Conceptual Model to Support PCB Management and Monitoring in the San Leandro Bay Priority Margin Unit

Phase I

Prepared by

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FINAL REPORT

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Support PCB Management and Monitoring in the
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Preface

The goal of RMP PCB special studies over the next few years is to inform the review and possible revision of the PCB TMDL and the reissuance of the Municipal Regional Permit for Stormwater, both of which are tentatively scheduled to occur in 2020. Conceptual model development for a set of four representative priority margin units will provide a foundation for establishing an effective and efficient monitoring plan to track responses to load reductions, and will also help guide planning of management actions. The Emeryville Crescent was the first PMU to be studied in 2015-2016. The San Leandro Bay PMU is second (2016-2017), Steinberger Slough in San Carlos is third (2017), and Richmond Harbor will be fourth (2018).

The conceptual model reports for these four PMUs will be developed and presented using a consistent framework, and will build on each other to form an integrated assessment of these four areas. The lessons learned from these analyses will also be more generally applicable to similar contaminated sites on the margins of the Bay.

This document is Phase One of a report on the conceptual model for San Leandro Bay. Funding for this project from the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) for conceptual model development was substantially augmented by funding from two Supplemental Environmental Projects (SEPs). This report is a deliverable for the first SEP. The SEP funding supported both development of the conceptual model and an extensive field study of PCB concentrations in San Leandro Bay. Results from sampling of sediment and water were available at the time this report was written, but results from fish sampling were not yet available. The report is therefore being presented in two phases. Phase Two will be completed by December 2017.

The outline below indicates which elements will be included in Phases One and Two. The report on Phase Two will incorporate the completed elements from Phase One to create a complete report.

1. Introduction (Phase 1, Phase 2)
2. Tributary Loading
   a. Load estimates from the PMU watersheds (Phase 1)
   b. The influence of lower watershed hotspots (Phase 2)
3. Initial Retention in the PMU (Phase 1)
4. Long-term Fate in the PMU
   a. Mass budget (Phase 1)
   b. Comparison of sediment data: 1998 vs. 2016 (Phase 1)
   c. Incorporate passive sampler data (Phase 2)
5. Bioaccumulation (Phase 2)
6. Answers to the Management Questions (Phase 2)

Acknowledgements

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1.   Introduction

The RMP PCB Strategy Team formulated a PCB Strategy in 2009. The Team recognized that a wealth of new information had been generated since the PCBs TMDL Staff Report (SFBRWQCB 2008) was prepared. The Strategy articulated management questions to guide a long-term program of studies to support reduction of PCB impairment in the Bay. The PCB Team recommended two studies to begin addressing these questions. The first recommended study was to take advantage of an opportunity to piggyback on the final year of the three-year prey fish mercury sampling in 2010 to collect data on PCBs in prey fish also. The second study that was recommended was a synthesis and conceptual model update based on the information that had been generated since the writing of the TMDL Staff Report.

The prey fish monitoring revealed extremely high concentrations of PCBs in the food web in several areas on the Bay margins (Greenfield and Allen 2013), and highlighted a need to develop a more detailed conceptual model than the one-box model used as a basis for the TMDL. A model that would support the implementation of actions to reduce loads from small tributaries, a primary focus of the TMDL, would be of particular value. A revised conceptual model was developed that shifted focus from the open Bay to the contaminated areas on the margins where impairment is greatest, where load reductions are being pursued, and where reductions in impairment in response to load reductions would be most apparent (Davis et al. 2014).

The margins appear to be a collection of distinct local food webs that share some general similarities but are largely functionally discrete from each other. Monitoring, forecasting, and management should therefore treat these margin locations as discrete local-scale units. Local-scale actions within a margin unit, or in upstream watersheds, will likely be needed to reduce exposure within that unit. Better characterization of impairment on the margins through more thorough sampling of sediment and biota would help focus attention on the margin units where the need for action is greatest ("priority margin units" or PMUs), and will also provide an important performance measure for load reduction actions taken in local watersheds. Davis et al. (2014) recommended a focus on assessing the effectiveness of small tributary load reduction actions in priority margin units, and provided an initial foundation for these activities.

The 2014 update of the PCB Strategy called for a multi-year effort to implement the recommendations of the PCB Synthesis Report (Davis et al. 2014) pertaining to:
1. identifying margin units that are high priorities for management and monitoring,
2. development of conceptual models and mass budgets for margin units downstream of watersheds where management actions will occur, and
3. monitoring in these units as a performance measure.

A thorough and thoughtful planning effort is warranted given the large expenditures of funding and effort that will be needed to implement management actions to reduce PCB loads from urban stormwater.

The goal of RMP PCB Strategy work over the next few years is to inform the review and possible revision of the PCB TMDL and the reissuance of the Municipal Regional Permit for Stormwater (MRP), both of which are tentatively scheduled to occur in 2020. Gilbreath et al. (2015) identified four margin units that are high priorities for management and monitoring. Conceptual model development for these four priority margin units will provide a foundation for establishing an effective and efficient monitoring plan to track responses to load reductions and also help guide planning of management actions. San Leandro Bay (Figures 1-1 and 102) is the subject of this report and the second PMU to be studied.

The goal of this report is to answer the following three questions related to management and monitoring of PCBs in priority margin units.
1. Can we expect a decline in any compartment of the PMU in response to projected load reductions in the PMU watershed?
2. How should tributary loads be managed to maximize PMU recovery?
3. How should the PMU be monitored to detect the expected reduction?

This report is intended to provide a technical foundation for answering these questions to the extent possible with existing information, and to identify the information that is most urgently needed to provide answers that are sufficient to support decision-making. The report is therefore intended for a technical audience.

The report includes four sections describing the major elements of the conceptual model for PCBs in San Leandro Bay (Figure 1-3):
- Section 2: loading from the watersheds;
- Section 3: initial deposition and retention;
- Section 4: processes determining the long-term fate of PCBs in sediment and water; and
- Section 5: bioaccumulation in the food web.
The last section (Section 6) presents answers to the management questions.

Figure 1-1.   San Leandro Bay.
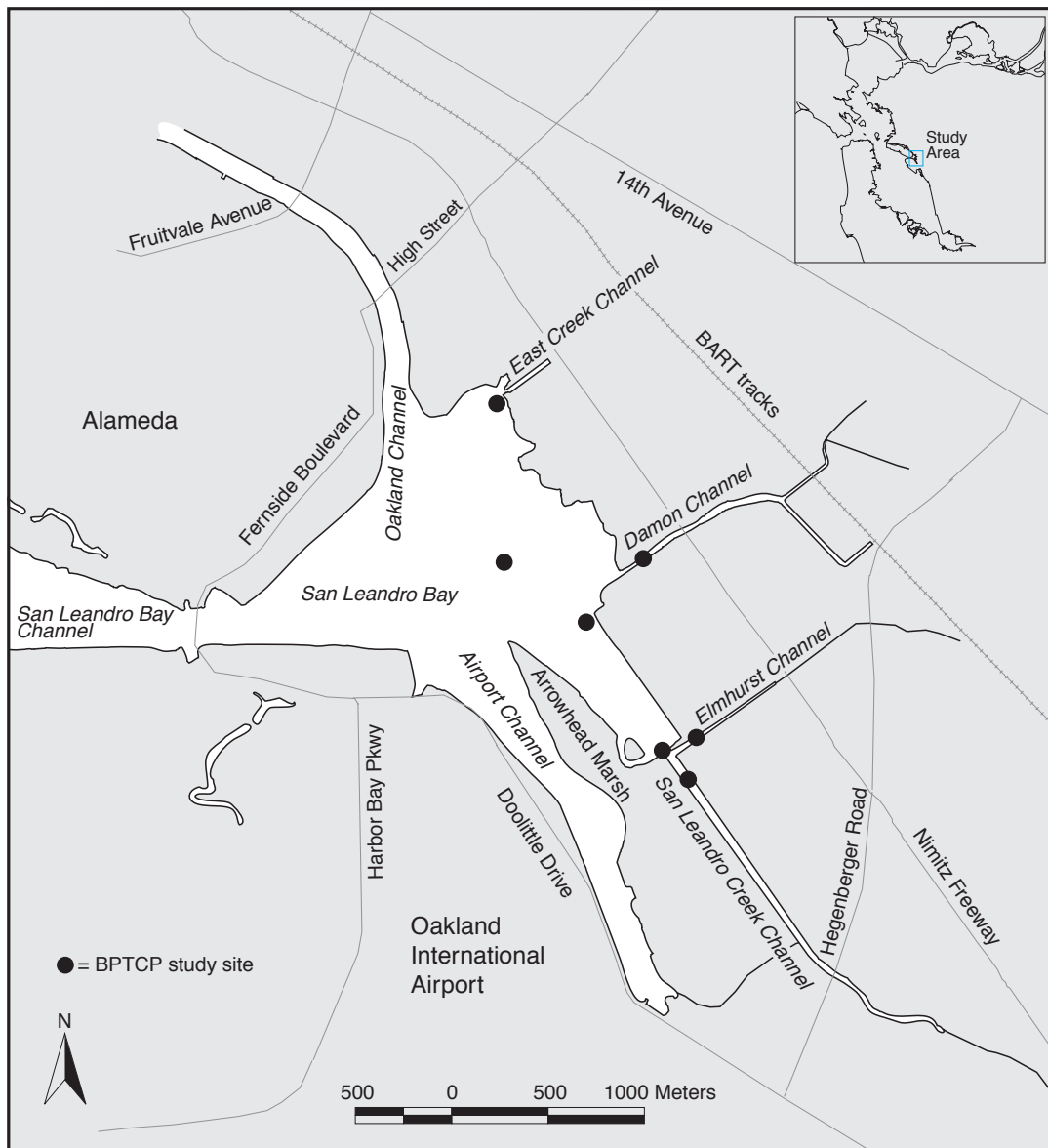
**San Leandro Bay sediment study area. San Leandro Bay is a shallow embayment of San Francisco Bay. It is formed by the confluence of East Creek, Damon Creek, Elmhurst Channel, San Leandro Creek Channel, Oakland Channel and San Leandro Bay Channel.**

Figure 1-2.   San Leandro Bay at low tide, March 2014. Marsh, intertidal mudflat, and subtidal areas are visible.

Figure 1-3.   Overall conceptual model.
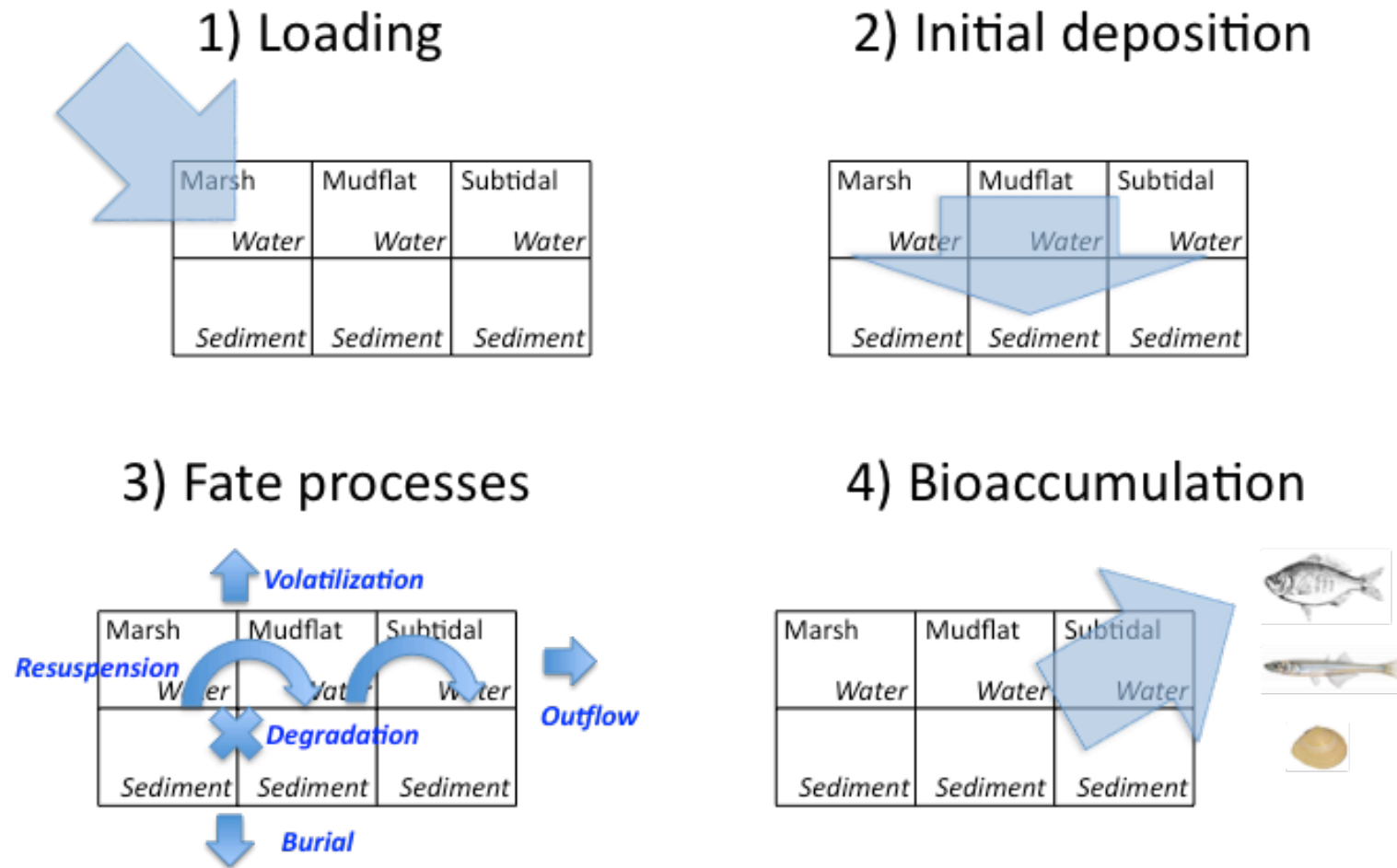
References

Davis, J.A., L.J. McKee, T. Jabusch, D. Yee, and J.R.M. Ross. 2014. PCBs in San Francisco Bay: Assessment of the Current State of Knowledge and Priority Information Gaps. RMP Contribution No. 727. San Francisco Estuary Institute, Richmond, California.

Gilbreath, A., D. Yee, L. McKee, and J. Davis. 2015. PCB Margin Unit Prioritization Final Report. SFEI Contribution #812.

Greenfield, B.A. and R.M. Allen. 2013. Polychlorinated biphenyl spatial patterns in San Francisco Bay forage fish. Chemosphere 90: 1693-1703.

SFBRWQCB. 2008. Total Maximum Daily Load for PCBs in San Francisco Bay: Final Staff Report for Proposed Basin Plan Amendment. San Francisco Bay Regional Water Quality Control Board, Oakland, CA.

SECTION 2: TRIBUTARY LOADING

a.   Tributary Watersheds: General Profiles

The watershed draining to the San Leandro Bay covers an area of 83.4 km^2 of mixed land use and drains areas of the southern parts of Oakland and northern part of San Leandro (Figures 2-1 and 2-2). Drainage into San Leandro Bay occurs from 15 identified drainage areas, but six of the larger, named creeks dominate, comprising 92% of the area. The nine smaller, unnamed drainage areas (referred to as "AC_unk[number identifier]" are each 2 km^2 or smaller and located immediately adjacent to the Bay. For the purposes of this analysis, the 15 drainages were grouped together into five main drainage areas.

- Drainage Area 1 (draining in to the Drainage Point 1 on the map) includes drainage from Sausal Creek and two very much smaller unnamed catchments designated as AC_unk14 and AC_unk15.
- Drainage Area 2 (draining in to the Drainage Point 2 on the map) includes drainage from Peralta and Courtland and Seminary Creeks and the unnamed catchment designated as AC_unk16.
- Drainage Area 3 (draining in to the Drainage Point 3 on the map) includes drainage from Arroyo Viejo Creek, Lion Creek, and three unnamed catchments designated as AC_unk17, AC_unk19 and AC_unk20.
- Drainage Area 4 (draining in to the Drainage Point 4 on the map) includes drainage from San Leandro Creek and Elmhurst Creek.
- Three additional small catchments drain through several dispersed outfalls into the San Leandro Bay, including the unnamed catchments AC_unk 18, AC_unk21 and AC_unk22.
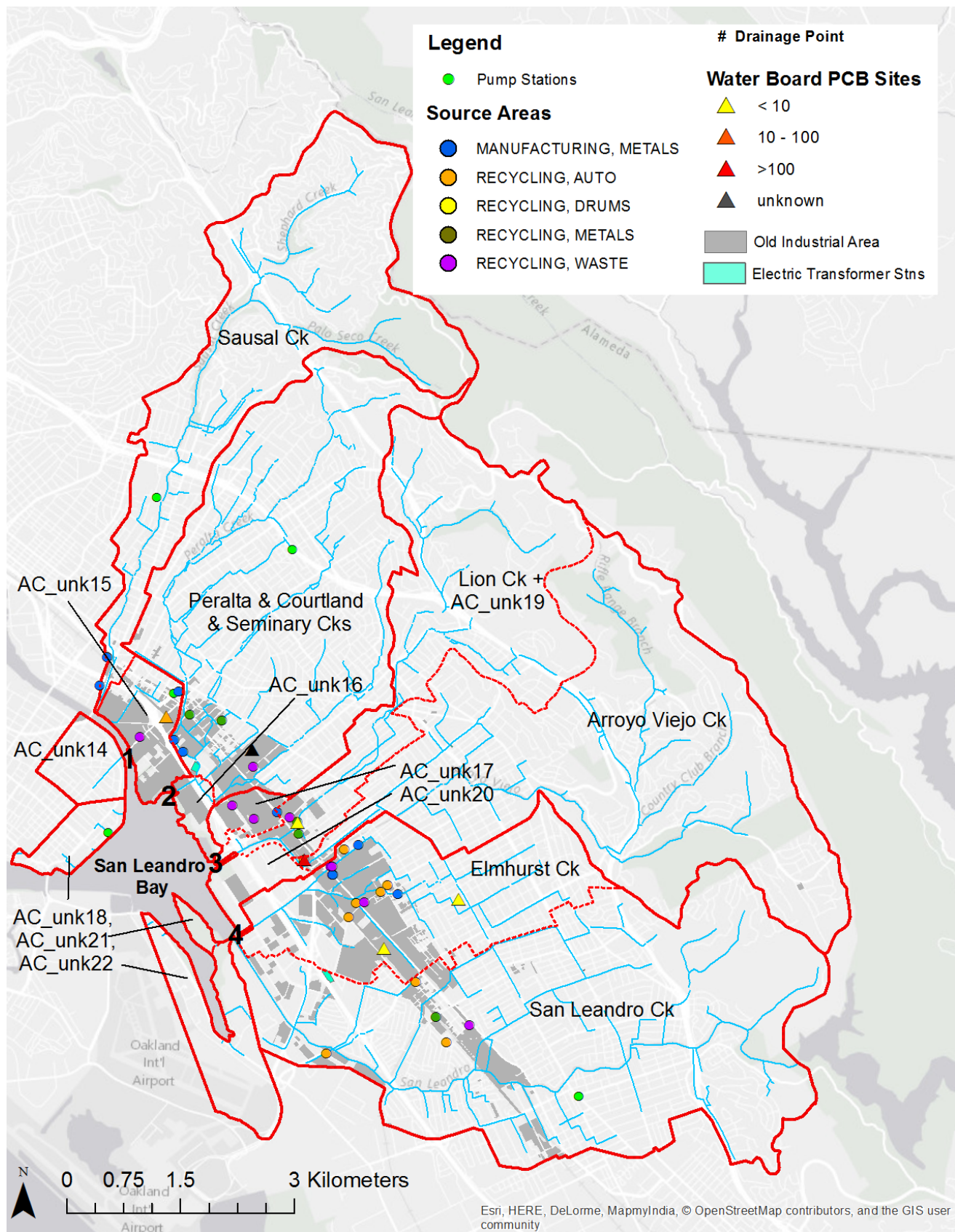
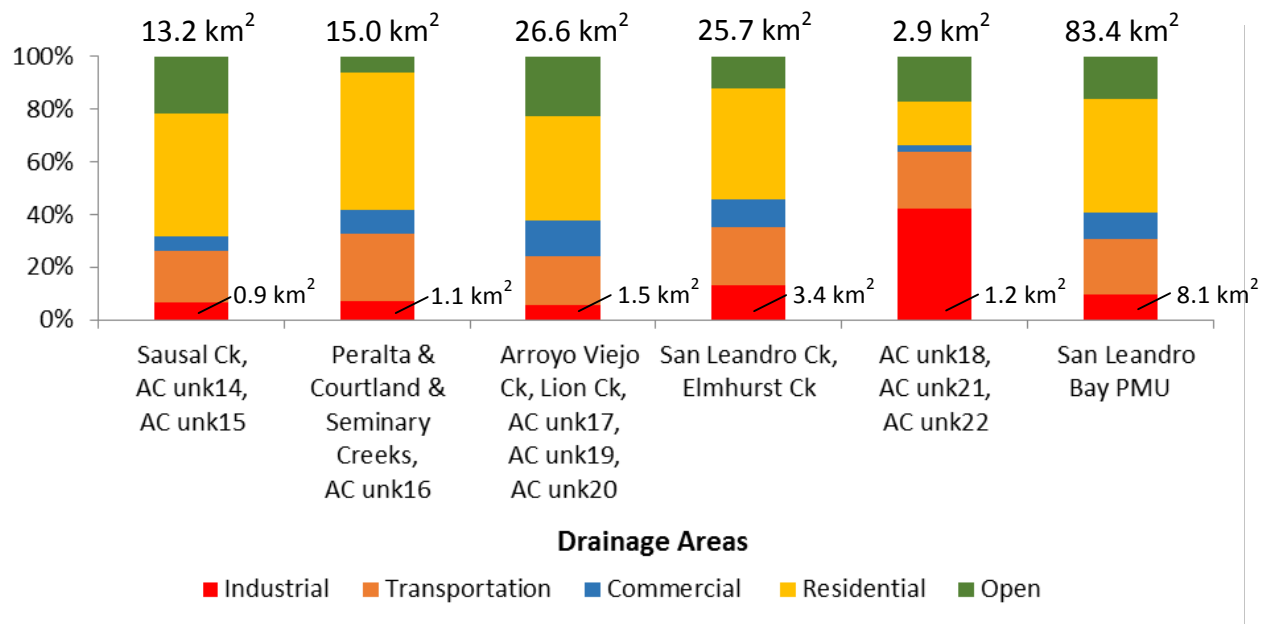Figure 2-1.   Main tributary watersheds to the San Leandro Bay PMU.

Figure 2-2.   Land use in the San Leandro Bay PMU watersheds.

Although a portion of the watershed consists of open space in the form of urban parks and some upland areas, the most dominant land use is a mix of medium to high residential, commercial properties, and transportation. Overall, the imperviousness of the whole drainage combined is 45%. Approximately 10% of the area is industrial (ABAG 2005; land use categories aggregated by SFEI), and 85% of that area is either older industrial or source areas that are conceptually associated with higher concentrations of PCBs.

b.   Current PCB Export to the PMU

In the absence of runoff and PCB concentration data from the SLB PMU subwatersheds, PCB export was estimated using the Regional Watershed Spreadsheet Model (RWSM; Wu et al., 2017). The RWSM applies regionally calibrated coefficients for runoff based on a combination of land use, slope, and soil type, and calibrated coefficients for PCB concentrations based on land use alone, to estimate the total PCB load export.

The RWSM estimates average annual flow volumes of 26.6 Mm3 (Table 2-1), equivalent to a runoff coefficient of about 0.52 (or 52% of mean annual rainfall) and conceptually reasonable given an impervious cover of 45%. The estimated range of PCB export to the SLB PMU is 462 – 1,747 g/yr, with a best estimate of 986 g/yr. Although for planning purposes these loads are conceptually reasonable, the main data weaknesses at this time are the lack of empirical flow and concentration data for all but one of these watersheds, the exception being San Leandro Creek where a monitoring station was maintained for three water years (2012-2014) to measure both of these parameters.

Table 2-1.   Average annual load estimates for the San Leandro Bay Margin Unit watersheds.

Watershed	Total Area (km²)	Total Runoff Volume (Mm³)	PCB Load - Low Estimate (g)	PCB Load - Best Estimate (g)	PCB Load - High Estimate (g)	PCB Yield -Best Estimate (ug/m²)
Sausal Ck, AC unk14, AC unk15	13.2	4.4	64	136	242	10.3
Peralta and Courtland and Seminary Creeks, AC unk16	15.0	4.9	82	175	307	11.6
Arroyo Viejo Ck, Lion Ck, AC unk17, ACunk19 and AC unk20	26.6	9.4	106	234	389	8.8
San Leandro Ck and Elmhurst Ck	25.7	7.1	166	350	635	13.6
AC unk18, AC unk21, AC unk22	2.9	0.8	44	91	175	31.2
Total for Margin Unit	83.4	26.6	462	986	1747	11.8

c.   Temporal Dynamics of Loading into the PMU

To better understand how the flow of stormwater, suspended sediments, and PCBs interact with or flush through the SLB, estimates of annual averages were derived for the following relevant storm styles or return intervals:
   i.   the load delivered during summer and winter non-storm flow;
   ii.   the load for an "average" storm;
   iii.   the load for a 1:1 year return interval storm;
   iv.   the load for a 1:5 year return interval storm; and
   v.   the load for a 1:10 year return interval storm.

This was accomplished using, as a surrogate, loads delivered for different sized storm events from three reference watersheds (Zone 4 Line A, Hayward; North Richmond Pump Station, Richmond; Sunnyvale East Channel, Sunnyvale) in which we have multiple years of continuous loads estimates, and which are similar in land use characteristics to the SLB watersheds (see Appendix 1 for method details). Each of the three reference watersheds yielded a slightly different percentage of load transported for each of the storm recurrence intervals. This range of load estimates (as a percentage of the total annual load) for the three reference stations for each storm recurrence interval was used to produce the range of load transport estimated for the SLB watersheds (Tables 2-2 and 2-3).

Table 2-2.   PCB loads transported for select return interval storms (load as a percentage of the average annual load) in reference watersheds.

	Low	High
% of load in average storm	0.4%	1.8%
% of load in 1:1 yr storm	4.6%	5.2%
% of load in 1:5 yr storm	9.5%	10.1%
% of load in 1:10 yr storm	11.6%	12.2%

Table 2-3.   PCB load estimates for the San Leandro Bay watersheds.

	Long Term (40 Year) Average Annual Load (g)	Long Term (40 Year) Average Annual Yield (g/km2)	Summer And Winter Non-Storm Flow PCB Load (g) - 6%	Estimated Load from a Single Average Storm (g)		Estimated Load from a Single 1:1 Year Storm (g)		Estimated Load from a Single 1:5 Year Storm (g)		Estimated Load from a Single 1:10 Year Storm (g)	
				Low	High	Low	High	Low	High	Low	High
Sausal Ck, AC unk14, AC unk15	136	10.3	8.2	0.5	2.5	6.3	7.1	12.9	13.8	15.8	16.6
Peralta and Courtland and Seminary Creeks, AC unk16	175	11.6	10.5	0.7	3.1	8.0	9.1	16.6	17.6	20.3	21.3
Arroyo Viejo Ck, Lion Ck, AC unk17 and AC unk20	234	8.8	14.0	0.9	4.2	10.8	12.2	22.2	23.6	27.1	28.5
San Leandro Ck and Elmhurst Ck	350	13.6	21.0	1.4	6.3	16.1	18.2	33.3	35.4	40.6	42.7
AC unk18, AC unk21, AC unk22	91	31.2	5.5	0.4	1.6	4.2	4.7	8.6	9.2	10.6	11.1
Total for Margin Unit	986	11.8	59	3.9	18	45	51	94	100	114	120

To support mass budget calculations for the SLB that include conservation of total load mass over a year or multiple years, we estimated a long-term, continuous dataset of daily PCB loads for the SLB. The Western Regional Climate Center Oakland Museum gauge daily rainfall (WYs 1971-2010) formed the foundation of the daily loads estimates, and continuous loads developed in an empirical study for a nearby watershed (Zone 4 Line A; Gilbreath and McKee, 2015) were used to estimate the distribution of loads to the SLB watersheds. A full description of the method is provided in Appendix 1. Results of this continuous daily PCB load estimate are illustrated in Figure 2-3 and Table 2-4.
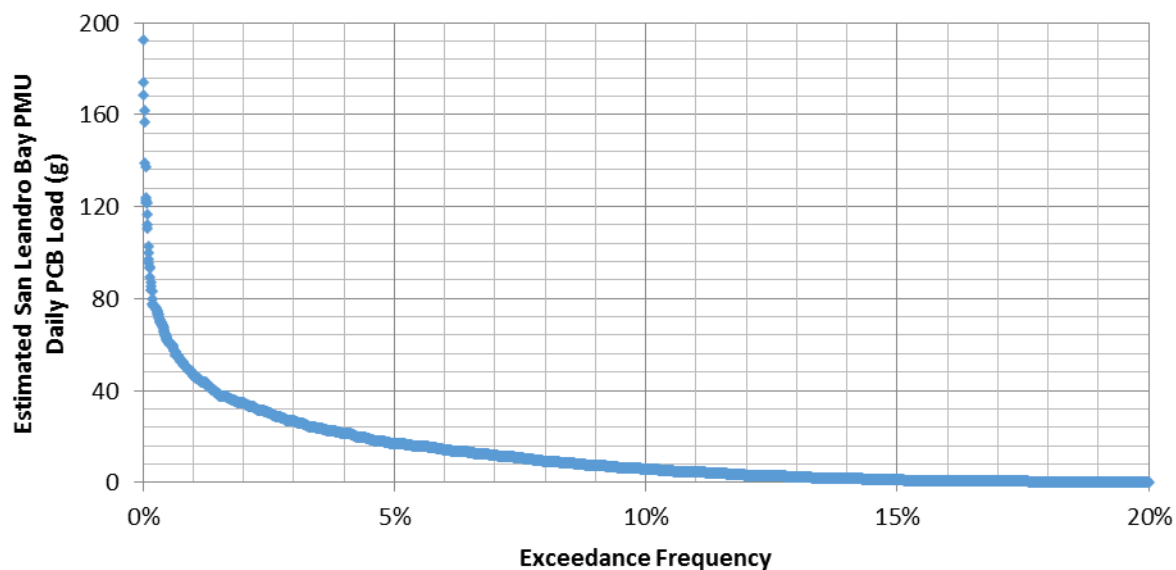
Figure 2-3.   Exceedance frequency of estimated daily SLB PCB loads over a 40-year time period (WY 1971 – 2010).

Table 2-4.   Summary of load exceedances in the San Leandro Bay watersheds.

	San Leandro Bay PMU
Average Annual Load (g)	986
Mean Daily Load (g)	2.7
Daily Load (g) Exceeded 1 % of time	47
Daily Load (g) Exceeded 2 % of time	35
Daily Load (g) Exceeded 5% of time	17
Daily Load (g) Exceeded 10 % of time	5.7
Daily Load (g) Exceeded 20 % of time	0.2

d.   Partitioning of PCB Exports from the Watersheds

Little is known regionally about the proportion of PCBs on varying grain size fractions. To our knowledge, the only estimates of PCB partitioning in the region were made by Yee and McKee (2010), who carried out settling experiments to estimate the portion of PCB loads that were in different size fractions. Data have also been collected more recently by BASMAA through the CW4CB project that may also be helpful if made available. The outcome of this simple apportionment exercise is to make some first order estimates for PCBs in each of three size fractions: <0.25 µm, 25-75 µm, and >75 µm.

The limited data available (Table 2-5, data from Yee and McKee, 2010) suggest that the percentage of PCB mass in different grain size fractions can vary widely, especially for the smallest fraction (<25 µm). We recommend using the minimum and maximum of the results available as an estimate of the range of PCB mass in different grain sizes, and the average as the best estimate.

Table 2-5.   The fraction of PCB mass in different grain size fractions. From Yee and McKee (2010).

Sample/site	PCB (ng/L)	% <25µm incl. dissolved	% 25-75 µm	% >75 µm
Z4-201	17	73	13	14
Z4-203	30	49	23	28
Z4-204	23	46	21	33
Z4-205	29	38	31	31
RS-1003	38	28	26	46
RS-1004	17	51	16	33

Range	17 - 38	28 - 73 %	13 - 31%	14 - 46%
Average	26	48%	22%	31%

PCBs in the Dissolved Fraction

To estimate dissolved phase PCBs in the SLB tributaries, we examined a combination of dissolved and particulate concentration data gathered in WY 2016 from five predominantly urban watersheds in the Bay Area and the PCB and SSC relationships for six other predominantly urban watersheds in the region. These empirical data were related to the percentage impervious and old industrial area in each of those watersheds as a surrogate for estimating the dissolved phase in the SLB watersheds (Table 2-6; see Appendix 1 for method details). This approach used data collected primarily in storm events and thus only represents the dissolved fraction during storm flow conditions. Based on this approach, estimates for the percentage of PCBs in the dissolved phase ranged between 5-37% for all 14 subwatersheds (Appendix 1, Table A1-5) and between 10-14% for the aggregated drainage area to the SLB PMU (Table 2-6).

Table 2-6. Estimates of dissolved phase PCBs for well-sampled watersheds (in white). The five SLB aggregated drainages were then estimated (in gray at the bottom) based on the dissolved phase and imperviousness or old industrial relationships in the well-sampled watersheds.

Watershed	PCB FWMC (ng/L)	Intercept	% Dissolved	% Impervious	% Old Industrial	Estimated % Dissolved based on:	
						% Impervious	% Old Industrial
Z4LA	14.7	1.4	10%	68%	9%		
Marsh Ck	1.97	0.177	9%	10%	0%		
N. Richmond PS	8.27	1.92	23%	62%	7%		
Sunnyvale East Ch	55.7	4.5	8%	59%	3%		
Pulgas Ck PS - South	137	30.6	22%	87%	46%		
Ettie St PS	58.6	12.5	21%	76%	10%		
Duane Ct and Ave Triangle SD (SC-049CZC200)			34%	79%	23%		
Victor Nelo PS Outfall (SC-050GAC190)			12%	87%	4%		
Forbes Blvd Outfall (SM-319)			3%	79%	0%		
Taylor Way SD (SM-32)			18%	67%	11%		
Tunnel Ave Ditch (SM-350/368/more)			6%	47%	8%		
Sausal Ck, AC unk14, AC unk15				33%	5%	10%	13%
Peralta and Courtland and Seminary Creeks, AC unk16				59%	5%	14%	13%
Arroyo Viejo Ck, Lion Ck, AC unk17 and AC unk20				32%	2%	10%	11%
San Leandro Ck and Elmhurst Ck				56%	9%	14%	14%
AC unk18, AC unk21, AC unk22				51%	0%	13%	10%
Total for Margin SLB Unit				45%	5%	12%	13%

We reviewed the literature to better understand characteristics of dissolved concentrations in runoff and to see if published observations of dissolved concentrations were similar to our estimates. The literature review supported the conclusion that PCBs have a high affinity for sorption to suspended sediment and organic matter in stormwater runoff, and lower suspended particulate concentrations tend to persist during periods of dry weather, so dry weather conditions would favor greater proportional transport of dissolved phase PCBs. When data from empirical studies in the literature review are stratified between dry and wet weather conditions, the data points representing dry weather sample collection have higher overall proportions of dissolved PCBs (Figure 2-4, 52-93% versus 10-52% for wet weather sampling).
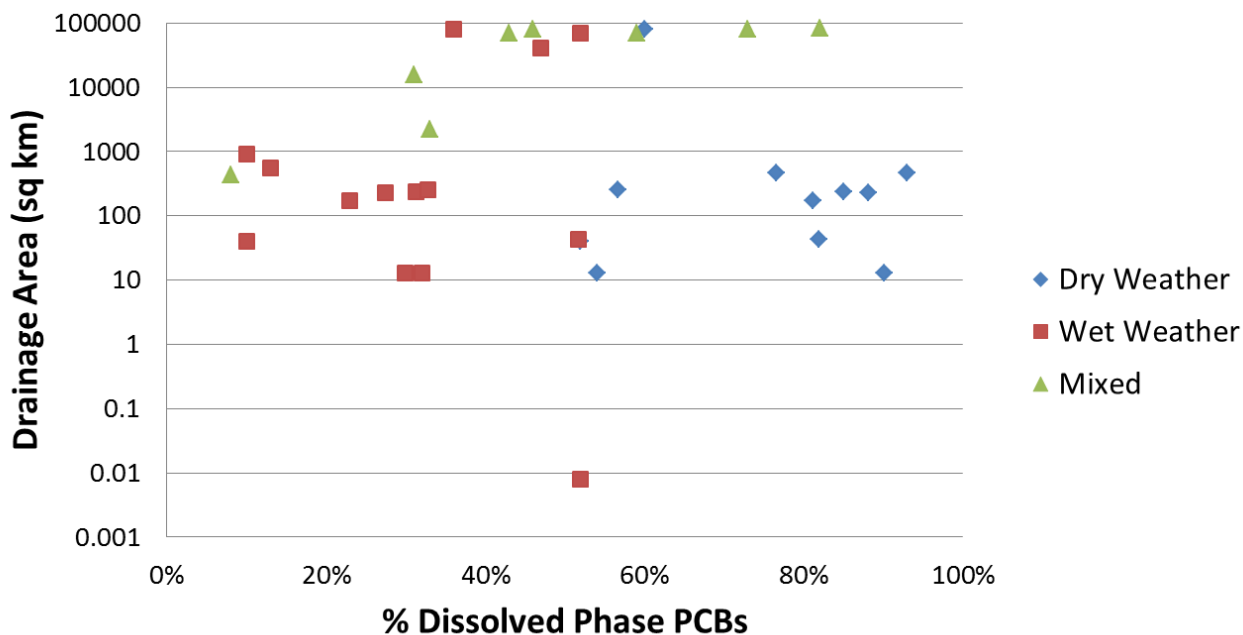

Figure 2-4.   Summary graph of literature review case examples. Studies include: Steuer et al., 1999; Foster et al., 2000a, 2000b; Verbrugge et al., 1995; Marti and Armstrong, 1990; Quemerais et al., 1994; Howell et al., 2011; Hwang and Foster, 2008; Tlili et al., 2012; Ko and Baker, 2004; Gomez-Gutierrez et al, 2006; Bressy et al., 2012; RMP samples.

These dissolved phase estimates for the SLB watersheds appear reasonable for storm flows relative to the results of the literature review, and support our estimates. The proportion of dissolved phase PCBs during non-storm flow is likely to be much greater based on data from the literature (52-93%), and we therefore recommend applying the median value from the literature review, or 81%.

e.   Loading Summary

Numerous improvements could be made to the loading estimates for the San Leandro Bay PMU and its subwatersheds (to be discussed later), but at this time, Table 2-7 summarizes our best estimates of the PCB loads transported to the PMU during different types of flow conditions, and the partitioning of

those loads. We estimate that an annual average of 986 g of PCBs is transported to the PMU from the combined 83.4 sq km of area from the five aggregated watershed groups. It is estimated that storm flows overwhelmingly deliver that load (94%), dominantly in the particulate phase (85% versus 15% dissolved). Although the 10-year storm event can transport approximately 11-16% equivalent of the average annual load, it is estimated that approximately 92% of the long-term load is transported during the dry season and storm events smaller than the 1:1 year return frequency. Non-storm related flows likely account for only about 6% of the total load and these flows are likely dominated by PCBs in the dissolved phase.

Inputs from Central Bay waters constitute about 20% of total annual PCB inputs into SLB, based on our current "best" estimate of watershed loads (~1kg/yr) and calculations of input tidal volumes and ambient Bay concentrations discussed later in Section 4. As watershed loads get reduced or eliminated, those Bay inputs could become the dominating factor determining the steady state concentrations in SLB. However, current watershed loads would have to reduce four-fold before the Bay concentrations became equally important.

f.   Projected Changes in Export to the PMU

The Municipal Regional Stormwater NPDES Permit includes provisions (C.11 and C.12) that require implementation of control measures to reduce PCBs in stormwater runoff. In August 2016, the Bay Area Stormwater Management Agencies Association (BASMAA) released a report detailing the accounting methodology that would be used to estimate load reductions as the result of various possible control measures (BASMAA, 2016). No specific projects have yet been identified by BASMAA for the San Leandro Bay watershed, however, it is likely that control measures will target this area among others.

In addition to the MRP requirements, two major clean-up efforts are currently underway in the San Leandro Bay watershed. First, DTSC is leading a clean-up at the General Electric site located at 5441 E. 14th St. in Oakland between 54th and 57th Avenues (pers. comm. Katherine Baylor, USEPA; Geosyntec Consultants, 2011). This location was formerly a transformer and electrical equipment facility from approximately the mid-1920's until nearly 2000. Surface soil samples at this site measured up to 11,000 mg/kg. The area has been nearly completely capped and there is almost no remaining exposed soil. Second, USEPA is leading the cleanup of an old Union Pacific Railroad site at 701 73rd Avenue just east of the Coliseum in Oakland (pers. comm. Janet O'Hara, SFBRWQCB). This location was formerly a rail station and then a salvage yard. Soil samples at this site measured up to 420 mg/kg.

[Phase 2 analysis: The influence of lower watershed hotspots].

In summary, control measures to meet MRP requirements are not currently identified but are likely, and two major clean-up efforts are currently underway. In light of management actions currently in an early phase of a longer-term effort, and in light of the longer-term TMDL goal of a 90% reduction in PCB load, this analysis considers a range of possible load reduction levels in the PMU mass budget: 25%, 50% and 75%.

Table 2-7.   Summary table with load and partitioning estimates during different types of flows.

Watershed	Total Area (km²)	Total Runoff Volume (Mm³)	Total Annual Load - Best Estimate	[1]During storms	[2]During non-storm periods	[3]Dry Season and storms smaller than the 1:1 year event	[4]1:10 year event	[5]Dissolved phase during storms	[6]Assoc. with particles <25 µm during storms	[7]Assoc. with particles 25-75 µm during storms	[8]Assoc. with particles >75 µm during storms	[9]Dissolved phase during non-storm periods
									Annual PCB loads transported during different flow and partitioning characteristics (g)			
Sausal Ck, AC unk14, AC unk15	13.2	4.4	136	128	8.2	125	19	15	46	28	39	6.6
Peralta and Courtland and Seminary Creeks, AC unk16	15.0	4.9	175	164	10.5	161	24	23	55	36	51	8.5
Arroyo Viejo Ck, Lion Ck, AC unk17 and AC unk20	26.6	9.4	234	220	14.0	215	33	25	80	48	68	11.4
San Leandro Ck and Elmhurst Ck	25.7	7.1	350	329	21	322	49	49	107	71	101	17.0
AC unk18, AC unk21, AC unk22	2.9	0.8	91	86	5.5	84	13	10.5	30	19	26	4.4
Total for Margin Unit	83.4	26.6	986	927 (94%)[a]	59 (6%)[a]	848 (86%)[a]	138 (14%)[a]	114 (12%)[b]	326 (35%)[c]	201 (22%)[c]	286 (31%)[c]	48 (81%)[d]

[a] Percentage relative to the average annual load
[b] The percentage dissolved is watershed specific based on Table 2-6
[c] Percentage relative to the total storm-related annual load

[d] Percentage relative to the non-storm-related annual load

[1] 94% of the average annual load; based on the average of storm-related flows measured at Zone 4 Line A and North Richmond Pump Station

[2] 6% of the average annual load; based on the average of summer and winter non-storm flow measured at Zone 4 Line A and North Richmond Pump Station

[3] 86% of the average annual load; based on the continuous loads method and subtracting non-storm flows.

[4] 14% of average annual load; this number is the average of the two methods (the recurrence interval method and the continuous loads method) used to estimate the loads delivered to the PMU in different types of storm events.

[5] The percentage dissolved is watershed specific and based on the average estimated by the relationship of the dissolved proportion and imperviousness or old industrial area in six measured Bay Area watersheds.

[6] 33% of the load; based on the average of six samples collected in Zone 4 Line A and a sampling site in Richmond (48% of the storm-related PCB load) - the estimated dissolved portion (15%).

[7] 22% of the storm-related PCB load; based on the average of six samples collected in Zone 4 Line A and a sampling site in Richmond.

[8] 31% of the storm-related PCB load; based on the average of six samples collected in Zone 4 Line A and a sampling site in Richmond.

[9] 81% of the PCB load transported during non-storm periods; based on the average of 10 watersheds discussed in the literature which had distinct storm versus dry weather sampling.

g.   **Monitoring Recommendations**

Over the past 17 years, the Sources, Pathways, and Loadings Workgroup has developed and implemented a number of field-intensive monitoring protocols designed to characterize concentrations, particle ratios, and watershed loadings during storms. In addition, most recently, the Workgroup has been developing and testing remote sampling techniques that, if successful, may reduce the field effort required for each individual sample, potentially allowing for a greater number of samples with a fixed budget or reduced overall budget. Each of these monitoring protocols is tailored to suit specific questions and needs (Table 2-8). Presently, these same monitoring designs are being explored for their value in measuring trends in storm water concentrations and loads in response to management efforts.

Short-Term Data Gathering

The focus of any short term (near term) data gathering is to improve the current estimates of concentrations and loads that have been used to support the SLB PMU conceptual model of initial retention (section 3 of this report) and the long term fate one-box model (section 4 of this report). The main data weaknesses associated with the loading estimates are the lack of monitoring data during storms in the SLB subwatersheds, apart from San Leandro Creek (flow and PCBs for three water years). Such data would allow for relative ranking of loading from each of the subwatersheds and help to provide a better calibration for the load estimates generated by the RWSM. Flow data from these subwatersheds would also allow for better calibration of the RWSM for hydrology. Another major weakness is the lack of information on PCBs in relation to fraction (dissolved or particle-bound) and particle size. In the near-term these data gaps can be filled using either the wet weather single storm reconnaissance composite sampling design or the wet weather single storm reconnaissance discrete sampling design. The discrete method is slightly better in that measures the variability in the relationships between flow and PCBs and between the dissolved and particulate phase over a storm. If these data were coupled with stage and flow measurement, we could determine a storm-specific load which would help to provide a reality check on the annual-scale loads estimates for each of the PMU sub-watersheds. These recommendations could be implemented in a phased approach. In the first phase, remote samplers could be used to rank the relative particle concentrations between the subwatersheds. In a second phase, active water sampling during multiple storms (four may be a good starting point) could be completed for the highest priority locations and analyzed to determine dissolved concentrations and concentrations for several grain sizes. The resulting whole water concentrations could be converted to particle ratios to compare with other sites, used to better understand the congener profile variability in relation to possible watershed sources, and used to further improve the calibration of the RWSM.

Long-term Monitoring

The focus of long term monitoring is to ensure there is sufficient baseline data to observe change in relation to management effort. As will be argued in section 4 of this report, the results of the one-box model suggest that PCB loading from watershed sources will likely have a large effect on the decline of concentrations of PCBs in the PMU and improvement of biologically relevant water quality. Hence, initiatives in the watershed leading to significant reductions in PCB loadings to the PMU could produce significant and measureable improvements in water quality in terms of declining concentrations of PCBs.

If San Leandro Bay and its watersheds are chosen as a focus area for management, a higher level of monitoring effort (wet weather multi-storm discrete sampling coupled with stage, flow, and turbidity measurement) could be desirable. The key question for implementation of this level of effort (the highest level identified in Table 2-8) is, over what time frame and what magnitude of change would it be desirable to observe? If the SLB watershed ends up having a lot of focused management effort aimed at PCBs or redevelopment more generally (perhaps focused around the BART station and the Coliseum), are baseline data suitable for determining long term trends in storm water concentrations and loads needed? These questions need to be reconciled as we learn more about SLB or as we continue to work on other PMUs such as Steinberger Slough, where further insights will be gained as to the sensitivity of the model of Bay margin processes to data weaknesses. For trends in relation to management effort, the best-case scenario would be a trends monitoring program downstream from where management effort is occurring, and intensified sampling in the PMU to assist our understanding of processes of biological uptake and change through time. As will be shown in section 4 of this report, model results clearly illustrate that a fine temporal resolution of loading information is not required to better understand the processes of PCB fate in the PMU. So if a monitoring program to address loading trends is set up, the focus of the design should be on where best to monitor in relation to management effort and how many and what types of samples under what storm conditions will be needed to see a change. Currently baseline data are lacking in areas downstream from watershed PCB source areas. So if a significant amount of source control and redevelopment takes place, the baseline data to measure, detect and evaluate the success of recovery is currently lacking.

As indicated in Table 2-8, dynamic simulation models can be used to estimate loads. As the stormwater permittees move through the process of defining and implementing accounting and modeling methods to support reasonable assurance analysis (RAA), there will be a greater need for BMP effectiveness information, model input and calibration data, and trends verification data. The minimum monitoring method suitable for input to and calibrating the dynamic simulation model that is included in Table 2-8 is the wet weather multi-storm discrete sampling protocol coupled with stage and flow measurement. Obviously, if more years of data were collected, a greater accuracy would be achieved but with gradually diminishing returns. We recommend making decisions about what kinds of accounting and modeling tools to apply to the SLB watershed as an efficient framework for designing any further monitoring.

Table 2-8.   Monitoring protocols available to support characterization of concentrations, phase distribution, particle ratios, or PCB loadings during storms.

	Name of protocol				
	Remote sampler (Walling tube/ Hamlin)	Wet weather single storm reconnaissance (composite)	Wet weather single storm reconnaissance (discrete) coupled with stage and flow measurement	Wet weather multi-storm discrete) coupled with stage and flow measurement	Wet weather multi-storm discrete) coupled with stage, flow, and turbidity measurement
	Relative level of effort				
Data uses	Low	Medium	Medium-high	High	Very high
Trends	Maybe	Maybe	Maybe	Yes (lower certainty)	Yes (high certainty)
Relative PMU sub-watershed rankings	Yes	Yes	Yes	Yes	Yes
Quantification of PCB concentrations on sediment size fractions	Yes	Yes	Yes	Yes	Yes
Quantification of dissolved phase		Lower certainty	Lower certainty	High certainty	High certainty
Support for RWSM to estimate loads				Calibration only	Calibration and verification
Measured storm specific loads			Yes	Yes	Yes
Support for dynamic model (e.g. SWMM) to estimate continuous tidal loads estimates			Calibration only	Calibration only	Calibration and verification
Measured wet season loads				Yes (lower certainty)	Yes (high certainty)
Measured continuous loads estimates					Yes (high certainty)

g.   San Leandro Bay versus Emeryville Crescent PMU loads

Stormwater runoff into the SLB PMU drains from an area over twice the size of the Emeryville Crescent and more than eight times the industrial area. For the Emeryville Crescent, the most industrialized and source area dense portion of the watershed drainage area (the Ettie St. Pump Station Watershed) had been sampled several times and therefore had a decent empirical dataset from which to compute first order loads. On the other hand, stormwater data is not available for the San Leandro Bay PMU watersheds (several of these watersheds were sampled in a single storm event in WY 2017 but the data is not available as of the time of this reporting) and therefore loads estimation is entirely dependent on the RWSM. One aspect of PCB loading into the PMU that is important that is not well captured in the available data is the likely very high variability of concentrations between storms. Recent data on sediment concentrations verify that there are locations with high concentrations but we presently have no understanding of how these few and likely smaller areas generate loads that might affect the overall PCB mass balance for the system. The question in ecology is always, what is the balance between the collective influence of a few areas that exhibit high concentrations or high rates of mass transport versus the more ubiquitous and constant concentrations and loads associated with a broader area of the landscape or at non-event timescales? Both PMUs appears to have the commonality of having these smaller, highly polluted areas but data are not sufficient to understand their overall importance on the mass balance and linkage to biological uptake at the base of the food web. Further work is needed, likely outside of the RWSM, to accurately locate more of these areas and to estimate the timing and loads associated with these highly polluted smaller areas. Also, these areas will be the most cost-effective to manage if there is a desire to address impacts associated with stormwater loads in the PMUs. It will be important to better understand the linkage between these highly polluted areas and their impact on water quality in the PMU. This is a key future area of research that is needed to better understand the impact of watershed activities on water quality in the PMU and the Bay.

h.   References

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3. INITIAL RETENTION IN THE PMU

   a. Factors influencing retention

   The general conceptual model of sediment associated contaminant fate and delivery in margin areas (Fig. 3-1) developed for Emeryville Crescent can also be applied to San Leandro Bay. Contaminants are delivered via tributary channels usually somewhere in the intertidal zone, with subsequent deposition, resuspension, and eventual (partial) transport out of the area. This section will focus on the short-term fate of discharged loads, i.e., the likely deposition zones for discharges.
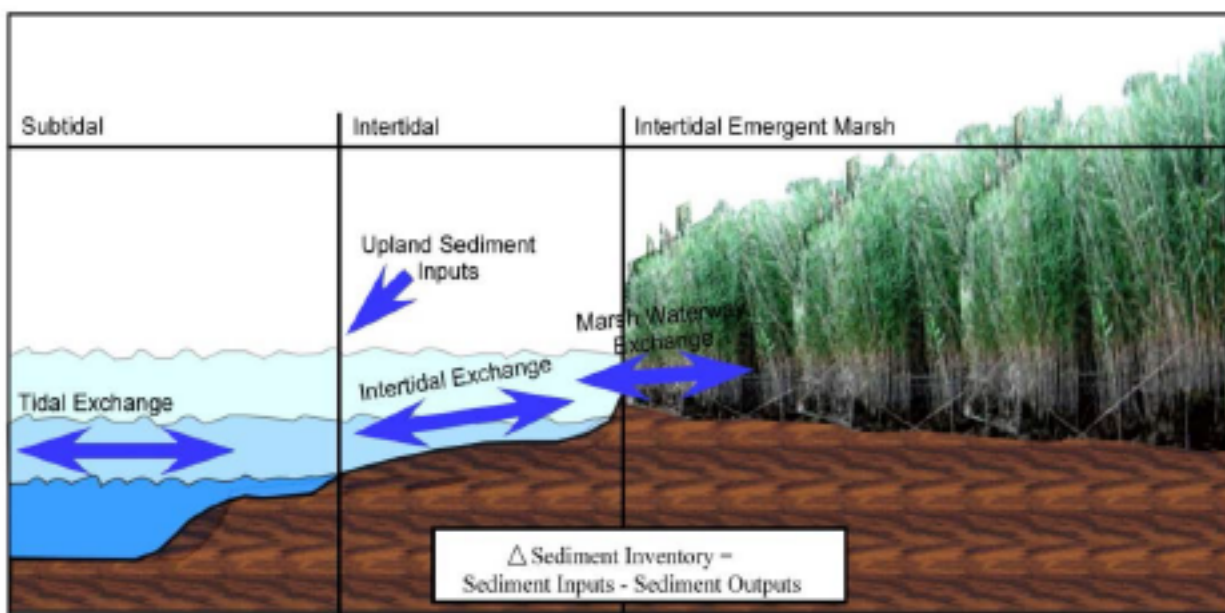

Figure 3-1. General conceptual illustration of margin sediment fate

      i. Tidal elevation

   Much of San Leandro Bay is very shallow, so the location of initial entry of contaminants into the area will depend on the portion of the tidal cycle at which the discharge occurs. Although there will also be spring-neap tidal cycles affecting the discharge, daily average diurnal tidal cycle statistics represent a reasonable starting point for characterizing the probable average locations of discharge over multiple decades.

   The MHHW (mean higher high water), MHW (mean high water), MSL (mean sea level), MLW (mean low water), and (mean lower low water) MLLW tidal elevations within San Leandro Bay are shown (Figure 3-2), with 200 to 300 m differences in the points of entry at MHHW versus MLLW for Area 2 (East Creek) and Area 3 (Damon Slough) along the eastern shoreline. The timing and duration of storm events is largely independent of tidal

influences (despite minor influences of lunar phase (Kohyama & Wallace 2016)), so the occurrence of a discharge at any given tidal elevation is probably best modeled as a random function of time. Given the sinusoidal pattern of tides, there is a slight propensity towards discharge at the upper and lower ends of tidal elevation under a random timing assumption.
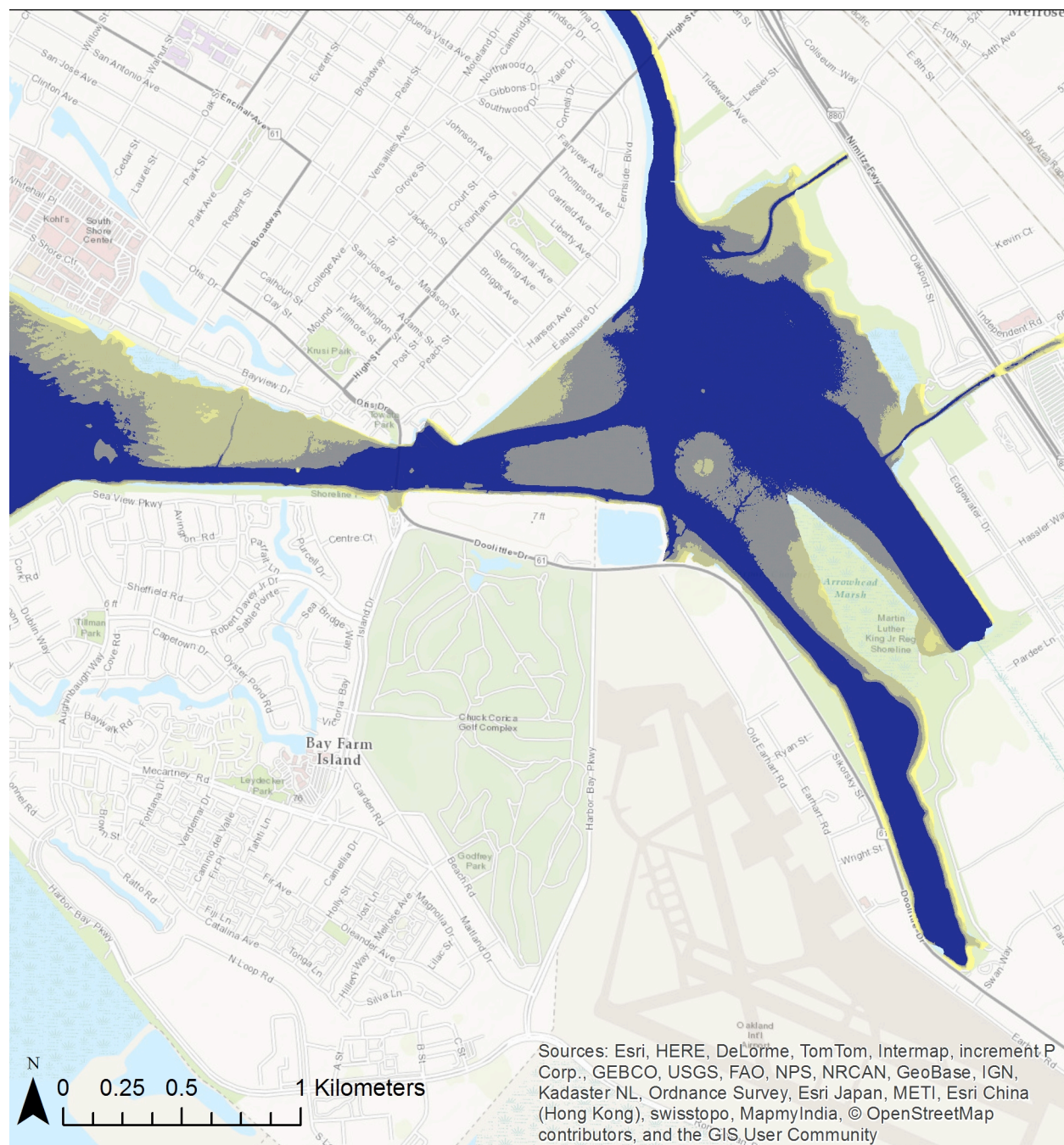

Figure 3-2. Tidal datums in San Leandro Bay. MLLW, MLW, MSL, MHW, and MHHW indicated by colored contours, from darkest (blue) to lightest (yellow), respectively.

ii. Settling rates

In addition to the timing and thus location of discharge, the propensity of discharged loads to remain in San Leandro Bay will depend on the characteristics of the discharged loads. A settling experiment in a previous study of stormwater samples from Hayward Z4LA and a Richmond storm drain (Yee and McKee 2010) indicated that between approximately 30% to 70% (towards the higher end at higher flows) of PCBs would settle out of a 30 cm settling column within 20 minutes, or roughly 1 m/hr settling. Typically half to two-thirds of that total (again on the higher end for higher flow and higher concentration samples) settled out within 2 minutes (10 m/hr).

Various factors may cause settling times faster or slower than those measured in the laboratory. Tidal currents and wind waves in the natural environment will result in longer settling times. Other processes such as flocculation of freshwater runoff entering a saline receiving water may increase settling rates. On the other hand, a buoyant plume of freshwater flow can carry loads further, but these phenomena will be highly event-dependent and it is hard to anticipate net effects without *in situ* empirical data. However, the laboratory settling rates obtained represent a simplistic (likely upper bound) estimate of likely deposition in the near field of any discharge. Much of San Leandro Bay is very shallow, less than 1 m deep at MLLW, so suspended sediments may often settle less than 1 m before encountering the sediment surface.

iii. Transport

Another major factor to consider in predicting the short-term fate of pollutants and sediment discharged to SLB is the speed of advective flows leaving the area. The ebb tide, occurring over around 6 hours, likely represents the largest pathway for removal, at least for fine suspended sediment and dissolved phase contaminants. It occurs twice daily, largely independent of any watershed flows, so for the majority of days in each year where there is only baseflow, tidal transport still occurs. Even for coarser-grained sediments only mobilized by large freshwater flow events or wave or tidal resuspension, such events would require concurrent outgoing tides to export appreciable mass before these coarser sediments settle out again. The volume in SLB at MLW is about 43% that at MHW, with a portion of that returning on the subsequent flood. An estimate of the returning portion will be discussed in a later section on an exploratory hydrodynamic model for SLB.

b. San Leandro Bay Compared to Other Bay Margin Areas

Comparisons to a range of other PCB contaminated areas (including SLB) within San Francisco Bay were made in the previous conceptual model report for Emeryville Crescent (Davis et al. 2017). With constricted connections to the open Bay, SLB is highly protected from strong waves and tidal currents in its interior, so concentrations and the rates of sediment turnover should be slower than more open shorelines such as Emeryville Crescent. It receives discharge from San Leandro Creek and numerous smaller watersheds.

Many of them contain older industrial areas with known or potential past PCB usage or disposal, including a Pacific Union yard and other properties along Damon Slough currently being investigated by EPA. As such, it may present a very complex picture of PCB sources to deconvolute. Nonetheless, there are some hints of possible gradients extending away from upland sources, for example a drop in PCBs with distance from the mouth of Elmhurst and San Leandro Creek (Figure 3-3). Although sources are likely to differ among watersheds, even when land uses are similar, we can apply simple models (e.g., the RWSM in the previous chapter, and a one-box fate model in the following chapter) to get general qualitative expectations of fate processes, and to identify important factors and information gaps to be addressed for better understanding of long-term PCB fate in the area. More recently-collected data for PCB concentrations in water and sediment from SLB will also be discussed in the next chapter.
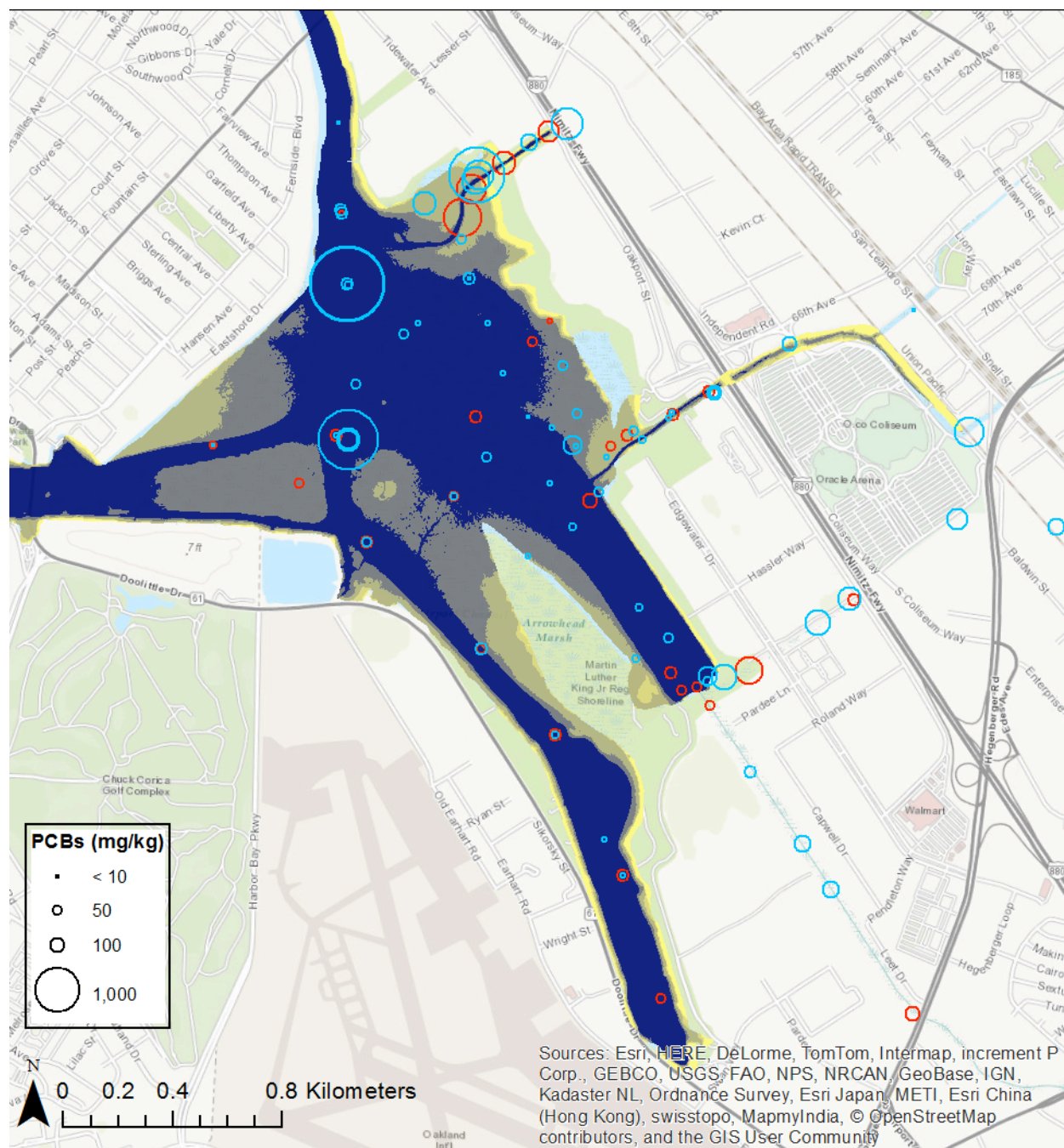
Figure 3-3.   Bubble plot of sediment PCB concentration distributions in and around San
               Leandro Bay (from Daum et al., 2000 in blue, and summer 2016, in red).

      c.   Hydrodynamic modeling

       Exploratory analyses have been carried out using a SUNTANS hydrodynamic model,
which includes tidal forcing in the coastal ocean, outflows from major rivers, and a
simplified wind field. Based on these inputs, the model predicts sea surface height and
depth-averaged current velocity. Though not calibrated for San Leandro Bay, this model

has been validated for tides and currents at a wide range of stations in Central Bay, South Bay, and San Pablo Bay. The model output has been analyzed for two specific purposes: (i) extracting local tidal datums for SLB, and (ii) characterizing tidal velocities and transport.

Tidal datums reported for SLB (Table 3-1) are tied to the NAVD88 vertical datum, allowing for direct comparison to tide gages around the Bay, such as the San Francisco Fort Point tide gage at the Golden Gate. The results show a small super-elevation of the mean water level, and 24% amplification in mean tidal range (MHW-MLW).

Table 3-1. Tidal datums for San Leandro Bay versus Fort Point (mouth of SF Bay).

Datum	San Leandro Bay (m NAVD88)	Fort Point (m NAVD88)
MLLW	-0.10	0.02
MLW	0.22	0.36
MSL	0.98	0.97
MHW	1.77	1.61
MHHW	1.96	1.80

Velocity data have been extracted from the model for a period of 18 days (April 4 to 23, 2016) in order to average over spring-neap variations in tides. The largest velocities occur near the mouth of SLB on the deeper (northern) side. Tides in SLB are highly asymmetric, with flood dominance at the western boundary (5.3x ebb), and ebb dominance (1.6x flood) to the north. Thus overall net flow is largely in from the west and out to the north.

Current speeds across a central transect of SLB (extending from Arrowhead Marsh, roughly bisecting the east and west sides) range from a neap-tide small ebb of xxx m/h, to a neap-tide large ebb of xxx m/h and spring-tide large ebb of xxx m/h. In general, velocities in the intertidal zone at the edges of SLB are much lower than in the central portion, so assumptions of uniform mixing (inherent in using a single box model) are likely oversimplistic and likely to result in some artifacts (discussed in the next section). RUSTY will get me stats Thurs.

d. Retention in moderate and large storms

The distance that suspended sediment in stormwater is carried will be highly dependent on the volume and velocity of the discharge, and the velocity of the receiving water (e.g., whether it is a high or low slack, flood, or ebb tide). Assuming that the discharge is occurring into a static water body (a slack tide) gives us at least a sense of scale for the likely discharge velocity extending into SLB. We consider the cases of 1 year and 10 year annual return interval (ARI) rainfall events to derive reasonable bounds for the volumes of discharge to SLB.

The 24 hour rainfall from a 1 year ARI storm event obtained from the NOAA record for Oakland indicates precipitation of about 1.9 inches. Data on rainfall from the Oakland Museum (supplemented by rain gauge data from Oakland Airport and Alameda where there were gaps) over a 40-year period (1970 to 2010) suggest a slightly lower but similar rainfall for the 40th largest day, 1.75 inches. Using runoff coefficients for the various land uses and running the RWSM, we estimated daily outflows of 314,000 m^3 per day for Area 1, 356,000 for Area 2, 600,000 for Area 3, 559,000 for Area 4, and 62,000 for the remaining area (discharging to west SLB) for a 1 year ARI rainfall event. A 10 year ARI 24 hour storm event (a threshold above which there are typically only 4 events in a 40 year history) will deliver about triple the volume for each of the areas.

As noted in the Emeryville Crescent conceptual report, the cumulative rainfall of all events greater than the 1 year ARI event in the 40 year Oakland Museum rain gauge data series accounts for only 8% of the 40 year total. These large events individually deliver relatively large volumes of discharge with large short-term impacts, but missing these largest events on a multi-decadal timescale may have only a relatively small impact on estimated loads for impervious urbanized watersheds, where constructed stormwater conveyances are generally designed to be self-cleaning. In contrast, for more pervious watersheds, small precipitation events are simply absorbed into the landscape. There are also non-linear relationships between runoff and sediment loads for pervious watersheds, with higher flows delivering sediments disproportionate to their volume. PCBs in urban conveyances are likely source-limited in the short term, so underestimates of PCB loads from missing large events are likely less than proportional to missed flow. Once recent build-ups are scoured, additional flow may deliver lower (perhaps negligible) additional loads until sufficient time has occurred for further release and build up.

The daily volume delivered to SLB in a 1 year ARI event is 1.89×10^6 m^3, about two-thirds of the volume in SLB at MLW (2.83×10^6 m^3). Thus an entire 1 year ARI 24 hour event's discharge occurring in the 3 hours immediately preceding and around low ebb would still largely be contained within SLB. Some dispersion and dilution would occur with the outermost waters delivered, but it is likely that much of the very rapid- (~10 m/hr) and moderately- (~1 m/hr) settling sediments containing the majority of PCBs in stormwater samples reported previously (Yee and McKee 2010) would settle out before exiting SLB.

A 1 year ARI daily total discharge occurring all in the last hours of an ebb tide are highly improbable however. An estimated rainfall of 1.85 inches over 3 hours represents a 25 year ARI event for Oakland, and 1.87 inches over 6 hours represents a 5 year ARI event. Water discharged at the MLLW line at low slack (even from Area 1 & 2) would largely be sent back with the incoming flood tide. Water discharged earlier in the tidal cycle starts nearer the shoreline (~MSL if in the last 3 hours of an ebb tide), and thus much of that water would also remain or return to SLB on a subsequent flood tide. Net export would require discharged material to roughly remain in place (i.e., settled out) during flood tide then require resuspension of sediment in place at that point during ebb tide (beneath ~1 m of water at high slack), with sufficient energy to keep it suspended until exit from SLB.

Similarly, although the volume of water delivered in a 10 year ARI daily rainfall event, 6.05×10^6 m^3, is over double the volume of SLB at MLW (2.83×10^6 m^3), much of it is likely to initially stay within SLB. It is highly improbable that a 10 year ARI daily rainfall could occur in the ~6 hours of a single tidal ebb. The 3.75 inches of a 10 year ARI daily rainfall, is greater than a 1000 year ARI for a 3 hour total event (3.07 inches), and greater than a 200 year ARI for a 6 hour event total (3.63 inches).

The unsettled fraction (<1 m/hr settling rate) in the BMP evaluation project (Yee and McKee 2010), 30% to 70% of stormwater total PCBs, provides an alternative reasonable estimate of the portion of PCB loads that might not be retained in SLB in the short term. Although this unsettled fraction may not be immediately delivered out of the area, while it remains unsettled, it can continuously disperse, dilute, and be advectively transported, and thus eventually be carried out of SLB after a number of tidal cycles. Quantifying the export rate for this fraction would require hydrodynamic modeling beyond the scope of this effort, but a roughly calibrated (focused mainly on generating approximately correct tidal heights) SUNTANS simulation described previously suggests about 25% of the volume in SLB at high tide is newly input from the west, whereas the flux volume from the north is smaller than the previous ebb discharge, so a large percentage would be returning water. With around 25% of the dissolved or unsettled fraction replaced on each tidal cycle, after 10 tidal cycles (5 days), only 6% of this initial unsettled fraction would remain, so it may be a reasonable approximation that this unsettled fraction effectively was immediately lost from SLB. A simple mass budget model in the following section will evaluate the impacts on net tidal export of various assumptions for PCB loads and concentrations inside and outside of SLB.

e.   Hypothesized initial deposition pattern

Unlike the case for Emeryville Crescent, a prior study of PCBs and other contaminants in SLB (Daum et al., 2000) and data for PCBs collected summer 2016 provide a relatively dense distribution of concentration data with which to evaluate deposition patterns. A bubble plot of PCB concentrations from those studies (Figure 3-3) shows generally higher concentrations in the sloughs leading to SLB, with generally decreasing concentrations moving from their entry points to deeper areas in SLB. The western side of SLB, draining smaller watersheds and with fewer expected PCB sources, also shows generally lower concentrations (although still relatively high compared to open water Central Bay sediment sites in the RMP).

With 30% to 70% of the PCBs in stormwater settling at a rate of 1 m/hr or more in lab experiments, and half to 2/3 of that fraction settling at over 10 m/hr, a large proportion of the total PCBs in sediment from any given stormwater discharge would be expected to rapidly drop out of the water column and be found near their entry point in the PMU. This fast settling fraction would especially be expected to be found in the near field; most of SLB is less than 1 m in depth at MLLW, and even at higher tides, some discharges will occur at the edge of the water line in the shallow sloped intertidal zone (i.e., discharged into a depth

< 1 m), and thus require little vertical settling distance to reach the bottom. Thus the axial travel distance of discharges in the first 0.1 hour (6 minutes) and 1 hour after entry can provide hints of the likely location of the majority of discharged contaminated sediments. These stormwater settling rates are much larger than those reported for the whole Bay one box model, but this may be expected. Open Bay rates settling rates are for sediments remaining largely suspended day-to-day in the Bay through typical tidal and wave action. Storm discharges represent episodic, higher velocity discharges, of which only a portion may remain suspended under normal tidal and wave action.

In order to estimate travel distances, velocities of discharges into the receiving water are needed. Measurements of discharge velocity in these tributary channels are not available, but we assumed an average flow velocity of around 1.7 m/sec, like that estimated for watershed discharges in the Emeryville Crescent conceptual model, and scaled discharge channel widths for all the areas in SLB to yield approximately the same linear velocities.   Similar to the case for Emeryville Crescent conceptual model report, we applied heuristic empirical calculations derived for turbulent jets (Cushman-Roisin, 2014). As previously noted, some conditions for those empirical relationships are violated (e.g., equal density of liquids, etc.), but these calculations can provide a rough sense of the distance over which discharged sediments are initially carried. The maximum velocity (umax) along the main discharge axis and mean velocity (umean) across at any given distance x can be estimated as a function of the jet outlet diameter, d, and the average velocity at the outlet, U:

$$umax(x) = 5 \, d \, U \, / \, x$$
$$umean(x) = 2.5 \, d \, U \, / \, x$$

In this equation x is the distance from a virtual point outlet, which occurs 2.5 d upstream of the actual outlet. At large distances from the actual outlet, the error of ignoring this factor is small (e.g., ~2.5% at 100 diameters downstream), but at shorter distances, using the distance from the actual rather than the virtual point outlet yields very large errors (for example, at the actual outlet, using x = 0 rather than the correct x = 2.5 d yields an undefined umean, rather than the correct mean velocity of U at the actual outlet).

An integration of the estimated umax from the input over the first hour of discharge for a 1 year ARI rainfall discharged over 3 hours for the various SLB areas suggests a maximum travel distance of around 600 to 700 m for an hour of flow along the main axis. The zones of greatest concentration on initial discharge will be in the cones downstream of the discharge, over a width about 40% of the distance from the virtual outlet, with the highest concentrations near the central axis of the discharge. These hypothetical cones of discharge are overlaid as yellow triangles on the PMU map in Figure 3-5
at high slack (near the MHW line), with red triangles indicating the travel distance over 0.1 hour (around 190 to 220 m for the different areas) where the fastest settling material is likely to deposit. For Area 1, entering flow is orthogonal to a strong current much of the time, so the entering plume will be sheared in the direction of the current, basically following the main current, depending on the portion of the tidal cycle in which discharge occurs. The zone of higher deposition for this area is simply illustrated as a band of higher concentration in the channel that would occur at high slack tide. For the area to the west of Arrowhead Marsh, the discharges are disperse from multiple points, so no cones of

discharge are pictured. At low tide, the discharge points for Area 2 and Area 3 will move 200 to 300 m away from the shore, while for Area 4, the entry point of discharge will change very little as it adjoins an excavated portion of SLB.
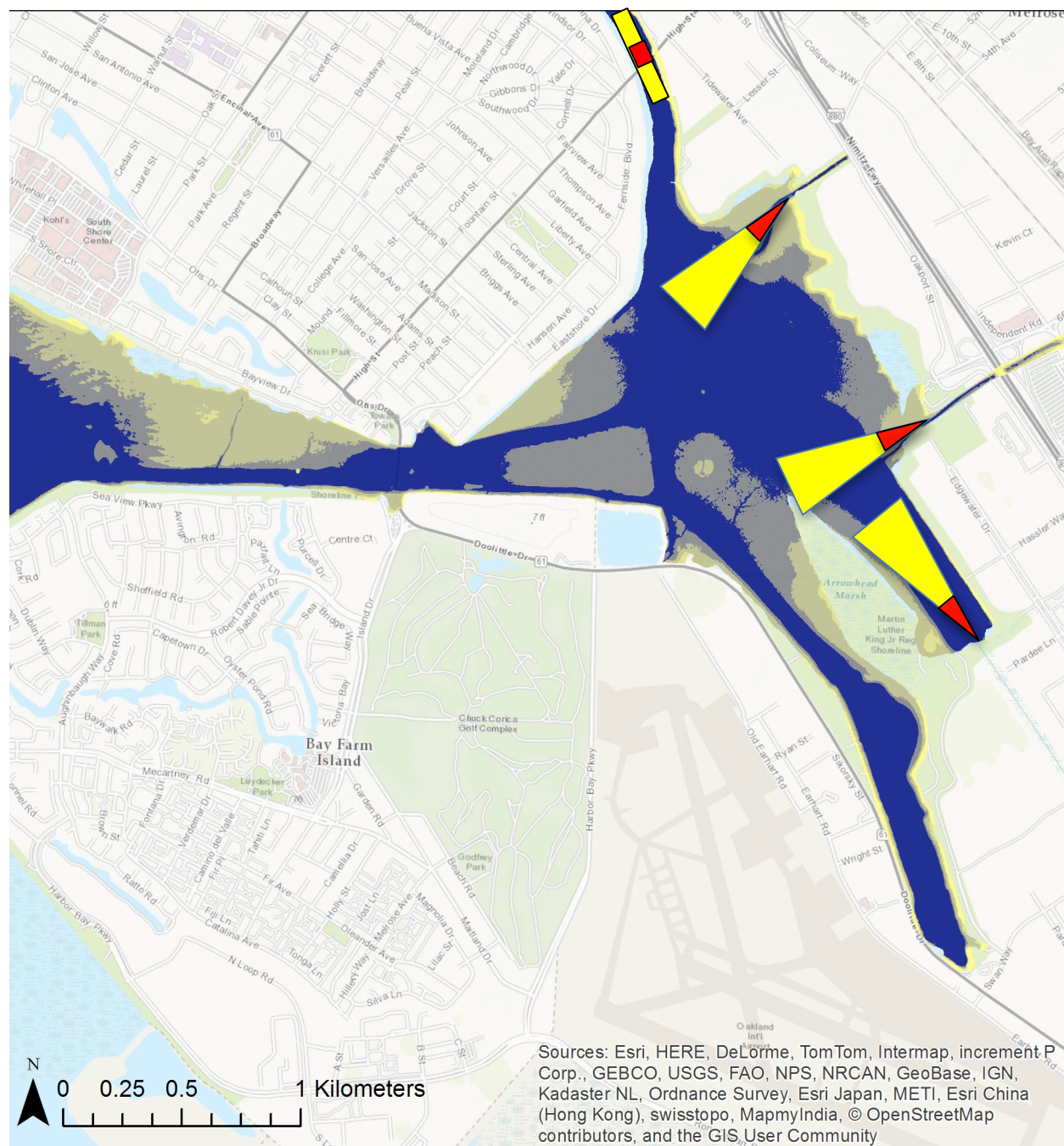
Figure 3-2.   Hypothesized short-term deposition zones at high tide. Yellow triangles represent 1 hour settling areas for each area. Red triangles indicate fast settling (0.1 hour) areas. The zone affected by discharge from Area 1 has no direction at high slack, so is pictured as a band rather than a conical plume, but this discharge will be stretched in the main direction of channel flow for other times.

Over time, resuspension and tidal currents will tend to disperse the initial discharge deposits, but some signal of the initial deposits may remain, especially for heavier discharged sediments, particularly in areas at the upper end of the tidal range, which would be subject to resuspension and transport for a lower proportion of time. Vegetated areas would similarly see less reworking, as they are typically even higher in elevation (e.g., in much of the emergent marsh above MHW), and the vegetation would dissipate wave energy and buffer tidal flows that might otherwise carry away contaminated sediment.

f.   Monitoring recommendations

Because SLB had previously been extensively sampled (Daum et al., 2000), continued sampling (such as that conducted summer 2016) should include at least a subset of sites previously reported. With a primary objective being to identify monitoring locations that are disproportionately influenced by recent discharge from the watersheds, the focus should also be in the near field of discharge channels from the watersheds of interest, and high in the intertidal zone where the time for resuspension and dispersion is reduced. A monitoring plan was developed for SLB using this general approach and executed in summer 2016. For Areas 2, 3, and 4, samples were taken where major channels enter SLB at high tide, 20 m downstream, and 100 m downstream. Samples were also taken by boat within the discharge channels, at the first pedestrian bridges in each major channel, and by foot from the banks of the channels where major roads (Highway 880 and Hegenberger Road) cross. For the rest of SLB, samples were taken for a subset of sites previously reported (Daum et al., 2000). Shallow surface sediment grabs (to 5 cm depth) were taken, to reflect the combined effects of short-term environmental processes (e.g., including bioturbation). At a subset of sites, the top 1 cm of sediment was separately analyzed, to determine whether recently deposited sediment would show different concentrations. Results for this monitoring effort will be further discussed in the following section on long-term fate.

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4.   **LONG-TERM FATE IN THE PMU**

   a. Fate conceptual model

        As mentioned in the previous section, the indicators of interest are dependent on the
prioritization among various questions to be answered.   For biotic exposure, we may be
interested the entire zone of sediment utilized by a species. For characterizing effects of
watershed management, we may be most interested in characterizing recently deposited
sediment, occurring after actions have been taken. The sampling effort conducted in summer
2016 largely focused on the first, with most samples reported for the top 5 cm only. At sites
inside channels and within ~20 m from the mouth of entering channels (for Areas 2, 3, 4), we
also examined top 1 cm sediments to compare to sediments from 1 to 5 cm, taken from the
same set of grabs.

        i. Simple box model

        A fate model developed by Dr. Frank Gobas' group at Trent University models the
exposure and bioaccumulation of persistent organic pollutants (POPs) by organisms exposed to
a heterogeneous mix of contamination (Gobas 2011). This model is similar to that group's
previous fugacity-based exposure models, with the main change being the ability to explicitly
model exposure from different zones, rather than derive a single spatially averaged exposure.
Similar to the Emeryville Crescent, SLB can be broken up into three zones, the vegetated
intertidal marsh (mostly in Arrowhead Marsh, and some on the eastern shoreline, with the
other areas largely hemmed in by roads and other hardscape and thus very little or narrow
vegetated marsh), the unvegetated intertidal mudflat, and the always submerged subtidal zone.
Some species such as small prey fish may occupy all these habitats at different times (e.g., when
the water depth is appropriate).   Others may be more restricted to one or two of these zones,
or even just one portion of one of the zones (e.g., the portion of mudflat below MLLW for
organisms preferring or requiring cooler and constantly submerged conditions). The Gobas
multi-compartment model currently only considers the biological exposure and fate aspects of
POP fate, so the environmental concentrations of the contaminants of interest are required
input parameters for each of the compartments. Gobas' group is also working to develop a
model of abiotic fate and transport to link with the biotic model, but for the short term, we
would need to use empirical data or separately devise a simple model of contaminant fate.

        ii. Congeners modeled

        The previous study of SLB (Daum et al., 2000) provided a reasonably good distribution
of samples to estimate average concentrations for the area (with more sites than the 2016
effort), so we used those results exclusively for modeling initial concentrations (rather than
mixing with BPTCP and other studies) to minimize concerns over inter-lab variation. Following
the approach used in the whole-Bay one box model of PCB fate (Davis 2004) and the previous
conceptual model for the Emeryville Crescent PMU, we first consider the fate of PCB 118, with
physico-chemical properties in the mid-range of PCB congeners, while acknowledging the
uncertainty bands of having selected only one congener representing "Total PCBs". Fate

predictions based on the physico-chemical properties of select lighter and heavier congeners is later briefly described. Ideally, each of the congeners could be considered and modeled separately to yield a true estimate of the fate of "Total PCBs", which would likely illustrate different evolution of the fate profiles for the various congeners. However, that is a bigger effort to be considered for the future (e.g., to model fate of specific dioxin-like PCBs, or to calibrate to observed congener profiles in discharges versus the ambient sediment in SLB). Another likely even larger challenge is to develop fate models for the different sub-habitats within SLB. Transport of sediment and contaminants between these habitat compartments is not continuous, so devising schemes for representing and estimating rates for these transfers (even on a pseudo-continuous time-averaged basis) presents a significant challenge in the absence of a series of continuous monitoring stations and a locally calibrated 3d hydrodynamic model. The mass budget presented here therefore represents primarily an initial scoping effort to evaluate the likely range of responses in the environment that might be observed, for different assumptions of loading and critical environmental parameters.
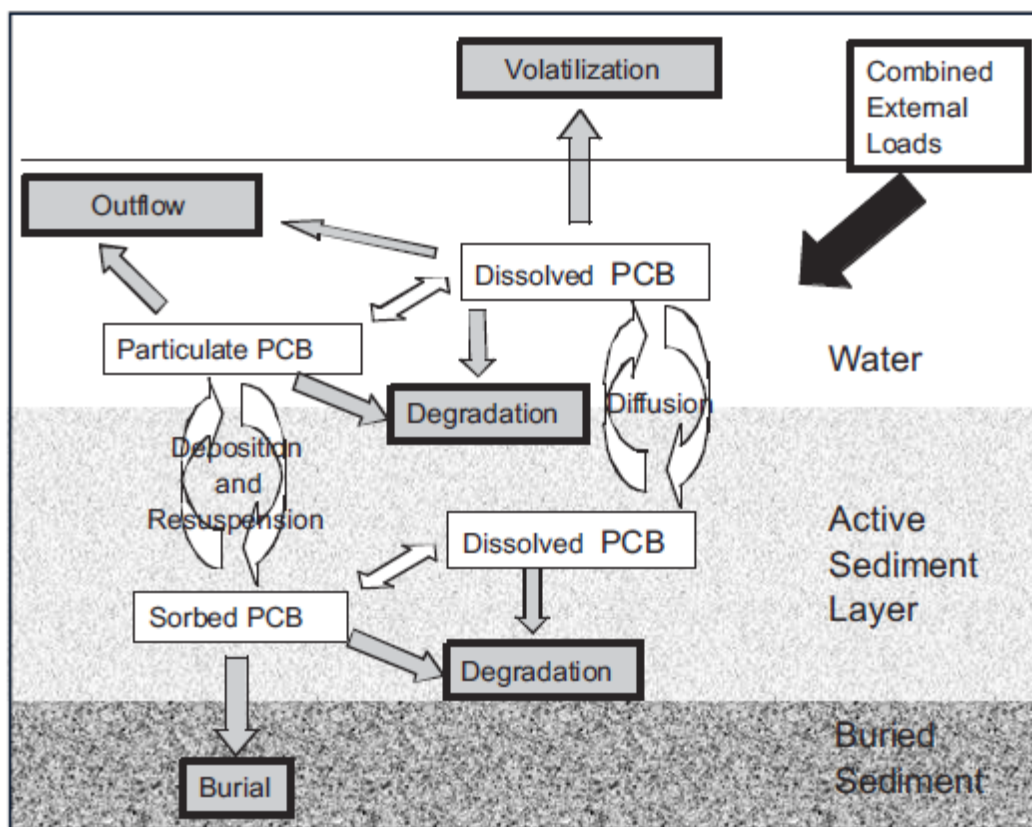

Figure 4-1. PCB Fate Conceptual Model (from Davis, 2004)

b. Mass budget

        A conceptual illustration of the components in the simple mass budget model is shown
(Figure 4-1). One uncertainty is the initial inventory of PCBs in SLB, but relative to the previous
conceptual model of Emeryville Crescent, there is an abundance of data (from Daum et al.,
2000). The Daum et al. data show a general pattern with the highest concentrations in channels
from the surrounding watersheds, and generally higher concentrations in SLB areas east of
Arrowhead (average 147 ng/g dw) compared to those to the west (average 101 ng/g dw), with
an area-weighted average of 125 ng/g dw for SLB. The second large element of uncertainty is
the depth of the "active" sediment layer, which impacts the calculated inventory. In the San
Francisco Bay one-box fate model (and Emeryville Crescent conceptual model), an active
sediment layer depth of 15 cm was used. We therefore again use 15 cm as our baseline
assumption here, but consider alternative depths of 5, 10, 20, and 25 cm. Table 4-1 presents
the range of PCB mass inventories for assumptions covering a range of active layer depths and
average PCB concentrations. Since the estimated inventory is a product of the sediment volume
(proportional to mixed layer depth) and sediment concentration, the calculated initial
inventory is linearly proportional to both these parameters. Other underlying assumptions and
parameters used for this simple model will be discussed in the following section.

Table 4-1. Time zero sediment PCB mass (kg) for the mass budget in relation to varying
assumptions of initial PCB concentration and mixed layer depth.

	5 cm	10 cm	15 cm	20 cm	25 cm
25 ng/g	1.6	3.2	4.7	6.3	7.9
50 ng/g	3.2	6.3	9.5	12.6	15.8
100 ng/g	6.3	12.6	19.0	25.3	31.6
200 ng/g	12.6	25.3	37.9	50.6	63.2

1. Inputs

        Primary inputs of PCBs to SLB originate either from the surrounding watersheds, or
from adjacent areas in Central Bay. Section 2 described the process for calculating average
annual PCB loads from these watersheds, using long term precipitation records, runoff
coefficients for various land uses, and a flow-proportional (i.e., constant water concentration)
assumption, yielding 986 g per year.   For our base case scenario we assume that this entire
annual load remains and is incorporated into SLB inventory. For 1 year ARI events and smaller,
which account for the vast majority of the overall load, this complete retention assumption may
be reasonable, as the discussion on discharge jet extents in the previous section suggest
discharged volume from most areas would remain largely in SLB, even if discharged at MLLW.
The major exception may be discharges from Area 1 (into the channel between Oakland and
Alameda), where channel ebb flows are 1.6x flood flows, so about 40% of discharges on ebb
events may never enter SLB. Some of the discharges from Area 2 (particularly early on an ebb
tide) may also exit SLB and not return, but these at least have some opportunity to settle out
and mix in with SLB waters and sediment before exiting.

A reasonable alternative scenario is to assume that the portion that settles at rates <1 m/hr in a quiescent lab scenario will not settle at all in the ambient environment with tidal currents, wind waves, and other forces tending to keep particles in suspension. With 30% to 70% of PCBs slowly or not settling in a lab setting, a 50% reduction in watershed loads from the base case can illustrate the impact of reduced initial retention on long term fate. Impacts of lowered loads from lowering estimated retention of initial loads will be examined in the discussion of the influence of external loads on mass budget model outputs later.

RMP station BC10 is nearby, and of the currently available data may represent the most reasonable long-term record of ambient Bay water concentrations exchanging with SLB. Since RMP has gone to random spatially distributed sites for water sampling since 2003, only historical stations are repeated each sampling, so the distance from SLB of other Central Bay sites will vary by year. Total water PCBs at BC10 have averaged around 200 pg/L in samples collected since 2006. Although much of the water returning on each flood tide from the north was exported on the previous ebb tide, as described previously in Section 3, a majority of water entering from the west is newly from the open Central Bay. Combining approximately twice daily tidal inflows from the west with the adjacent BC10 water concentrations, an estimated 0.65 g of PCBs is supplied to SLB per day, about one quarter the 2.7 g daily averaged loading rate from the watersheds. The watershed loads are episodic and associated primarily with storm events, so on any given day during the rainy season, watershed inputs may might be much higher, but in considering multi-decadal fate, the long-term average load is more important than capturing any single spike or event.

2. Internal processes

Important internal processes affecting the long-term fate of contaminants are the mixing and dispersion of bed sediment, and the settling and resuspension of sediment in the water column. For the purposes of the one-box model as an integrative framework for assessing available data and gaps and uncertainties, SLB is treated as a single homogenous compartment, but we recognize that heterogeneous contaminant distributions were found in SLB previously and also in the 2016 sampling. The one-box model applied here treats the water column and mixed sediment layer each as instantaneously (within the annually averaged parameters in the model) uniform compartments. Similar to the case for simple one–box models applied to the Bay and to the Emeryville Crescent, overall this tends to accelerate apparent changes. New contaminant loads are instantly spread throughout the PMU, and water column exports are modeled from compartment-averaged concentrations rather than on integrated flux of concentrations at the boundary. Even in the case of reducing loads, a simple instantly mixing model system as a whole overall responds more quickly than in the real world. Newly deposited cleaner sediment may persist on the surface in the real world, creating a faster short term response in the sub-habitat for surface feeding biota, but conversely resulting in slower response to the final steady state in the overall contaminant inventory for deeper feeding organisms. More realistic modeling of bioturbation and resuspension would transport deeper contaminated sediments to the surface more slowly, reducing their potential rate of eventual removal from the margin area. Only in the case of rapid burial with decreasing PCB loads

would more realistic slow mixing improve the recovery rate; the deepest and presumably more contaminated sediment would be buried first and be pushed out of the zone of potential mixing. A more mechanistic handling of processes would require a multi-compartment hydrodynamic model, and a multi-compartment (both laterally and vertically) sediment fate model. This is a much larger effort than possible with the available data and for the scope of this conceptual model study. However, we can characterize the results of our simplifying assumptions, and how they may mis-estimate the actual environmental processes.

Although this simple box model does not explicitly describe a bed sediment mixing rate, a key parameter for simulating these processes is the mixed sediment layer depth. The selection of the mixed sediment depth effectively defines the contaminant inventory and inertia of the system. A large mixed layer depth defines a large sediment mass, so new contaminant inputs are effectively diluted over a larger mass and thus averaged concentrations change slowly. Similarly, effects of decreases in loads occur more slowly, as the selection of a large mixed layer depth includes a large inventory of contamination that is presumed to continue to interact with the water column and resident biota in the long term. Conversely, a small mixed layer depth implies a small inventory and little inertia, with changes manifested relatively rapidly. A good selection of mixed layer depth can provide an appropriate approximation of the average system response for an indicator of interest at a whole compartment level (e.g., spatially averaged concentration, or wide scale exposure for a biosentinel species), but effects of lateral heterogeneity cannot be captured without explicit multi-compartment modeling.   The whole Bay model mixed sediment layer depth of 15 cm was selected as a reasonable starting point based on burrowing depths, radiotracer penetration, and other data, while recognizing that this key parameter may be spatially heterogeneous. The applicability of the same value to shallow margin areas is particularly uncertain, as the resident (bioturbating) species may differ from those in the open Bay. The depth of wave-driven sediment mixing also differs from that in the open Bay, perhaps episodically much larger in places like Emeryville Crescent, due to the shallowness of much of the area and a relatively open shoreline, but likely much lower in SLB, being enclosed by land on all sides, and with a relatively short fetch in most directions. Localized benthic biota surveys, and tracer horizon studies may provide some better information on sediment mixing in the area.

Suspended solids settling and sediment resuspension are major pathways for transfer of PCBs between the water column and bed sediment. Key parameters affecting suspended solids settling are the average water depth and the average settling rate of solids. A settling rate of 1.0 m d-1 was used as in the whole Bay model, and with an average depth of 2.6 m for SLB, about one-fifth of the suspended solids are settled out each tidal cycle, and the PCBs in the particulate water column fraction are transferred to the sediment. However, this rate of settling would result in rapid net accretion of sediment within SLB, so an offsetting resuspension rate is calculated as the difference between settling and net burial. If we presume no net burial, the settling and resuspension rates are equal. The flux of PCBs from the sediment to the water is calculated as the sediment resuspension flux multiplied by the averaged sediment concentration. A key parameter in both these rates (especially in the resuspension flux) is the suspended solids concentration. Due to the large tidal exchange for SLB, with over half of its volume exiting on each tide, the influence of this parameter on net PCB export is very large (approximately linearly proportional).

3. Losses

In the whole Bay box model the base case assumption was that the burial rate was negligible or zero. Here we make the same assumption, but other assumptions can be evaluated simply based on the ratio of burial rate in cm per year, relative to the mixed layer depth. For example, a 3 mm per year burial rate (approximately keeping up with sea level rise) on a 15 cm mixed sediment layer represents a 2% loss of older PCBs per year (the addition of 3 mm on top from the water column solids in this scenario may increase or decrease net sediment inventory, depending on initial concentrations relative to incoming ones).

Volatilization is modeled as exchange from the water column to the air. Major factors in the computation for volatilization are the chemical properties of PCBs, wind speed, air PCB concentrations, the water surface area, and water PCB concentrations,. Relative the the whole Bay model, we only changed the latter two factors to be specific for SLB. For SLB, due to the steep edge for much of the armored shoreline, the difference in area between MHW and MSL is only 5.5%. Compared to Emeryville Crescent, the area at MLW is relatively larger, 83% of the MHW area, so direct volatilization from exposed sediment should play a smaller part. Estimated volatilization losses only account for less than 1% loss of PCB 118 from SLB based on exposed area at MHW. The volatilization rates should differ among congeners however, so for lighter congeners, volatilization is likely to contribute relatively more to losses. As an example, for PCB 18, volatilization loss rates would be about 11% of its mass each year, but tidal outflow losses would still be larger.

Water column and sediment degradation of PCBs is also presumed to be relatively slow; a large part of the problem with PCBs is their persistence in the environment. As in the whole Bay mass budget, we used a default half-life of 56 years. This resulted in around 1% loss of PCBs per year. Adjustments to the assumed half-life in sediment inversely proportionally increased degradation loss rates; assuming a 11 year half-life increased degradation losses to around 5% per year.

The dominant factors in the PCB mass budget for SLB are the assumptions that directly impact advective (primarily tidal) export. Around 60% of the volume of SLB exits and enters on each tide, and on average about 25% of the volume at high slack was "new" water not in SLB on the previous high, so any PCBs remaining in the water column over a tidal cycle will be rapidly lost. Due to the much larger spatial extent and tidal volume of San Francisco Bay relative to its tidal prism, rather than using a whole Bay average concentration to estimate export as would be the expected case for a pure one-box model, an adjustment using the near exit station average concentration (i.e., presuming only waters near the Golden Gate leave the Bay on any given tide) was made for the previous model. In contrast, for SLB, due to two boundaries and complex circulation patterns, a relatively large portion (25%) of the total volume leaves and does not return (is replaced by new water) on each tidal cycle. However, even for this small area with a larger tidal prism relative to its volume, some adjustments are needed to account for likely spatial gradients.

We measured three water column PCB concentrations for SLB in the 2016 sampling (range 700 to 1500 pg/L, with a mean ~ 900 pg/L), but all were taken as single grab samples, so might not be fully representative of typical long-term conditions. As a first order upper bound, we derived the steady state water column concentrations, taking average suspended sediment concentrations previously used for the Bay one box PCB mass budget multiplied by average local (SLB) sediment PCB concentrations. However, with 25% of the water on each high tide not previously from SLB, this assumption would likely be a moderate overestimate. We therefore adjusted that initial estimate, assuming that on each high tide, 75% of the water contained solids equivalent to/in steady state with sediments in SLB, with the remaining "new" volume equivalent to waters outside of SLB, near the long-term average concentration at RMP station BC10 (around 200 pg/L total PCBs). The model in the long term is not sensitive to the assumed initial water column concentration however, because the water inventory rapidly adjusts in response to the combination of watershed loads, resuspension from bed sediment, and import/export with the open Bay.

The net export is adjusted similarly to the calculation of initial concentration. About 75% of the volume is presumed in local steady state, with the remaining 25% of volume equivalent to new open Bay (BC10) water. With net northeastward flow (more new water in from the west on flood tide, and more out the north on ebb than coming back in the subsequent flood tide), the transported water generally follows a first-in-first-out (FIFO) pattern, so the proportion of equilibrated water may be somewhat higher. However, for this simple model we assume uniform mixing, and the average water exiting is the volume weighted average of the new (25% external) and local (75% equilibrated) waters.

Another parameter to which the modeled export is extremely sensitive is the assumed suspended sediment concentration. Using the value from the whole Bay model (8.5×10^{-5} kg/L), even adjusting for the assumed mixing between "new" and returning water PCB concentrations, we obtain an annual tidal export equivalent to around 1/3 of the initial sediment PCB inventory. At steady state, that exported mass is offset by import from the open Bay, combined with loading from surrounding watersheds. Based on the one-box model results discussed in this chapter, the apparent half-response time is several years, and changes in response to changing loads are relatively rapidly manifested. Given the persistence of highly contaminated areas for other sites, such rapid turnover is highly unlikely, or would require high ongoing loading rates to maintain locally elevated concentrations. Adjusting the suspended sediment concentration up or down increases and decreases the export rate respectively, so clearly a better quantification of the suspended sediment pool available for tidal export is needed to generate accurate fate scenarios for PCBs in SLB. In addition to better quantification of local suspended sediment in SLB, a more detailed or realistic model of sediment resuspension across the intertidal zone may be needed to estimate the proportion of sediment that is resuspended versus imported from outside SLB on the flood tide. An improved model could account for the depth and exposure time for different parcels of water entering and exiting over a tidal cycle to calculate the percentage of suspended sediment originating from local bed sediment, and ideally link to modeled or empirically mapped sediment PCB concentrations for the area. Such improvements would require either explicit modeling of different zones within SLB (i.e., a multi-box model), or a simplified (e.g., spatially and temporally averaged) approximation of these complex processes.

iii.   Forecasts

Figure 4-2 shows recovery trajectories for different starting sediment concentration scenarios ranging from 12.5 to 200 ng/g. In this simple model, annual loads and fate processes are assumed to be interannually consistent. This is seldom the case, but even so, the model can illustrate the long-term temporally-averaged fate (e.g., actual concentrations and loads each year would vary around the modeled steady state). Based on ambient concentrations from SLB in the previous study (Daum et al., 2000) a concentration of 125 ng/g was selected as the base case initial state for other scenarios, and could possibly be the long-term steady state under a no action scenario. Although the initial inventories of PCBs varied with the starting sediment concentration, the half-response times and the final steady state concentrations were identical, as would be expected. These mass budget model results suggest ongoing loading rates would support ambient concentrations in SLB near 35 ng/g PCBs (the scenario about midway between 25 and 50 ng/g starting points, where the final steady state inventory is nearest the initial mass). However, there are considerable uncertainties in the degree of water column exchange with the open Bay, as well as in exchange with bed sediment, extremely important parameters for the model in this area given its shallow depth, with the tidal prism constituting much of its total volume. Given the dynamic changes in depth and volume of SLB over the course of a tidal cycle, application of a one-box fate model may be insufficient, and various processes may need to be explicitly mechanistically modeled or otherwise approximated through additional adjustment factors.
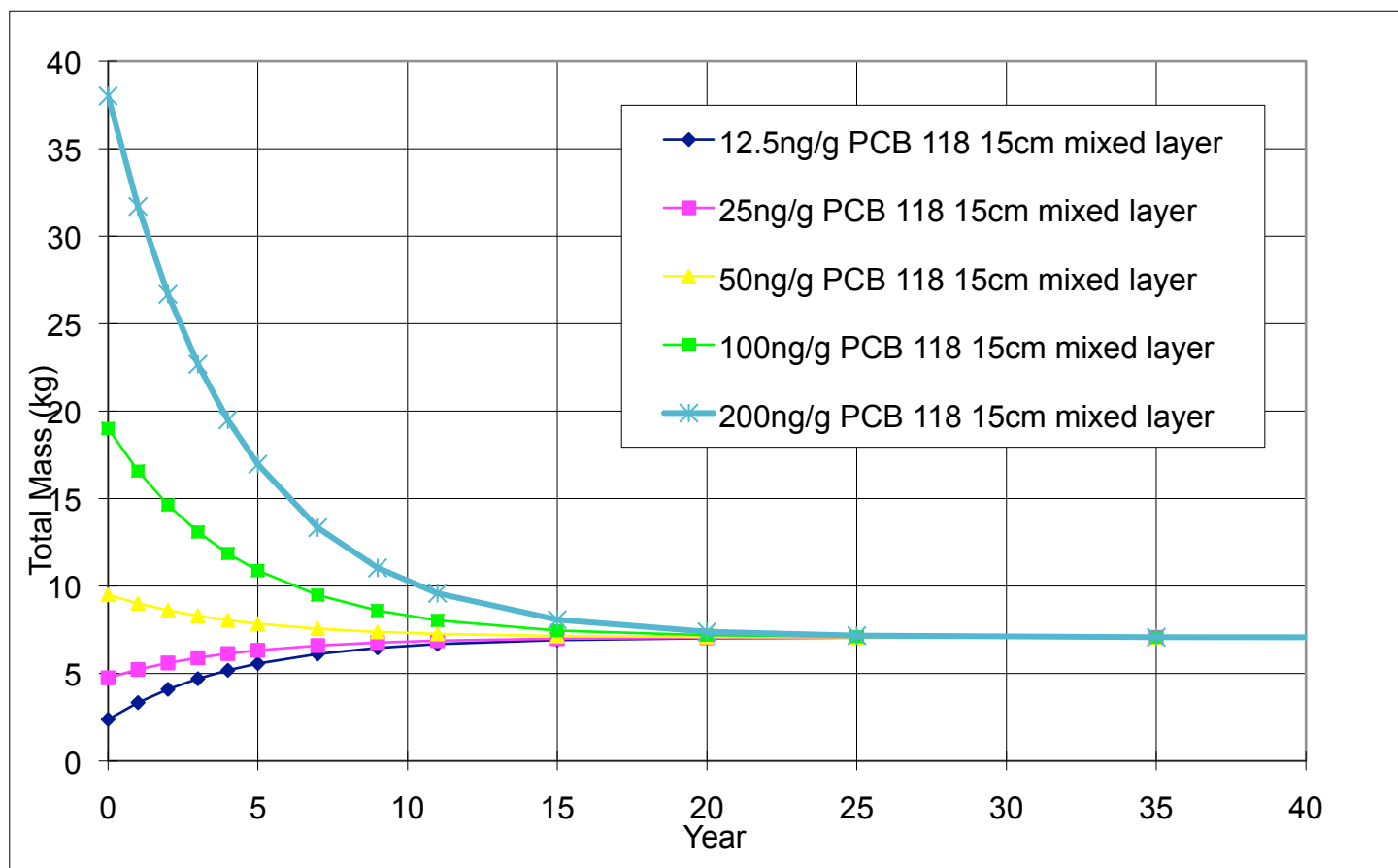
Figure 4-2. Recovery trajectories from differing starting concentrations, constant watershed and Bay loading, other parameters from open Bay 1 box PCB model (15 cm mixed layer, Bay SSC, 1 m/day settling, no burial, etc.). Around 35 ng/g sediment concentration would be supported at steady state with current watershed and Bay loads

Figure 4-3 shows recovery trajectories for different watershed loading rates, assuming that initial bed sediment concentrations average 125 ng/g. In these scenarios, the half response times remain the same, but the final steady state masses are linearly proportional to watershed loads added to the no (0x) load case, where the only new PCBs are contributed by exchange with the open Bay. Our base case is 1x load, but a reasonable alternative scenario is that about half of the total load (0.5x load) is dissolved or unsettled (an assumption about midway between the minimum and maximum proportion settling at <1m/hr in lab experiments), with that portion of the load effectively lost from SLB after one or more tidal cycles. Although actual changes in watershed loads are not likely to occur all at T=0 as illustrated in these trajectories, the plots are useful for illustrating the half response time to asymptote to a new steady state with any change in loading. This response time is the same for all the constant loading scenarios, with only the final steady state mass differing. In a situation with continually changing loads, the recovery slope would continually adjust towards the final steady state, with the same response time relative to the last change in load.
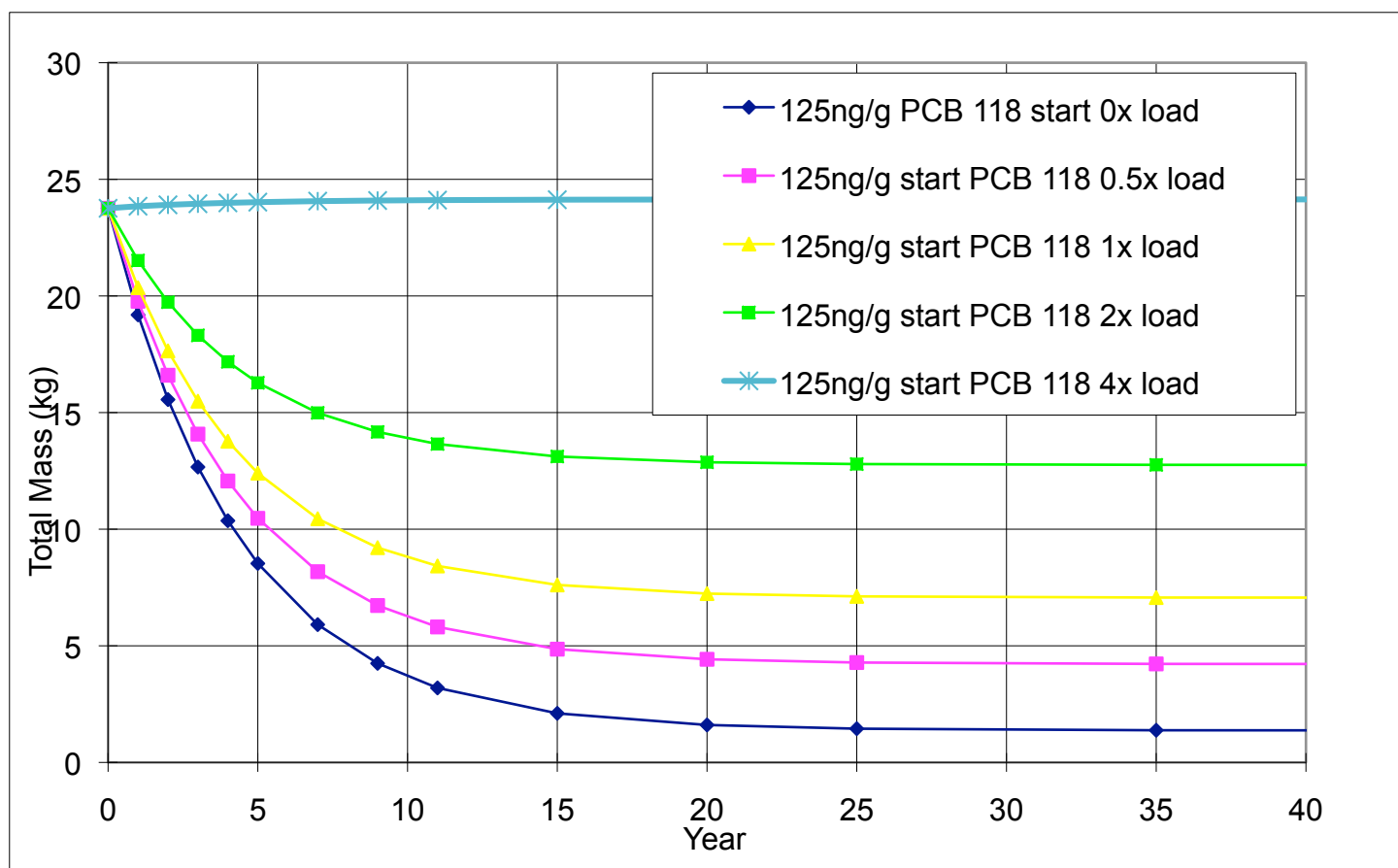
Figure 4-3. Trajectories with 125 ng/g starting concentration, differing watershed (WS) loads, other parameters same as in Figure 4-2. In the base (1x = 986 g/yr) load case, WS load is 4x the tidal load from the Bay.

1. Uncertainty of estimates

Like the previous Emeryville Crescent one box model, the response of the model system is highly dependent on various model parameters. However, given the shallowness and large tidal prism relative to volume for SLB, unlike the whole Bay model where the starting inventory and net sediment processes strongly affected the response and long-term trajectory, SLB is similar to the case for Emeryville Crescent, with the most influential parameters being those affecting net loading and export. Although the initial sediment concentration dominates the inventory initially, the base case model (Figure 4-2) for all starting bed sediment concentrations at 10 years is within 10% of the final steady state inventory supported by current ongoing loads. The PCB mass in sediment responds similarly quickly to increases or decreases in loads (Figure 4-3). As would be expected, given the large tidal exchange relative to total volume, adjustments to parameters affecting SSC and tidal export (i.e., increased or decreased proportion of new water) are highly influential, leading to nearly directly proportionally higher and lower final steady states and export rates (Figure 4-4).

These two-fold increases and decreases in SSC and net tidal exchange explored represent considerable uncertainties in model parameters that require much more site-specific data to better constrain. The nearly directly proportional increases and decreases in steady state concentrations resulting from changes in these model parameters also correspond to increases and decreases in half-response times of approach to these new steady states. In the base case, the half-response time is about 3 years, a rapid decrease to within 10% of steady state within about 10 years. In contrast, the 0.5x SSC or 0.5x tidal exchange cases greatly slow down the response; in addition to the higher final steady state, the half-response time increases to about 4.5 years, nearly 50% slower response. Two-fold increases in SSC or tidal exchange have an opposite effect, with the final steady state decreasing nearly two-fold (in the increased SSC case), and the half-response time shrinking to only about 1.5 years.
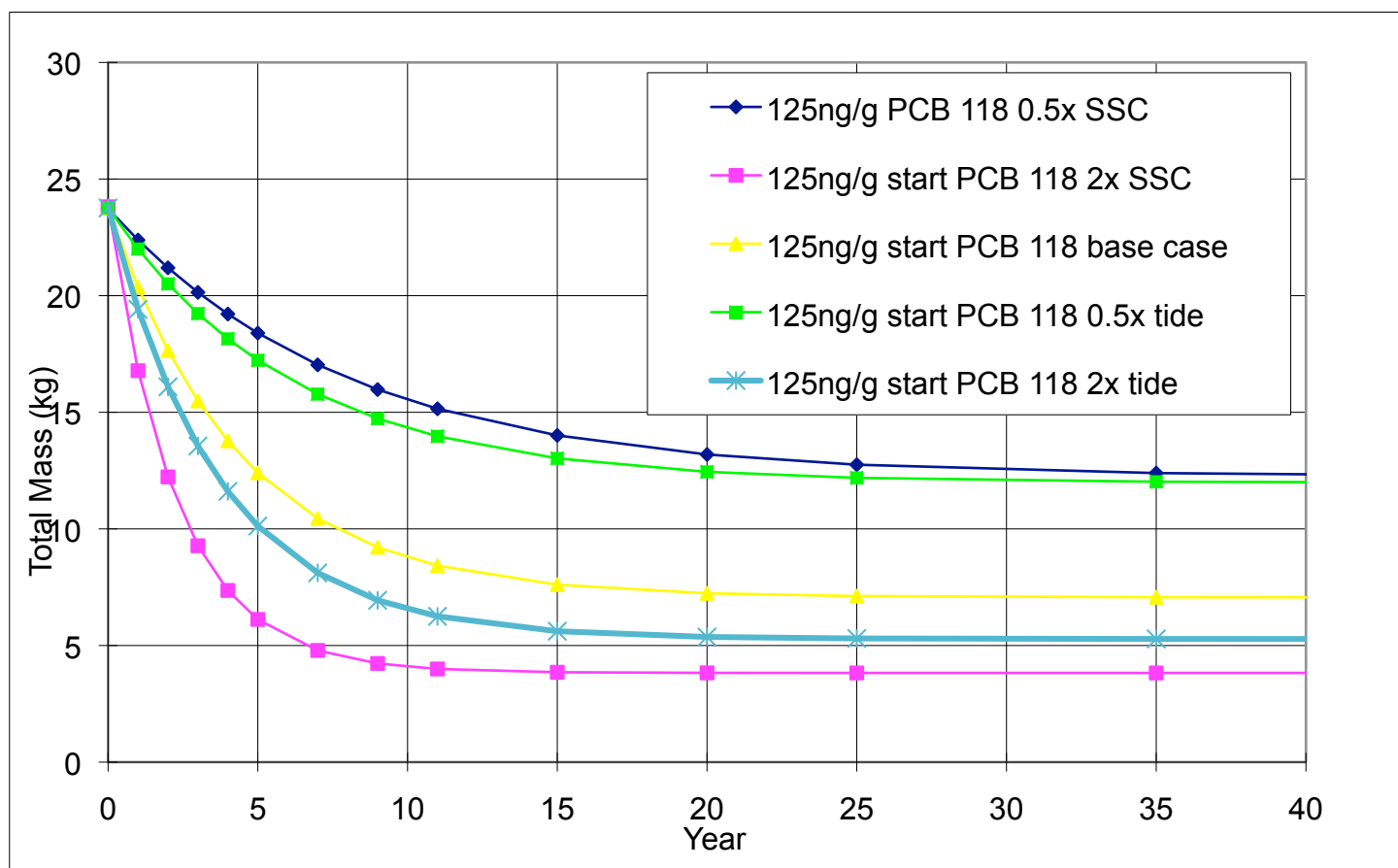

Figure 4-4. Trajectories under base case loads, with different SSC and tidal export
          parameterization

Similar to the case for Emeryville Crescent, other factors affecting the sediment layer fate such as burial and erosion rates, and degradation rates, had only minor impact on fate, even when starting with higher sediment concentrations than would be supported by

estimated ongoing loads. Similarly, increasing the mixed sediment layer thickness, shows only modest effect of increasing the response time.

As mentioned previously, the selection of congener to represent PCBs also had a moderately large influence, as more is lost by solubilization and volatilization for lighter congeners. Ideally, rather than selecting a single congener to represent all PCBs, individual congener fates should be tracked separately, but that would require a much higher level of effort.

c.   Discrepancies of the mass budget model with recent monitoring

Relative to the case for Emeryville Crescent, the distribution of sediment contamination within SLB in the past and the present is better known, and the available data are useful for both evaluating the current severity of contamination within SLB, and for validating the trend expected from the simple mass budget fate model. Sediment concentrations of PCBs from a round of sampling conducted in summer 2016 are shown in Figure 4-5, plotted along with results for sites reported previously (from Daum et al., 2000).

PCB concentrations in this more recent round of sampling were spatially similar to those in the earlier study, with generally higher concentrations on the east side of SLB, and the highest concentrations in the channels. The overall concentrations were also very similar, suggesting that the simple mass budget model as currently parameterized is flawed, or that differences in analytical methods have obscured potential changes. The mass budget model predicts a ~90% decrease (or increase, if loads were high enough) towards new steady state concentrations that would be supported by the current loads within about 10 years.

However, the base case (current loads) for the model suggests a steady state ambient concentration around 35 ng/g, whereas many of the samples in recent sampling (not including the upstream channel sites) were well over 50 ng/g. The PCB analytical methods likely differed between the Daum study and current samples, with the magnitude of difference potentially about two-fold higher for the new method (similar to the differences we saw using this new method for archive samples). The Daum results even using a two-fold increase to roughly match the current method would start at 250 ng/g (above the 200 ng/g top line in Figure 4-2), but even in this highest starting concentration case, nearly all the projected concentrations at 15 years would approach very close to the 35 ng/g final steady state.
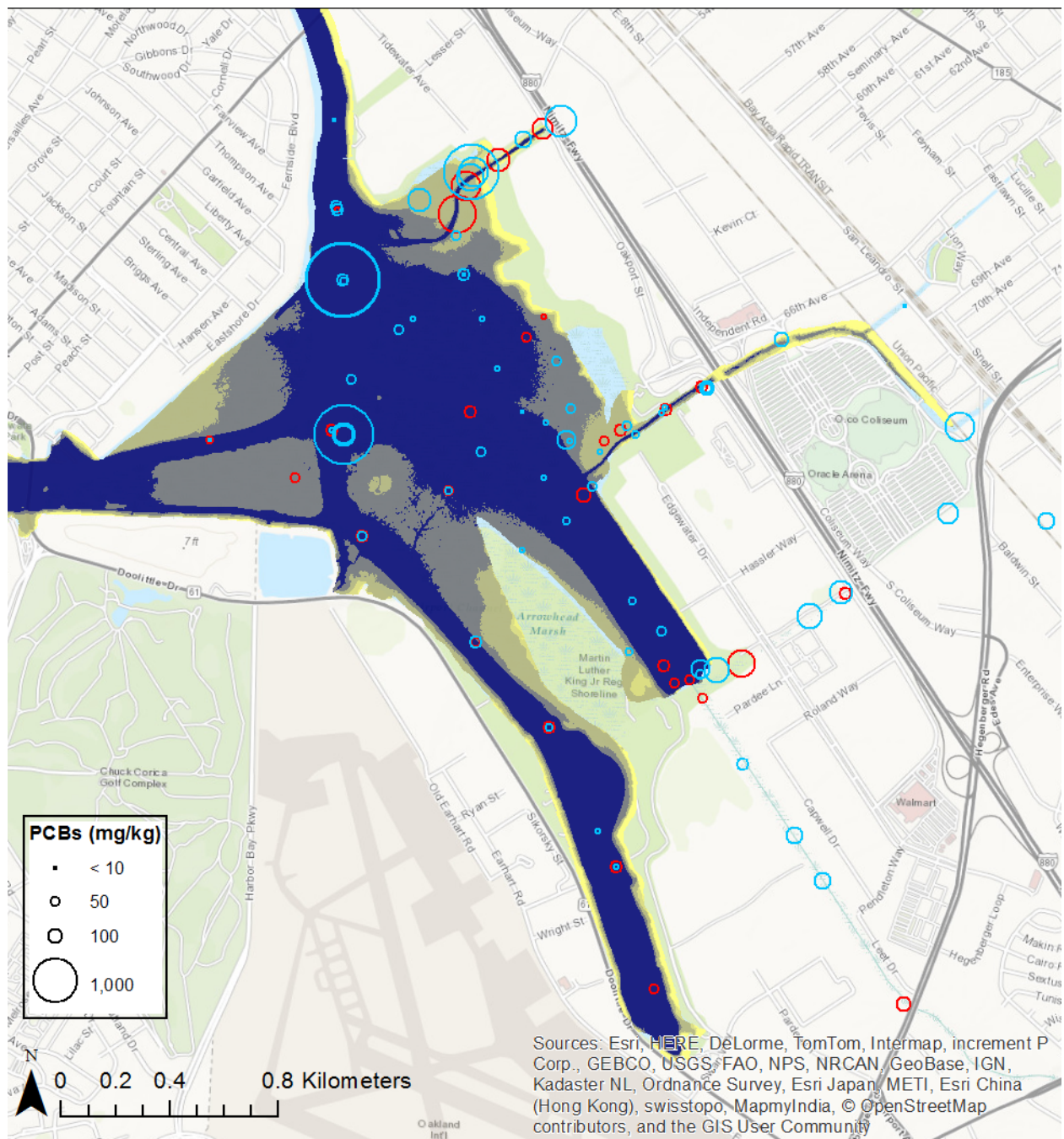
Figure 4-5. Bubble Plot of PCB concentrations in SLB, from Daum et al., (2000) and summer
          2016.

The single box handling of the area is likely a major contributor, as changes in loading
are instantly propagated, which accelerates both projected export and import fluxes of PCBs
and/or cleaner sediment. A more spatially realistic model would show gradients of likely lower
concentration near the western open Bay input, and higher concentration on the eastern side
near channels from the watersheds. Inclusion of such gradients would reduce the speed of

recovery trajectories; inputs of cleaner sediments would distribute more slowly through the rest of the area, and contaminated sediments in the interior of SLB would take longer to disperse to possible exit points.

Another major weakness of the single box mass budget model is in handling of sediment-water exchange.   Averaged SSC concentrations from the open Bay, although useful for evaluating order-of-magnitude effects in conceptual models, will likely need to be more site-specifically established to get more realistic estimates of PCB flux and fate. Although several water grab samples were collected with the survey of sediment in SLB, a year-round characterization of typical suspended sediment concentrations at numerous points would be needed to generate a more accurate pictures of sediment flux and resultant PCB transport. The grab water samples collected in 2016 ranged from 700 to 1500 pg/L (mean around 900 pg/L) for total (RMP Sum of 40) PCBs, about a factor of five to ten times lower than average equilibrium concentrations predicted for SLB even after using an adjustment factor of 25% open Bay water mixing in (~8000 pg/L initially, assuming 125 ng/g in sediment, reducing to ~2300 pg/L for a 35 ng/g end steady state at current loads). Thus the 0.5x SSC scenario, with its much more modest decrease in PCBs over time, and a higher steady state under current loads, may be a more realistic representation of current flux. A 0.25x lower SSC scenario, or less complete mixing with resuspended sediment, might even be warranted, with the same net effect of lowered export rate, slower recovery, and a higher steady state concentration under current loads.

Collection of cores or other means of evaluating the vertical distribution of contaminants may be useful for validating assumptions about mixed sediment layer depth, but the one-box model currently suggests relative insensitivity to these assumptions, and the newly collected data suggest relative uniformity at most sites, at least in the top 5 cm. The data from 3 sites where top layer surface sediments (0 to 1 cm depth) were compared to slightly deeper layer sediments (1 to 5 cm depth), and integrated depth (0 to 5 cm depth) replicate grabs, showed no strong or consistent tendencies, with top (0 to 1 cm) concentrations 73, 91, and 130% those of lower (1 to 5 cm) sediment PCB concentrations. The volume weighted results (i.e., 20% 0-1 cm PCBs added to 80% 1-5 cm results) were also virtually identical, 99, 89, and 109% respectively, of 0-5 cm replicate samples separately composited and analyzed. The remaining group of samples analyzed as separate layers (in-channel and near-mouth sites, without whole depth composites to which they could compared) were also variable, with top layers of 99, 106, 125, 257, and 325% of deeper concentrations. These results collectively are qualitatively consistent with the conceptual model described in the section on initial retention, with initially discharged sediments retained in the nearfield of inputs, gradually mixed deeper into sediments or dispersed to the rest of receiving water over time (e.g., with more uniform concentrations in the deeper samples away from channel inputs). That the top layers are seldom lower in concentration than deeper layers suggests a scenario of ongoing loads entering SLB with generally higher concentration than sediments already in place.

Although generation of a multi-box model for SLB or other PMUs may result in more realistic projections of recovery trajectories, unless there are decisions to be made contingent on quantitative model outcomes rather than general qualitative insights, the expense and effort of such more intensive modeling may not be warranted.   The existing data, such as in recently

measured water PCB concentrations, suggest possible relatively simple adjustments (e.g., reducing the SSC concentration, or reducing the proportion of suspended sediment in equilibrium with the sediment) to the mass budget framework may be enough to result in outcomes more congruent with observed concentrations or trends. Another possible explanation for the incongruity between the base case model prediction (projected steady-state concentrations ~35 ng/g) and the most recent data (many near or above 50 ng/g in 2016 sampling) is that loads from the tributaries are greater than we are estimating. The potential influence of the large masses of PCBs directly upstream (UPRR, etc.) is one element not calibrated well in our current RWSM tool for estimating watershed loads, as the main application for the RWSM is to derive accurate regional average loads, rather than optimization to local site characteristics.

d.   Conclusions and Future Work

The questions presented in Section 1 of this report have been informed by this fate modeling effort, with our resulting conclusions presented below.

1. Can we expect a decline in any compartment of the PMU in response to projected load reductions in the PMU watershed?
   Yes, at least conceptually we are likely to eventually see changes in both water and sediment compartments, likely propagating to local biotic exposure and accumulation, although the timing and magnitude of any decline are highly uncertain, due to uncertainties in source release and transport processes and loading, natural climatic variability, uncertainties in numerous modeled parameters, and simplifying assumptions used in this initial modeling.

2. How should tributary loads be managed to maximize PMU recovery?
   The PMU should benefit from reduced loads in all the local tributaries, with the greatest benefits likely seen for reductions in loads from areas 2, 3, and 4 (discharging to East Creek, Damon Slough, and Elmhurst/San Leandro Creek) on the east side of SLB, where the largest loads occur. Furthermore, within these areas, efforts should be concentrated in the lower, more highly industrialized and urbanized sections of these watersheds. Although in this effort, we did not sample further upstream to demonstrate some of the gradients seen in a previous study (Daum et al., 2000), a regionwide conceptual model of relatively low PCB yields from residential and open spaces should also apply here. Any increases or decreases in concentrations from watershed loads should have nearly proportional impacts on SLB ambient concentrations, until or unless they are reduced to nearly as low as open Bay ambient concentrations.

3. How should the San Leandro Bay PMU (SLB) be monitored to detect the expected reduction?
   Continued sampling of resident biota (sport fish and prey fish) should be combined with future continued sampling of abiotic components of loads and ambient concentrations, in order to track or distinguish trends occurring due to factors unrelated to loading (shifts in species composition or diet) versus those resulting from management actions to reduce loads. Although reductions in biotic exposure due to any

cause are welcomed, responses to loads management are particular desired as evidence of whether or not the extensive efforts planned to reduce tributary loads will have any observable benefit.

As budget allows, monitoring to better understand parameters affecting fate processes within SLB may also be helpful. Although such information is not directly informing the status or trends of PCB contamination in SLB, it may help better explain the presence or lack, or speed of observed changes relative to estimates from loads monitoring and simple fate models. Sampling PCBs and SSC in water grabs or composites around the Bay Farm Island inlet over different incoming tides (e.g. spring, neap, and intermediate periods), combined with continuous turbidity monitoring over at least a complete spring/neap cycle in wet and dry seasons can provide an indication of how close to reality modeled tidal inputs from Central Bay are. Likewise, composited PCB and SSC samples, and continuous turbidity over the same periods for the entry to the channel to the Oakland Estuary in the North can provide a reality check on or better constrain the estimated PCB export, reduce the uncertainties in those estimates, and identify the most critical components for better projecting contaminant fate and responses to management.

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