850

Table C-2 Stormwater volume from different land uses estimated using rainfall from water years 2005-2014.

Study Area	Land Use	Annual Runoff (MG/yr)		
		95% LCL	Mean	95% UCL
Duwamish Estuary/ Inner Elliott Bay	Commercial	6,547	7,190	7,725
	Industrial	24,805	27,238	29,265
	Residential	16,909	18,568	19,950
	Open Space	989	1,091	1,167
	Vacant	8,115	8,911	9,575
Lake Union/Ship Canal	Commercial	8,928	9,803	10,533
	Industrial	2,551	2,802	3,010
	Residential	17,867	19,619	21,080
	Open Space	568	624	670
	Vacant	492	541	581

Table C-3 Highway runoff volume estimated using rainfall from water years 2005-2014.

Treated	Treatment	Waterbody	Location	Area (acres)	Annual Flow (MG/yr)		
					95% LCL	Mean	95% UCL
Yes	Biofiltration Swale	Duwamish Estuary	SR 99 Duwamish River Crossing	0.18	0.18	0.20	0.21
Yes	Biofiltration Swale	Duwamish Estuary	SR 99 Duwamish River Crossing	0.45	0.45	0.50	0.53
Yes	Wet Pond to Wetland Mitigation	Duwamish Estuary	SR 99 Duwamish River Crossing	0.73	0.72	0.79	0.85
Yes	Wet Pond to Wetland Mitigation	Duwamish Estuary	SR 99 Duwamish River Crossing	0.42	0.42	0.46	0.49
No	None	Duwamish Estuary	SR 99 Duwamish River Crossing Grated bridge Deck	0.42	0.41	0.45	0.49
Yes	Biofiltration Swale	Duwamish Estuary	I-5 Duwamish River Crossing	0.26	0.26	0.29	0.31
Yes	Biofiltration Swale	Duwamish Estuary	I-5 Duwamish River Crossing	0.31	0.30	0.33	0.36

Treated	Treatment	Waterbody	Location	Area (acres)	Annual Flow (MG/yr)		
					95% LCL	Mean	95% UCL
No	None	Duwamish Estuary	Arterial Roads	5.29	5.28	5.79	6.24
No	None	Lake Union/ Ship Canal	Ship Canal bridge	1.38	1.38	1.51	1.63
No	None	Lake Union/ Ship Canal	SR 520 Portage Bay Crossing	2.98	2.97	3.26	3.51
No	None	Lake Union/ Ship Canal	SR 99 Lake Union Crossing	1.14	1.14	1.25	1.35
No	None	Lake Union/ Ship Canal	Arterial Roads	4.08	4.07	4.46	4.81

Table C-4 King County and Seattle owned uncontrolled and controlled CSO annual flow volume.

Categories	Major Pathways	Study Area	Water Years	Annual Flow (MG/yr)		
				95% LCL	Mean	95% UCL
Uncontrolled CSOs	Uncontrolled King County CSOs	Duwamish Estuary/Elliott Bay	2005-2014	304.53	523.13	835.36
	Uncontrolled Seattle CSOs	Duwamish Estuary/Elliott Bay	2009-2014	1.69	5.71	13.29
	Uncontrolled King County CSOs	Lake Union/Ship Canal	2005-2014	70.64	122.89	206.23
	Uncontrolled Seattle CSOs	Lake Union/Ship Canal	2009-2014	28.59	56.84	82.85
Controlled CSOs	Controlled King County CSOs	Duwamish Estuary/Elliott Bay	2005-2014 or 32 years modeled data	0.91	2.87	8.79
	Controlled Seattle CSOs	Duwamish Estuary/Elliott Bay	2009-2014	0.08	0.89	2.34
	Controlled King County CSOs	Lake Union/Ship Canal	2005-2014 or 32 years modeled data	0.61	1.84	5.83
	Controlled Seattle CSOs	Lake Union/Ship Canal	2009-2014	0.00	2.46	9.26
Wet Weather Treatment Facilities	Elliott West	Duwamish Estuary/Elliott Bay	2006-2014	157.66	218.53	319.01
	Henderson Norfolk	Duwamish Estuary/Elliott Bay	2007-2014	2.50	8.26	16.21

Table C-5 King County wet weather treatment facilities annual flow volume.

Wet Weather Treatment Facilities	Study Area	Water Years	Annual Flow (MG/yr)		
			95% LCL	**Mean**	**95% UCL**
Mercer/Elliott West	Duwamish Estuary/Elliott Bay	2006-2014	157.66	218.53	319.01
Henderson/MLK	Duwamish Estuary/Elliott Bay	2007-2014	2.50	8.26	16.21

Appendix D: Green River Loads Estimated Based on Relationship with Flow

Green River Loads Estimated Based on Relationship with Flow

To estimate the Green River contaminant concentration based on daily flow at the Auburn USGS gage, best-fit regressions were computed relating chemical concentrations with observed flow on the date of sampling. The regression equations were then applied using daily discharge data at the gage from 2000 to 2009 to estimate the daily concentration. The observed daily discharge was then multiplied by the predicted concentration to create a daily load, and the daily loads were summed to generate an estimated annual load.

The same Green River data used for estimating Green River chemical concentrations were used for this analysis (see Section 2.1.1). These data were collected between 2000 and 2009 from sites A310 and 3106. These data were check for quality following the steps outlined in Section 3.1.

The regression functions between chemical concentrations and discharge were calculated using the 'survreg' function in the 'survival' package for R (v3.2.2). The 'survreg' function fits a parametric survival regression function, which allows for the presence of non-detects in the dependent variable. The data were assumed to have a log-normal distribution for the purposes of the 'survreg' function; this validity of this assumption was also assessed.

If the p-value of the regression at an α=0.05 level of significance, the regression function was then used to estimate the chemical concentration for every day from 2000 to 2009 based on the observed discharge at the Auburn gage. Confidence intervals around these predictions were calculated via bootstrapping using the 'boot' function in the 'boot' package for R; the regression and resulting predictions were recalculated 1000 times based on randomized resampling (with replacement) of the dataset. The bias-corrected bootstrap percentile (BCa) intervals were used.

The following pages present two plots per chemical. The first plot is of cumulative probability distribution and log-normal fits of the data. This plot allows an examination of the assumption of a log-normal distribution used for the regression equation. The second plot is of the chemical concentration regressed on discharge, the regression line as a solid black line, the regression equation on the upper right corner, and the regression p-value on the upper left corner. In the plots, non-detects are represented as vertical dashed lines denoting the MDL and the associated discharge. Note that both the axes are presented on a log-scale.

For all analytes, the assumption of a log-normal distribution is supported by a visual analysis of the cumulative probability plots.

Table D-1 Relationship of analytes with flow and estimated annual loads using daily-flow-based and annualized averages. All values in kg/yr unless noted otherwise.

Analyte	Significant Relationship with Flow ($p \leq 0.05$)?	Estimated Load Using Daily Flow			Estimated Load Using Annualized			Ranges Overlap?
		LCL	Mean	UCL	LCL	Mean	UCL	
Fecal Coliform (trillion CFU/yr)	Yes	350	430	530	950	1,800	5,000	No
Total Nitrogen	No	570,000	610,000	670,000	590,000	730,000	870,000	Yes
Total Phosphorus	No	42,000	46,000	50,000	47,000	59,000	73,000	Yes
Total Suspended Solids (million kg/yr)	Yes	13	15	18	11	17	32	Yes
Arsenic, Total	Yes	670	730	810	740	960	1,200	Yes
Copper, Total	Yes	1,700	2,100	2,800	1,700	2,500	4,600	Yes
Lead, Total	Yes	460	660	930	610	940	1,400	Yes
Mercury, Total	Yes	2.6	3.7	5.3	2.2	3.2	5.1	Yes
Zinc, Total	Yes	3500	4600	6100	4,700	6,800	10,000	Yes
Benzyl butyl phthalate	NE	NE	NE	NE	NE	NE	NE	NA
Bis(2-ethylhexyl)-phthalate	NE	NE	NE	NE	NE	NE	NE	NA
Total PAHs	Yes	13	18	26	25	47	88	Yes
Total PCBs (g/yr)	NE	NE	NE	NE	240	630	1400	NA

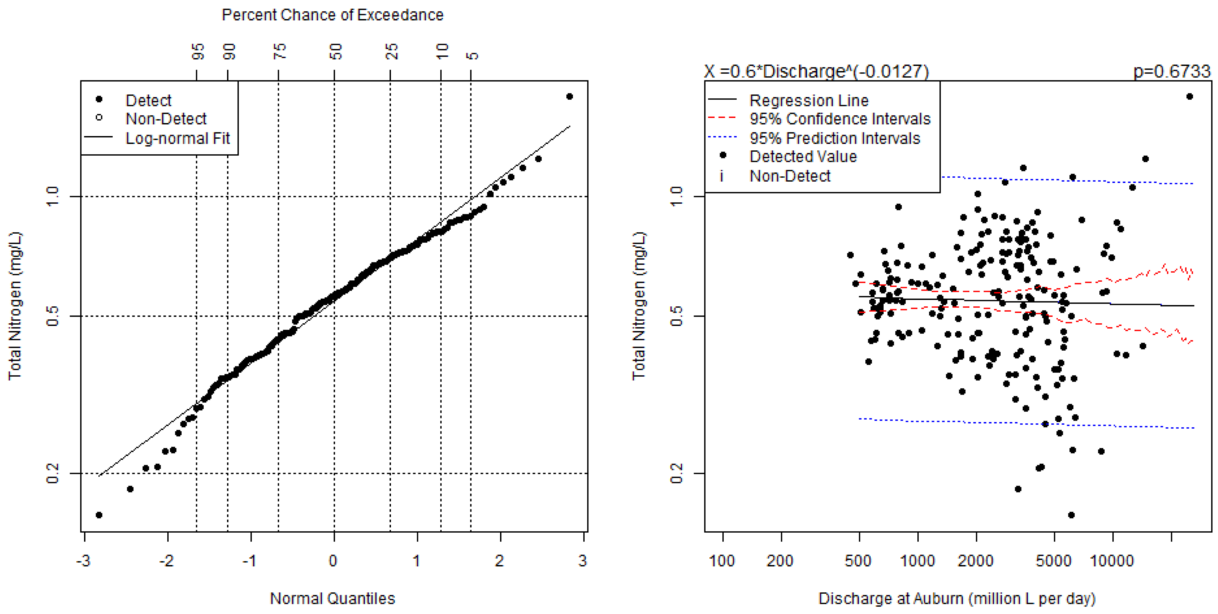

Figure D-1. Cumulative distribution (left) and discharge regression (right) plots for total nitrogen.

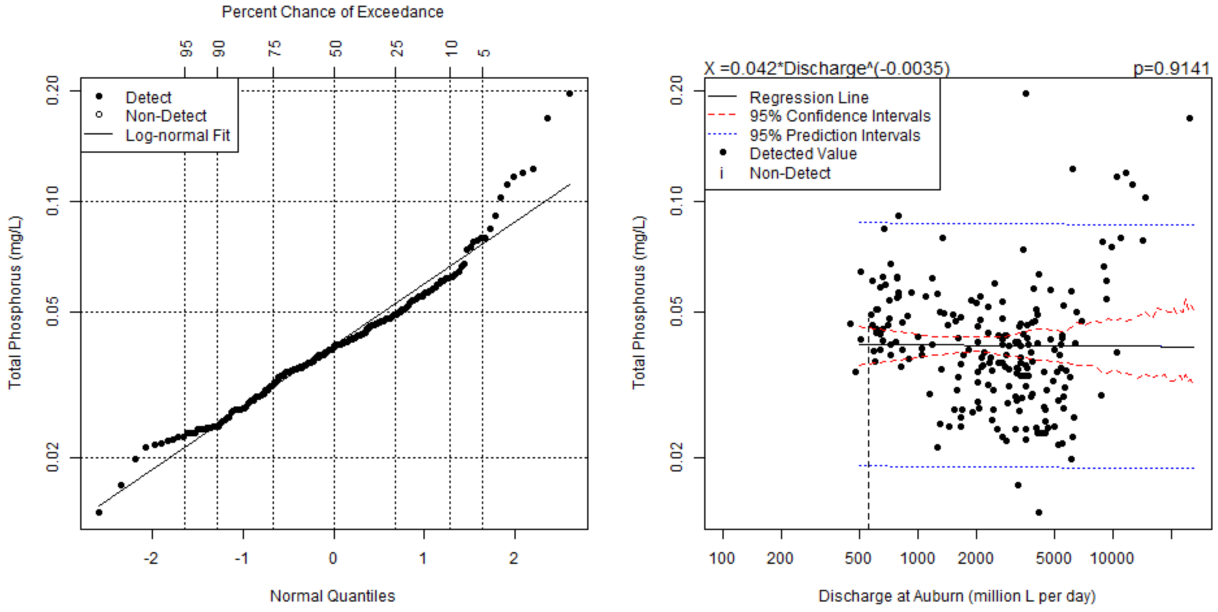

Figure D-2. Cumulative distribution (left) and discharge regression (right) plots for total phosphorus.

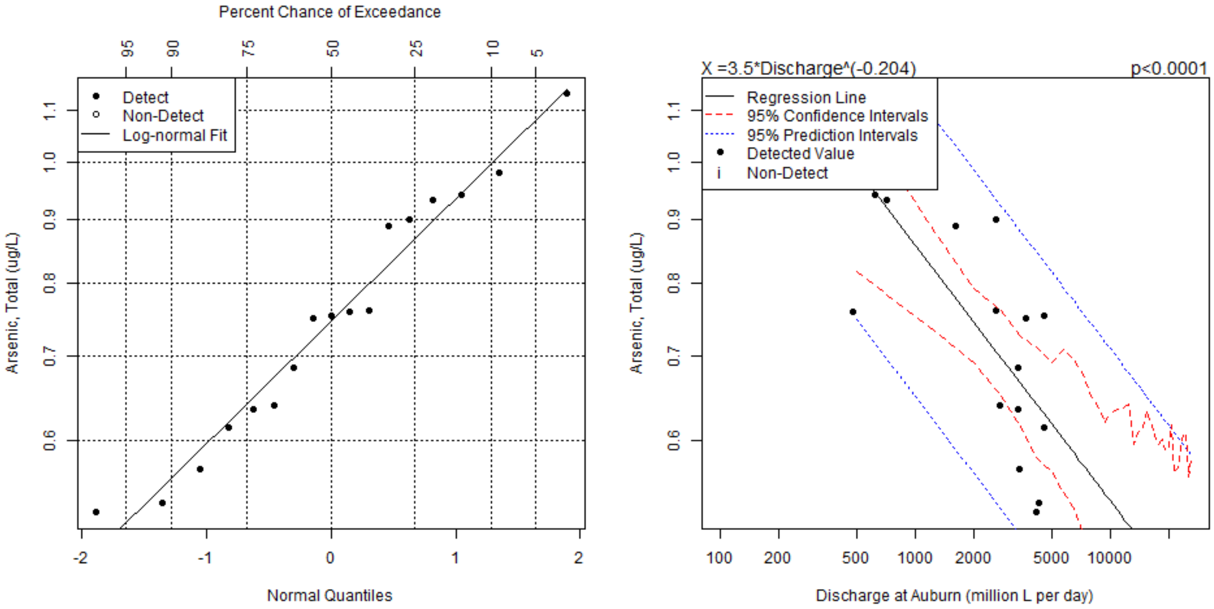

Figure D-3. **Cumulative distribution (left) and discharge regression (right) plots for total arsenic.**

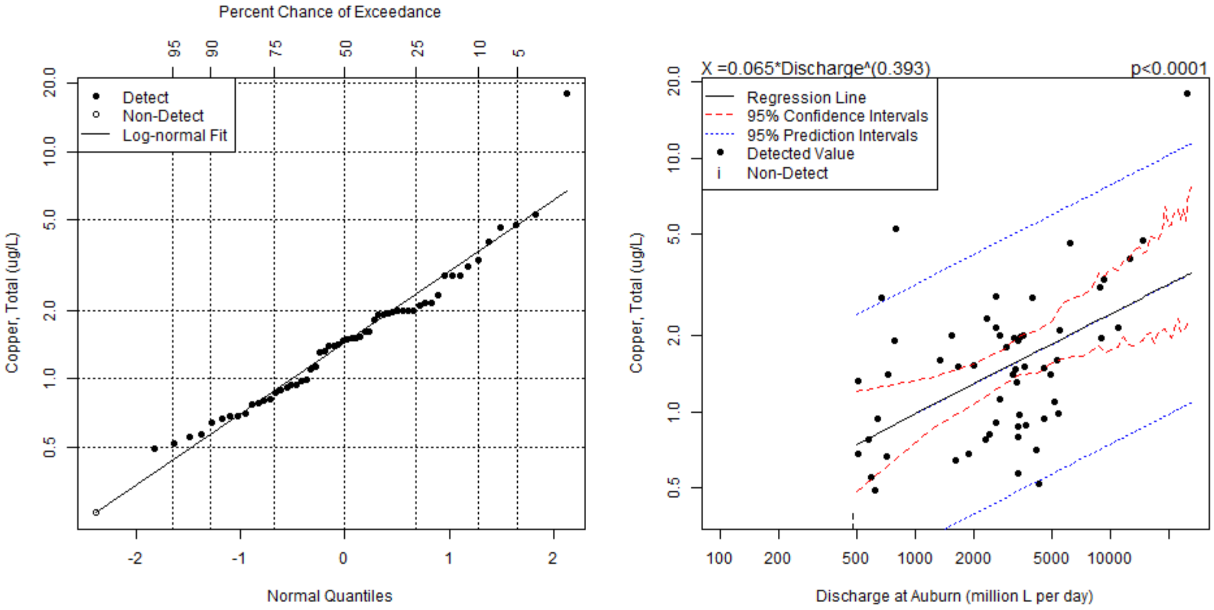

Figure D-4. **Cumulative distribution (left) and discharge regression (right) plots for total copper.**

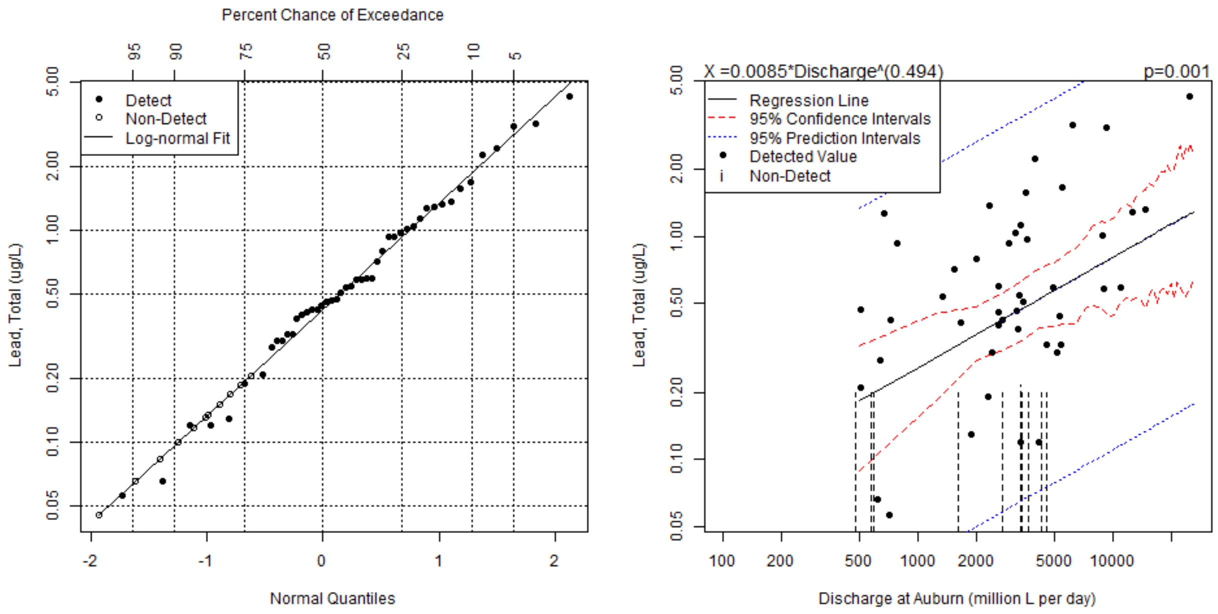

Figure D-5. **Cumulative distribution (left) and discharge regression (right) plots for total lead.**

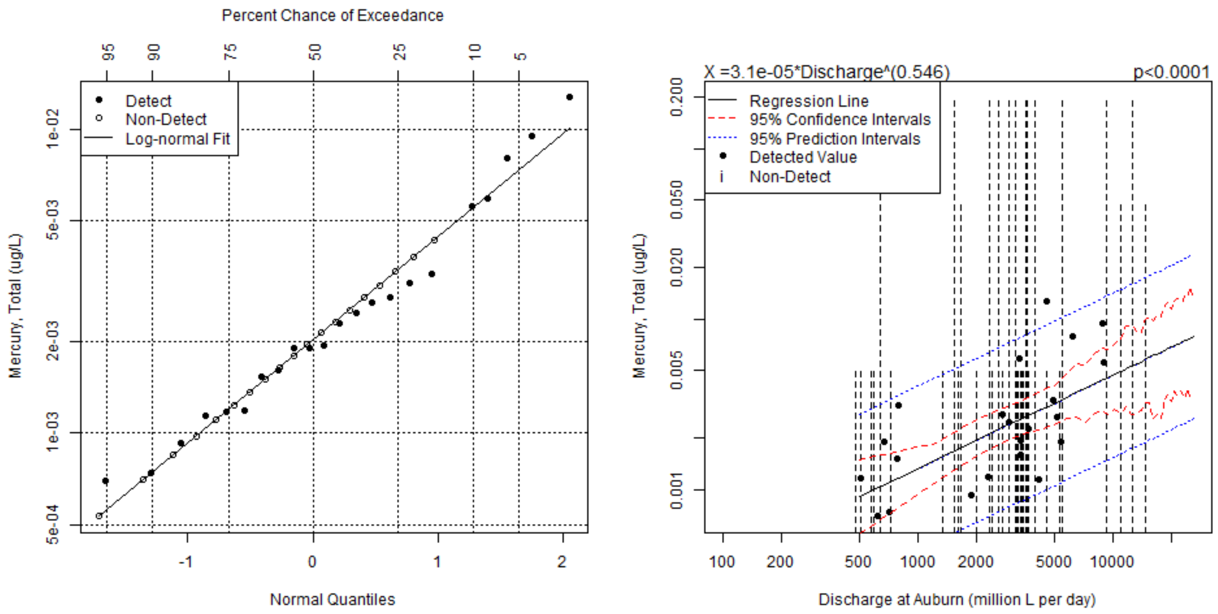

Figure D-6. **Cumulative distribution (left) and discharge regression (right) plots for total mercury.**

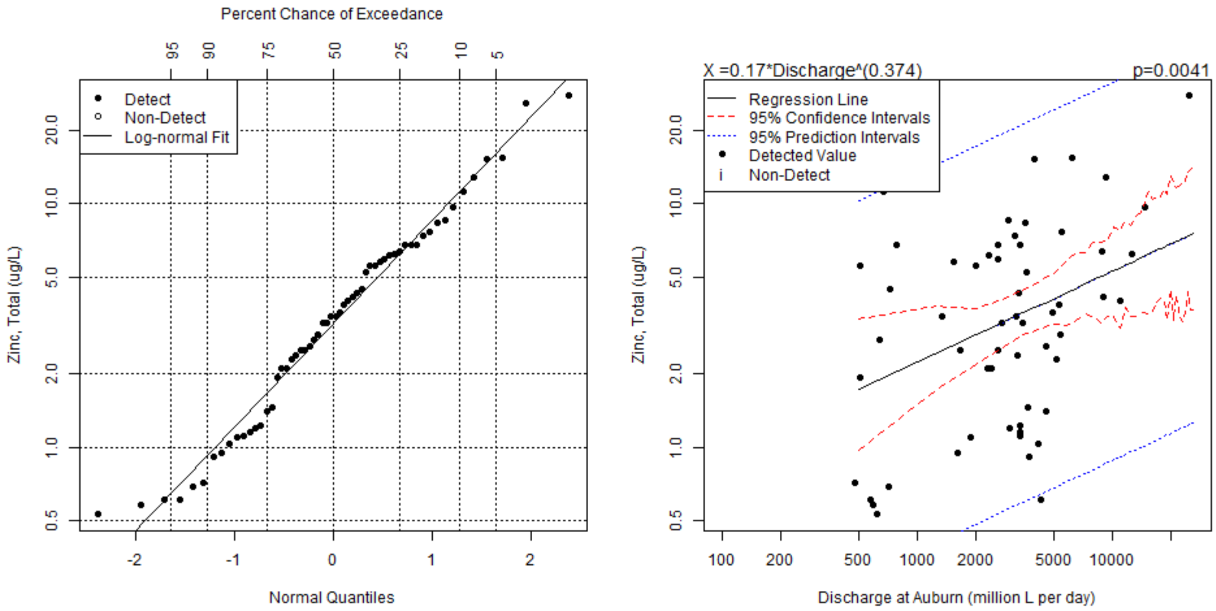

Figure D-7. **Cumulative distribution (left) and discharge regression (right) plots for total zinc.**

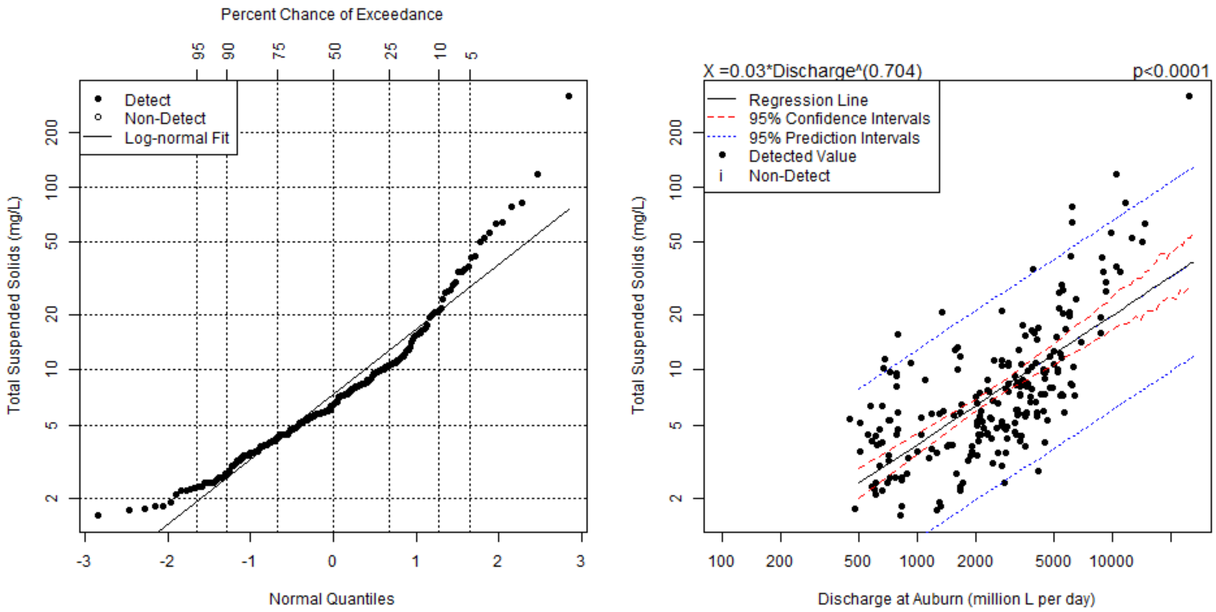

Figure D-8. **Cumulative distribution (left) and discharge regression (right) plots for TSS.**

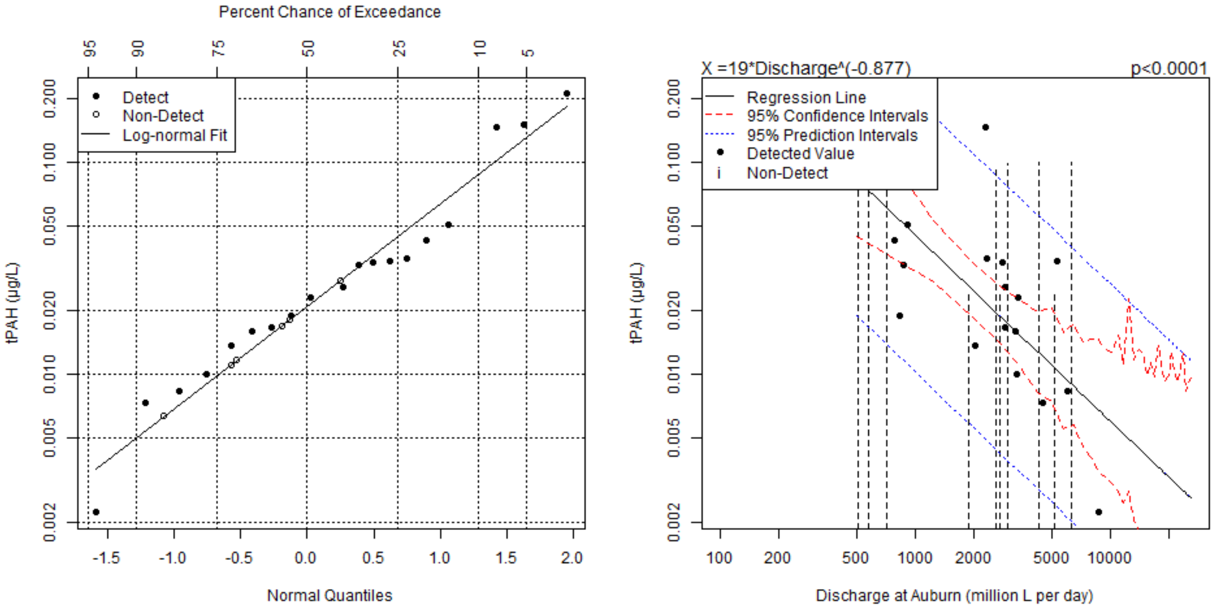

Figure D-10. Cumulative distribution (left) and discharge regression (right) plots for total PAHs.

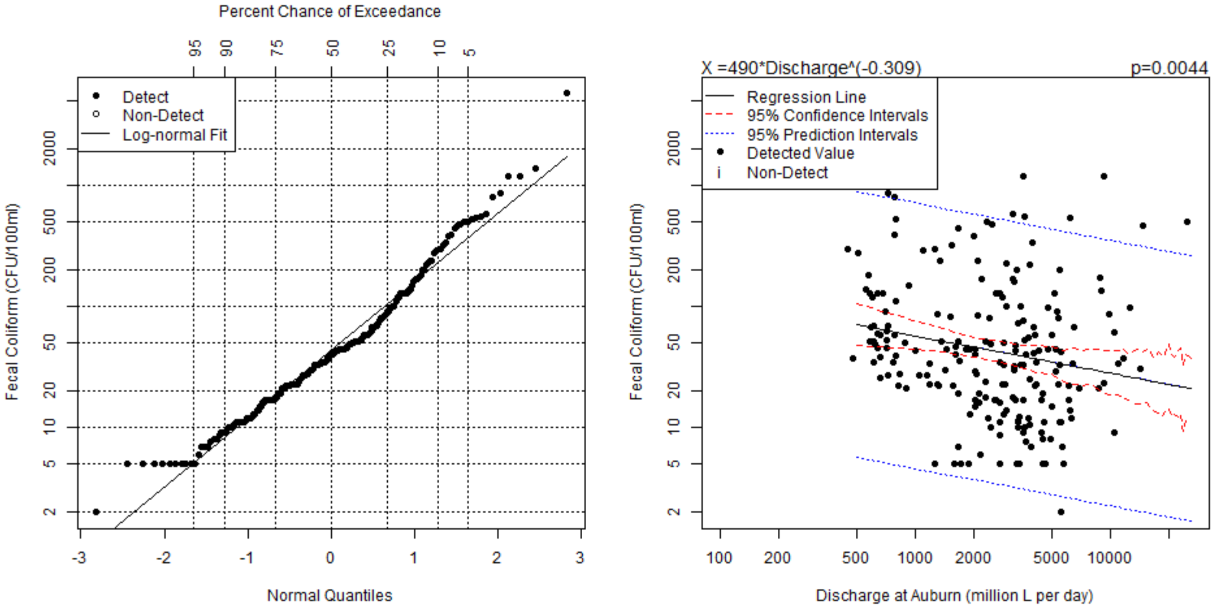

Figure D-11. Cumulative distribution (left) and discharge regression (right) plots for fecal coliform.

Appendix E: Water Quality Data Available for Loading Estimates

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Table E-1 Duwamish Estuary/Elliott Bay data available (number of samples detected/total number of samples) for estimating contaminant loadings of the major pathways.

Parameters	Green River	Stormwater	Local Tributary	Uncontrolled CSOs	Controlled CSOs	Wet weather treatment facilities	Highway Bridges	Atmospheric Deposition	Antifouling Paint	Treated Pilings
Fecal Coliform	G: 136/136; B: 174/174	com: 182/197; ind: 41/41; res: 42/42	base=135/135; storm=197/197	77/77	77/77	EW: Yes; H: Yes**	***NE (treated: 0/0; untreated: 100%*)***	***NA***	***NA***	***NA***
Total Nitrogen	G: 137/137; B: 176/176	com: 234/266; ind: 52/65; res: 64/70	***NE (0/0)***	39/39	39/39	***NE (0/0)***	Treated: 29/30; untreated: 100%*	***NE (0/0)***	***NE***	***NE***
Total Phosphorus	G: 136/136; B: 175/175	com: 228/237; ind: 50/51; res: 61/63	base: 14/14; storm: 48/48	44/44	44/44	EW: 5/5; H: 10/10	Treated: 29/31; untreated: 98.6%*	***NE (0/0)***	***NE***	***NE***
TSS	G: 150/150; B: 176/176	com: 250/250; ind: 62/62; res: 68/68	base: 10/14; storm: 48/48	126/126	126/126	EW: Yes; H:Yes**	Treated:27/31; untreated:99.5%*	***NA***	***NA***	***NA***
Total Arsenic	G: 17/17; B: 36/36	all: 110/140	base: 14/14; storm: 48/48	143/152	143/152	EW: 29/29; H: 34/34	***NE (treated: 0/0; untreated: 100%*)***	108/108	***NE***	***NE***
Total Copper	G: 57/58; B: 36/36	com: 261/261; ind: 66/66; res: 68/68	base: 14/14; storm: 48/48	148/148	148/148	EW: 29/29; H: 34/34	treated: 23/23; untreated: 98.3%	108/108	Yes; see Section 3.9	***NE***
Total Lead	G: 47/58; B: 36/36	com: 264/264; ind: 66/66; res: 69/69	base: 12/14; storm: 48/48	140/148	140/148	EW: 29/29; H: 34/34	***NE (treated: 0/0; untreated: NR)***	108/108	***NE***	***NE***
Total Mercury	G: 22/58; B: 21/35	com: 82/263; ind: 8/66; res: 5/36	base: 13/14; storm: 48/48	81/154	81/154	EW: 14/28; H: 18/33	***NE (treated: 0/0; untreated: 100%*)***	108/108	***NE***	***NE***
Total zinc	G: 58/58; B: 36/36	com: 260/260; ind: 65/65; res: 69/69	base: 8/14; storm: 40/48	148/148	148/148	EW: 29/29; H: 34/34	treated: 20/23; untreated: NR	108/108	***NE***	***NE***
Benzyl butyl Phthalate	G: 3/20; B: 3/8	com: 69/262; ind: 10/64; res: 8/69	***NE (base: 0/14; storm: 3/48)***	87/124	87/124	EW: 20/27; H: 14/33	***NE (treated: 0/0; untreated: 100%*)***	***NE (0/0)***	***NE***	***NE***
Bis(2-Ethylhexyl) Phthalate	***NE (G: 2/20; B: 2/8)***	com: 198/253; ind: 40/63; res: 43/69	base: 1/14; storm: 17/48	91/122	91/122	EW: 18/27; H: 16/18	***NE (treated: 0/0; untreated: 100%*)***	***NE (0/0)***	***NE***	***NE***
Total PAHs	G: 19/29; B: 5/8	com: 221/263; ind: 54/64; res: 51/59	base: 2/14; storm: 33/48	97/120	97/120	***NE (EW: 3/24; H: 0/0)***	***NE (0/0)***	110/110	***NE***	Yes; see Section 3.10
Total PBDEs	***NE (0/0)***	All: 25/25	base: 9/14; storm: 25/32	8/8	8/8	***NE***	***NE (treated: 0/0; untreated: 4/4)***	14/14	***NE***	***NE***
Total PCBs	G: 15/15; B: 10/10	com: 8/8; ind: 8/8; res: 16/16	base: 9/14; storm: 22/24	49/88	49/88	***NE***	***NE (treated: 0/0; untreated: 4/4)***	54/54	***NE***	***NE***

G=Green River; B=Black River; com=commercial land use; ind=industrial land use; res=residential land use; base=baseflow; storm=stormflow; NE=not estimated due to limited flow or water quality data available; NA=not applicable; NR=not reported in Herrera (2007a);

*Percentage reported is average percent detected across monitoring sites in western washington (from Herrera 2007a).

**Wet weather treatment facility fecal coliform and TSS loading were estimated using data associated with all recorded discharge events at facilities.

Table E-2 Lake Union/Ship Canal data available (number of samples detected/total number of samples) for estimating contaminant loadings of the major pathways.

Parameters	Lake Washington	Stormwater	Local Tributary	Uncontrolled CSOs	Controlled CSOs	Wet Weather Treatment Facilities	Highway Bridges	Atmospheric Deposition	Antifouling Paint	Treated Pilings
Fecal Coliform	84/100	com: 182/197; ind: 41/41; res: 42/42	***NA***	77/77	77/77	***NA***	untreated: 100%*	***NA***	***NA***	***NA***
Total Nitrogen	101/101	com: 234/266; ind: 52/65; res: 64/70	***NA***	39/39	39/39	***NA***	untreated: 100%*	***NE (0/0)***	***NE***	***NE***
Total Phosphorus	97/99	com: 228/237; ind: 50/51; res: 61/63	***NA***	44/44	44/44	***NA***	untreated: 98.6%*	***NE (0/0)***	***NE***	***NE***
TSS	100/106	com: 250/250; ind: 62/62; res: 68/68	***NA***	126/126	126/126	***NA***	untreated: 99.5%*	***NA***	***NA***	***NA***
Total Arsenic	21/21	***NE (0/0)***	***NA***	143/152	143/152	***NA***	untreated: 100%*	108/108	***NE***	***NE***
Total Copper	21/21	com: 261/261; ind: 66/66; res: 68/68	***NA***	148/148	148/148	***NA***	untreated: 98.3%*	108/108	Y	***NE***
Total Lead	21/21	com: 264/264; ind: 66/66; res: 69/69	***NA***	140/148	140/148	***NA***	untreated: NR	108/108	***NE***	***NE***
Total Mercury	20/21	com: 82/263; ind: 8/66; res: 5/36	***NA***	81/154	81/154	***NA***	untreated: 100%*	108/108	***NE***	***NE***
Total zinc	17/20	com: 260/260; ind: 65/65; res: 69/69	***NA***	148/148	148/148	***NA***	untreated: NR	108/108	***NE***	***NE***
Benzyl butyl Phthalate	***NE (0/30)***	com: 69/262; ind: 10/64; res: 8/69	***NA***	87/124	87/124	***NA***	untreated: 100%*	***NE (0/0)***	***NE***	***NE***
Bis(2-Ethylhexyl) Phthalate	4/12	com: 198/253; ind: 40/63; res: 43/69	***NA***	91/122	91/122	***NA***	untreated: 100%*	***NE (0/0)***	***NE***	***NE***
Total PAHs	4/13	com: 221/263; ind: 54/64; res: 51/59	***NA***	97/120	97/120	***NA***	***NE (0/0)***	110/110	***NE***	Y
Total PBDEs	6/6	All: 25/25	***NA***	8/8	8/8	***NA***	untreated: 4/4	14/14	***NE***	***NE***
Total PCBs	6/6	com: 16/16; ind: 6/9; res: 17/26	***NA***	49/88	49/88	***NA***	untreated: 4/4	54/54	***NE***	***NE***

G=Green River; B=Black River; com=commercial land use; ind=industrial land use; res=residential land use; base=baseflow; storm=stormflow; EW=Mercer/Elliott West treatment facility; H=Henderson/MLK treatment facility; NE=not estimated due to limited flow or water quality data available; NA=not applicable; NR=not reported in Herrera (2007a); Y=yes; loading estimated calculated, see methods for pathways.
*Percentage reported is average percent detected across monitoring sites in western washington (same as reported in Herrera 2007a)

Table E-3 Duwamish Estuary/Elliott Bay comparison of contaminant concentrations for pathways with monitored water quality data.

Parameters	Green River	Black River	Stormwater	Local Tributary	Uncontrolled CSOs	Controlled CSOs	Wet Weather Treatment Facilities	Highway Bridges
Fecal Coliform (CFU/100ml)	LCL 82.03; mean 135.01; UCL 333.81	LCL 434; mean 685; UCL 1,454	com: LCL 2,674, mean 8,757, UCL 32,850; ind: LCL 1,722, mean 4,461, UCL 15,475; res: LCL 2,131, mean 3,545, UCL 6,805	***NR***	LCL 1,378,957; mean 2,169,626; UCL 4,145,072	LCL 1,378,957; mean 2,169,626; UCL 4,145,072	Monitored data for each discharge event	***NE (treated: no data; untreated: LCL 367, mean 1,763, UCL 3,159)***
Total Nitrogen (mg/L)	LCL 0.55; mean 0.58; UCL 0.62	LCL 0.99; mean 1.02; UCL 1.05	com: LCL 1.49, mean 1.8, UCL 2.93; ind: LCL 0.92, mean 1.11, UCL 1.28; res: LCL 1.49, mean 1.66, UCL 1.88	storm: LCL 0.71, mean 1.02, UCL 1.04; base: LCL 0.92, mean 1.35, UCL 2.55	LCL 6.64; mean 8.02; UCL 10.02	LCL 6.64; mean 8.02; UCL 10.02	***NE***	Treated: LCL 0.24, mean 0.33, UCL 0.44; untreated: LCL -2.56, mean 9.66, UCL 21.88
Total Phosphorus (mg/L)	LCL 0.04; mean 0.05; LCL 0.05	LCL 0.13; mean 0.13; UCL 0.14	com: LCL 0.15, mean 0.17, UCL 0.18; ind: LCL 0.18, mean 0.21, UCL 0.27; res: LCL 0.15, mean 0.18, UCL 0.22	storm: LCL 0.05, mean 0.07, UCL 0.08; base: LCL 0.04, mean 0.07, UCL 0.10	LCL 1.24; mean 1.5; UCL 1.85	LCL 1.24; mean 1.5; UCL 1.85	EW: LCL 0.82, mean 1.03, UCL 1.13; H: LCL 0.66, mean 0.82, UCL 0.96	Treated: LCL 0.51, mean 0.93, UCL 2.0; untreated: LCL 0.16, mean 0.22, UCL 0.28
TSS (mg/L)	LCL 10.69; mean 13.82; UCL 23.82	LCL 7.95; mean 9.27; UCL 11.18	com: LCL 62.9, mean 72.5, UCL 84.4; ind: LCL 50.4, mean 65.1, UCL 89.4; res: LCL 48.2, mean 58.8, UCL 71.8	storm: LCL 14.5, mean 17.4, UCL 31.7; base: LCL 1.7, mean 2.9, UCL 4.6	LCL 119.38; mean 135.67; UCL 159.38	LCL 119.38; mean 135.67; UCL 159.38	Monitored data for each discharge event	Treated: LCL 14.6, mean 21.7, UCL 35.6; untreated: LCL 87.8, mean 118.9, UCL 150.0
Total Arsenic (µg/L)	LCL 0.69; mean 0.77; UCL 0.86	LCL 1.4; mean 1.6; UCL 1.93	all: LCL 1.6, mean 1.9, UCL 2.3	storm: LCL 0.92, mean 0.99, UCL 1.38; base: LCL 1.02, mean 1.72, UCL 2.26	LCL 2.48; mean 2.68; UCL 2.98	LCL 2.48; mean 2.68; UCL 2.98	EW: LCL 2.33, mean 2.47, UCL 2.66; H: LCL 2.18, mean 2.36, UCL 2.61	***NE (treated: no data; untreated: LCL 2.03, mean 2.39, UCL 2.75)***
Total Copper (µg/L)	LCL 1.55; mean 1.95; UCL 3.28	LCL 3.91; mean 4.77; UCL 5.65	com: LCL 23.9, mean 26.7, UCL 30.0; ind: LCL 17.1, mean19.5, UCL 22.8; res: LCL 12.1, mean 13.7, UCL 15.5	storm: LCL 3.29, mean 3.48, UCL 5.18; base: LCL 0.93, mean 1.30, UCL 1.90	LCL 33.9; mean 38.8; UCL 47.5	LCL 33.9; mean 38.8; UCL 47.5	EW: LCL 45.8, mean 70.8, UCL 145.1, H: LCL 12.6, mean 13.7, UCL 15.5	treated: LCL5.6, mean 7.7, UCL 10.6; untreated: LCL 22.1, mean 28.0, UCL 34.0
Total Lead (µg/L)	LCL 0.56; mean 0.74; UCL 0.99	LCL 1.58; mean 2.09; UCL 2.80	com: LCL 22.1, mean 26.1, UCL 31.1; ind: LCL 8.1, mean 9.7, UCL 13.2; res: LCL 12.5, mean 14.8, UCL 17.6	storm: LCL 1.20, mean 1.29, UCL 2.04; base: LCL 0.15, mean 0.22, UCL 0.32	LCL 25.5; mean 29.7; UCL 36.0	LCL 25.5; mean 29.7; UCL 36.0	EW: LCL 14.1, mean 19.2, UCL 36.7; H: LCL 4.40, mean 5.09, UCL 5.95	***NE (treated: no data; untreated: LCL 14.3, mean 37.4, UCL 60.5***
Total Mercury (ng/L)	LCL 2.04; mean 2.64; UCL 3.68	LCL 1.92; mean 2.67; UCL 3.78	com: LCL 17.5, mean 20.9, UCL 26.9; ind: LCL 22.3, mean 25.6, UCL 29.6; res LCL 0, mean 42.7, UCL 66.8	storm: LCL 7.20, mean 7.54, UCL 11.0; base: LCL 2.45, mean 3.54, UCL 5.08	LCL 56.6; mean 66.1; UCL 79.9	LCL 56.6; mean 66.1; UCL 79.9	EW: LCL 38.9, mean 47.7, UCL 65.3; H: LCL 27.6, mean 35.1, UCL 45.9	***NE (treated: no data; untreated: LCL 20.0, mean 20.0, UCL 20.0)***
Total zinc (µg/L)	LCL 4.03; mean 5.08; UCL 6.86	LCL 21.59; mean 25.94; UCL 30.91	com: LCL 132.2, mean 146.8, UCL 170.3; ind: LCL 119.0, mean 133.9, UCL 155.1; res: LCL 48.3, mean 54.6, UCL 62.5	storm: LCL 24.0, mean 34.1, UCL 45.4; base: LCL 5.29, mean 8.41, UCL 12.2	LCL 131.7; mean 146.7; UCL 166.6	LCL 131.7; mean 146.7; UCL 166.6	EW: LCL 99, mean 109, UCL 122; H: LCL 45.6, mean 49.9, UCL 55.8	treated: LCL 26.5, mean 41.4, UCL 73.1; untreated: LCL 121.6, mean 162.0, UCL 202.4
Benzyl butyl Phthalate (µg/L)	LCL 0; mean 0.13; UCL 0.20	LCL 0; mean 0.09; UCL 0.18	com: LCL 0.28, mean 0.32, UCL 0.37; ind: LCL 0.20, mean 0.22, UCL 0.24; res: LCL 0.18, mean 0.19, UCL 0.22	***NE***	LCL 0.54; mean 0.75; UCL 1.52	LCL 0.54; mean 0.75; UCL 1.52	EW: LCL 0.47, mean 0.63, UCL 0.76; H: LCL 0.23, mean 0.39, UCL 0.85	***NE (treated: no data; untreated: LCL 0.45, mean 0.63, UCL 0.81)***
Bis(2-Ethylhexyl) Phthalate (µg/L)	***NE***	***NE***	com: LCL 2.87, mean 3.36, UCL 4.19; ind: LCL 1.26, mean 1.58, UCL 2.11; res: LCL 1.13, mean 1.47, UCL 2.01	storm: LCL 0.21, mean 0.37, UCL 0.62; *base: data limitations*	LCL 4.41; mean 5.46; UCL 7.17	LCL 4.41; mean 5.46; UCL 7.17	EW: LCL 3.6, mean 4.2, UCL 5.8; H: LCL 1.40, mean 2.20, UCL 3.37	***NE (treated: no data; untreated: LCL 4.68, mean 4.68, UCL 4.68)***
Total PAHs (µg/L)	LCL 0.02; mean 0.04; UCL 0.06	LCL 0.04; mean 0.09; UCL 0.17	com: LCL 2.93, mean 4.28, UCL 7.47; ind: LCL 0.27, mean 0.41, UCL 0.69; res: LCL 0.14, mean 0.19. UCL 0.26	storm: LCL 0.10, mean 0.15, UCL 0.21; *base: data limitations*	LCL 1.46; mean 1.79; UCL 2.31	LCL 1.46; mean 1.79; UCL 2.31	***NE***	***NE***
Total PBDEs (ng/L)	***NE***	NE	all: LCL 16.83, mean 17.5, UCL 38.33	storm: LCL 5.43, mean 23.2, UCL 74.6; base: LCL 0.15, mean 1.22, UCL 7.50	LCL 0.08; mean 0.08; UCL 0.14	LCL 0.08; mean 0.08; UCL 0.14	***NE***	***NE (treated: no data; untreated: LCL 14.1, mean 72.8, UCL 178.2)***
Total PCBs (ng/L)	LCL 0.22; mean 0.50; UCL 1.00	LCL 0.65; mean 1.08; UCL 1.9	com/ind: LCL 2.29, mean 7.52, UCL 21.99; res: LCL 1.82, mean 2.93, UCL 4.95	storm: LCL 1.89, mean 0.51, UCL 13.5; base: LCL 0.13, mean 0.39, UCL 0.92	LCL 0.04; mean 0.05; UCL 0.07	LCL 0.04; mean 0.05; UCL 0.07	***NE***	***NE (treated: no data; untreated: LCL 4.2, mean 9.4, UCL 13.0)***

G=Green River; B=Black River; com=commercial land use; ind=industrial land use; res=residential land use; base=baseflow; storm=stormflow; EW=Mercer/Elliott West treatment facility; H=Henderson/MLK treatment facility; NE=not estimated due to limited flow or water quality data available; NA=not applicable; NR=not reported in Herrera (2007a);

Table E-4 Lake Union/Ship Canal comparison of contaminant concentrations for pathways with monitored water quality data.

Parameters	Lake Washington	Stormwater	Uncontrolled CSOs	Controlled CSOs	Highway Bridges
Fecal Coliform (CFU/100ml)	LCL 3.09; mean 3.78; UCL 4.88	com: LCL 2,674, mean 8,757, UCL 32,850; ind: LCL 1,722, mean 4,461, UCL 15,475; res: UCL 2,131, mean 3,545, UCL 6,805	LCL 1,378,957; mean 2,169,626; UCL 4,145,072	LCL 1,378,957; mean 2,169,626; UCL 4,145,072	untreated: LCL 367, mean 1,763, UCL 3,159
Total Nitrogen (mg/L)	LCL 0.26; mean 0.27; UCL 0.28	com: LCL 1.49, mean 1.8, UCL 2.93; ind: LCL 0.92, mean 1.11, UCL 1.28; res: LCL 1.49, mean 1.66, UCL 1.88	LCL 6.64; mean 8.02; UCL 10.02	LCL 6.64; mean 8.02; UCL 10.02	untreated: LCL -2.56, mean 9.66, UCL 21.88
Total Phosphorus (mg/L)	LCL 0.01; mean 0.01; UCL 0.01	com: LCL 0.15, mean 0.17, UCL 0.18; ind: LCL 0.18, mean 0.21, LCL 0.27; res: LCL 0.15, mean 0.18, UCL mean 0.22	LCL 1.24; mean 1.5; UCL 1.85	LCL 1.24; mean 1.5; UCL 1.85	untreated: LCL 0.16, mean 0.22, UCL 0.28
TSS (mg/L)	LCL 1.15; mean 1.25; UCL 1.36	com: LCL 62.9, mean 72.5, UCL 84.4; ind: LCL 50.4, mean 65.1, 89.4; res: LCL 48.2, mean 58.8, UCL 71.8	LCL 119.38; mean 135.67; UCL 159.38	LCL 119.38; mean 135.67; UCL 159.38	untreated: LCL 87.8, mean 118.9, UCL 150.0
Total Arsenic (µg/L)	LCL 0.73; mean 0.76; UCL 0.79	all: LCL 1.6, mean 1.9, UCL 2.3	LCL 2.48; mean 2.68; UCL 2.98	LCL 2.48; mean 2.68; UCL 2.98	untreated: LCL 2.03, mean 2.39, UCL 2.75
Total Copper (µg/L)	LCL 1.00; mean 1.02; UCL 1.04	com: LCL 23.9, mean 26.7, LCL 30.0; ind: LCL 17.1, mean19.5, UCL 22.8; res: LCL 12.1, mean 13.7, UCL 15.5	LCL 33.9; mean 38.8; UCL 47.5	LCL 33.9; mean 38.8; UCL 47.5	untreated: LCL 22.1, mean 28.0, UCL 34.0
Total Lead (µg/L)	LCL 0.06; mean 0.07; UCL 0.09	com: LCL 22.1, mean 26.1, UCL 31.1; ind: LCL 8.1, mean 9.7, UCL 13.2; res: LCL 12.5, mean 14.8, UCL 17.6	LCL 25.5; mean 29.7; UCL 36.0	LCL 25.5; mean 29.7; UCL 36.0	untreated: LCL 14.3, mean 37.4, UCL 60.5
Total Mercury (ng/L)	LCL 0.39; mean 0.47; UCL 0.57	com: LCL 17.5, mean 20.9, UCL 26.9; ind: LCL 22.3, mean 25.6, UCL 29.6; res L LCL 0, mean 42.7, UCL 66.8	LCL 0.06; mean 0.07; UCL 0.08	LCL 0.06; mean 0.07; UCL 0.08	***NE (treated: no data; untreated: LCL 20.0, mean 20.0, UCL 20.0)***
Total zinc (µg/L)	LCL 0.58; mean 0.65; UCL 1.07	com: LCL 132.2, mean 146.8, UCL 170.3; ind: LCL 119.0, mean 133.9, UCL 155.1; res: LCL 48.3, mean 54.6, UCL 62.5	LCL 131.7; mean 146.7; UCL 166.6	LCL 131.7; mean 146.7; UCL 166.6	untreated: LCL 121.6, mean 162.0, UCL 202.4
Benzyl butyl Phthalate (µg/L)	***NE***	com: LCL 0.28, mean 0.32, UCL 0.37; ind: LCL 0.20, mean 0.22, UCL 0.24; res: LCL 0.18, mean 0.19, UCL 0.22	LCL 0.54; mean 0.75; UCL 1.52	LCL 0.54; mean 0.75; UCL 1.52	untreated: LCL 0.45, mean 0.63, UCL 0.81
Bis(2-Ethylhexyl) Phthalate (µg/L)	LCL 0; mean 1.9; UCL 5.05	com: LCL 2.87, mean 3.36, UCL 4.19; ind: LCL 1.26, mean 1.58, UCL 2.11; res: LCL 1.13, mean 1.47, UCL 2.01	LCL 4.41; mean 5.46; UCL 7.17	LCL 4.41; mean 5.46; UCL 7.17	untreated: LCL 4.68, mean 4.68, UCL 4.68)
Total PAHs (µg/L)	LCL 0.05; mean 0.06; UCL 0.07	com: LCL 2.93, mean 4.28, UCL 7.47; ind: LCL 0.27, mean 0.41, UCL 0.69; res: LCL 0.14, mean 0.19. UCL 0.26	LCL 1.46; mean 1.79; UCL 2.31	LCL 1.46; mean 1.79; UCL 2.31	no data
Total PBDEs (ng/L)	LCL 0.63; mean 0.65; UCL 1.07	all: LCL 16.83, mean 17.5, UCL 38.33	LCL 0.08; mean 0.08; UCL 0.14	LCL 0.08; mean 0.08; UCL 0.14	untreated: LCL 14.1, mean 72.8, UCL 178.2)
Total PCBs (ng/L)	LCL 0.11; mean 0.11; UCL 0.17	com/ind: LCL 2.29, mean 7.52, UCL 21.99; res: LCL 1.82, mean 2.93, UCL 4.95	LCL 0.04; mean 0.05; UCL 0.07	LCL 0.04; mean 0.05; UCL 0.07	untreated: LCL 4.2, mean 9.4, UCL 13.0

G=Green River; B=Black River; com=commercial land use; ind=industrial land use; res=residential land use; base=baseflow; storm=stormflow; NE=not estimated due to limited flow or water quality data available; NA=not applicable; NR=not reported in Herrera (2007a)

Appendix F: Area-Weighted Annual Loading Estimates

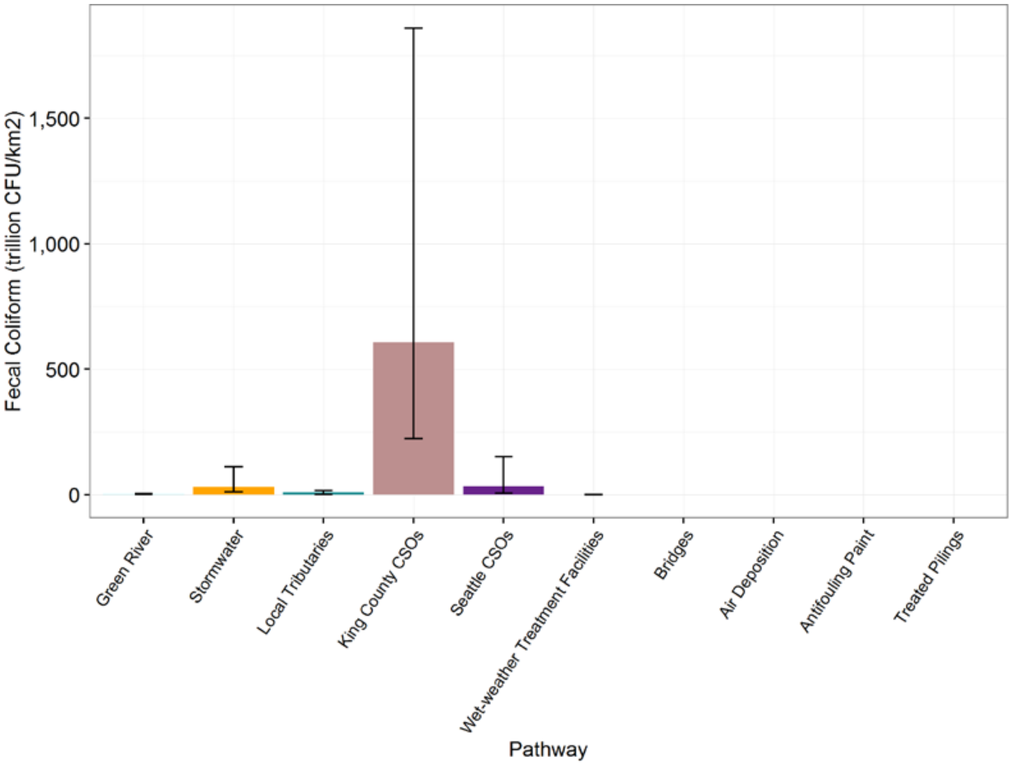

Figure F-1. Duwamish Estuary/Elliott Bay area weighted fecal coliform loading.

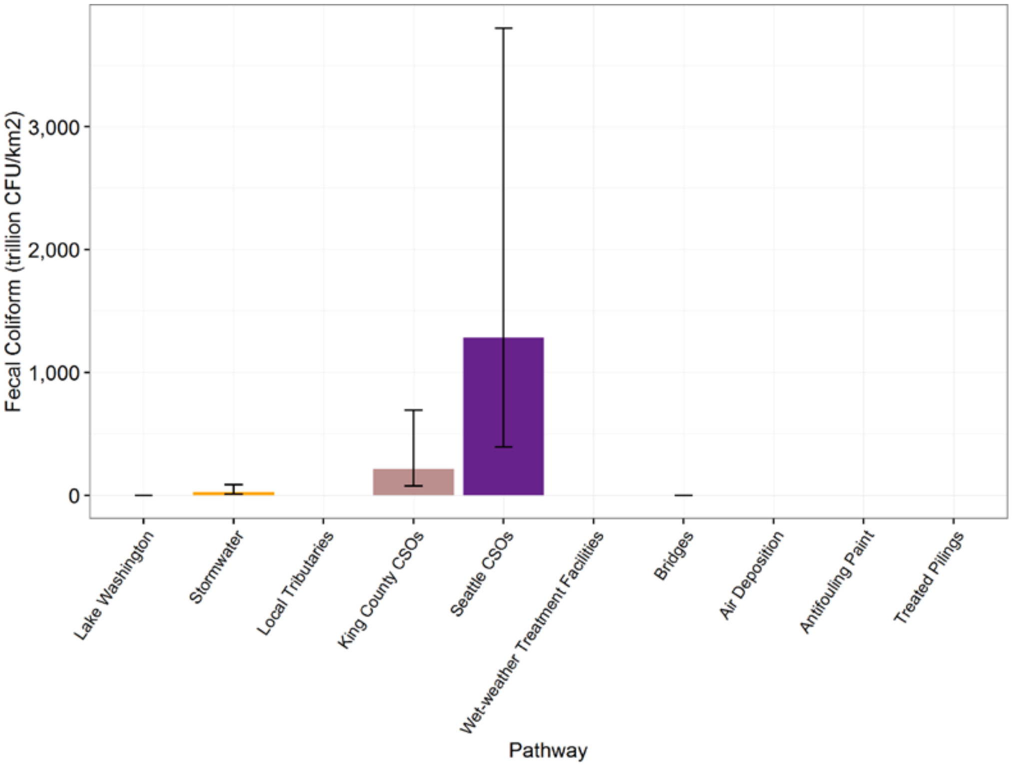

Figure F-2. Lake Union/Ship Canal area weighted fecal coliform loading.

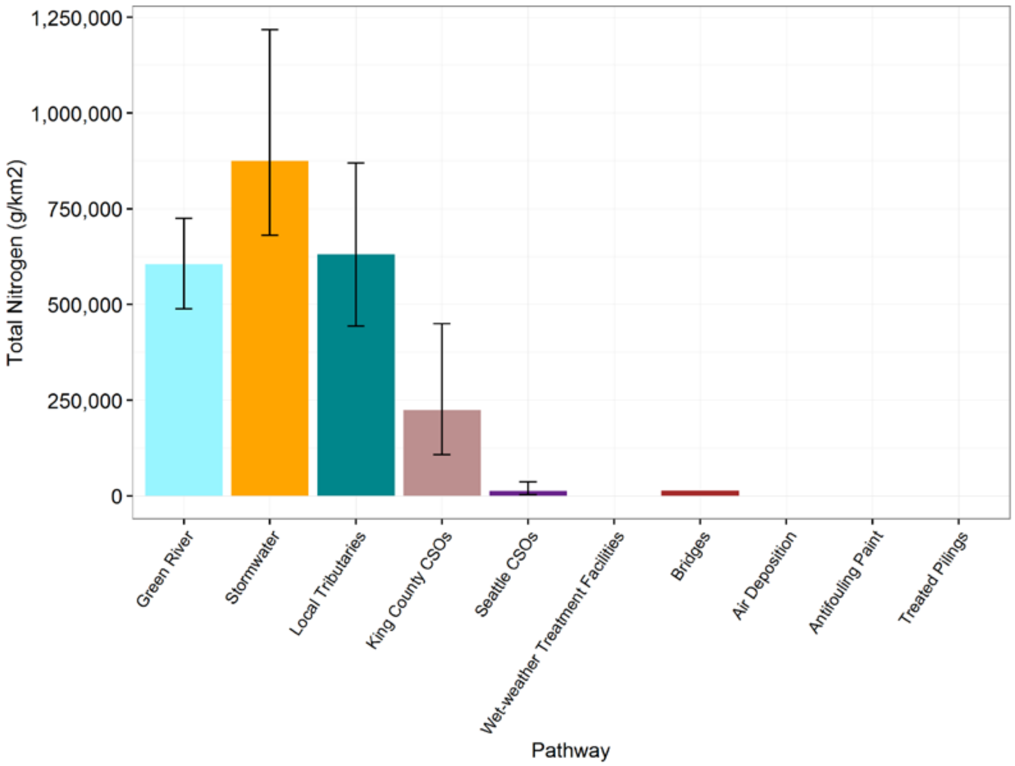

Figure F-3. **Duwamish Estuary/Elliott Bay area weighted total nitrogen loading.**

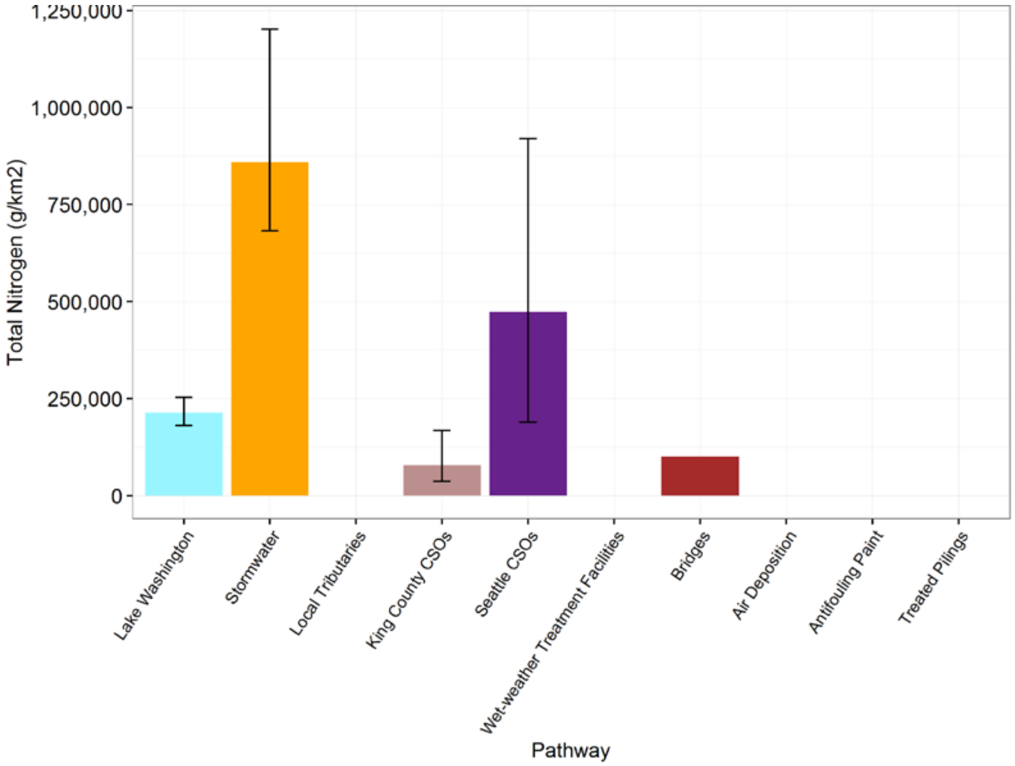

Figure F-4. **Lake Union/Ship Canal area weighted total nitrogen loading.**

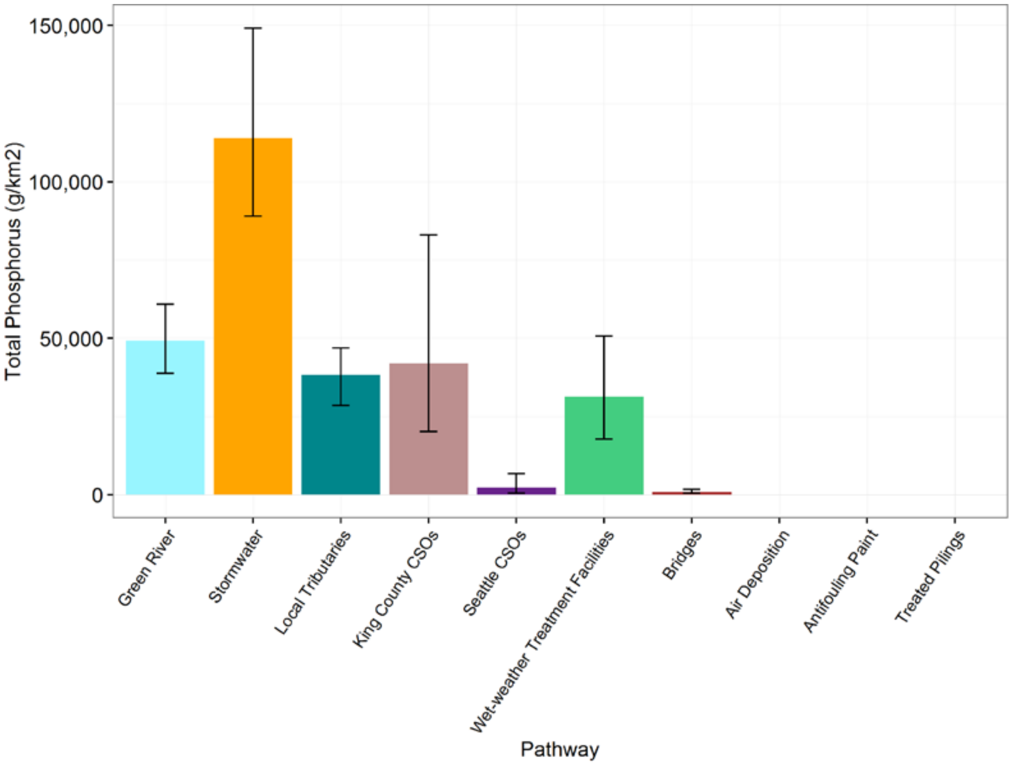

Figure F-5. **Duwamish Estuary/Elliott Bay area weighted total phosphorus loading.**

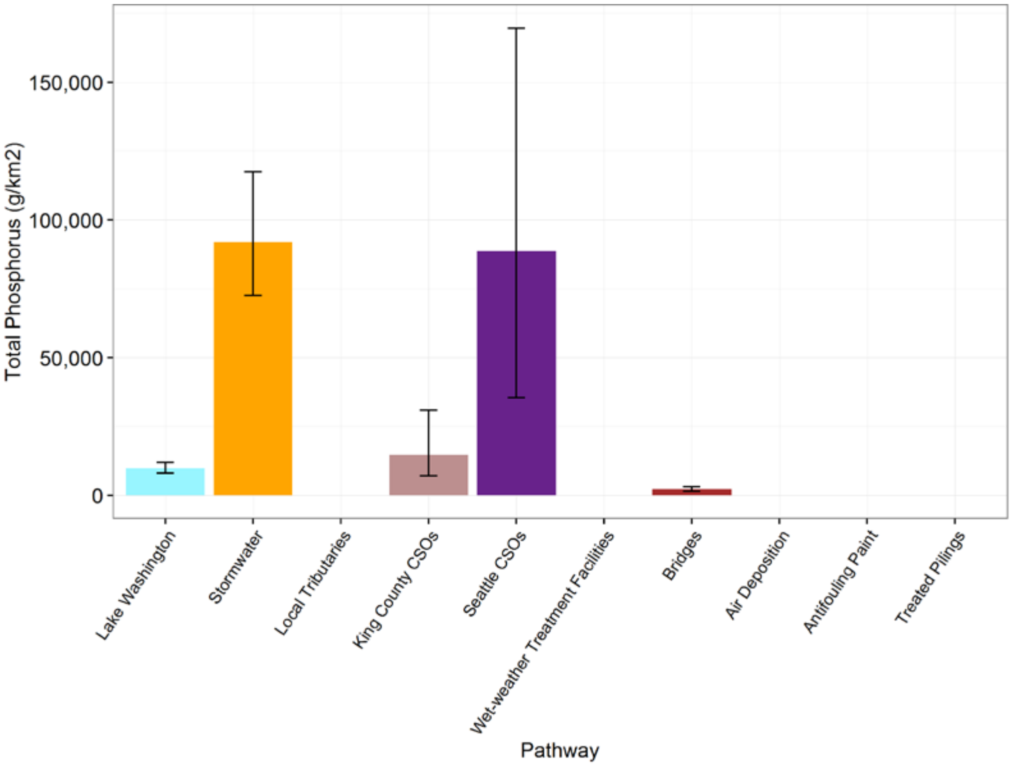

Figure F-6. **Lake Union/Ship Canal area weighted total phosphorus loading.**

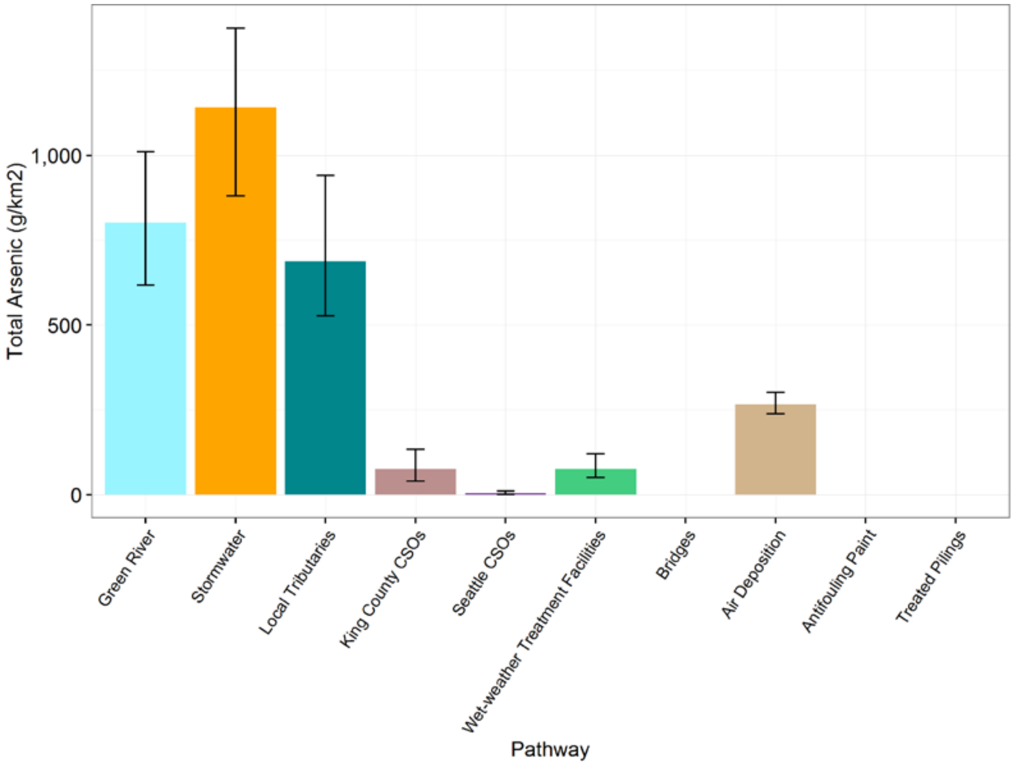

Figure F-7. **Duwamish Estuary/Elliott Bay area weighted total arsenic loading.**

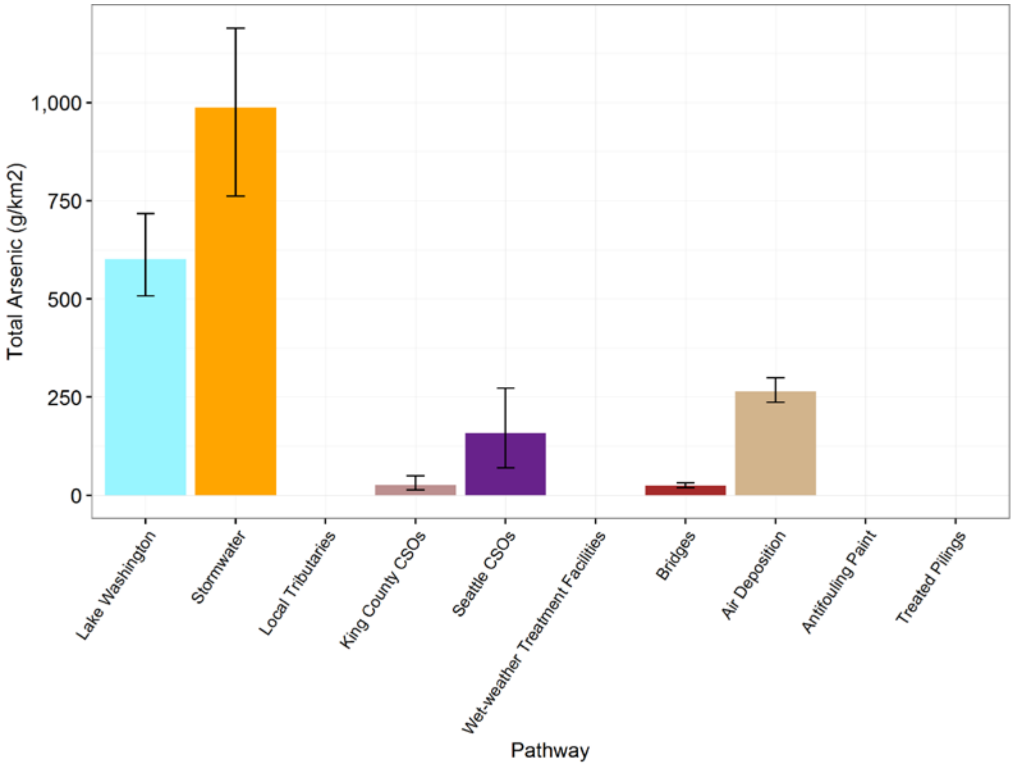

Figure F-8. **Lake Union/Ship Canal area weighted total arsenic loading.**

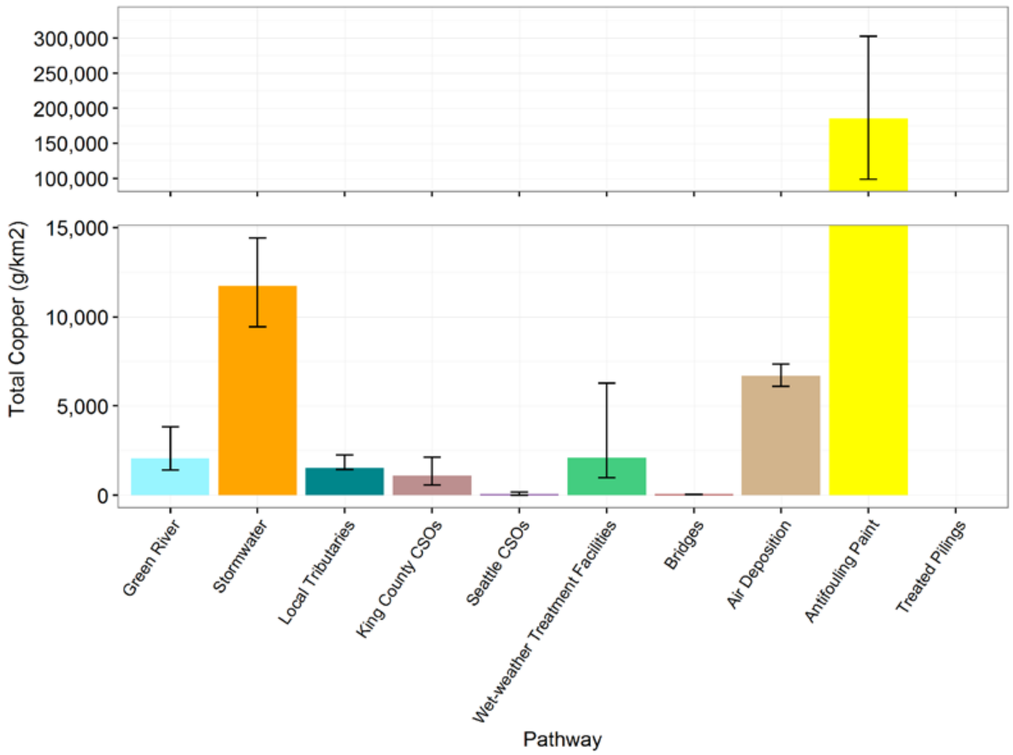

Figure F-9. **Duwamish Estuary/Elliott Bay area weighted total copper loading.**

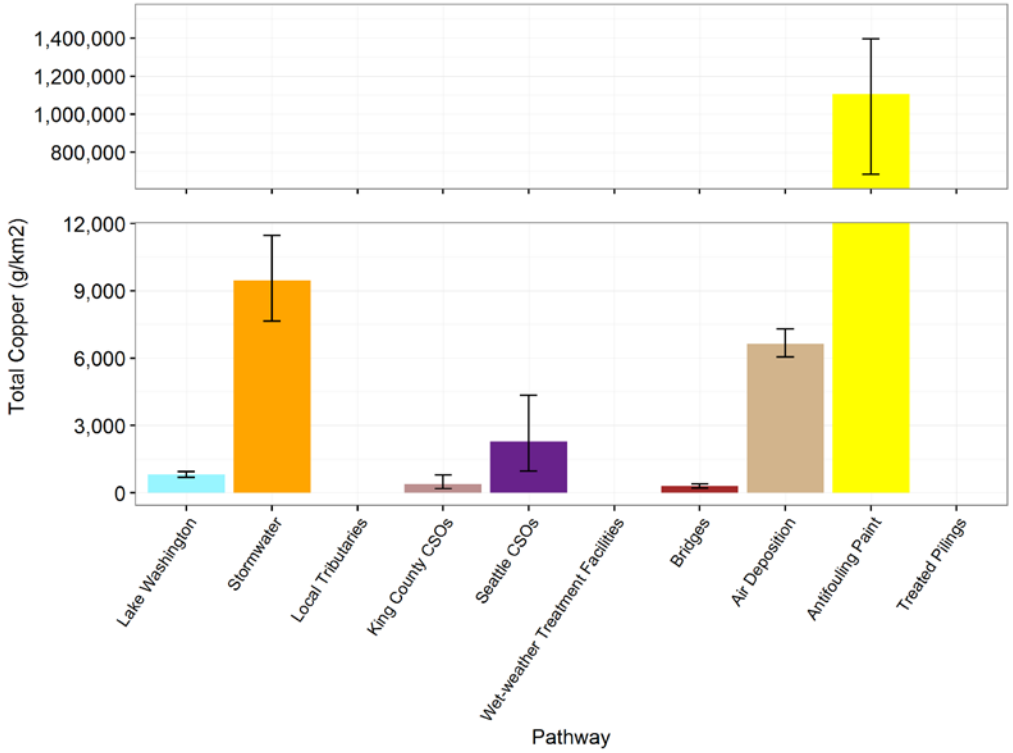

Figure F-10. **Lake Union/Ship Canal area weighted total copper loading.**

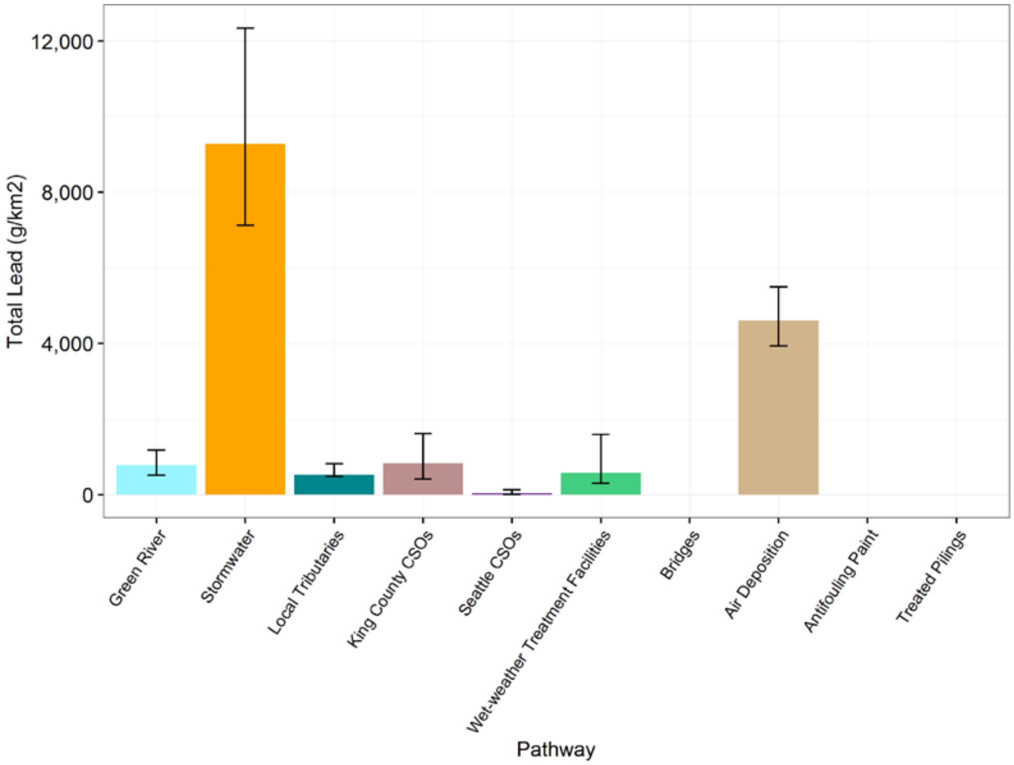

Figure F-11. Duwamish Estuary/Elliott Bay area weighted total lead loading.

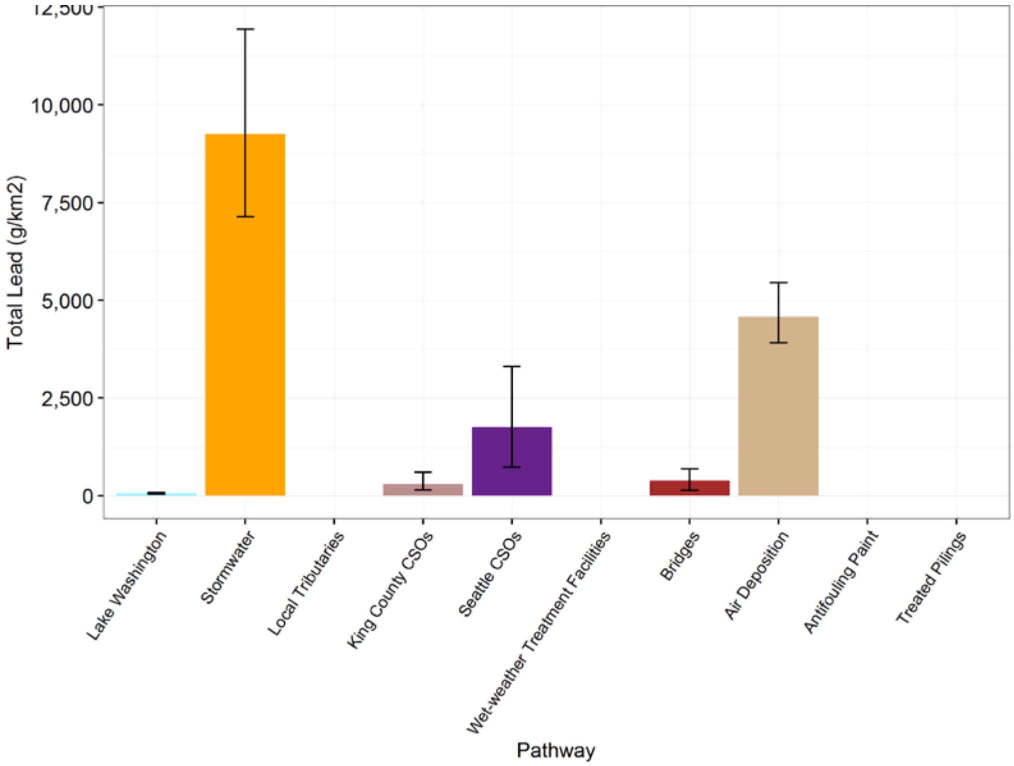

Figure F-12. Lake Union/Ship Canal area weighted total lead loading.

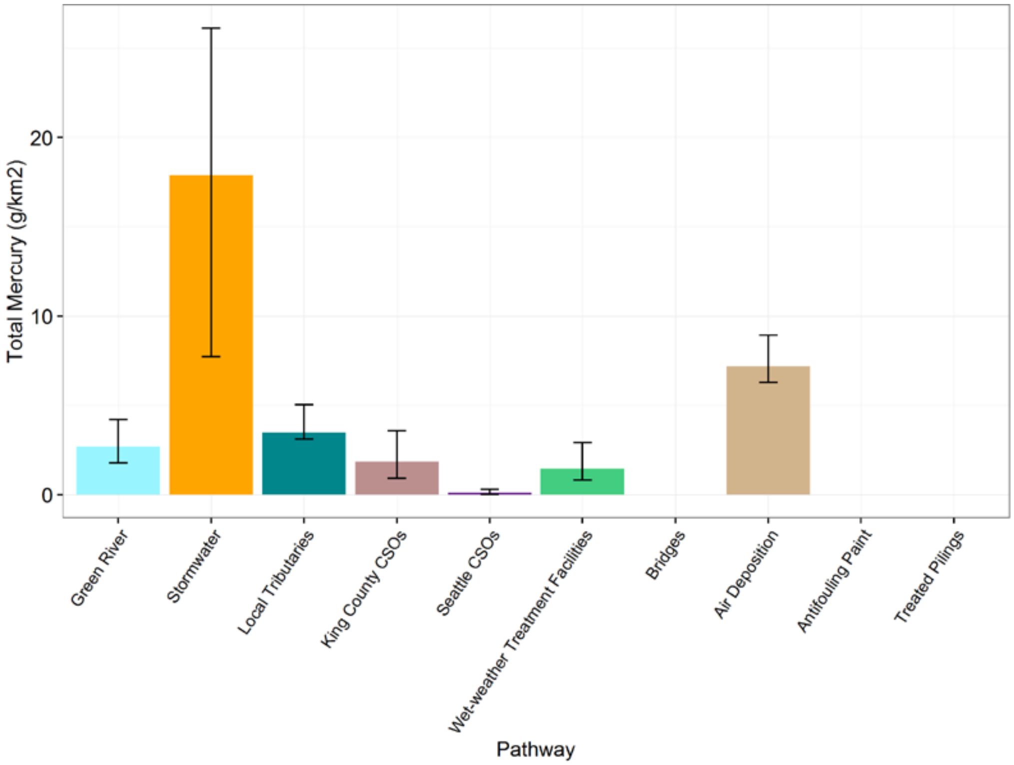

Figure F-13. **Duwamish Estuary/Elliott Bay area weighted total mercury loading.**

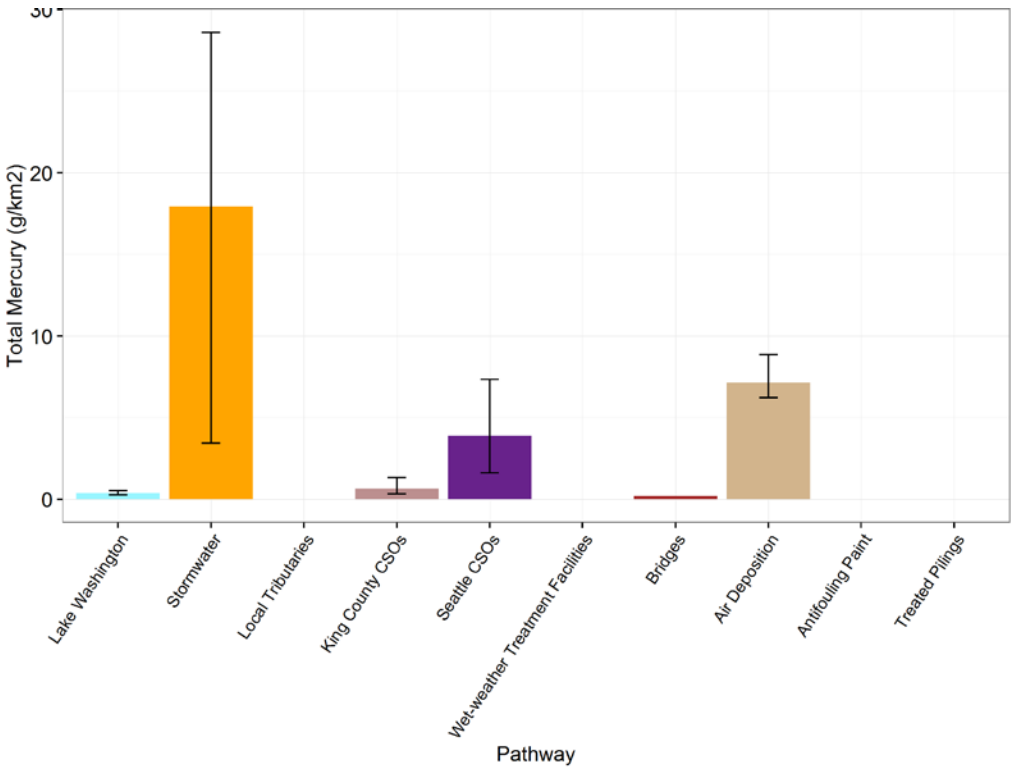

Figure F-14. **Lake Union/Ship Canal area weighted total mercury loading.**

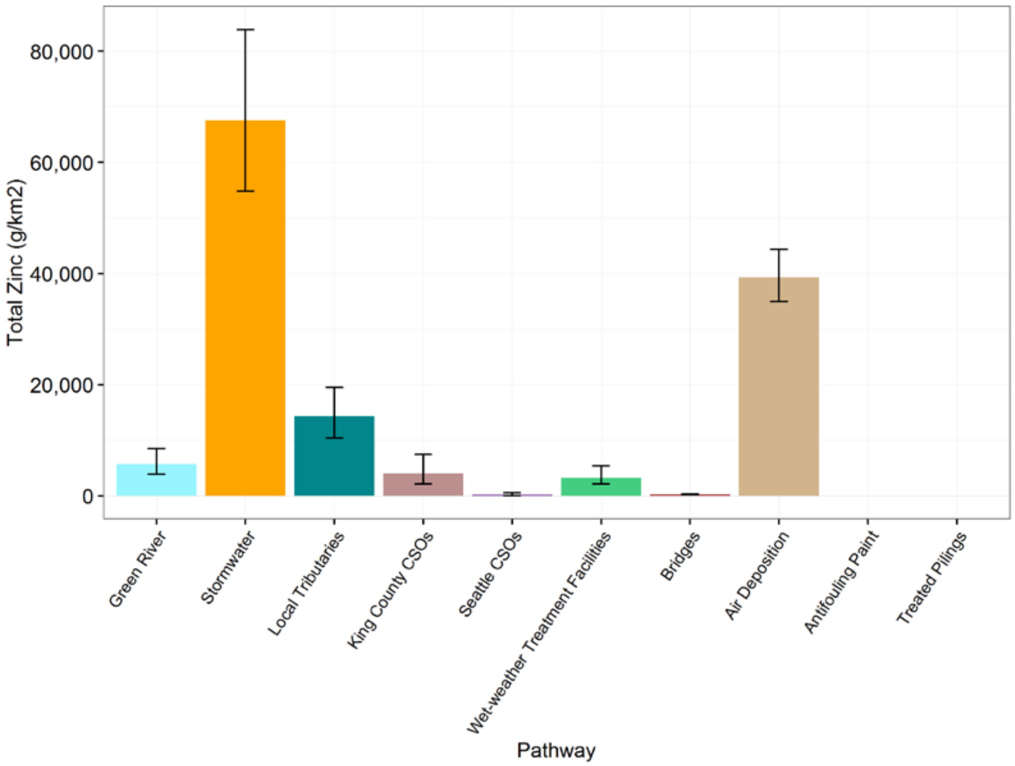

Figure F-15. **Duwamish Estuary/Elliott Bay area weighted total zinc loading.**

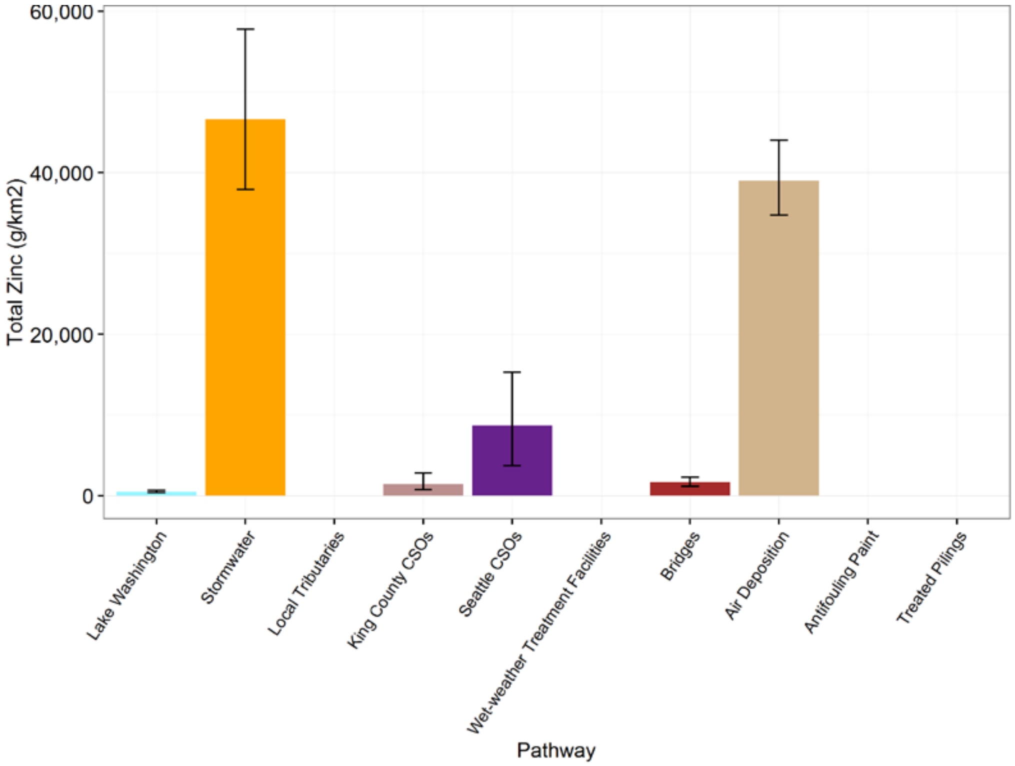

Figure F-16. **Lake Union/Ship Canal area weighted total zinc loading.**

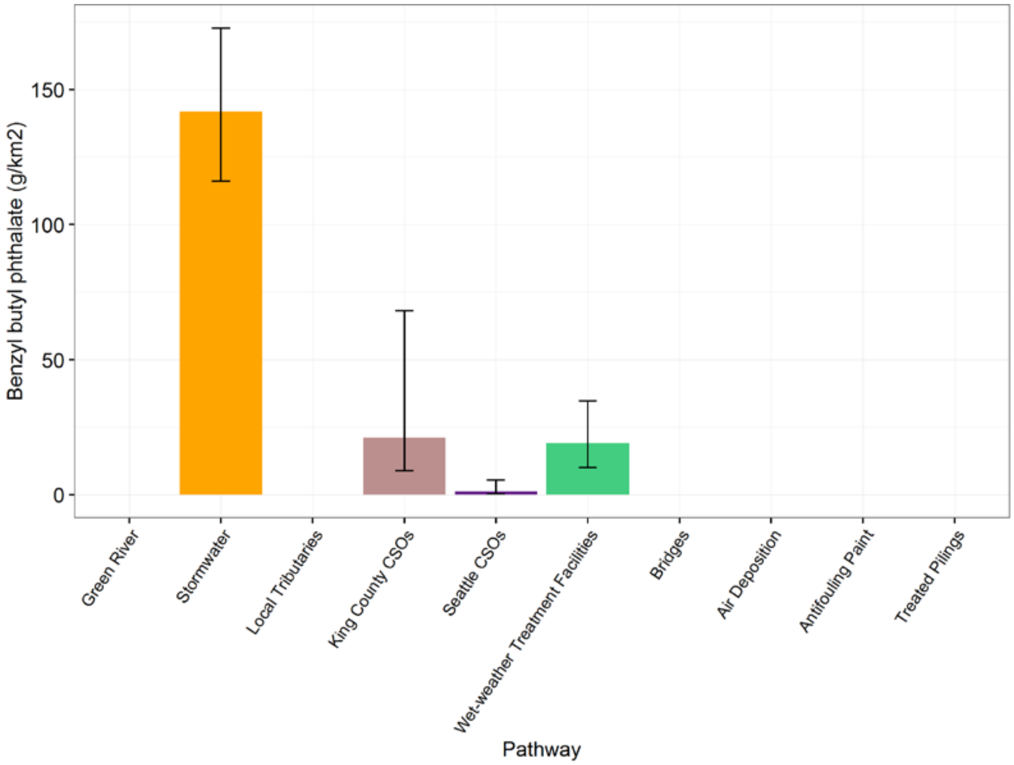

Figure F-17. Duwamish Estuary/Elliott Bay area weighted benzyl butyl phthalate loading.

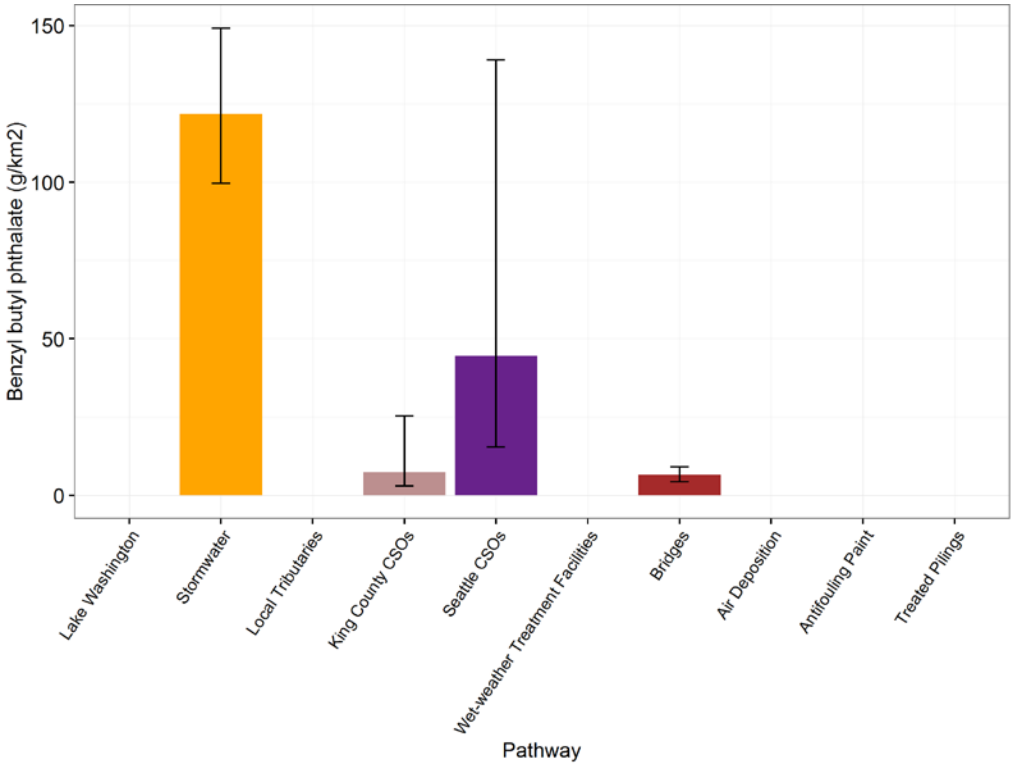

Figure F-18. Lake Union/Ship Canal area weighted benzyl butyl phthalate loading.

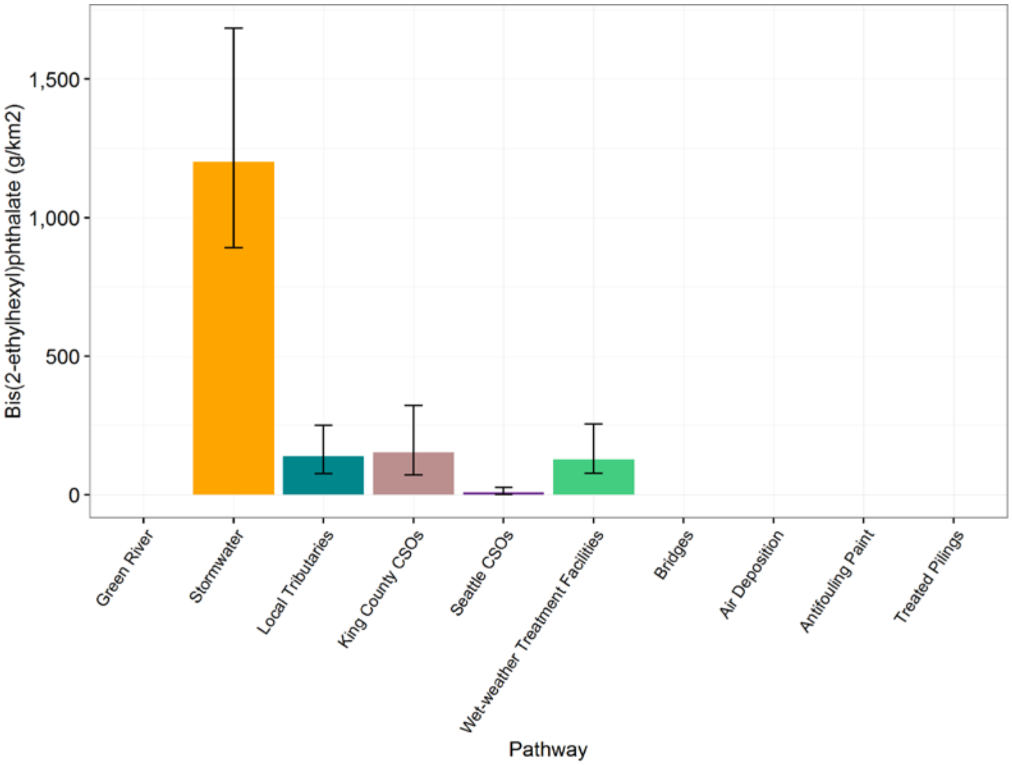

Figure F-19. **Duwamish Estuary/Elliott Bay area weighted bis(2-ethylhexyl) phthalate loading.**

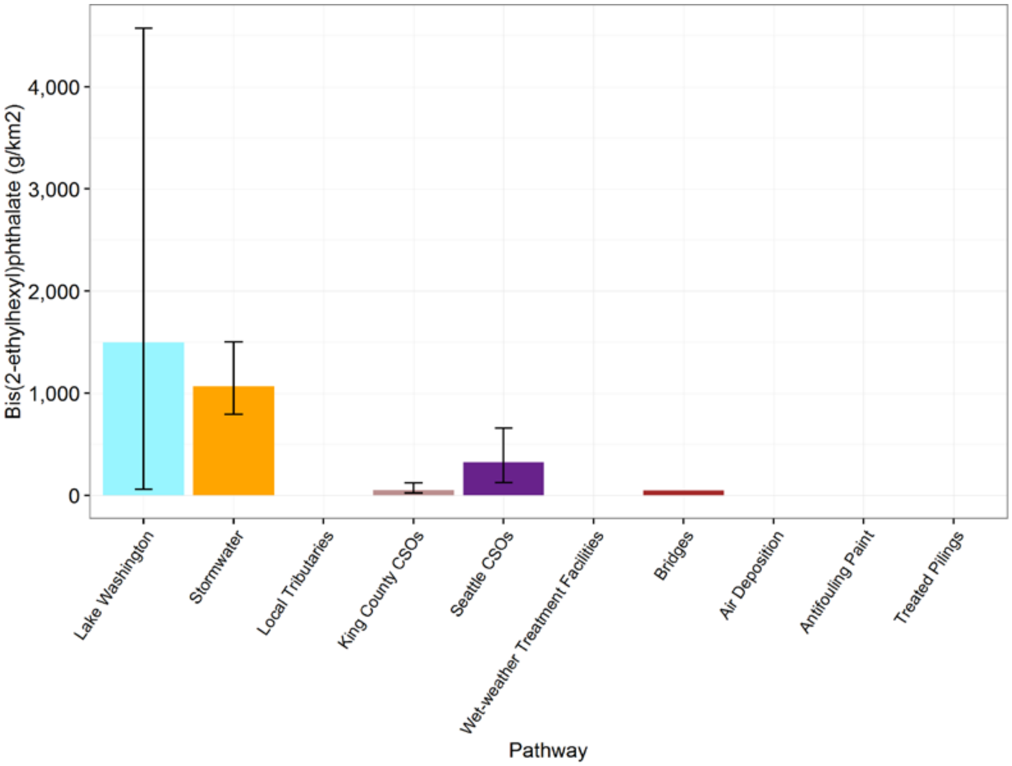

Figure F-20. **Lake Union/Ship Canal area weighted bis(2-ethylhexyl) phthalate loading.**

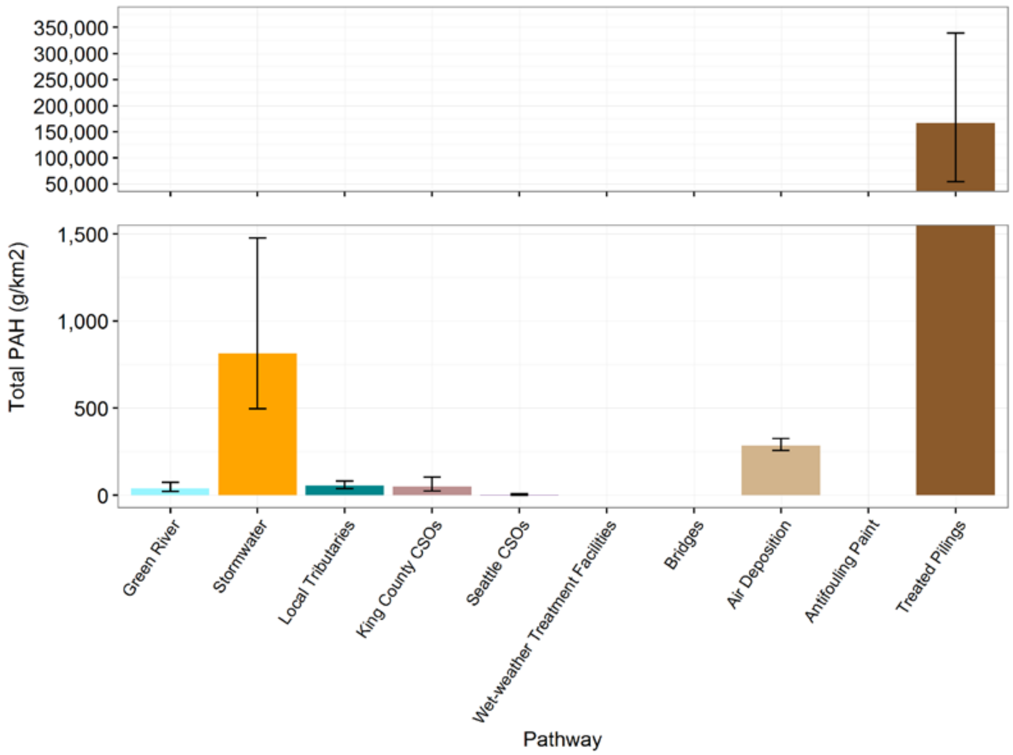

Figure F-21. **Duwamish Estuary/Elliott Bay area weighted total PAH loading.**

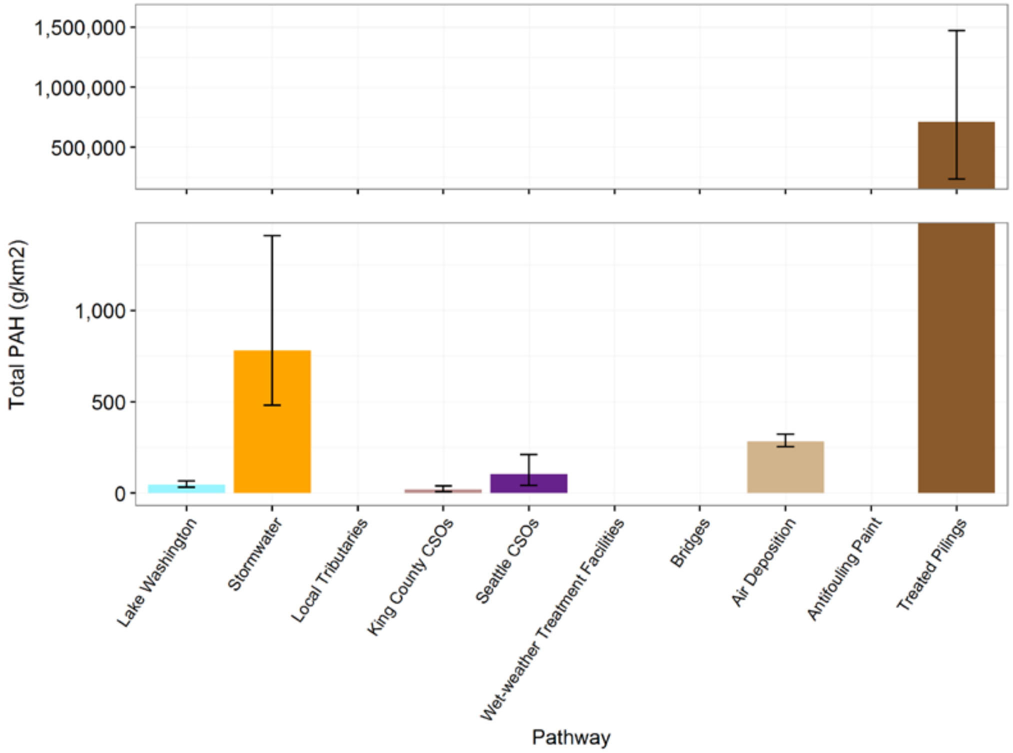

Figure F-22. **Lake Union/Ship Canal area weighted total PAH loading.**

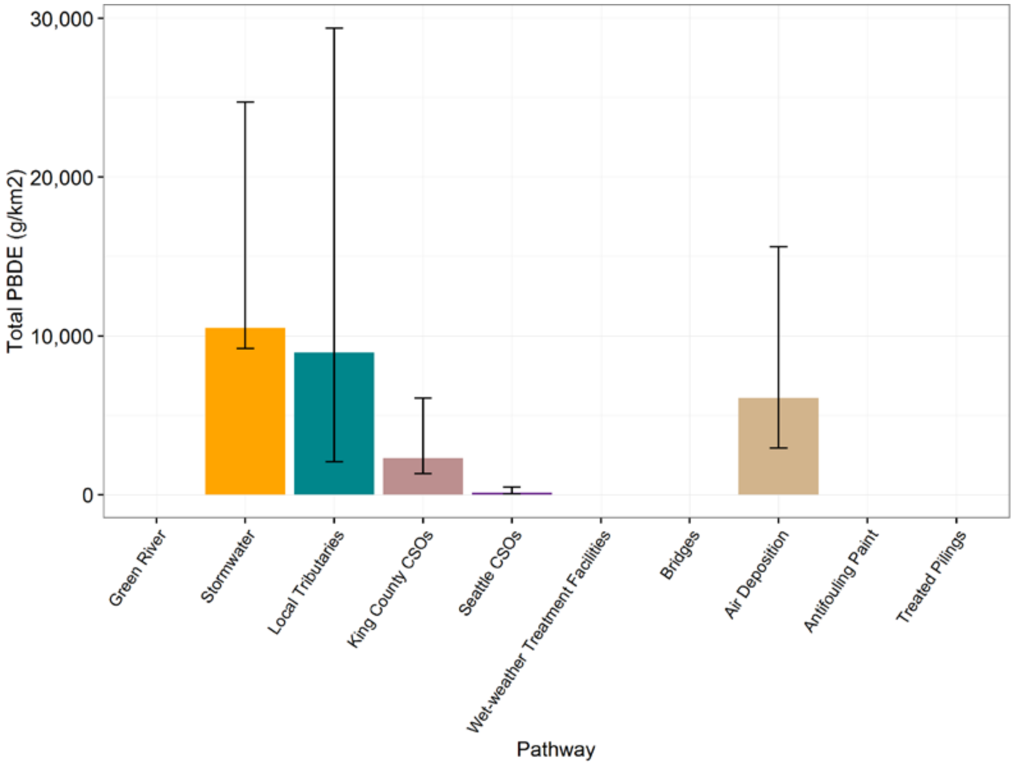

Figure F-23. **Duwamish Estuary/Elliott Bay area weighted total PBDE loading.**

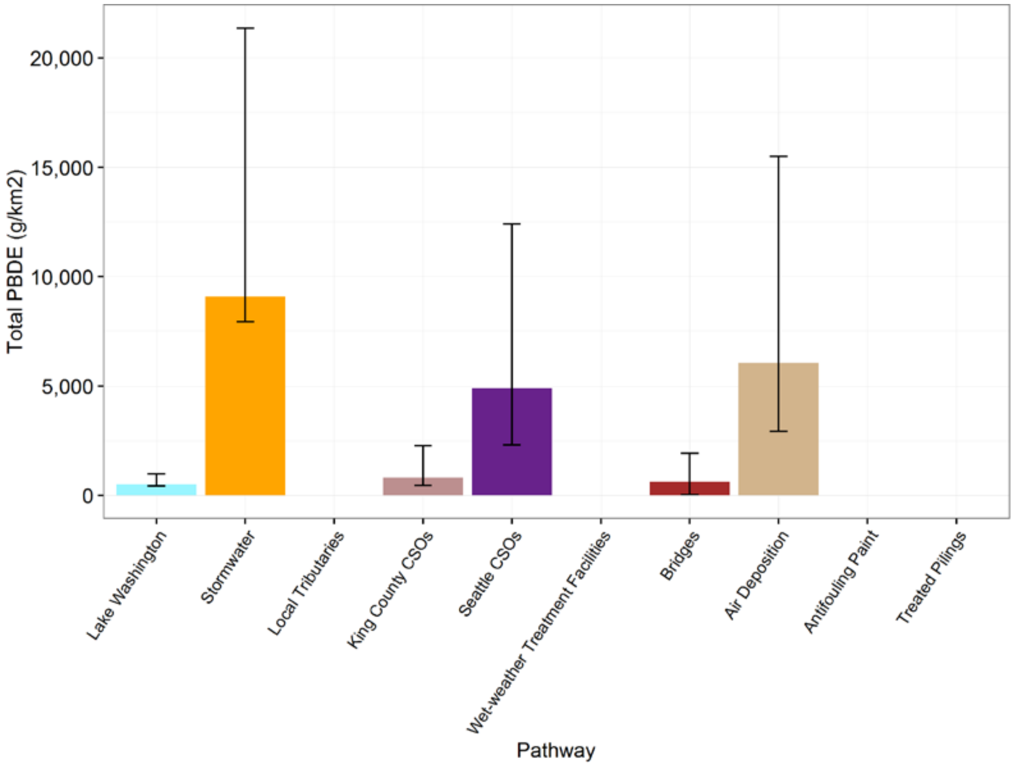

Figure F-24. **Lake Union/Ship Canal area weighted total PBDE loading.**

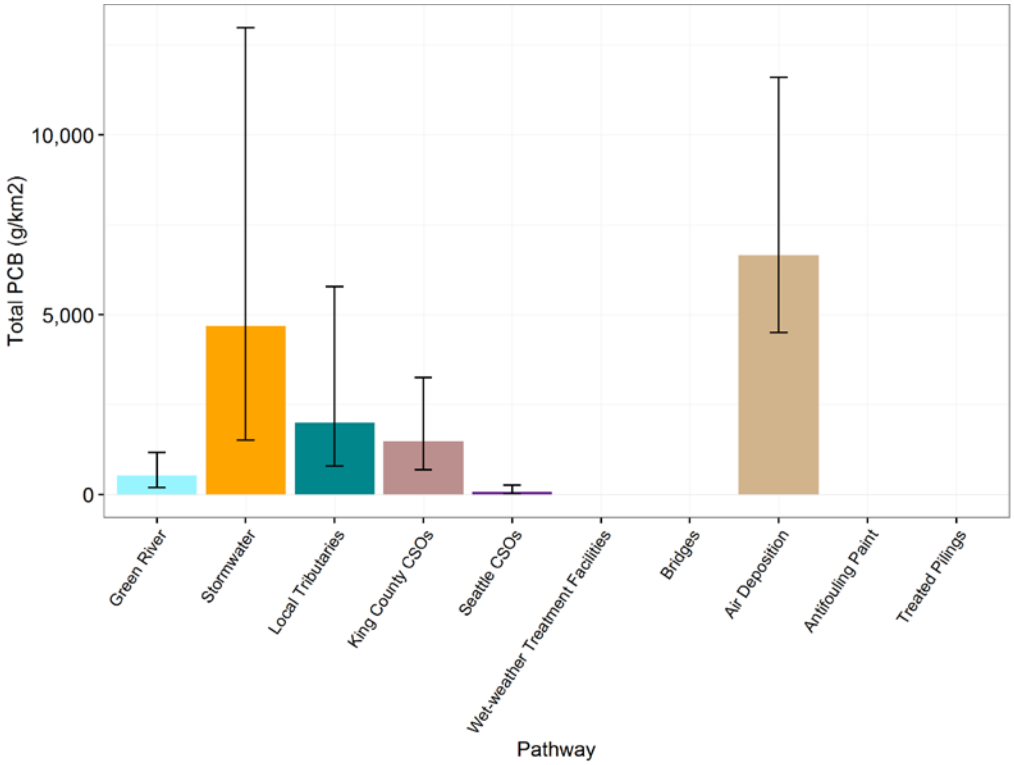

Figure F-25. Duwamish Estuary/Elliott Bay area weighted total PCB loading.

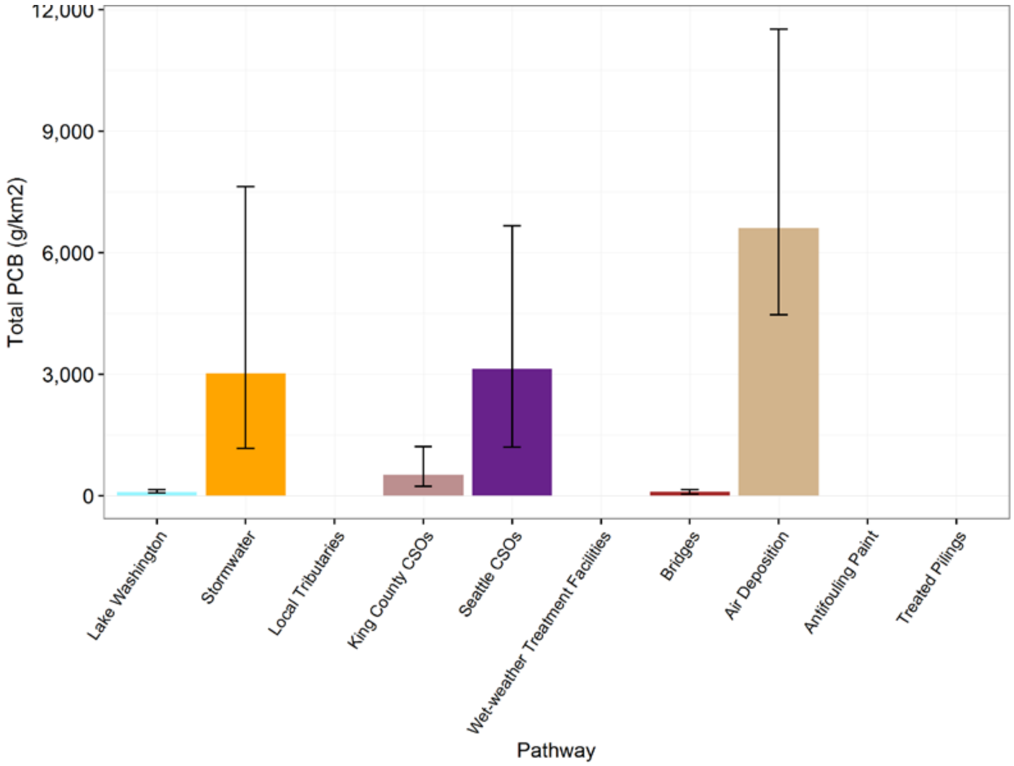

Figure F-26. Lake Union/Ship Canal area weighted total PCB loading.

Table F-1 Duwamish Estuary/Elliott Bay Area-Weighted Annual Loading Estimates

Pathway	Fecal Coliform (trillion CFU/km2)	TSS (kg/km2)	Total Phosphorus (g/km2)	Total Nitrogen (g/km2)	Total PAHs (g/km2)	Total PCBs (mg/km2)	Total PBDEs (mg/km2)	BEHP (g/km2)	Arsenic (g/km2)	Copper (g/km2)	Lead (g/km2)	Mercury (g/km2)	Zinc (g/km2)	BBP (g/km2)
Green River	0.8 - 4.1	9,000 - 27,000	39,000 - 61,000	490,000 - 720,000	21 - 73	200 - 1,170	-	-	620 - 1,010	1,400 - 3,800	510 - 1,180	1.8 - 4.2	3,900 - 8,500	-
Stormwater	11 - 111	29,000 - 53,000	90,000 - 150,000	680,000 - 1,220,000	500 - 1,480	1,500 - 13,000	9,000 - 25,000	900 - 1,700	900 - 1,400	9,000 - 14,000	7,100 - 12,300	8.0 - 26	55,000 - 84,000	120 - 170
Local Tributary	1.8 - 17	5,700 - 13,300	28,000 - 47,000	440,000 - 870,000	38 - 81	800 - 5,800	2,100 - 29,400	80 - 250	530 - 940	1,400 - 2,200	480 - 820	3.1 - 5.0	10,000 - 20,000	-
KC CSOs	220 - 1,860	1,900 - 7,200	20,000 - 83,000	110,000 - 450,000	24 - 104	700 - 3,300	1,300 - 6,100	70 - 320	40 - 134	600 - 2,100	410 - 1,620	0.9 - 3.6	2,100 - 7,500	9.0 - 68
Seattle CSOs	10 - 263	90 - 1,010	900 - 11,800	5,000 - 64,000	1.0 - 15	30 - 460	60 - 860	3.0 - 46	1.8 - 19	20 - 300	18 - 229	0.04 - 0.51	90 - 1,060	0.4 - 9.6
Wet-weather Treatment Facility	0.06 - 0.69	1,800 - 4,100	18,000 - 51,000	-	-	-	-	80 - 260	50 - 121	1,000 - 6,300	300 - 1,590	0.8 - 2.9	2,100 - 5,400	10 - 35
Bridges	-	120 - 260	39,000 – 61,000	0.0 - 35,000	-	-	-	-	-	32 - 60	-	-	180 - 370	-
Atmospheric Deposition	-	-	-	-	260 - 330	4,500 - 11,600	2,900 - 15,600	-	240 - 300	6,100 - 7,400	3,900 - 5,500	6.3 - 8.9	35,000 - 44,000	-
Antifouling Paint	-	-	-	-	-	-	-	-	-	100,000 - 300,000	-	-	-	-
Treated Pilings	-	-	-	-	50,000 - 340,000	-	-	-	-	-	-	-	-	-

Table F-2 Lake Union/Ship Canal Area-Weighted Annual Loading Estimates.

Pathway	Fecal Coliform (trillion CFU/km2)	TSS (kg/km2)	Total Phosphorus (g/km2)	Total Nitrogen (g/km2)	Total PAHs (g/km2)	Total PCBs (mg/km2)	Total PBDEs (mg/km2)	BEHP (g/km2)	Arsenic (g/km2)	Copper (g/km2)	Lead (g/km2)	Mercury (g/km2)	Zinc (g/km2)	BBP (g/km2)
Lake Washington	0.021 - 0.044	800 - 1,240	8,200 - 11,900	180,000 - 250,000	32 - 65	74 - 154	440 - 970	100 - 4,600	510 - 720	690 - 950	40 - 79	0.27 - 0.52	400 - 650	-
Stormwater	11 - 87	25,000 - 43,000	73,000 - 117,000	680,000 - 1,200,000	480 - 1,410	1,200 - 7,600	8,000 - 21,400	800 - 1,500	760 - 1,190	7,600 - 11,500	7,100 - 12,000	3.0 - 29	38,000 - 58,000	100 - 150
Local Tributary	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KC CSOs	80 - 690	700 - 2,700	7,000 - 31,000	37,000 - 168,000	8.0 - 39	240 - 1,210	460 - 2,270	25 - 120	14 - 50	190 - 790	140 - 600	0.32 - 1.34	700 - 2,800	3.0 - 25
Seattle CSOs	400 - 980	900 - 3,800	9,000 - 44,000	50,000 - 240,000	11 - 55	310 - 1,720	600 - 3,200	32 - 169	18 - 70	250 - 1,120	190 - 850	0.4 - 1.9	1,000 - 3,900	4.0 - 36
Wet-weather Treatment Facility	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bridges	0.035 – 0.36	800 – 1,700	1500 - 3200	0.0 – 250,000	-	39 - 160	30 – 1,900	-	19 – 31	210 - 380	140 – 680	-	1,200 – 2,300	4.3 – 9.1
Atmospheric Deposition	-	-	-	-	250 - 320	4,500 - 11,500	2,900 - 15,500	-	240 - 300	6,100 - 7,300	3,900 - 5,500	6.2 - 8.9	35,000 - 44,000	-
Antifouling Paint	-	-	-	-	-	-	-	-	-	700,000 - 1,400,000	-	-	-	-
Treated Pilings	-	-	-	-	230,000 - 1,470,000	-	-	-	-	-	-	-	-	-

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Appendix G: Comparison to 2015 USGS Green River Instantaneous Load Study

This appendix provides a brief comparison to the results of a USGS study that collected data between 2013 and 2015 (Conn et al., 2015). The study collected representative samples of water, suspended sediment, or bed sediment from a continuous stream gaging station during 28 periods of differing flow conditions. From this discrete data, combined with the continuous streamflow record, estimates of instantaneous sediment and chemical loads from the Green River to the Lower Duwamish Waterway were calculated. For most compounds, loads were higher during storms than during baseline conditions because of high streamflow and high chemical concentrations. The highest loads occurred during dam releases (periods when stored runoff from a prior storm is released from the Howard Hanson Dam into the upper Green River) because of the high river streamflow and high suspended-sediment concentration, even when chemical concentrations were lower than concentrations measured during storm events.

Generally, the load estimates in this report were similar magnitude to that of the baseflow and stormflow loads within the USGS study. The instantaneous loads associated with the releases from Howard Hanson dam for metals were about an order of magnitude greater than this study's upper bound estimates (Table G-1). Exceptions are for total PCBs and total PAHs where the USGS study estimates median instantaneous loads for dam release flows are within this loading report's 95 percent confidence interval range for loading from the Green River to the study area. This may be because concentrations of metals were typically higher during dam release than during base or storm flow, but the concentrations of PAHs and PCBs, as well as dioxins/furans, were not.

The USGS study did not scale the instantaneous loads upwards to an annual load. This would require an estimate of the temporal distribution of the three flow regimes.

Table G-1 USGS (Conn et al., 2015) instantaneous load estimates compared to estimates from this study.

Parameter	Units	Baseflow, median instantaneous load	Storm, median instantaneous load	Dam Release, median instantaneous load	Loading Report, 95% confidence interval of mean load[a]
Arsenic, Total	g/hr	85.3	223	1,420	85 - 140
Copper, Total	g/hr	79.1	421	4,800	190 – 520
Lead, Total	g/hr	11.7	160	1,050	70 – 160
Mercury, Total	g/hr	<0.305	<0.394	14.1	0.24 – 0.58
Zinc, Total	g/hr	<58.6	657	9,750	530 – 1,200
PCBs, Total	mg/hr	7.59	60.2	161	27 – 160
Dioxins/furans, Total	mg/hr	151	7,460	11,300	NA
LPAHs	g/hr	<0.868	<1.27	<5.17	NA
HPAHs	g/hr	<0.493	1.25	<2.90	NA
PAHs, Total	g/hr	<1.361	<2.52	<8.07	2.9 – 10.0

a. Back-calculated to hourly rate from estimated annual load.

References:

Conn, K.E., R.W. Black, A.M. Vanderpool-Kimura, J.R. Foreman, N.T. Peterson, C.A. Senter, and S.K. Sissel. 2015. Chemical concentrations and instantaneous loads, Green River to the Lower Duwamish Waterway near Seattle, Washington, 2013–15: U.S. Geological Survey Data Series 973, http://dx.doi.org/10.3133/ds973.