Modeling PCB Loadings Reduction Scenarios to the Lake Washington Watershed: Final Report

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King County

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Technical Advisory Panel Members (in alphabetical order) were:

- Fred Bergdolt, WA Dept. of Transportation
- Betsy Cooper, King County Wastewater Treatment Division
- Jonathan Frodge, Seattle Public Utilities
- Jenny Gaus, City of Kirkland
- Joan Hardy, WA Dept. of Health
- Rachel McCrea, WA Dept. of Ecology
- Doug Navetski, King County Water and Land Resources Division
- Andy Rheaume, City of Redmond
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EXECUTIVE SUMMARY

Washington Department of Health (WADOH) issued a fish consumption advisory on Lake Washington northern pikeminnow, cutthroat trout and yellow perch in 2006 because of human health risks from PCB contamination (WADOH 2004). Given concerns about how to address the advisory, in 2010, King County was awarded a U.S. Environmental Protection Agency (USEPA) Puget Sound Scientific Studies and Technical Investigations Assistance Grant to estimate loading of total polychlorinated biphenyls (tPCBs) and total polybrominated diphenylethers (tPBDEs) to Lake Washington, Lake Union, and Puget Sound. The grant also supported modeling the potential decrease in Lake Washington resident fish tissue concentrations associated with select PCB loading reduction scenarios. This report is the final product of the grant project, which synthesizes:

a) The field study components (King County 2013a),
b) Estimates of tPCB loadings to Lakes Washington and Union, and the subsequent load exported to Puget Sound by the Ship Canal (King County 2013b),
c) Modeling efforts to describe fate of tPCB loads in the lake and tPCB bioaccumulation in fish (King County 2013c), and
d) Load reduction scenario outcomes.

The project elements were developed in conjunction with the project's advisory panel. The findings include their collective recommendations for further technical and management actions. This report also presents recommendations for next steps to better understand PCB sources, pathways, and bioaccumulation in Lakes Washington and Union, and subsequent inputs to Puget Sound.

The project's field study component collected and analyzed 146 samples for PCBs and PBDEs from:

1) Ambient Lake Washington waters
2) Ambient Lake Union and Ship Canal waters

And also from the following six input pathways:

3) Three creeks during both base flow and storm conditions,
4) The Cedar and Sammamish Rivers,
5) Three combined sewer overflow (CSO) discharge locations,
6) Six municipal stormwater discharge locations,
7) Two combined wet and dry atmospheric deposition locations, and
8) One highway bridge stormwater discharge.

The major findings are as follows. tPCB loadings to Lake Washington were estimated at 672 g/yr which is more than the estimated 140 g/yr load exported from the lake outlet at the Montlake Cut. Therefore, Lake Washington serves as a partial sink (repository) for PCBs, primarily due to sediment accumulation and burial. Lake Washington PCBs are exported to Lake Union and the Ship Canal and they also volatilize from the lake surface. Of the estimated 2,023 g/yr tPBDE load to the lake, only 800 g/yr exits at the Montlake Cut to Lake Union and the Ship Canal, thus Lake Washington acts as a sink for PBDEs as well.

Lake Union and Ship Canal tPCB and tPBDE loads increase from the outlet of Lake Washington at the Montlake Cut to Puget Sound, partially due to loads from the combined sewer/stormwater system in Seattle. CSO discharges are estimated to contribute more tPCBs and tPBDEs to Lake Union and the Ship Canal than to Lake Washington. Average tPCB loading from the Ship Canal's Hiram M. Chittenden Locks to Puget Sound was estimated at 360 g/yr. Normalized to watershed area, 360 g/yr equals 6.27×10^{-4} $g/km^2/day$ which is comparable to other published urban watershed rates, but higher than rural Puget Sound watershed rates. Average tPBDE loading from the Ship Canal's Hiram M. Chittenden Locks to Puget Sound was estimated at 990 g/yr tPBDEs. Based on fate modeling of instantaneous tPCB load reductions, the largest changes in Lake Washington sediment and water concentrations would occur within 20 years; up to 40 years is required to reach equilibrium. While 20 to 40 years is a long time, in the absence of substantial watershed-wide efforts to reduce tPCB loads, the existing fish consumption advisory is projected to remain indefinitely.

Despite a ban on the production and many uses of PCBs in the late 1970s, food web bioaccumulation modeling predicts that approximately an additional 85 percent reduction in tPCB loading is required to reduce Lake Washington fish tissue concentrations and remove the existing WADOH fish consumption advisory. To progress toward reductions of this magnitude we recommend:

- Trace and identify ongoing PCB sources in current and historically used materials.
- Developing a state-wide and/or regional PCB inventory to enable targeted source control actions,
- Conduct outreach and engage decision-makers and the community in discussion about the widespread sources of PCBs, and the financial and regulatory challenges inherent in controlling such sources,
- Evaluate the effectiveness of treatment technologies and best management practices for PCB removal, and
- Develop bulk deposition/washoff models to determine contribution of atmospheric PCB deposition to stormwater runoff.

1.0. INTRODUCTION

Washington Department of Health issued a fish consumption advisory on northern pikeminnow, cutthroat trout and yellow perch in 2006 because of human health risks from PCB contamination (WADOH 2004). In addition, a similarly persistent and more modern chemical, polybrominated diphenyl ethers (PBDEs) is also bioaccumulating in Lake Washington fish (King County unpublished data). Elevated concentrations of PCBs and PBDEs are not unique to Lake Washington, as evidenced by chemical concentrations measured in marine mammal and fish tissue from Puget Sound (Ross et al. 2000, Ross et al. 2004, Krahn et al. 2007, West et al. 2008, Sloan et al. 2010, Cullon et al. 2005). However, to date there have not been any studies focused on how these chemicals are getting into Lake Washington fish or the quantity of these chemicals entering Lake Washington, Lake Union and the Ship Canal (Lake Union), and Puget Sound from this watershed. Therefore, primary goals of this project are to help fill PCB and PBDE data gaps for the Lake Washington watershed and Puget Sound basin and provide information and tools needed to direct management of PCBs and reduce health risks associated with Lake Washington fish consumption.

In 2010, King County was awarded a U.S. Environmental Protection Agency (USEPA) Puget Sound Scientific Studies and Technical Investigations Assistance Grant to (1) estimate loading of total polychlorinated biphenyls (tPCBs) and total polybrominated diphenylethers (tPBDEs) to Lake Washington, Lake Union and Puget Sound, and (2) model the potential decrease in Lake Washington fish tissue concentrations associated with select PCB loading reduction scenarios. tPCBs were the focus of the modeling because Lake Washington's carp and northern pikeminnow are currently unsafe to eat in any amount and cutthroat trout or large yellow perch are only safe in limited amounts (WADOH 2004). While smallmouth bass are not part of the Washington Department of Health (WADOH) advisory (2004), they have since been found (King County 2013e) to have similar tPCB concentrations to those in northern pikeminnow.

Understanding the root causes of the high PCB levels in fish is critical to attaining safe tissue concentrations. tPCBs were not modeled in Lake Union due to a lack of resident fish tissue data for Lake Union. tPBDEs were also not modeled because they are not part of the existing Lake Washington fish consumption advisory and information about their concentrations in invertebrates and prey fish was lacking.

To focus the field and modeling efforts, three management questions were developed:

1) Which types of import pathways are the highest priorities for tPCB/tPBDE loading reduction?
2) How will potential loading reductions from these pathways reduce the magnitude of resident fish tissue PCB concentrations and the need for a fish consumption advisory on Lake Washington?
3) How long might the system take to respond to these hypothetical tPCB loading reductions?

This report is the final product of the grant project which synthesizes:

a) The field study components (King County 2013a),
b) Loading estimates to Lakes Washington and Union, and the load exported to Puget Sound by the Ship Canal (King County 2013b),
c) Modeling efforts describing the fate of PCB loads in the lake and PCB bioaccumulation in resident Lake Washington fish (King County 2013c), and
d) Load reduction scenario outcomes, Section 2.5 of this report.

The project elements were developed in conjunction with the project's advisory panel. The findings include their collective recommendations for further technical and management actions.

This project collected the first extensive measurements of low level tPCB and tPBDE concentrations in whole water from Lake Washington and the Ship Canal, as well as in a variety of other water input pathways (King County 2013a). The pathways included wet and dry bulk atmospheric deposition (dust and rainfall) because PCBs and PBDEs are semi-volatile compounds which may seasonally cycle between soils, water, and the atmosphere (Hornbuckle et al. 1994, Kaya et al. 2012). The tPCB and tPBDE water and deposition data were then used to estimate contaminant loadings to Lakes Washington and Union and subsequently from the majority of the (WRIA 8) watershed to Puget Sound via the Hiram M. Chittenden Locks. Loadings estimates are presented in a separate report (King County 2013b) that addressed the first management question above.

Historical and project PCB data (King County 2013a) were then used to develop fate and bioaccumulation models for Lake Washington (King County 2013c). In combination with the loadings information, these models were used to inform priority loading reduction pathways and estimate the length of time the Lake Washington ecosystem might take to respond to changes in tPCB loadings.

This final report concludes with a description of the magnitude of loading reductions needed to achieve safe fish tissue levels. Suggestions and recommendations are also provided for next steps to better understand PCB sources, pathways, and bioaccumulation in Lakes Washington and Union, and subsequent inputs to Puget Sound. These include actions that may be used to reduce PCB loads to Lake Washington from the watershed.

2.0. PROJECT FINDINGS

The project consisted of four components: a field study, loadings analysis, fate and bioaccumulation modeling, and load reduction tissue recovery scenarios. Details of the first three components are provided in prior reports (King County 2013a, b, c) and are summarized below. A detailed description of the scenarios examined to reduce fish tissue concentrations is also presented in this section.

2.1 Field Study

This project collected and analyzed samples from lake receiving waters and six different lake input pathway types to support development of mass loadings estimates of tPCBs and tPBDEs to Lakes Washington and Union, and subsequently to Puget Sound from the majority of the greater Cedar-Sammamish Lake Washington Water Resource Inventory Area (WRIA 8). The receiving waters evaluated included: (1) Lake Washington and (2) Lake Union and the Ship Canal. The input pathways included: (1) three creeks in the watershed; samples were collected during both base flow and storm conditions; (2) the Cedar and Sammamish Rivers; (3) three combined sewer overflow (CSO) locations; (4) six stormwater discharge locations; (5) highway bridge runoff; and (6) combined wet and dry atmospheric deposition. A total of 146 samples were collected and analyzed for PCB and PBDE congeners and select conventional parameters. Whole water samples (which included bulk air deposition) were successfully collected according to the study design specified in the Quality Assurance Project Plan (QAPP) (King County 2011a) with a few modifications (King County 2013a). An overview of the sampling locations by type is provided in Figure 1.

Some of the anticipated data quality objectives of precision for PCB and PBDE congeners[1] were not met as outlined in the QAPP. Particularly low reproducibility occurred in ambient lake and river waters: Lake Washington, the Ship Canal, and the Cedar and Sammamish rivers. This study was unable to reliably measure these low to moderate tPBDE concentrations in regional ambient lake and river samples because of background laboratory contamination and the overall ubiquity of PBDEs.

[1] There are 209 unique PCB and 209 unique PBDE congeners. Each has slightly different chemical properties based on their specific formula and shape. This project analyzed all PCB congeners, but results are expressed as a sum (total). The project only analyzed the most common nine PBDE congeners and reported their totals.

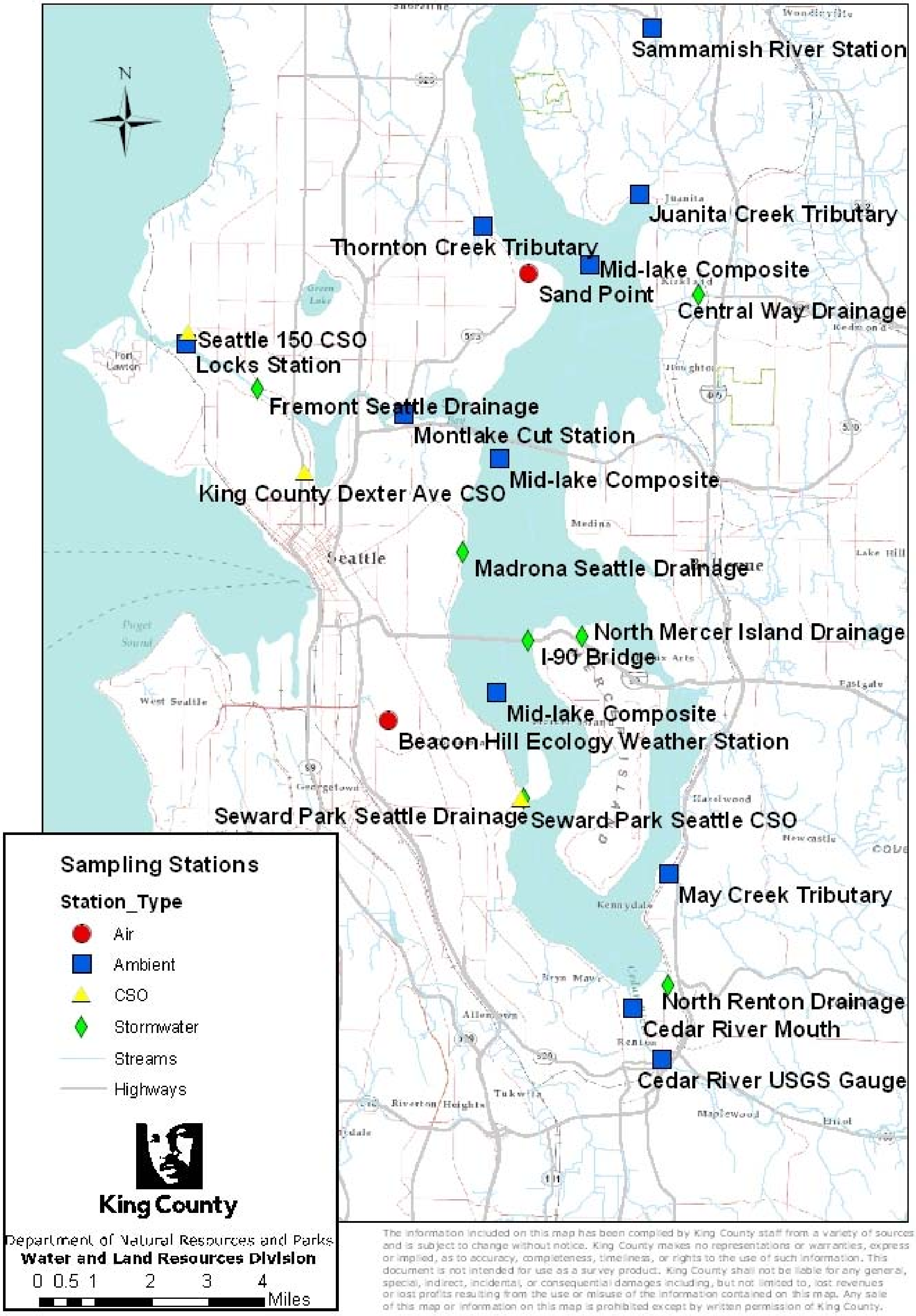


Figure 1. Field study sampling stations.

tPCB and tPBDE concentrations detected in Lake Washington and river samples were the lowest of all samples measured. This was expected given that particle-associated contaminants like PCBs and PBDEs are provided a long settling time in the lake and the large surface area of the lake provides an additional loss pathway for these contaminants through volatilization. Thus, detected tPCB concentrations in Lake Washington ranged from 36 to 415 pg/L and from 32 to 1,572 pg/L for tPBDEs. When data collected from Lake Washington and the two Ship Canal stations are compared, the highest detected tPCB concentrations were at the Ballard Locks station (up to 583 pg/L) indicating inputs into Lake Union/Ship Canal represent a substantial contribution of tPCBs. tPBDE concentrations in Lakes Washington and Union and the Ship Canal were often too close to method blank concentrations to reliably measure (i.e., they were not detected); however, the three highest measurements were also detected at the Ballard Locks and Montlake Cut locations (up to 2,148 pg/L). Compared to other input pathways and the lake itself, tPCB and tPBDE concentrations in the Cedar and Sammamish Rivers were both relatively low. The tPCBs in the Cedar and Sammamish rivers ranged from 10 to 267 pg/L, while tPBDEs ranged from 3 to 3,150 pg/L. These levels are similar to tPCB and tPBDE concentrations measured by Herrera Environmental Consultants (2011a) in forested, agricultural, and residential tributaries to the Snohomish and Puyallup Rivers, which are also in Western Washington. Compared to the current study, tPCBs were higher during storm events in the commercial/industrial tributaries sampled by Herrera (2011a); however, this was not the case for tPBDEs.

tPCB and tPBDE concentrations measured in major creeks differed by location, with Thornton Creek exhibiting the highest concentrations, up to 10,527 pg/L tPCBs and 20,910 pg/L tPBDEs during storms. As expected, tPCB and tPBDE concentrations were lower in creeks during base flow conditions (minima of 105 and 59 pg/L, respectively). tPCB and tPBDE concentrations varied widely in stormwater and highway runoff. The highest tPCB concentration was observed in the Fremont stormwater (165,685 pg/L), while the second highest concentration was detected in the highway bridge runoff (16,133 pg/L). tPBDE concentrations in stormwater runoff were similar between Seattle discharges (Madrona, Seward Park and Fremont Drainages), while smaller city discharges (Kirkland, Mercer Island and Renton) exhibited more variability, but were generally lower than those in Seattle.

The highest tPCB and tPBDE concentrations detected at CSO locations were always observed at the Dexter CSO (up to 565,108 and 212,174 pg/L, respectively). For both tPCBs and tPBDEs, the Seward Park CSO had the lowest reported concentrations (minima of 2,301 and 6,703 pg/L for tPCBs and tPBDEs, respectively), while concentrations at the Ballard 150 CSO were intermediate. The average tPBDE concentration for all CSOs was 82,898 pg/L (N=8), while the average CSO tPCB concentration (101,426 pg/L, N=8) was an order of magnitude higher than the average tPCB concentration of any other aqueous input pathway. The high variability of CSO tPCB concentrations generated significant uncertainty around this arithmetic average concentration. Because an arithmetic average CSO tPCB concentration was required for modeling and loadings estimates, additional data (45 samples) collected from CSOs in the Lower Duwamish River Basin Waterway were included to enhance the reliability of the estimated concentration. The 53 sample combined dataset had a more reliable arithmetic average of 70,543 pg/L, lower than this project's CSO average, but still much higher than any other measured input pathway's average concentration. Figures 2 and 3 below summarize the average tPCB and tPBDE water concentrations found in the field component of the project.

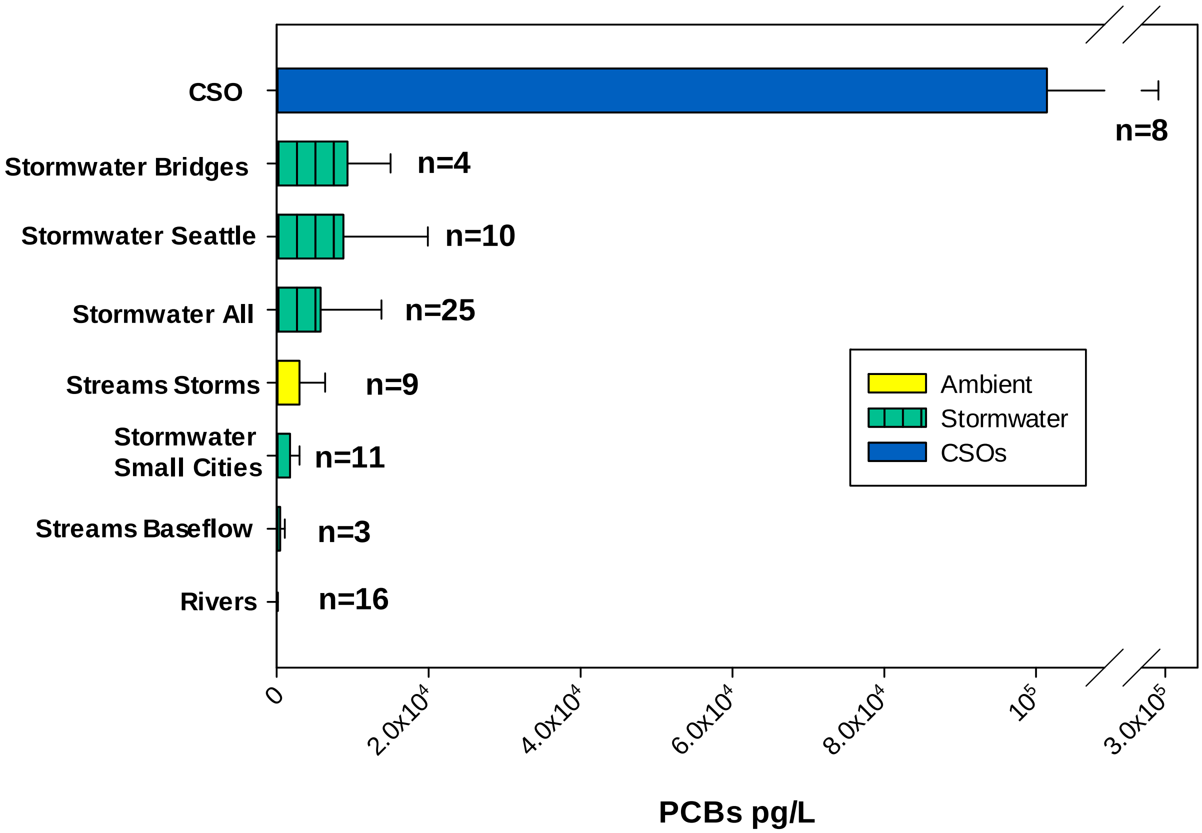


Figure 2. **tPCB average and standard deviation concentrations in major water pathways. Stormwater All is the average and standard deviation of Seattle, small city, and bridge runoff measurements.**

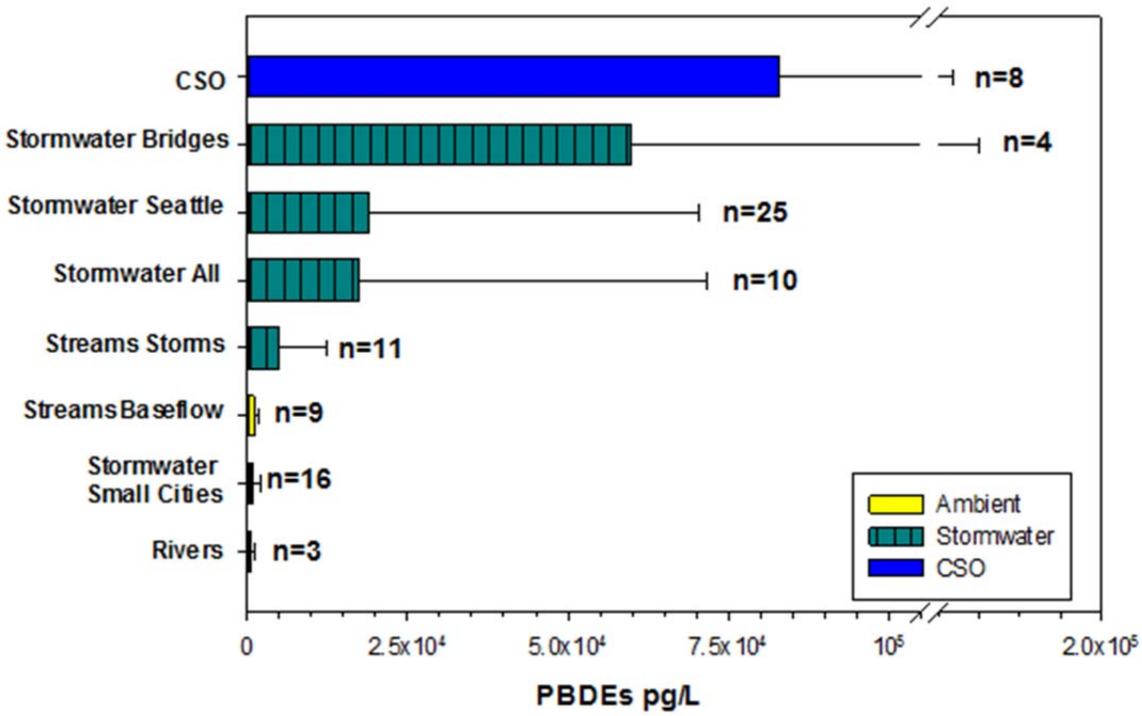


Figure 3. tPBDE average and standard deviation concentrations in major water pathways. Stormwater All is the average and standard deviation of Seattle, small city and bridge runoff measurements.

Of the two air deposition sampling locations, air deposition rates for Beacon Hill were consistently higher than Sand Point. However, the difference in tPCB deposition rates between sites is generally within a factor of two. tPBDE deposition rates were about four times higher at Beacon Hill than Sand Point. Average tPCB deposition rates were 3.4 ng/m^2/d, while average tPBDE deposition rates were 18.1 ng/m^2/d.

This project's data provide the first extensive measurements of low-level tPCB and tPBDE concentrations in whole water from Lake Washington and the Lake Union/Ship Canal, as well as from the river, creek, stormwater, bulk deposition, CSO, and highway runoff pathways to Lake Washington. These data were used in the loadings analysis and modeling phases of the project (King County 2013b, c), which are summarized below.

2.2 tPCB Loadings Estimates

Following completion of the field study, contaminant loading pathways to Lakes Washington and Union were developed by combining contaminant concentration data with long-term flow estimates. tPCB and tPBDE mass loading estimates to Lake Washington and Lake Union/Ship Canal as well as the contaminant export to Puget Sound were developed. Details of the tPCB and tPBDE loading calculation approach and resulting estimates are presented in a previous report (King County 2013b). tPCB findings are highlighted below as the project used these loading estimates to develop fate and bioaccumulation models.

Approximately 70 percent of the tPCB load to Lake Washington comes from local tributary watersheds around the lake and their stormwater runoff. The three sampled creeks (Thornton, Juanita and May) represent a range in the type and intensity of development and land use. Among these creeks, the Thornton Creek's basin had the highest amount of commercial/industrial development that occurred prior to the ban on PCB manufacture and use limitations in the late 1970s. This basin had the highest estimated tPCB mean loading of 56 g/yr (2.0 g/km^2/yr). The May Creek basin had the lowest amount of pre-1979 commercial/industrial development and also the lowest estimated tPCB mean loading of 23 g/yr (0.66 g/km^2/yr). The Juanita Creek basin had an intermediate amount of pre-1979 commercial/industrial development and an estimated tPCB mean loading of 17 g/yr (0.93 g/km^2/yr), which falls between the areal estimates for Thornton and May creeks. These loading estimates and additional correlation analyses (King County 2013b) suggest that the predominant source of tPCBs to Lake Washington is stormwater runoff from developed areas – possibly linked to pre-1979 commercial/industrial development. These results are consistent with the conceptual model of tPCB sources and pathways emerging from other studies (Belton et al. 2007, Diamond et al. 2010, Rodenburg and Meng 2013) that suggest PCB sources are concentrated in urban centers containing older commercial and industrial buildings where transformers, light ballasts, paints, caulks, and sealants were used. Therefore, extrapolation of the sampled drainages to tributaries without concentration or flow monitoring was done based on their percentage of pre-1979 industrial/commercial land use and rainfall. This produced an estimated total local drainage load of 450 g/yr (1.2 g/km^2/yr) (King County 2013b).

Loading estimates for the two major rivers to Lake Washington (Cedar and Sammamish) suggest tPCB loads of 56 and 41 g/yr, respectively (97 g/yr combined). These are somewhat lower than the tributary load, although there is a high degree of uncertainty in these estimates due to the low reported tPCB concentrations in rivers; concentrations were close to those detected in method blanks. The contribution of atmospheric deposition to the surface of Lake Washington was also estimated to be relatively significant for tPCBs (110 g/yr) representing 14 percent of the total load to the lake.

Despite having the highest measured concentrations, CSOs and highway bridge runoff contributed relatively little to the overall tPCB loads to Lake Washington, 12 and 2.9 g/yr respectively. Together these pathways contribute approximately 2.2 percent of the tPCB annual load to Lake Washington (14.9 g/yr). These loadings were relatively small, despite their high concentrations, due to their small contributing volumes.

Estimated average tPCB loading of 672 g/yr to Lake Washington is greater than the estimated load exported from the lake outlet (140 g/yr). This is because the lake acts as a partial sink for PCBs, primarily as the result of sediment accumulation and burial. PCBs are also lost from the lake surface by volatilization back into the atmosphere.

tPCB concentrations, and hence loading, increase from the outlet of Lake Washington to the outlet of Lake Union/Ship Canal to Puget Sound. This is partially due to CSOs which discharge a larger mass of PCBs to Lake Union and the Ship Canal (58 g/yr) than to Lake Washington (12 g/yr). The average tPCB loading estimate from Lake Union and the Ship Canal to Puget Sound was 360 g/yr.

The 360 g/yr loading rate from the Ship Canal's Hiram M. Chittenden Locks to Puget Sound represents about 4.5 percent of the median total load of PCBs to the entire Puget Sound as summarized by Norton et al. (2011). Gries and Sloan (2009) estimated tPCB loads to the Duwamish River from the Green River using seven suspended particulate samples. They estimated that 0.6 to 1.21 g/day tPCBs enter the Duwamish River from the Green River (at the confluence with the Black River in Tukwila). Their flow rating analysis suggests this would result in the discharge of 153.3 to 2,263 g/yr tPCBs from the Green River into the Duwamish Waterway. These loadings are within a similar range and bound those estimated in this study. However, Gries and Sloan's (2009) study may underestimate loadings by excluding the dissolved fraction of PCBs. In comparison, the Lake Washington project based loadings estimates on whole water results at the Hiram M. Chittenden Locks. As with many field efforts, loading estimates from both studies are not directly comparable (e.g., different methods of estimating annual flow) and have substantial associated uncertainties such as limited sample sizes.

On an area basis, the Greater Lake Washington (Cedar-Sammamish) watershed is 1,572 km^2; therefore, the 360 g/yr loading rate to Puget Sound equals an area-normalized loading rate of 6.27×10^{-7} $kg/km^2/day$. This area loading rate is nearly an order of magnitude higher than the 7.39×10^{-8} $kg/km^2/day$ maximum rate calculated by Gries and Osterberg (2011) from five other Puget Sound watersheds: the Skagit, Snohomish, Nooksack, Stillaguamish, and Puyallup. However, these watersheds have relatively less pre-1979 development, have less urban area overall, and have more agricultural and forest land than the Greater Lake Washington watershed. Approximately 600,000 people live in the Greater Lake Washington watershed (US Census 2010), and PCB sources are part of the overall older infrastructure supporting these people - nearly 10 percent of the statewide population. Therefore, while the estimated loading rate from the Lake Washington watershed is the highest of the six watersheds, this is plausible.

The tPCB loading estimates documented in King County's loadings report (2013b) were the first estimates of PCB loadings in this major metropolitan watershed. A summary of the mean loads by pathway, along with their 25^{th} and 75^{th} percentile values, is provided in Table 1. These estimates were used in the fate and bioaccumulation models discussed below to simulate the response of Lake Washington fish tissue concentrations to reductions in tPCB loading.

Table 1. Average, 25th and 75th percentile tPCB loading rates for pathways to Lake Washington, Lake Union/Ship Canal, and to Puget Sound (g/yr).

Pathway	25th Percentile	Mean	75th Percentile
Local drainages and rivers to Lake Washington	190	450	620
Highway runoff to Lake Washington	1.7	2.9	4.1
CSOs to Lake Washington	4.9	12	12
Direct atmospheric deposition to Lake Washington	84[a]	110	140[a]
Totals to Lake Washington	333	672	889
Lake Washington to Lake Union/Ship Canal	73	140	140
Local drainages to Lake Union/Ship Canal	22	40	53
Highway runoff to Lake Union/Ship Canal	0.52	0.87	1.2
CSOs to Lake Union/Ship Canal	23	58	59
Direct atmospheric deposition to Lake Union/Ship Canal	3.6[a]	4.8	6.0[a]
Lake Union/Ship Canal to Puget Sound	190	360	540

[a] Minimum and maximum reported because only 2 locations were sampled.

2.3 tPBDE Loadings Estimates

Similar to the tPCB loads described above, tPBDE mass loading estimates to Lake Washington and Lake Union/Ship Canal were developed as well as the load exported to Puget Sound. tPBDE loadings were, in general, more uncertain than tPCB loading estimates. This was due to the analytical challenges in measuring low level PBDEs in rivers and Lake Washington. The estimates are likely biased low, because only nine of the most common PBDEs were quantified by the chosen method. Despite the analytical challenges and the more limited analyte list, overall PBDE loadings to Lake Washington were more than double tPCB loadings. Table 2 illustrates that the 25th to 75th percentile ranges of PBDE loading estimates span an order of magnitude for most pathways, whereas for tPCBs (Table 1) the 25th and 75th percentile loadings spanned less an order of magnitude for all pathways.

As with tPCBs, local drainages comprised the majority of the tPBDE load to Lake Washington (820 g/yr). Atmospheric deposition to the lake surface also contributed a relatively large mass. As is the case for tPCBs, a portion of the tPBDE loadings are sequestered in sediments or volatilize from the surface of Lake Washington. Of the 2,023 g/yr tPBDE load to the lake, only 800 g/yr exits at the Montlake Cut to Lake Union and the Ship Canal. This is augmented by CSOs, local drainages and atmospheric deposition to 990 g/yr tPBDEs that are exported to Puget Sound via the Hiram H. Chittenden Locks.

Table 2. Average, 25th and 75th percentile tPBDE loading rates for pathways to Lake Washington, Lake Union/Ship Canal, and to Puget Sound (g/yr).

Pathway	25th Percentile	Mean	75th Percentile
Local drainages and rivers to Lake Washington	200	820	1,200
Highway runoff to Lake Washington	1.3	19	19
CSOs to Lake Washington	3.3	14	26
Direct atmospheric deposition to Lake Washington	190[a]	590	980[a]
Totals to Lake Washington	416	2,023	2,755
Lake Washington to Lake Union/Ship Canal	330	800	940
Local drainages to Lake Union/Ship Canal	28	69	95
Highway runoff to Lake Union/Ship Canal	0.39	5.6	5.8
CSOs to Lake Union/Ship Canal	16	68	120
Direct atmospheric deposition to Lake Union/Ship Canal	8.3[a]	25	42[a]
Lake Union/Ship Canal to Puget Sound	280	990	1,400

[a] Minimum and maximum reported because only 2 locations were sampled.

2.4 Lake Washington PCB Fate model

The fate model was originally developed by Gobas et al. (1995) and has been applied to Lake Ontario, San Francisco Bay and Puget Sound (Gobas et al. 1995, Davis 2004, Pelletier and Mohamedali 2009). It incorporates multiple processes including partitioning to particulates and organic carbon, Lake Washington-specific sedimentation rates, and volatilization from the lake surface. Both the fate and bioaccumulation models use the physical/chemical parameters of PCB-118 as a surrogate for the range of PCB chemical properties across all congeners. The chemical characteristics of other congeners within the range of the PCBs most commonly found in Lake Washington fish tissue were examined in the sensitivity sections of the fate model (King County 2013c).

The fate and bioaccumulation models for Lake Washington were developed to reliably forecast the recovery of fish from PCB contamination under hypothetical management scenarios. The first modeling objective was to develop a quantitative understanding of the long-term fate of PCBs in Lake Washington. The second objective was to provide quantitative estimates of the time and magnitude of the response of lake water, sediment and fish tissue to reductions in PCB loading. These two modeling objectives address overall project study questions 2 and 3 described in Section 1.0 above.

Although the fate model is a simple, two-compartment box model, it performed well when tested against observed water and sediment concentrations. The predicted equilibrium water tPCB concentration (95 pg/L) closely matches the 92 pg/L volume-weighted best estimate of current concentrations in Lake Washington. The predicted equilibrium sediment tPCB concentration (18 µg/kg dry) was approximately one-third the mean observed concentration based on observed data (55 µg/kg dry, N= 69). However, the mean observed sediment tPCB concentration is suspected to be biased high due to non-random study designs (King County 2013c). Many sediment samples were collected from greater than 3 cm deep (e.g., 0-10 cm grabs), which reflect older, more contaminated sediment as described in USGS and Ecology (Ecology 2010) sediment cores. Thus, the model-predicted sediment concentration may be closer to the true mean sediment concentration than indicated by comparisons to available data. The fate model estimates about 98 percent of the total tPCB mass resides in the surface sediment compartment; examining all compartments, biota are a small (~4 percent) reservoir for PCBs (King County 2013c).

The Lake Washington import and export loadings estimates indicate that Lake Washington is a partial sink for PCBs; the export load is smaller than the total import load. The fate model demonstrated that sediment burial (44%) is the dominant loss pathway of PCBs from Lake Washington, followed by volatilization (24%). Loss by outflow (16%) and degradation (9%) are less important pathways. The remaining seven percent of tPCB mass remains in Lake Washington's water.

According to model testing, the response time for Lake Washington sediment and water concentrations to reach equilibrium under a constant loading is approximately 40 years; however, the most rapid changes occur for water and within the first 20 years. Sensitivity analysis of the fate model found it to be very sensitive to the logarithm of the octanol-water partition coefficient (log K_{ow})[2] and PCB loads. When these inputs were varied in the uncertainty analysis independently and together, it was determined that tPCB loading estimates contributed much more uncertainty than log K_{ow}. However, fate model uncertainty remained within the range of estimated uncertainty in observed water and sediment concentrations. Therefore, uncertainty in the fate model-predicted water and sediment concentrations is less than uncertainty associated with observed water and sediment data.

2.5 Lake Washington PCB Bioaccumulation model

The bioaccumulation model (King County 2013c) was originally developed by Gobas et al. (1995), Arnot and Gobas (2004), and adapted for use in San Francisco Bay (Gobas and Arnot 2005), and the Strait of Georgia (Condon 2007). Further adaptations allowed modeling contaminant bioaccumulation in select Puget Sound biota (Pelletier and Mohamedali 2009). Both the fate and bioaccumulation models selected for Lake Washington have demonstrated histories of utility and success.

Bioaccumulation model testing used best estimates of water and sediment tPCB concentrations from observed data as well as the water and sediment concentrations which were generated by the fate model with 672 g/yr tPCB load to Lake Washington.

[2] The octanol-water partitioning coefficient is a unitless measure of a chemical's hydrophobicity.

Bioaccumulation model output tissue concentrations were then compared to observed tissue concentrations. The bioaccumulation model-predicted tissue concentrations matched observed concentrations better when the fate model output sediment concentration was used as an input (18 µg/Kg dry) rather than observed sediment data (55 µg/Kg dry).

Testing indicated the model performed adequately and similarly to applications of this model in Puget Sound, Georgia Basin and San Francisco Bay (Gobas and Arnot 2005, Condon 2007, Pelletier and Mohamedali 2009) with a bias[3] of 1.2, i.e., the model over-predicts Lake Washington tissue concentrations by 20 percent (King County 2013c). Similar to the fate model, the bioaccumulation model is highly sensitive to log K_{ow}. This means that the fish tissue concentrations predicted by the bioaccumulation model can change significantly with the value selected for the log K_{ow}. However, uncertainty analysis indicated that variability in the observed tissue data was greater than model uncertainty for several fish species including smallmouth bass, cutthroat trout and northern pikeminnow. These uncertainty results indicate there is more uncertainty in the observed fish tissue data than the model-predicted tissue concentrations for these species. For large yellow perch, uncertainty in the model-predicted concentrations was greater than the observed tissue data.

Although sediment concentrations are orders of magnitude higher than water concentrations, lower trophic level biota associated with water (e.g., daphnia, copepods) play an important role in the bioaccumulation of PCBs in upper trophic level fish of Lake Washington. The modeled species best matching observed tissue data were northern pikeminnow and smallmouth bass, two species of high concern in the WADOH (2004) consumption advisory. Modeled large yellow perch concentrations tended to overestimate the observed tissue data. The cause of this difference is unknown; however, yellow perch diets shift, becoming more piscivorous with age. To estimate yellow perch fish body burden more accurately would require additional data on Lake Washington yellow perch diets throughout their development and seasonally.

2.6 Load Reduction Tissue Recovery Scenarios

In the final project phase, the fate and bioaccumulation models were coupled to test tPCB loading reduction scenarios and inform water quality managers, stakeholders and others of the magnitude of change needed to reach PCB fish fillet concentrations that are safe for human consumption (defined as the WADOH unrestricted consumption screening level for PCBs). The load reduction scenarios did not include active cleanups of existing contaminated sediments (e.g., dredging, capping) or the exclusive reduction of any particular pathway/source.

The methods and results of these scenario model runs are presented below. To help understand how potential loading reductions will reduce fish tissue tPCB concentrations in

[3] Model bias is the geometric mean of the differences between observed and predicted tissue concentrations for each modeled species or taxon. Model bias above 1.0 indicates the model over-predicts tissue concentrations, while bias below 1.0 indicates under-prediction.

Lake Washington resident fish, the current estimated tPCB load of 672 g/yr was reduced by 10, 25 and 50 percent and each reduced total load was used as input to run the fate model. The resulting predicted steady-state sediment and water concentrations (Table 1) were then used as inputs to the bioaccumulation model. The predicted whole fish tissue concentrations were approximately proportional to the corresponding percent reduction in total tPCB load (Figure 2).

Table 3. Predicted steady state tPCB concentrations in Lake Washington water and sediment under selected load reduction scenarios.

tPCB Loading Reduction Scenario	Water (pg/L)	Sediment (µg/kg dw)
Base case (load = 0.672 kg yr-1/logKow = 6.65)	95	18
10% tPCB load reduction	85	17
25% tPCB load reduction	71	14
50% tPCB load reduction	47	9
Observed 25th and 75th-percentile concentrations	51 - 118	11 - 53

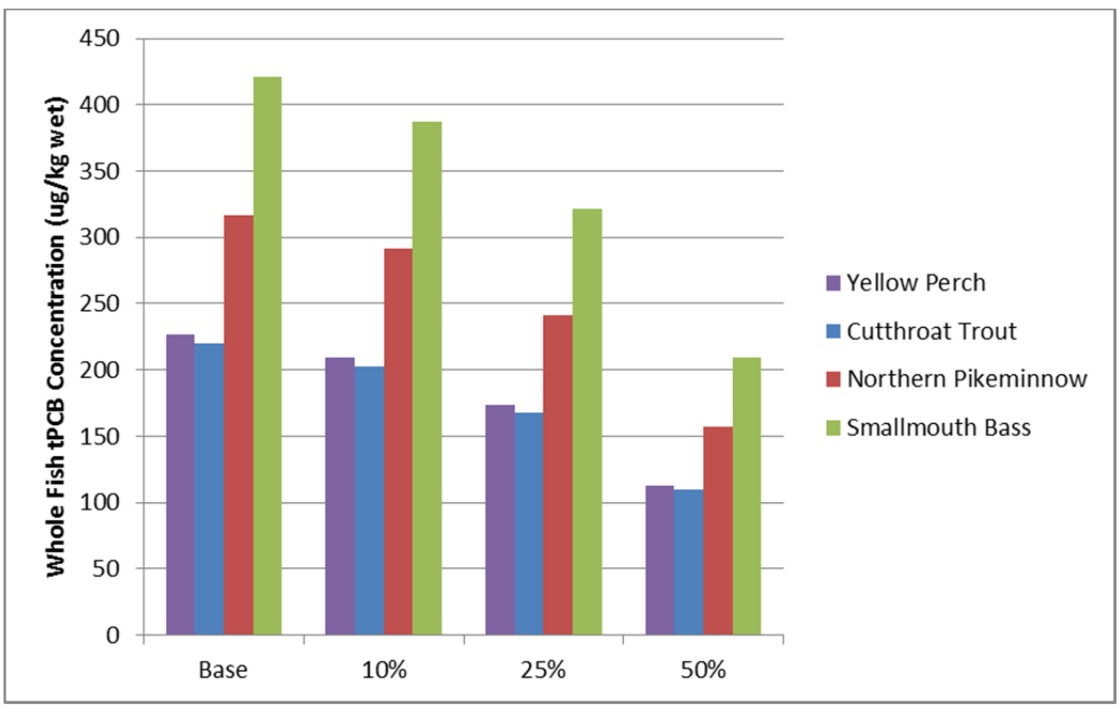


Figure 4. Predicted whole fish tissue concentrations with PCB load reductions.

The fate model-predicted response time to changes in the total tPCB load scenarios, suggests that the response of water concentrations is relatively quick, perhaps a year or two (Figure 5). However, the overall system response is limited by the sediments, which require about 20 years for the majority of change to occur and about 40 years to reach steady-state equilibrium with the reduced tPCB load (Figure 6). Relative to sediment, the typical response time of organisms to changes in PCB loads is very short (days) (Gobas and Arnot 2010).

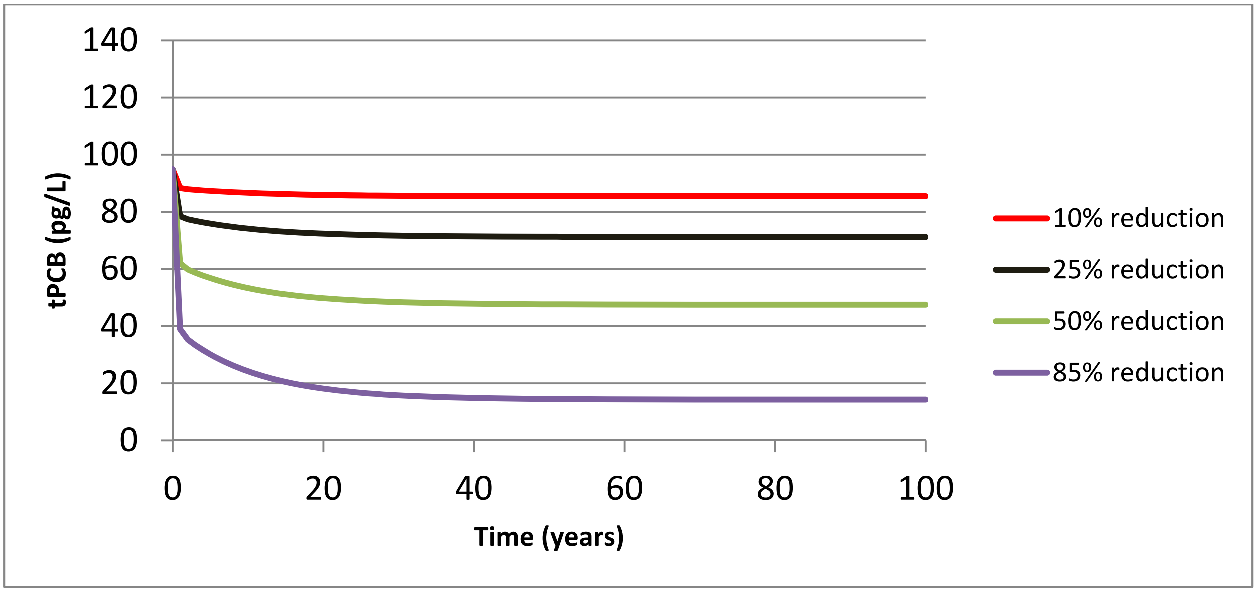


Figure 5. Predicted response of water column tPCB concentrations to 10, 25, 50, and 85 percent tPCB load reductions.

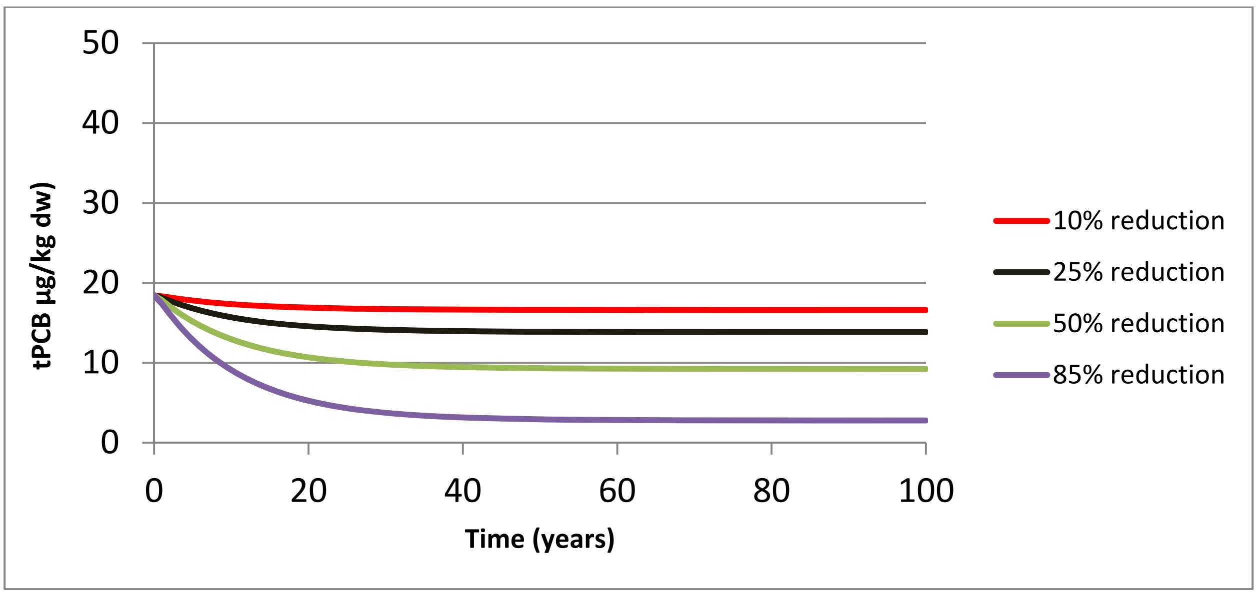


Figure 6. Predicted response of tPCB sediment concentrations to 10, 25, 50, and 85 percent tPCB load reductions.

To estimate the magnitude of change needed to reach safe tPCB levels in fish, the water and sediment concentrations used in the bioaccumulation model were decreased by 10, 25, 50, 80 and 90 percent, and the resulting predicted whole body tissue concentrations were converted to fillet concentrations for species included in the current Lake Washington fish consumption advisory: cutthroat trout, large yellow perch, northern pikeminnow as well as smallmouth bass. Fillet concentrations were then compared to WADOH human health screening concentrations (McBride unpublished memorandum). WADOH developed fillet tPCB screening concentrations to evaluate fish tissue data for possible restrictions on human consumption. These screening concentrations account for loss of PCBs by cooking and are based on mean concentrations in skin-on fillets (Table 3). The predicted tissue concentrations from the bioaccumulation model are based on whole fish. Thus, species-specific whole-to-fillet ratios based on DOH (2004) were used to convert the predicted whole tissue to fillet tissue concentrations.[4]

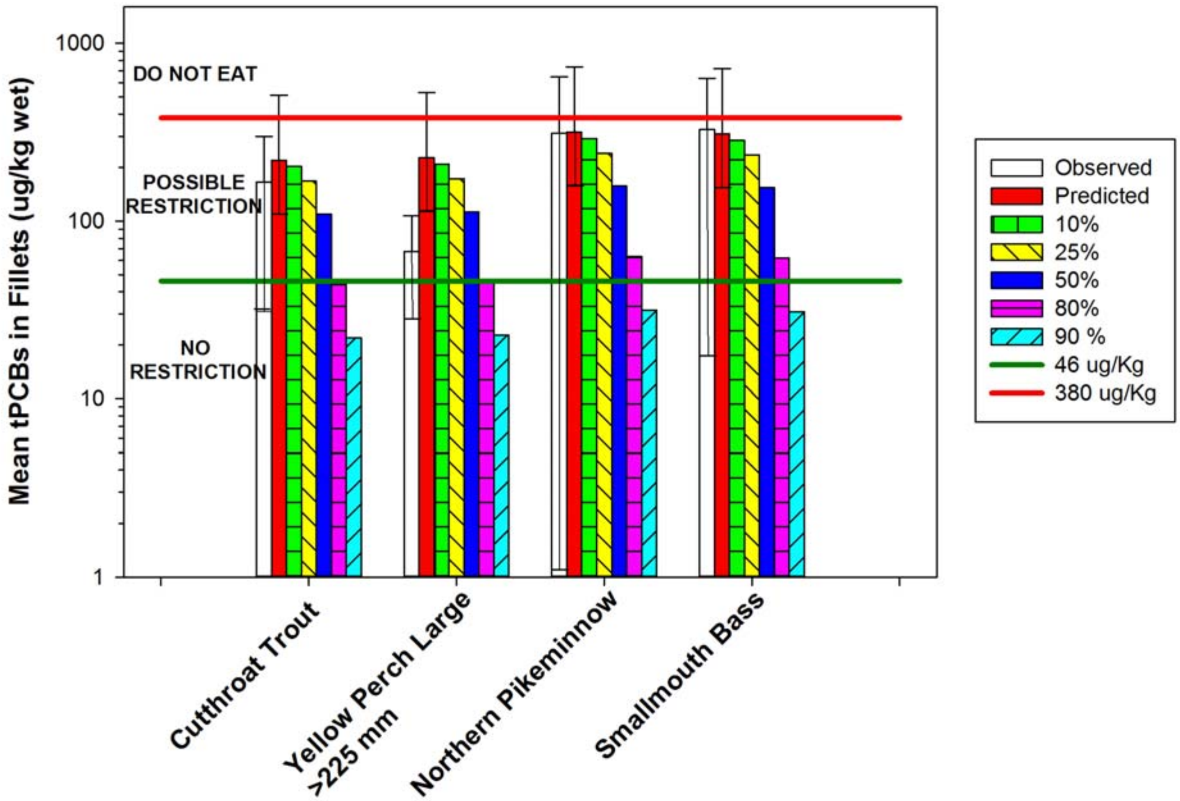
Table 4. WADOH fillet screening concentrations for tPCBs.

Consumption Restriction	Screening PCB Concentrations in Fillet (ug/kg wet)
No Restriction ("safe")	<46
Possible Restriction	46-380
Do Not Eat	>380

The comparison of predicted fillet tissue concentrations with WADOH screening levels indicates that substantial (approximately 85%) reductions in sediment and water concentrations are required to bring the average fish fillet concentrations of all four species to the "No Restriction" level (<46 ug/kg ww, Figure 7). The predicted tissue concentration in Figure 7 is based on the fate model-predicted sediment and water concentrations under a zero reduction assumption. Error bars were added on the observed and predicted mean for comparison and show variability can exist for some species in both actual tissue data and that predicted by the bioaccumulation model. For example, the standard deviation on the mean northern pikeminnow fillet concentration is orders of magnitude larger than the error on the predicted mean concentration (tissue concentrations based on low or 25th percentile and high or 75th percentile estimates of tPCB loads, see note in Figure 5).

It should be noted that this analysis is only useful as a general indication of the required magnitude of sediment and water concentrations reductions necessary, because in addition to uncertainties associated with the bioaccumulation model and observed tissue data, there are also uncertainties in the whole-to-fillet ratios and WADOH fish tissue screening levels. There is additional uncertainty associated with predicted concentrations in large yellow perch due to their overall poorer model fit, although their current tPCB concentrations are not as high as other species. Nevertheless, this analysis demonstrates that very large reductions in tPCB loads are needed to bring Lake Washington cutthroat trout, northern pikeminnow and smallmouth bass tissue concentrations down to levels that are safe for human consumption.

[4] Whole-to-fillet ratios of 0.5 were used for smallmouth bass, yellow perch and northern pikeminnow and 0.68 for cutthroat trout.



Error bars on Observed are standard deviations on the mean. Error bars on Predicted are tissue concentrations using low and high tPCB load estimates.

Figure 7. Predicted fillet concentrations of tPCBs under 10, 25, 50, 80, and 90 percent loading reduction scenarios compared to WADOH human health fillet screening concentrations.

3.0. NEXT STEPS AND RECOMMENDED ACTIONS

At the outset of this project, an advisory panel consisting of representatives from several jurisdictions and agencies was established to provide input on project design and execution, as well as brainstorm future actions and recommendations. Panel members were:

- Fred Bergdolt, WA Department of Transportation
- Betsy Cooper, King County Wastewater Treatment Division
- Jonathan Frodge, Seattle Public Utilities
- Jenny Gaus, City of Kirkland
- Joan Hardy, WA Department of Health
- Rachel McCrea, WA Department of Ecology
- Doug Navetski, King County Water and Land Resources
- Andy Rheaume, City of Redmond
- Ronald Straka, City of Renton
- Heather Trim, People for Puget Sound/FutureWise
- Bruce Tiffany, King County Wastewater Treatment Division
- Patrick Yamashita, City of Mercer Island

Throughout the three-year project, advisory panel members reviewed and critiqued the field study design, modeling framework and assumptions, and all project deliverables. Project team and advisory panel members also discussed the scenario results describing the ~85 percent reduction in tPCB loadings required to achieve fish tissue concentrations that are below the WADOH "No-Restriction" screening level. As part of this discussion, the advisory panel provided recommendations for next steps and actions, focusing on tPCBs. The following sections describe the collective recommendations of the panel. Many of these ideas address some form of PCB source control, although they may not meet the definitions of source control used in potentially applicable laws and regulations such as the Model Toxics Control Act (Chapter 70.105D RCW). Source control is seen as the ultimate solution to reducing PCB loadings to Lake Washington. However, source control is a slow process; therefore, additional actions are recommended that can also reduce PCB loadings to the Lake. Advisory panel members, other jurisdictions, businesses, and governmental and non-governmental organizations are encouraged to consider implementing one or more of these next steps throughout the region.

3.1 Update the Conceptual Model of PCBs in the Local Environment

Perhaps one of the most fundamental findings of this study is the pervasive and active nature of PCB sources throughout the watershed. Local tributaries to the lake are responsible for approximately 70 percent of the estimated 672 g annual loading to the lake (333 to 889 g/yr estimated range). In urban areas like Seattle and the surrounding metropolitan area, PCBs are not just legacy contaminants present in sediment. The emerging conceptual model for Lake Washington is similar to those developing in other urban areas such as San Francisco Bay (Tsai et al. 2002), Camden, NJ (Belton et al. 2007), Chicago (Rodenburg and Meng 2013) and Toronto, Canada (Robson et al. 2010). These models postulate, investigate, and describe an urban plume or dome of PCBs in and around cities; conceptually similar to the pollution plumes atmospheric scientists have described for heat, carbon dioxide, particulates, and other air pollutants (Huddart and Stott 2010). Urban areas are long known to trap heat, CO_2 and particulates beneath an inversion layer which may elongate downwind depending on prevailing winds (Munn 1976). PCBs also form an urban plume of air pollution as they volatilize from caulks (Robson, et al. 2010), paints, and older light ballasts, particularly those ballasts which fail (Guo et al. 2011). These gaseous PCBs can then precipitate onto particulates or surface films and get picked up in stormwater runoff or dissolve directly into rain or water bodies. PCBs can also wash directly into water bodies from flaking paint or from abraded joint caulks used in concrete surfaces (Ecology 2011, City of Tacoma 2013). PCBs, while ubiquitous in the urban environment appear to be concentrated in older (e.g., pre-1979) buildings and infrastructure. Previous studies suggest that residential buildings and structures older than 1945 and newer than 1980 are less commonly associated with PCB-containing building materials (Robson et al. 2010, Ecology 2011).

All of these processes are part of the emerging understanding that PCBs are not simply historical contaminants, but instead have numerous on-going, diffuse urban sources (Diamond et al. 2010). The size of the greater Lake Washington PCB plume is unknown, but Brandenberger et al. (2010) found that urban Puget Sound PCB deposition was more than three times higher than in rural areas.

This conceptual model of diffuse sources throughout the watershed, as opposed to distinct releases and point emissions, is consistent with findings of previous attempts to identify hot spots of PCB contamination in Lake Washington surface sediments (Era-Miller et al. 2010). To date, no PCB surface sediment hot spots have been found. This project focused on PCB transport pathways; future investigations will need to investigate these pathways to trace and identify PCB sources in current and historically used materials.

3.2 Source Control - Develop a PCB Inventory

The first step in source control is identifying where sources are located. Therefore, we recommend conducting an urban inventory of PCB stocks. Developing a list of currently used products and in-situ sources such as paints, caulks, ballasts, and contaminated sites with historical releases to soil, sediments and/or groundwater would emphasize and reinforce the cross-basin collaboration necessary by regional partners to identify the materials contributing PCBs to the region's environmental media.

As part of an inventory, a ranking of the relative mass and contributions from different sources is recommended. For instance, Robson et al. (2010) estimated that 13 metric tons of PCBs remain in building sealants in Toronto, a city with a population of 2.6 million. The Greater Seattle metropolitan area has 3.5 million residents. While this project is unable to account for differences in building age between Toronto and Seattle, scaling for population suggests that the Seattle region could have 17+ metric tons of PCBs in current use as sealants and caulks alone. Ecology (2011) estimated 850 g (0.00085 metric tons) of PCBs were currently in paint alone on 2,286 buildings constructed between 1950 and 1977 in the Diagonal Avenue South sub-basin of the Duwamish Waterway – an area of about 9,000 acres with a total of 27,000 buildings.

While conducting source tracing activities in the Lower Duwamish Waterway area, Ecology (2011) developed a partial inventory of PCB-containing building materials. However, getting property access and permission to sample was challenging; only 32 of the 92 contacted property owners agreed to composite sample collection (materials combined from multiple buildings). Ecology's (2011) inventory used composite sampling to allow individual property owners to remain anonymous. It is likely that liability concerns and the general lack of awareness regarding the widespread nature of PCB sources are significant barriers to creating a local, actionable inventory. Nevertheless,

3.2.1 Perform Regional Source Tracing Using Congener Data

Narrowing the list of buildings, sites, and products containing PCBs to a sub-basin level would also allow for development and testing of pilot projects in some of the most contaminated areas and/or on the more contaminated runoff. This project's dataset presents a rich opportunity for researchers to analyze PCB congener patterns and potentially match them to urban sources. Ecology recently funded a Spokane River Toxics Task Force project to analyze for PCBs in commonly used municipal products, such as paints, caulks and sealants, and results of this effort may be combined with efforts to link sources to loads in the Greater Lake Washington water and air sheds. Efforts to better understand and identify PCB sources in the Lake Washington water and air sheds would form the basis for future source control actions.

3.3 Conduct Outreach and Education

In addition to updating the conceptual model and developing an actionable inventory of PCB sources, an outreach and education strategy is needed to engage decision-makers and the community at large in a discussion of the financial and regulatory challenges facing efforts to reduce PCB loadings to Lake Washington and other waterbodies. These discussions have begun in the Lower Duwamish and Spokane River watersheds, but to date have yet to occur within the Lake Washington watershed.

PCBs present in building materials, whether associated with caulk, paints, or from spills of transformers or capacitors, are regulated by EPA and Ecology (EPA 2005, WAC 173-303-9904). The federal regulatory threshold for most products and wastes is 50 mg/kg;

transformer and capacitor waste (even when drained of PCB oils) is regulated above 2 mg/kg by Ecology (Model Toxics Control Act dangerous waste code WPCB, WAC 173-303-9904). These levels are orders of magnitude higher than PCB levels of concern in the environment. Lake Washington jurisdictions are encouraged to support efforts to reform federal regulations for PCB-containing materials remaining in use.

The degree to which suspect paint or caulks are tested prior to building demolition or renovation is unknown. Paints, caulks or spilled PCB-containing oils can also contaminate underlying/adjacent plaster, wood, masonry, and concrete. EPA (undated) has issued guidance for contractors; however, this is an emerging area of waste management. Knowledge of these requirements for both protection of water quality and worker health is unknown. Enhanced screening of buildings potentially containing PCB-laden caulks or paints is one strategy to further limit releases of PCBs from these materials. Given the reluctance of Lower Duwamish area property owners to consent to sampling their buildings' paints and caulks (Ecology 2011), financial or regulatory incentives to facilitate testing and safe PCB removal during demolition or renovations of 1950-1980 era industrial, commercial and institutional buildings and infrastructure may encourage wider testing and source control. For instance, building owners that voluntarily test their building materials for inventory purposes could receive an in-use grace period to allow them to gradually remove the paint, caulk, etc. while such materials discovered through other investigations (e.g., city or county stormwater source control studies) would require more urgent removal. These types of regulatory changes and approaches require broader community and legislative education and discussions.

While the timeframe necessary for Lake Washington fish tissue concentrations to substantively decline under a "no action" scenario is currently unknown, under any load reduction scenarios, at least 20 to 40 years are required to reach new equilibrium. Lake Washington surface sediment concentrations have declined substantially since their peak in the 1970s (Era-Miller et al. 2010) but the rate of decline as evidenced by sediment cores, has slowed over the past 2 decades. Based on the relatively constant surface sediment concentrations over the past two decades, current sediment and water concentrations are likely in rough equilibrium with current loadings. This plateau of sediment concentrations indicates that the current rate of PCB source removal such as building renovation and transformer replacement results in a slow to no decline in overall PCB loading. Continuing the status quo will result in the current fish advisory potentially remaining indefinitely.

Ecology's "Chemical Action Plan" (Ecology 2013) for PCBs is currently in preparation and presents an ideal opportunity to develop an education and outreach strategy aimed at overcoming the financial and regulatory challenges facing efforts to reduce PCB loadings.

3.4 Evaluate Effectiveness of Stormwater Treatment and LID Methods

To date, literature reviews have not found any studies testing the effectiveness of various technologies for treating PCB-contaminated stormwater runoff (Herrera 2011b). Several promising technologies have been and continue to be tested in the Lower Duwamish area (Kalmar 2010, Schmoyer 2012). Electro-coagulation and chitosan-enhanced sand filtration are two of these more intensive stormwater treatment technologies. These expensive treatment technologies are typically used in discrete wastewater and construction stormwater settings to address specific, contaminated sources or discharges. Funding such technologies on the scale necessary to reduce Lake Washington PCB loadings ~85 percent would be extremely challenging and to date it is unknown if they are effective at reducing modest (ng/L or less) PCB concentrations in water. The cost of stormwater runoff treatment needs to be evaluated at the basin scale to estimate the cost per mass of PCBs removed. This information should then be compared to the effectiveness of other PCB removal options (e.g., paint removal, conveyance pipe cleaning, etc.) to identify the best options to maximize the environmental benefit of limited public funds.

High efficiency-street sweeping to capture smaller particulates is a basic source control technique that has the potential to reduce loadings from impervious surfaces. Similarly, catch basin and stormwater conveyance pipe cleaning are other possible tools, which may reduce stormwater runoff loadings, particularly from historic sources. Both rely on bulk solids removal to potentially remove PCBs that have adhered to solids present on the street surface and within the conveyance system. The efficacy and cost-benefit of these strategies has also yet to be demonstrated for widespread use in western Washington urban watersheds or for PCBs. More extensive use of rapid and relatively low cost (<$100/sample) immunoassay analytical methods (EPA 1996) to screen PCB-contaminated materials including street dirt/solids is encouraged.

EPA, Ecology, and other regulatory agencies are moving toward low impact development (LID) as a preferred stormwater management tool (EPA et al. 2007, EPA 2013). However, recent reviews of LID technologies (Herrera 2011b, Taylor and Cardno 2013) have been unable to document the effectiveness of LID in reducing PCB loads. For instance, even though technologies like permeable pavements may reduce stormwater flows through infiltration, their PCB contaminant loads may remain trapped on surface particulates with some portion re-volatilizing later into the urban atmosphere and depositing elsewhere. Additional LID design considerations such as incorporation of specific soil amendments like biochar (charcoal) may enhance PCB retention in swales, bioretention facilities like rain gardens, or green roofs. Unfortunately, the efficacy of any specific amendment or design element is currently unknown, as LID stormwater management practices have not been evaluated for impacts on urban PCB cycling. Given the substantial interest in LID technology for stormwater flow control, volume reduction, and other contaminant removal (e.g., dissolved copper), understanding the efficacy and design requirements for PCB removal is necessary and timely.

3.5 Develop Airshed & Washoff Models

The current data suggest that bulk (wet and dry forms) aerial deposition is a significant contributor to stormwater loads; however, the degree to which bulk aerial deposition contributes to PCB stormwater loads from different land surfaces such as grass, pavement, or roofing is unknown. Furthermore, the relative contribution to Lake Washington air deposition from the Lower Duwamish Valley, an identified regional PCB hotspot, is unknown. Wind patterns are likely to carry PCBs volatilized from the Lower Duwamish water, sediments, and uplands towards Lake Washington’s watershed and may contribute to the regional air deposition that influences watershed loadings. The regional effects of future cleanups in the Lower Duwamish or elsewhere have not been estimated nor quantified.

Most PCB control studies have focused on tracing prominent PCB sources (Belton et al. 2007, Botts et al. 2007, Cargill 2008, KCIW and SPU 2005, Schmoyer 2007, King County, 2011). These types of investigations have focused on in-pipe stormwater system sampling and analysis to trace and identify PCB contributions from commercial or industrial sources. If one can be developed, a regional runoff or washoff model could be used to prioritize land uses or sub-basins for more rigorous source tracing sampling and analysis efforts such as these.

A washoff model would simulate the relationships between bulk aerial deposition and runoff from different surfaces and land uses. A washoff model is necessary to define the role of aerial deposition in stormwater contamination and extend the predictive capability of the bulk deposition data to different land surfaces or development types, which would help focus source control studies. For example, stormwater samples exceeding expected concentrations from bulk deposition alone could be the focus of additional source tracing efforts. Such an air-land-water model, whether statistical or mechanistic, would be multivariate as multiple factors such as particulates, temperature, rainfall and wind speed all correlate with bulk deposition data (King County 2013d). Further understanding of PCB volatilization and cycling from urban surfaces in Western Washington or a similar climate would be necessary to develop a useful, predictive washoff model. The development of simple relationships between bulk deposition and stormwater concentrations similar to the relationships tested in the regional drainage extrapolations (King County 2013b) would be a good first step toward developing a washoff model.

4.0. CONCLUSIONS

This project evaluated six major PCB and PBDE contaminant pathways to Lakes Washington, Union and the Ship Canal in Seattle, Washington to estimate loadings. The loadings were linked with a fate model and a bioaccumulation model to further understand how changes in loadings affect fish tissue concentrations of PCBs.

The most significant load to Lake Washington was from local drainage stormwaters (stormwater discharges and creek storm flows), which contribute approximately 67 percent of the annual tPCB load. Direct atmospheric deposition and rivers contribute approximately 14 percent of the annual tPCB load. Despite having the highest average measured concentrations by at least an order of magnitude, the overall loads from CSOs and highway bridge runoff combined were less than three percent of the estimated total tPCB loading. Combined, the six pathways are estimated to contribute approximately 672 g/yr of PCBs on average to Lake Washington (25^{th} percentile - 333 g/yr, 75^{th} percentile - 889 g/yr). Lake Washington out-flow accounts for 140 g/yr of PCBs entering Lake Union where it is augmented to 360 g/yr by CSOs, local stormwater drainages, and atmospheric deposition before discharging to Puget Sound. Much of the remaining load is buried in Lake Washington sediments or volatilized through the lake surface. Thus, Lake Washington acts as both a source and a sink for PCBs. Estimates of tPBDE loadings to Lakes Washington, Union and Puget Sound were completed, but considered more uncertain due to the challenges posed by measuring PBDEs in ambient waters at levels close to those in method blanks. The average total tPBDE load from all assessed pathways to Lake Washington is estimated to be 2,023 g/yr (25^{th} percentile – 416 g/yr, 75^{th} percentile – 2,755 g/yr).

Lake Washington biota bioaccumulate PCBs resulting in the current fish tissue concentrations which are some of the most contaminated in the state (WADOH 2004, Jack and Colton 2011). The bioaccumulation model indicates that a substantial reduction (~85%) in current PCB loads is necessary to reduce PCB body burdens in resident fish to safe levels (below public health fish consumption advisory limits) and eliminate the current fish consumption advisory (WADOH 2004). The fate and bioaccumulation models developed for this project predict a large ~80-85 percent reduction in PCB loadings is necessary to remove the current fish consumption advisory for northern pikeminnow, cutthroat trout, and yellow perch. Although not currently subject to the consumption advisory, an 85 percent reduction should also reduce PCB concentrations in smallmouth bass to below WADOH screening levels. Carp were not included in the modeling effort; additional data would be necessary to determine if an 85 percent PCB load reduction would result in tissue concentrations sufficient to remove the carp consumption advisory. Lake sediment and water concentrations would decline substantially within 20 years of reduced loadings. However, steady-state conditions between loadings, water, and sediment concentrations will theoretically take approximately 40 years to achieve. While 20 to 40 years is a long time, in the absence of substantial watershed-wide efforts to reduce tPCB loads, the existing fish consumption advisory is projected to remain indefinitely.

The project's advisory panel discussed a number of potential strategies to help target and eventually reduce overall PCB loadings. Supporting Washington State and regional partners in developing an urban inventory of potential PCB sources is one of the project's top recommendations. A second recommendation is to develop an outreach strategy which engages decision makers while actively educating the community-at-large about the financial and regulatory challenges facing efforts to reduce PCB loadings to Lake Washington and other waterbodies. Also, a number of jurisdictions and stormwater managers are already actively pursuing LID technologies to treat or manage stormwater volumes, nutrients, metals, and suspended sediment. Since stormwater, as direct discharge or storm flows in creeks, is the most significant loading pathway (estimated to be about 70 percent of the total loading to Lake Washington), studying and understanding the efficacy of LID technologies and ensuring they are effective at PCB removal is an important next step. Lastly, further investigation of PCB air deposition, volatilization, cycling, and washoff in Western Washington urban areas is recommended, since wet and dry deposition are both suspected to be important contributors to overall stormwater loads.

In conclusion, a combination of aggressive source identification, removal, and stormwater treatment are recommended to work towards achieving the estimated ~85 percent load reduction necessary to lower Lake Washington fish tissue concentrations to safe levels.

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