APPENDIX K – DIRECT ATMOSPHERIC DEPOSITION EVALUATION

EAST WATERWAY OPERABLE UNIT FEASIBILITY STUDY

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1 DIRECT ATMOSPHERIC DEPOSITION EVALUATION

Direct atmospheric deposition is a pathway for chemicals to deposit directly on the water surface of the East Waterway (EW). Atmospheric deposition can occur through wet deposition, dry deposition, or gaseous exchange across the air/water interface. This appendix compares estimated flux-based annual mass to the EW of select risk driver chemicals from direct atmospheric deposition and direct discharge pathways.

Direct atmospheric deposition consists of the settling of particles present in the atmosphere directly onto the water surface of EW. The direct discharge pathway consists of combined sewer overflows [CSOs] and storm drain [SD] discharges. This comparison provides an indication of the importance of the direct atmospheric pathway relative to direct discharge pathways. Note that material from the atmosphere also settles onto the CSO and SD drainage basins, and some portion of that material from the atmosphere is entrained into stormwater that discharges via CSOs and SDs.

To determine the relative importance of the direct atmospheric deposition, flux-based estimates were calculated for the pathways as described in Section 2. This evaluation compares the flux-based estimates and does not consider the following:

- What proportion, if any, of the material associated with the direct atmospheric deposition to the surface of the EW or direct discharges is retained in the bedded sediments of the EW (i.e., mass transfer through the EW water column to sediments).
- Indirect atmospheric deposition of material on the CSO and SD drainage areas, which are included as components of the direct discharge pathway.
- Duwamish/Green River sediment mass inputs, which are predicted to account for 98.4% to 99.05% of the total sediment mass input to that is deposited in the EW.
- Gas phase exchange of organic chemicals (from air to water or from water to air).

The source of atmospheric deposition flux rate estimates are the *Lower Duwamish Waterway Source Control: Bulk Atmospheric Deposition Study Draft Data Report* (2013 Report; King County 2013), and *Lower Duwamish Waterway Source Control Project: Passive Atmospheric Deposition Sampling, Lower Duwamish Waterway: Monitoring Report - October 2005 to April 2007* (2008 Report; King County 2008). These reports provide estimates of passive bulk deposition, which is primarily an estimate of wet and dry deposition. The direct discharge annual masses were calculated to be consistent with the current CSO and SD chemistry assumptions developed for the EW Feasibility Study (FS) presented in Table 5-6 of the FS and the total suspended solids mass presented in the Sediment Transport Evaluation Report (Anchor QEA and Coast & Harbor Engineering 2012) (see Appendix B of the FS for more details).

2 EVALUATION METHOD

Estimated annual inputs for the direct atmospheric deposition pathway and the direct discharge pathway were calculated as described below. The mean atmospheric deposition and direct discharge base case mass are presented in the Figures 1 through 6, with the range bars indicating measures of uncertainty in those estimates based on the datasets. The calculated masses were then compared to determine the relative importance of the direct atmospheric deposition.

Atmospheric flux data collected by King County in the vicinity of the EW was converted to an annual mass deposition rate (Table 1). The annual deposition mass rate was estimated by multiplying the total open-water area of the EW (134 acres, or 542,278 square meters [m^2]) by the bulk atmospheric flux data reported by King County in both the 2013 Report and 2008 Report. To provide a range of estimated flux-based annual mass (milligrams per year [mg/year]), the mean, 25th percentile, and 75th percentile of the bulk atmospheric flux data were used in the following equation (Table 1):

$$\text{Open-water area of the EW } (m^2) \times \text{bulk flux rate } (\mu g/m^2\text{-day}) \times (1 \text{ mg}/1{,}000\ \mu g) \times 365 \text{ days/year}$$

The 2013 Report included the bulk atmospheric flux data for dioxin/furans, arsenic, mercury, high-molecular-weight polycyclic aromatic hydrocarbons (HPAHs), and polychlorinated biphenyls (PCBs), and the 2008 Report included the bis(2-ethylhexyl)phthalate (BEHP), HPAH, and PCB data. The flux data from the 2013 Report was used to estimate atmospheric deposition inputs to the EW because the newer data are of better quality due to improvements in the analytical techniques used during the 2008 study. Only the BEHP flux data from the 2008 Report were used because BEHP was not analyzed in the newer study. Bulk atmospheric flux data was compiled from two sampling stations: Beacon Hill (representing urban residential neighborhoods) and Duwamish (representing industrial areas; Figure 7). These stations are the most representative of direct atmospheric deposition to the EW surface based on proximity to the EW.

Direct discharge annual mass contributions from the CSO and SD inputs was calculated by multiplying either the low bounding (median), base case (mean), and high bounding (90th percentile) lateral chemistry data from the CSOs and SDs by their respective annual low bounding (25th percentile), base case (mean), and high bounding (75th percentile) total suspended solids data using the following equation (Table 2):

Concentration (mg/kg) x mean sediment load (kg/year)

The base case, low bounding, and high bounding masses are the same chemistry values used for the direct discharge inputs to the EW particle tracking model (see Table 5-6 of the FS).

3 EVALUATION RESULTS

Estimated chemical masses from the atmospheric deposition pathway are compared to the inputs from the direct discharge pathway and presented in Table 3 and Figures 1 through 6. Overall, the direct atmospheric deposition pathway contributes less chemical mass to the EW than the direct discharge pathway. Where atmospheric deposition masses are within or close to the range of the direct discharge mass, they may be of significance to sediment recontamination potential in the EW.

The mean, 25th, and 75th percentile bounding estimates of direct atmospheric masses to the EW water surface for arsenic, HPAH, mercury, and total PCBs are all lower than the low bounding estimate of the direct discharge masses (Table 3). Based on this evaluation, the atmospheric deposition pathway is not as significant for these parameters as the direct discharge pathway[1]. The determination of relative importance for these parameters is consistent with recent studies conducted by the Washington State Department of Ecology (Ecology) for the Lower Duwamish Waterway (LDW; Leidos and NewFields 2013).

For dioxin/furans at the Beacon Hill station, the 75th percentile direct atmospheric deposition estimate was just below (i.e., 0.04 mg/year) the low bounding estimate for the direct discharge pathway (Table 3 and Figure 6). There is less certainty regarding the range of direct discharge masses due to the source tracing dioxin/furan dataset being relatively small compared to the other contaminants. With this in mind, the small difference between the low bounding direct discharge and 75th percentile direct atmospheric deposition estimates could indicate that the direct atmospheric deposition pathway may be significant for dioxin/furan.

In contrast, at the Duwamish station, the 75th percentile bounding estimates of the direct atmospheric deposition masses for BEHP are greater than the base case estimate of the direct discharge mass (Table 3 and Figure 4). Also for BEHP direct atmospheric deposition mass, the 25th percentile and the base estimates at the Duwamish station and the 75th percentile

[1] The HPAH direct atmospheric deposition masses are biased low based on quality control issues in the analytical method for benzo(a)pyrene (see King County 2013 report for more details); therefore, HPAHs could have higher mass input for direct atmospheric deposition pathway.

estimate at the Beacon Hill station are greater than low bounding estimates of the direct discharge mass (Table 3 and Figure 4). Therefore, the direct atmospheric deposition pathway may be significant for BEHP. BEHP results and the evaluation limitations and uncertainties are further detailed below.

The LDW study also concluded that BEHP results were more variable based on location than for other chemicals (Leidos and NewFields 2013). Some of this variability could be due, in part, to the laboratory blank issues typical with BEHP analyses. BEHP was of greatest importance for potential mass contribution from direct atmospheric deposition to the LDW in the Ecology study (Leidos and NewFields 2013).

This evaluation is based on available information and is subject to the following limitations and uncertainties:

- No evaluation was conducted to determine what, if any, of either pathway masses are retained in the EW. The direct discharge recontamination potential is discussed in Section 9 of the FS. The evaluation likely overestimates the significance of the direct deposition mass because atmospheric contaminants typically consist of fine particulate matter with low settling rates through the water column. There are relatively few coarse particles compared to fine particles in the atmosphere, but coarse particles make up most of the mass of atmospheric particulate matter (Leidos and NewFields 2013). However, fine particles have more surface area than the coarse particles, so most chemicals are bound to the fine particulates. Therefore, it is likely that at least some of the direct fine particles, and the chemical mass, deposited in the EW will exit the site. This is consistent with the findings of the particle tracking model results for EW lateral particle inputs (Anchor QEA and Coast & Harbor Engineering 2012; Section 7.3.5).
- Gas-phase transfer rates were not evaluated. Gas-phase transfer can account for either a gain or loss of contaminants from the water column. Gas exchange can potentially represent a larger pathway to the water surface than wet or dry deposition (Leidos and NewFields 2013). However, the passive bulk deposition sampling method used to calculate flux rates did not measure atmospheric contaminant concentrations. Therefore, the gas exchange pathway cannot be estimated without a high degree of uncertainty without additional study data.

- An unknown amount of the atmospheric contaminant masses originate from outside of the EW source control area.
- Indirect atmospheric deposition of contaminants onto the CSO or SD basins was not quantified. However, the quantitative evaluation of the direct discharge pathway addresses all inputs from the SD and CSO basins regardless of source, including atmospheric deposition.
- Information on seasonal[2] and annual variability in the atmospheric deposition data has not been quantified.
- Relatively small atmospheric deposition data sample size for some contaminants results in relatively high uncertainty in the annual estimates.

As stated above, the indirect atmospheric deposition onto the upland drainage basins also contributes to the direct discharge pathway, but the contribution of such atmospheric deposition to the total direct discharges was not estimated as part of this evaluation. A preliminary estimate of indirect atmospheric deposition conducted for the LDW indicated that indirect deposition could potentially be a significant contribution to the total direct discharge. However, the wide ranging indirect deposition estimates yielded results with a high degree of uncertainty, therefore producing a better estimate of indirect loadings was identified as a data gap for the LDW (Leidos and NewFields 2013).

Most of the contribution from atmospheric deposition is likely captured in the direct discharge pathways inputs. Direct atmospheric deposition to the EW surface does not appear to be a significant pathway for most contaminants to the EW. However, the small difference between the low bounding direct discharge and 75th percentile direct atmospheric deposition estimates could indicate that the direct atmospheric deposition pathway may be significant for dioxin/furan and BEHP. Due to uncertainties in estimates and methods to evaluate the entire pathway to the sediment, direct atmospheric deposition quantitative estimates were not included in modeling for recontamination potential or future average site-wide surface sediment concentrations.

[2] Except for metals and PAHs, which were evaluated over all seasons over approximately a 1-year period.

4 REFERENCES

Anchor QEA and Coast & Harbor Engineering, 2012. Final Sediment Transport Evaluation Report (STER), East Waterway Operable Unit Supplemental Remedial Investigation/ Feasibility Study. Prepared for Port of Seattle. August.

King County, 2008. Lower Duwamish Waterway Source Control Project: Passive Atmospheric Deposition Sampling, Lower Duwamish Waterway: Monitoring report - October 2005 to April 2007. King County Department of Natural Resources and Parks, Seattle, WA.

King County, 2013. Lower Duwamish Waterway Source Control: Bulk Atmospheric Deposition Study Draft Data Report. King County Department of Natural Resources and Parks, Seattle, WA.

Leidos and NewFields, 2013. Lower Duwamish Waterway Air Deposition Scoping Study Data Gaps Report. Prepared for Washington State Department of Ecology, Toxics Cleanup Program. December.

TABLES

Table 1
Direct Atmospheric Deposition Pathway Flux Rates and Annual Mass Rates

Inputs	Arsenic		Mercury		Total HPAHs		BEHP		Total PCBs		Dioxin/Furan TEQ	
	Flux Rate[1] (µg/m²-day)	Annual Mass to the EW[2] (mg/yr)	Flux Rate[1] (µg/m²-day)	Annual Mass to the EW[2] (mg/yr)	Flux Rate[1] (µg/m²-day)	Annual Mass to the EW[2] (mg/yr)	Flux Rate[1] (µg/m²-day)	Annual Mass to the EW[2] (mg/yr)	Flux Rate[1] (µg/m²-day)	Annual Mass to the EW[2] (mg/yr)	Flux Rate[1] (µg/m²-day)	Annual Mass to the EW[2] (mg/yr)
Duwamish Station												
mean	1.1	217,723	0.023	4,552	0.73	144,489	4.7	928,490	0.012	2,395	0.0000050	0.980
25th percentile	0.71	141,322	0.0077	1,526	0.45	89,069	1.8	353,107	0.0051	1,005	0.0000027	0.53
75th percentile	1.4	274,529	0.025	4,968	0.85	168,439	6.5	1,291,692	0.021	4,216	0.0000078	1.55
Beacon Hill Station												
mean	0.38	75,213	0.011	2,177	0.28	55,420	1.6	324,605	0.0044	867	0.0000072	1.43
25th percentile	0.25	48,493	0.0061	1,215	0.12	23,554	1.2	227,818	0.0023	463	0.0000049	0.96
75th percentile	0.50	99,361	0.015	2,969	0.34	66,505	2.0	394,475	0.0054	1,078	0.0000097	1.91

Notes:
1. Flux rates from King County (2013) report.
2. Annual mass calculated by multiplying flux rate by the East Waterway open-water surface area (134 acres or 542,278 square meters).
3. Flux rates from King County (2008) report.
EW – East Waterway
µg/m²-day – microgram per square meter-day
BEHP – bis(2-ethylhexyl)phthalate
HPAH – high-molecular-weight polycyclic aromatic hydrocarbon
mg/yr – milligram per year
PCB – polychlorinated biphenyl
TEQ – toxic equivalent

Table 2
Direct Discharge Pathway Chemistry and Annual Mass Rates

Inputs	Arsenic		Mercury		Total HPAHs		BEHP		Total PCBs		Dioxin/Furan TEQ	
	Chemistry (mg/kg dw)[1]	Annual Mass to the EW[2] (mg/yr)	Chemistry (mg/kg dw)[1]	Annual Mass to the EW[2] (mg/yr)	Chemistry (mg/kg dw)[1]	Annual Mass to the EW[2] (mg/yr)	Chemistry (mg/kg dw)[1]	Annual Mass to the EW[2] (mg/yr)	Chemistry (mg/kg dw)[1]	Annual Mass to the EW[2] (mg/yr)	Chemistry (mg/kg dw)[1]	Annual Mass to the EW[2] (mg/yr)
Hinds CSO												
Base Case[3]	5	1,628	1.71	557	4,000	1,302	6,700	2,181	260	85	16	0.0052
Low Bounding[4]	6	1,483	0.36	89	2,900	717	3,000	742	240	59	7.6	0.0019
High Bounding[5]	9	3,612	2.57	1031	10,000	4,013	23,000	9,230	630	253	37	0.015
Lander CSO												
Base Case[3]	2	25,800	0.21	2709	1,800	23,220	1,000	12,900	11	142	1.8	0.023
Low Bounding[4]	2	19,676	0.25	2460	2,200	21,644	800	7,870	11	108	1.8	0.018
High Bounding[5]	2	31,940	0.26	4152	2,700	43,119	1,700	27,149	18	287	2.6	0.042
Hanford #2 CSO												
Base Case[3]	6	145,140	2.00	48331	3,900	94,341	7,700	186,263	270	6,531	30	0.73
Low Bounding[4]	6	110,220	0.72	13226	3,100	56,947	3,300	60,621	250	4,593	30	0.55
High Bounding[5]	9	268,290	2.94	87641	6,200	184,822	27,000	804,870	510	15,203	44	1.3
Total CSO												
Base Case[3]	--	172,568	--	51,596	--	118,863	--	201,344	--	6,758	--	0.75
Low Bounding[4]	--	131,379	--	15,775	--	79,307	--	69,233	--	4,760	--	0.57
High Bounding[5]	--	303,842	--	92,825	--	231,954	--	841,249	--	15,743	--	1.37
Nearshore SDs[4]												
Base Case[3]	10	367,630	0.09	3,309	5,500	202,197	8,300	305,133	160	5,882	15	0.55
Low Bounding[4]	10	171,350	0.08	1,371	4,400	75,394	6,200	106,237	39	668	7.9	0.14
High Bounding[5]	15	712,500	0.14	6,650	14,000	665,000	19,000	902,500	440	20,900	32	1.52
S Lander St SD												
Base Case[3]	9	287,460	0.15	4,791	14,000	447,160	12,000	383,280	120	3,513	68	2.17
Low Bounding[4]	10	150,700	0.13	1,959	5,500	82,885	9,300	140,151	53	799	68	1.02
High Bounding[5]	20	845,600	0.29	12,261	17,000	718,760	21,000	887,880	280	11,838	93	3.93
All Non-nearshore SDs												
Base Case[3]	10	69,200	0.19	1,315	10,000	69,200	19,000	131,480	290	2,007	68	0.471
Low Bounding[4]	7	22,505	0.12	386	4,000	12,860	9,400	30,221	58	186	68	0.219
High Bounding[5]	20	204,600	0.32	3,274	11,000	112,530	24,000	245,520	460	4,706	93	0.951
Total SD												
Base Case[3]	--	724,290	--	9,414	--	718,557	--	819,893	--	11,402	--	3.2
Low Bounding[4]	--	344,555	--	3,716	--	171,139	--	276,609	--	1,653	--	1.4
High Bounding[5]	--	1,762,700	--	22,185	--	1,496,290	--	2,035,900	--	37,444	--	6.4
Total Direct Discharges (CSO + SD)												
Base Case[3]	--	**896,858**	--	**61,011**	--	**837,420**	--	**1,021,237**	--	**18,160**	--	**3.9**
Low Bounding[4]	--	**475,934**	--	**19,491**	--	**250,446**	--	**345,842**	--	**6,413**	--	**1.9**
High Bounding[5]	--	**2,066,542**	--	**115,010**	--	**1,728,244**	--	**2,877,149**	--	**53,188**	--	**7.8**

Table 2
Direct Discharge Pathway Chemistry and Annual Mass Rates

Notes:
1. Direct discharge chemistry values derived form source tracing dataset; see Table 5-6 of the Feasibility Study.
2. Annual mass calculated by multiplying annual average sediment load TSS Values (EW STER; Anchor QEA 2012) using the PTM approach, as follows:

50th Percentile:		25th Percentile:		75th Percentile:	
Hinds CSO =	326 kg	Hinds CSO =	247 kg	Hinds CSO =	401 kg
Lander CSO =	12,900 kg	Lander CSO =	9,838 kg	Lander CSO =	15,970 kg
Hanford #2 CSO =	24,190 kg	Hanford #2 CSO =	18,370 kg	Hanford #2 CSO =	29,810 kg
Nearshore SDs =	36,763 kg	Nearshore SDs =	17,135 kg	Nearshore SDs =	47,500 kg
S Lander St SD =	31,940 kg	S Lander St SD =	15,070 kg	S Lander St SD =	42,280 kg
Non-nearshore SDs =	6,920 kg	Non-nearshore SDs =	3,215 kg	Non-nearshore SDs =	10,230 kg

3. Mean chemistry values and 50th percentile TSS values are used for Base Case scenarios.
4. Median chemistry values and 25th percentile TSS values are used for Low Bounding case scenarios.
5. 90th percentile chemistry values and 75th percentile TSS values are used for High Bounding Case scenarios.

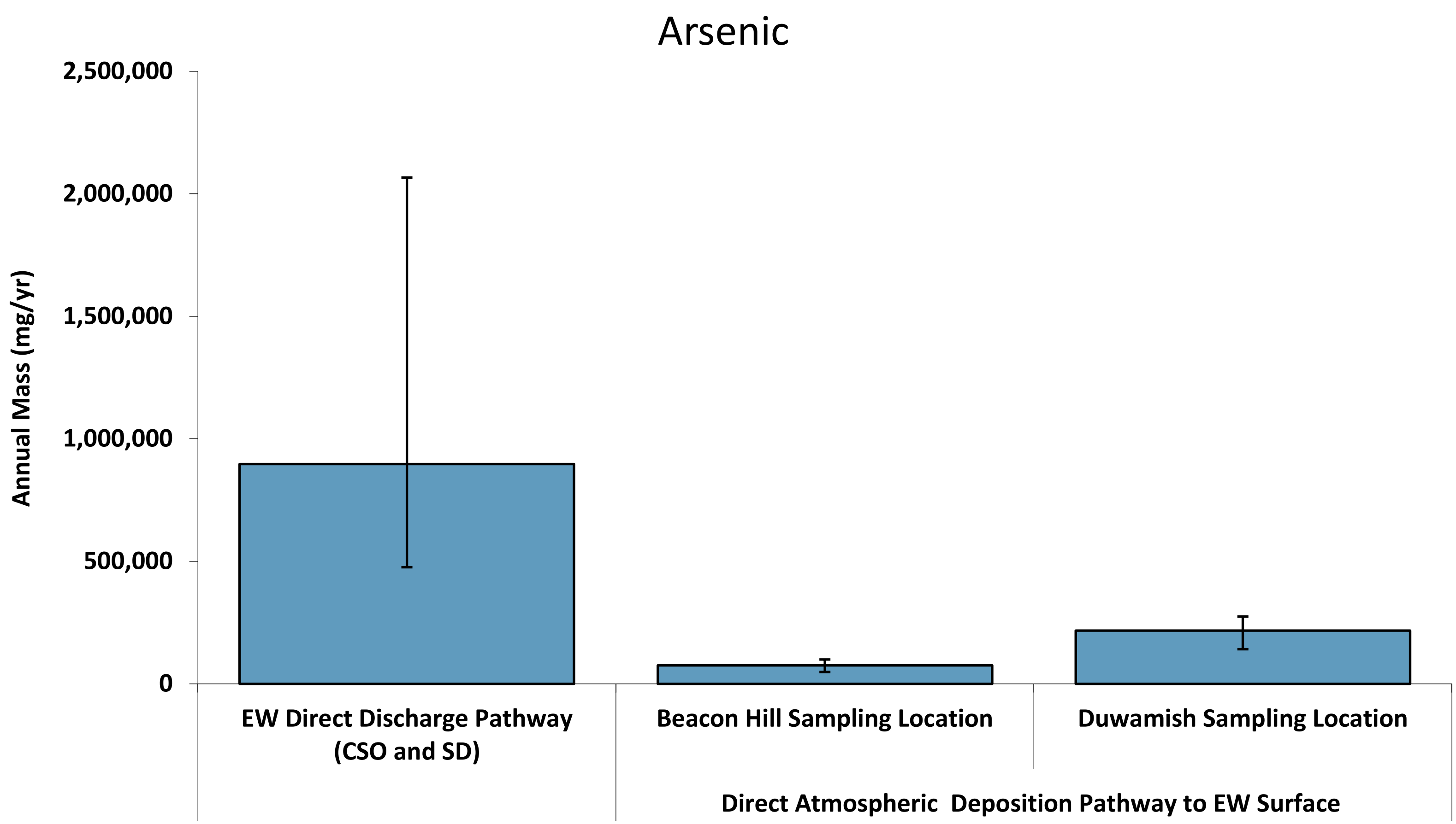
µg/kg dw – microgram per kilogram dry weight
BEHP – bis(2-ethylhexyl)phthalate
CSO – combined sewer overflow
EW – East Waterway
HPAH – high-molecular-weight polycyclic aromatic hydrocarbon
mg/yr – milligram per year
PCB – polychlorinated biphenyl
PTM – particle tracking model
SD – storm drain
TEQ – toxic equivalent
TSS – total suspended solids

Table 3
Direct Discharge and Direct Atmospheric Deposition Pathway Comparison

Inputs (mg/yr)	Direct Discharge Pathway	Direct Atmospheric Deposition Masses	
		Duwamish Station	Beacon Hill Station
Arsenic			
Base Case/mean	896,858	217,723	75,213
Low Bounding/25th percentile	475,934	141,322	48,493
High Bounding/75th percentile	2,066,542	274,529	99,361
Mercury			
Base Case/mean	61,011	4,552	2,177
Low Bounding/25th percentile	19,491	1,526	1,215
High Bounding/75th percentile	115,010	4,968	2,969
Total HPAHs			
Base Case/mean	837,420	144,489	55,420
Low Bounding/25th percentile	250,446	89,069	23,554
High Bounding/75th percentile	1,728,244	168,439	66,505
BEHP			
Base Case/mean	1,021,237	928,490	324,605
Low Bounding/25th percentile	345,842	353,107	227,818
High Bounding/75th percentile	2,877,149	1,291,692	394,475
Total PCBs			
Base Case/mean	18,160	2,395	867
Low Bounding/25th percentile	6,413	1,005	463
High Bounding/75th percentile	53,188	4,216	1,078
Dioxin/Furan TEQ			
Base Case/mean	3.95	0.98	1.43
Low Bounding/25th percentile	1.95	0.53	0.96
High Bounding/75th percentile	7.77	1.55	1.91

Notes:
(light blue shading) Indicates direct atmospheric deposition mass is greater than Low Bounding but less than Base Case direct discharge masses
(dark blue shading) Indicates direct atmospheric deposition mass is greater than Base Case but less than High Bounding direct discharge masses
BEHP – bis(2-ethylhexyl)phthalate
HPAH – high-molecular-weight polycyclic aromatic hydrocarbon
mg/yr – milligram per year
PCB – polychlorinated biphenyl
TEQ – toxic equivalent

FIGURES



Notes:

1. The blue bar is the base case/mean mass for both the direct discharge and direct atmospheric deposition. The range bar indicates 25th and 75th percentile mass for direct atmospheric deposition at each sampling station, or for direct discharge, the low bounding and the high bounding mass.

Figure 1

Relative Comparison of Arsenic Mass Based on Direct Discharge and Direct Atmospheric Deposition Pathways

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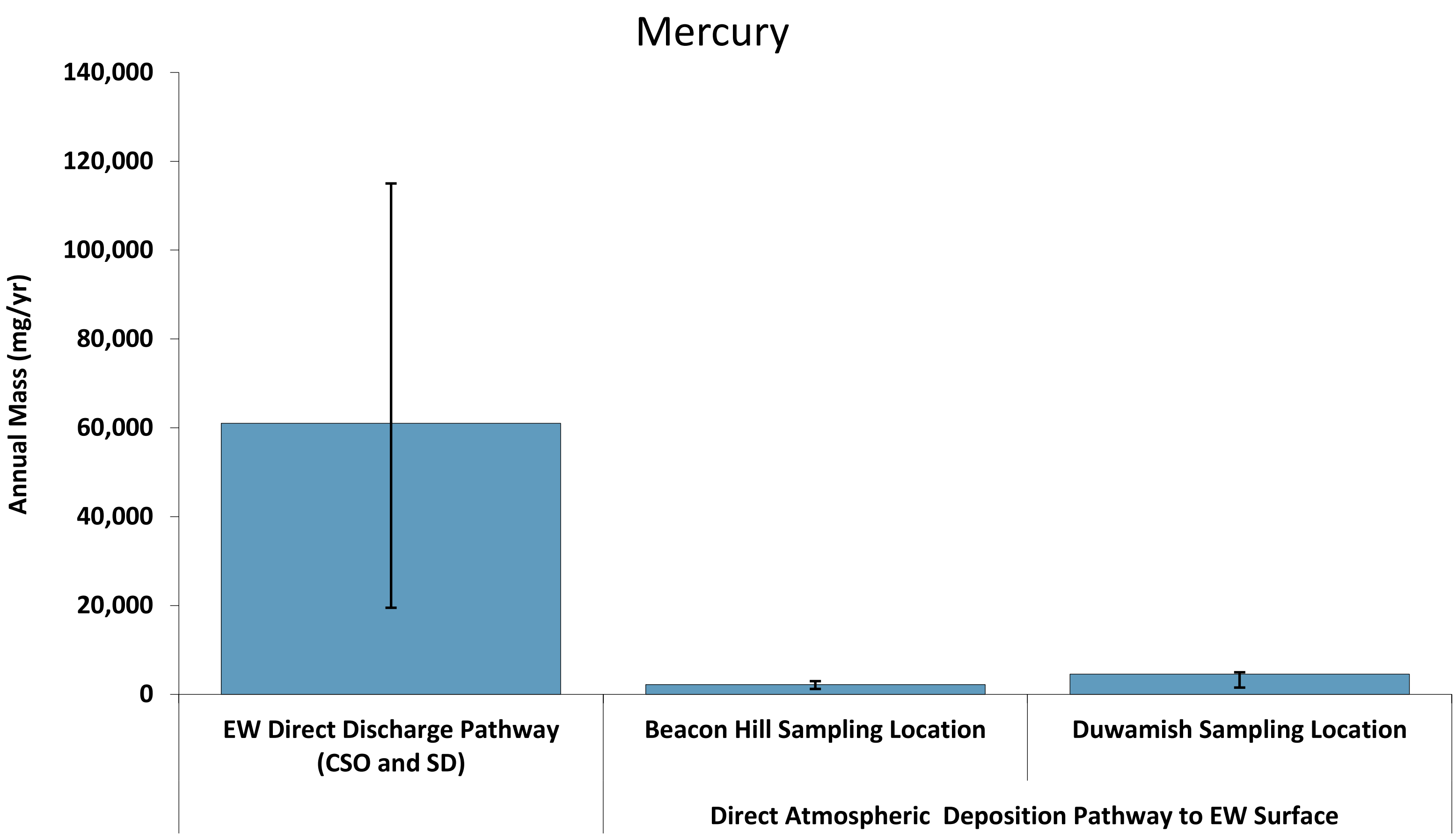
East Waterway Study Area



Notes:

1. The blue bar is the base case/mean mass for both the direct discharge and direct atmospheric deposition. The range bar indicates 25th and 75th percentile mass for direct atmospheric deposition at each sampling station, or for direct discharge, the low bounding and the high bounding mass.

Figure 2

Relative Comparison of Mercury Mass Based on Direct Discharge and Direct Atmospheric Deposition Pathways

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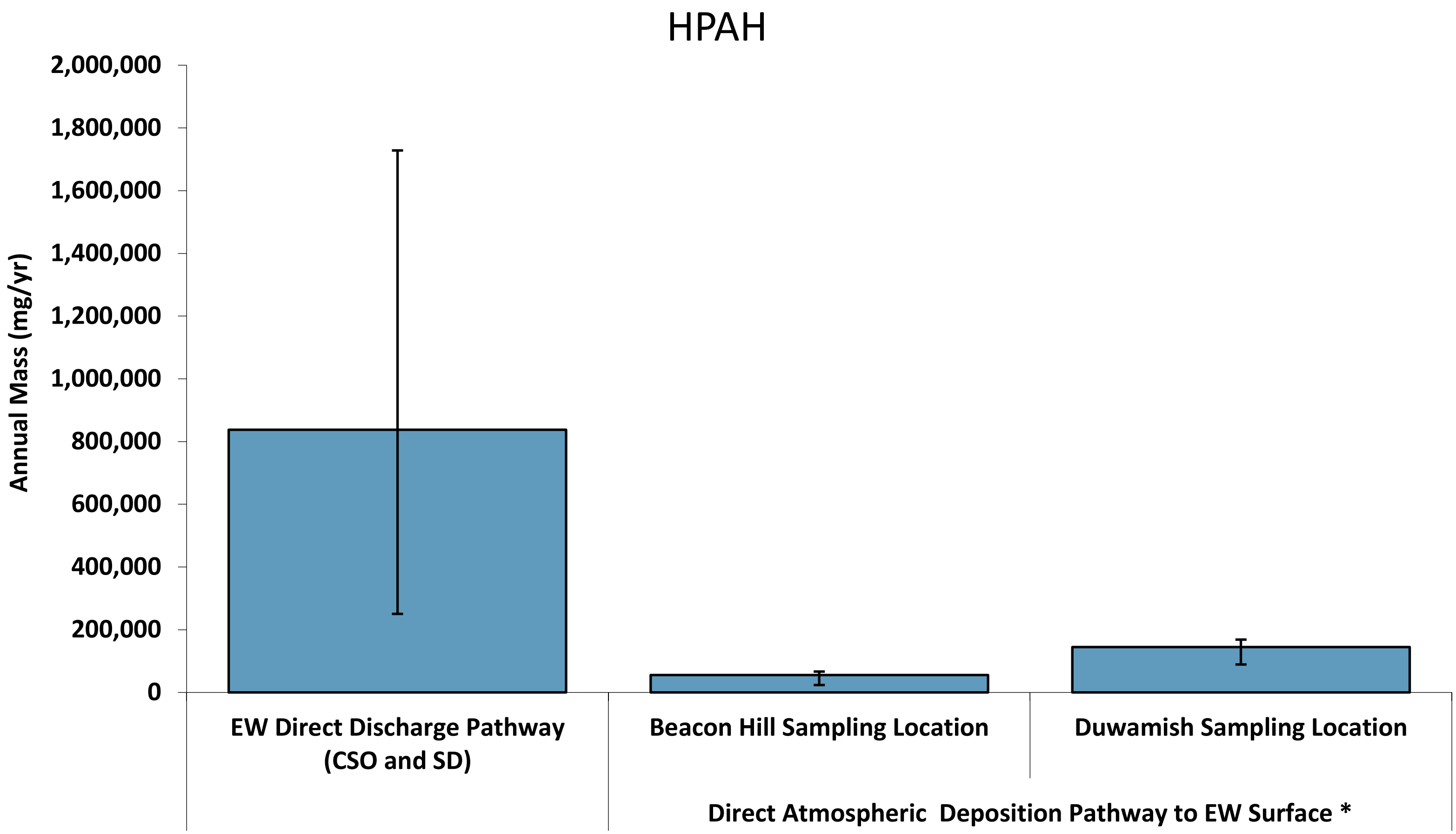
East Waterway Study Area



Notes:

* = The HPAH direct atmospheric deposition masses are biased low due to low laboratory recoveries for benzo(a)pyrene

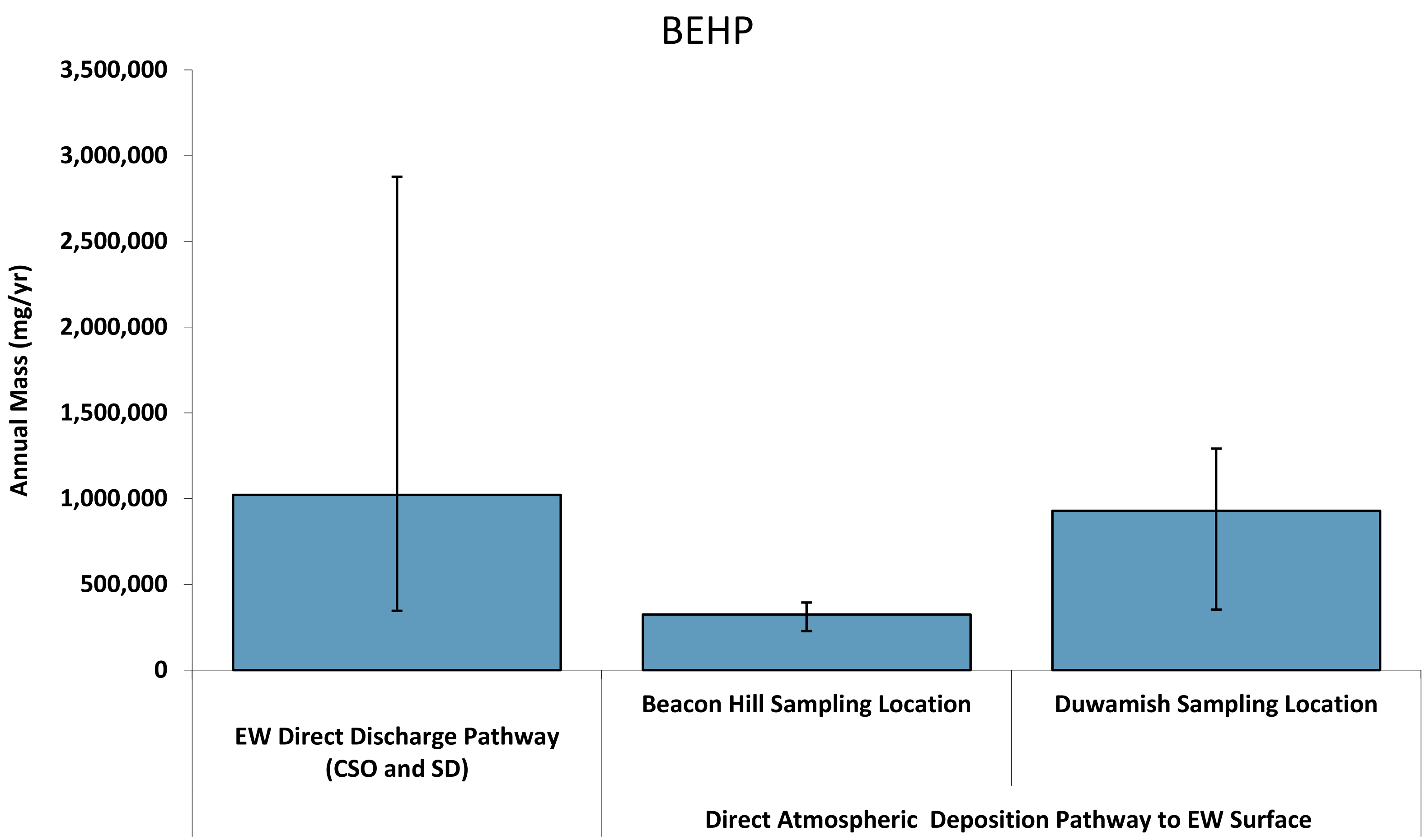
1. The blue bar is the base case/mean mass for both the direct discharge and direct atmospheric deposition. The range bar indicates 25th and 75th percentile mass for direct atmospheric deposition at each sampling station, or for direct discharge, the low bounding and the high bounding mass.

Figure 3

Relative Comparison of HPAH Mass Based on Direct Discharge and Direct Atmospheric Deposition Pathways

Feasibility Study - Appendix K

East Waterway Study Area



Notes:

1. The blue bar is the base case/mean mass for both the direct discharge and direct atmospheric deposition. The range bar indicates 25th and 75th percentile mass for direct atmospheric deposition at each sampling station, or for direct discharge, the low bounding and the high bounding mass.

Figure 4

Relative Comparison of BEHP Mass Based on Direct Discharge and Direct Atmospheric Deposition Pathways

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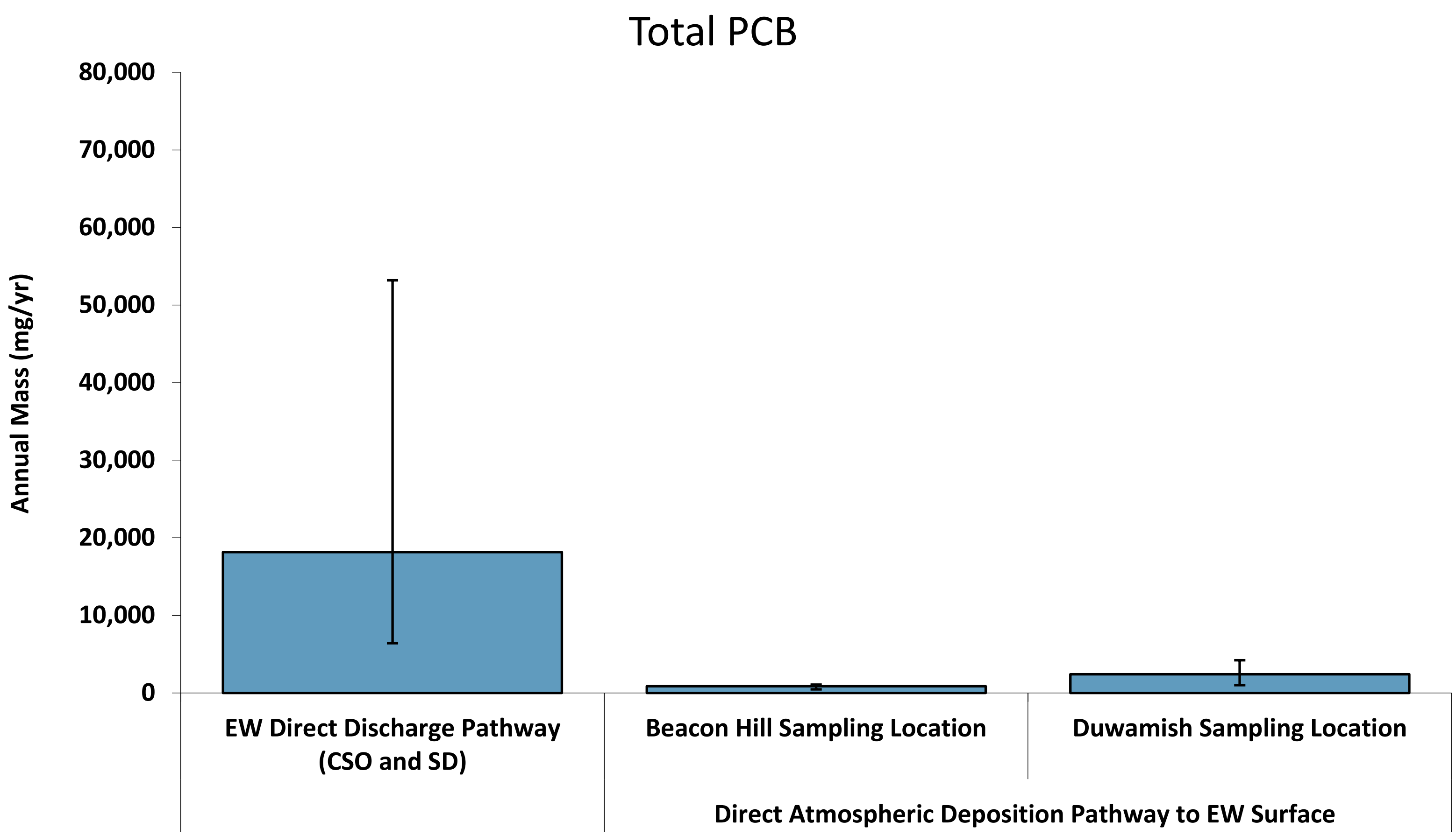
East Waterway Study Area

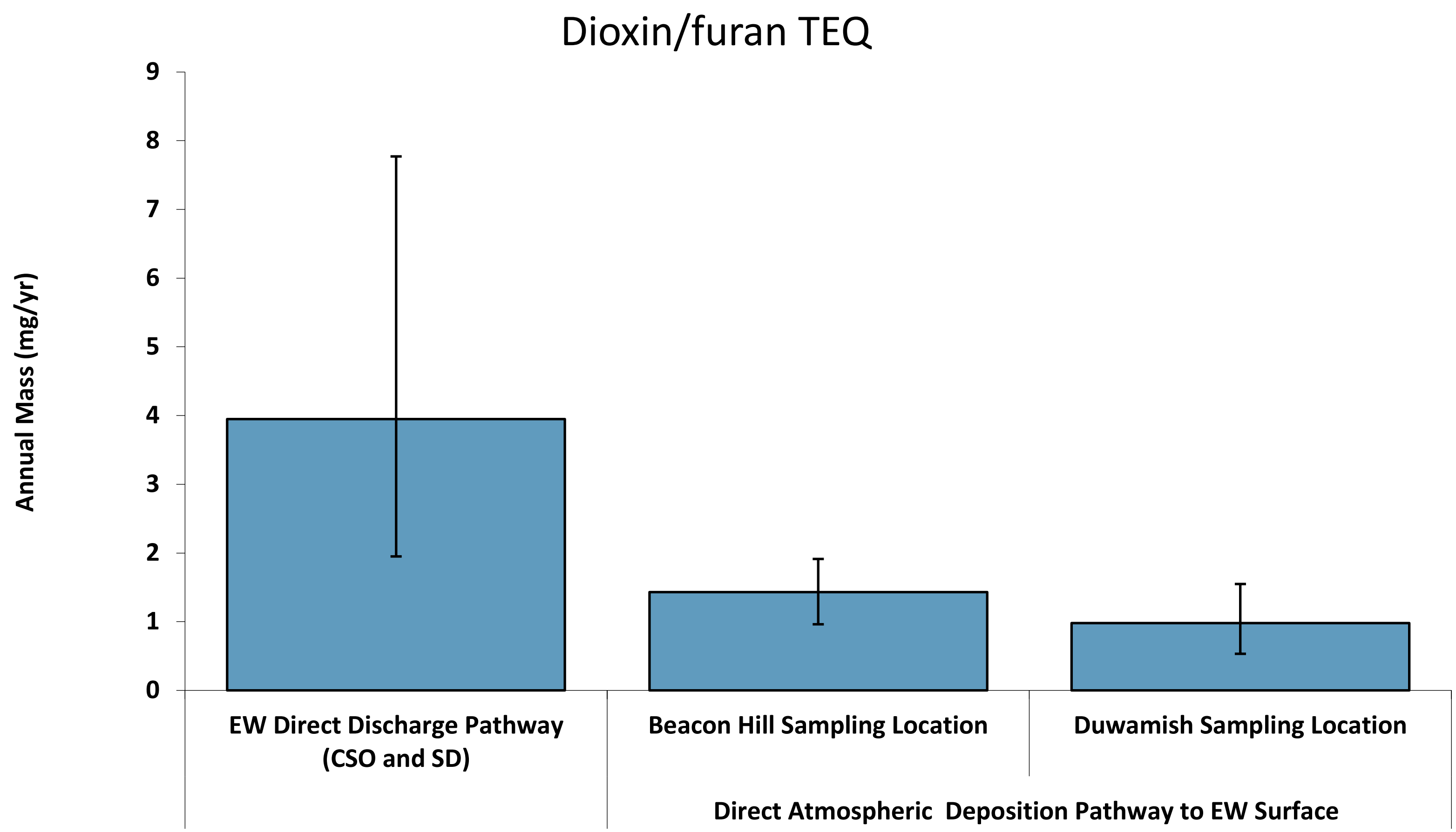


Notes:

1. The blue bar is the base case/mean mass for both the direct discharge and direct atmospheric deposition. The range bar indicates 25th and 75th percentile mass for direct atmospheric deposition at each sampling station, or for direct discharge, the low bounding and the high bounding mass.

Figure 5

Relative Comparison of Total PCB Mass Based on Direct Discharge and Direct Atmospheric Deposition Pathways



Notes:

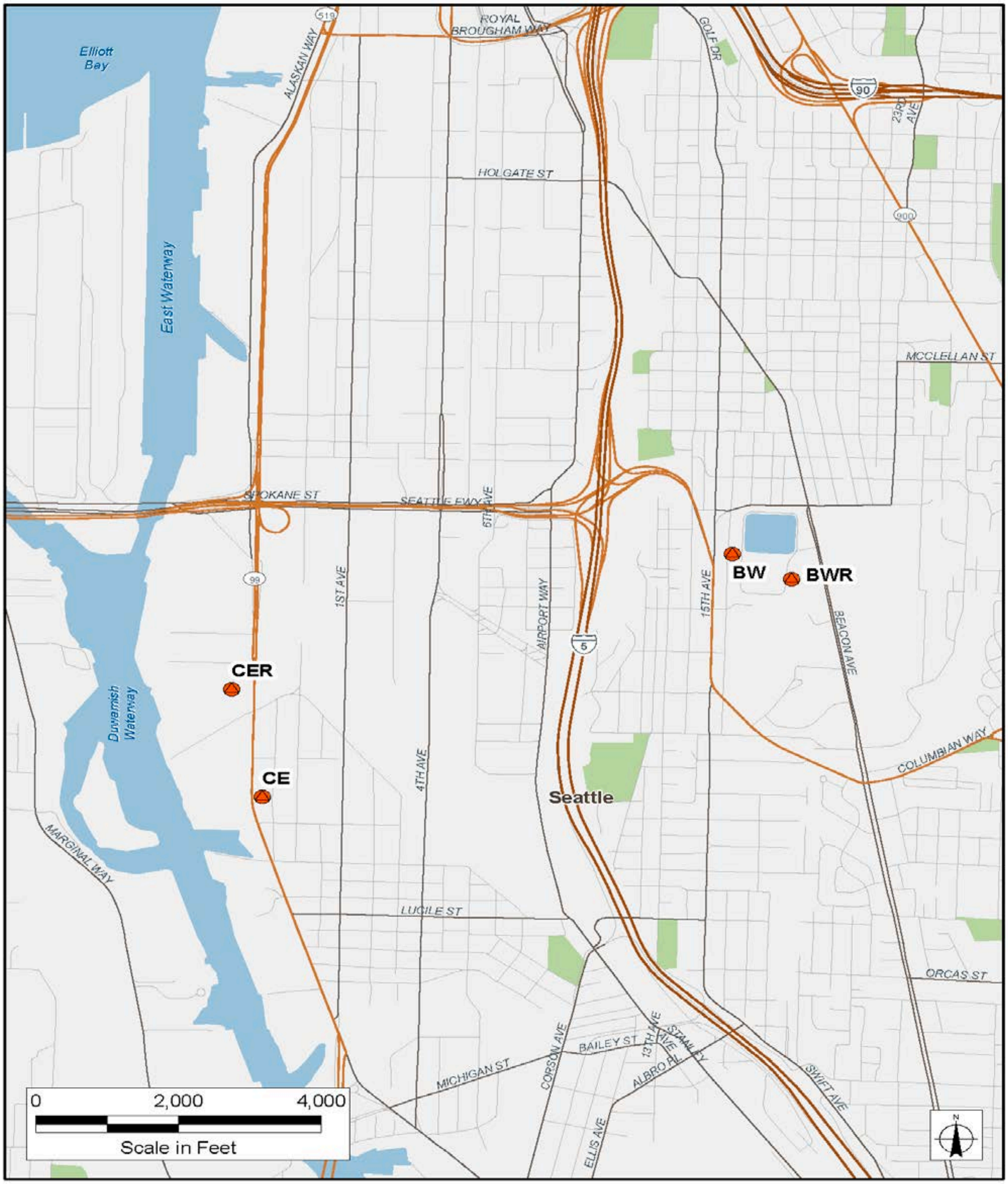
1. The blue bar is the base case/mean mass for both the direct discharge and direct atmospheric deposition. The range bar indicates 25th and 75th percentile mass for direct atmospheric deposition at each sampling station, or for direct discharge, the low bounding and the high bounding mass.

Figure 6

Relative Comparison of Dioxin/Furan TEQ Mass Based on Direct Discharge and Direct Atmospheric Deposition Pathways

Feasibility Study - Appendix K

East Waterway Study Area



Source: King County (2008)

Note: CE = Duwamish, CER = relocated Duwamish, BW = Beacon Hill, BWR = relocated Beacon Hill.
Data from the re-located stations were presented in the 2013 report, whereas data from both the original and relocated locations were used in the 2008 report.

Figure 7

Locations of Air Deposition Monitoring Stations from the King County LDW Study

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East Waterway Study Area