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

Prepared by:

Don Yee, Alicia N. Gilbreath, Lester J. McKee, and Jay A. Davis
San Francisco Estuary Institute

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Final Report

Donald Yee, Alicia N. Gilbreath,
Lester J. McKee, and Jay A. Davis
San Francisco Estuary Institute

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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 (2016-2018), Steinberger Slough in San Carlos is third (2018), and Richmond Harbor will be fourth (2018-2019).

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 Three of a report on the conceptual model for San Leandro Bay. A Phase One report (Yee et al. 2017) presented analyses of watershed loading, initial retention, and long-term fate, including results of sediment sampling in 2016. A Phase Two data report (Davis et al. 2017) documented the methods, quality assurance, and all of the results of the 2016 field study. This Phase Three report is the final report that incorporates all of the results of the 2016 field study, and includes additional discussion of the potential influence of contaminated sites in the watershed (Section 2), the results of passive sampling by Stanford researchers and a comparative analysis of long-term fate in San Leandro Bay and the Emeryville Crescent (Section 4), a section on bioaccumulation (Section 5), and a concluding section with answers to the management questions that were the impetus for the work (Section 6).

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). The SEP funding supported both development of the conceptual model and the extensive field study of PCB concentrations in San Leandro Bay.

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Appendix 1: Methods for Characterizing Temporal Dynamics of Loading

Appendix 2: San Leandro Bay PCB Passive Sampling – Results Memo

Executive Summary

The 2014 update of the RMP 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.

The goal of the effort 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. Conceptual model development for four priority margin units (PMUs) that are high priorities for management and monitoring will provide a foundation for establishing effective and efficient monitoring plans to track responses to load reductions, help guide planning of management actions, and inform the possible revision of the TMDL. The Emeryville Crescent was the first PMU to be studied (Davis et al. 2017). San Leandro Bay is the second and the subject of this report.

The goal of this report is to answer three questions related to management and monitoring of PCBs in priority margin units. To this end, a conceptual model was developed that includes four major elements:

1. loading from the watersheds;
2. initial deposition and retention;
3. processes determining the long-term fate of PCBs in sediment and water; and
4. bioaccumulation in the food web.

1) Can we expect a decline in any compartment of the PMU in response to projected load reductions in the PMU watershed?

A simple mass budget model suggests that conceptually we would expect to eventually see changes in both water and sediment compartments, although the timing and magnitude of any decline are highly uncertain. The response would be proportional to the change in loading. Evidence of responsiveness was observed in the wetland sediment core profile at Damon Slough, which indicated a substantial reduction in PCBs between the 1970s and the early 2000s. However, a comparison of the results of extensive sampling of San Leandro Bay surface sediment in 1998 and in 2016 suggest a lack of reduction over this more recent 18 year period. This latter finding suggests that continuing inputs are slowing the recovery of San Leandro Bay from PCB contamination.

Significant cleanup actions have been taken or are in process and scheduled for completion in the next two years at two highly contaminated properties a short distance upstream of San Leandro Bay. The portion of loads coming from these or other specific properties has not been quantified, but at least conceptually, these cleanups should also lead to lower concentrations in San Leandro Bay. Effects are likely to be most apparent in relatively unmixed depositional sites in the nearfield of the incoming loads.

Changes in surface sediment concentrations would lead to similar changes in PCB exposure in the food web. A significant amount of food web transfer of PCBs to species of interest occurs through benthos that are surface deposit feeders and filter feeders that can be expected to respond relatively quickly to reductions in ambient surface concentrations, which may in turn respond relatively quickly to reductions in tributary inputs.

2) How should tributary loads be managed to maximize PMU recovery?

Recovery of San Leandro Bay from PCB contamination would be maximized by pursuing a load reduction strategy that encompasses any remaining older industrial areas in the PMU watersheds. Old industrial represents around 3% of the watershed area, but the Regional Watershed Spreadsheet Model estimates that this land use category contributes 48% of the PCB load. PCB loads from contaminated areas in the lower watershed should be reduced as much as possible without impacting sediment supply from cleaner upper watershed areas, in order to provide diluting sediment.

Management attention should focus on loads from storms with magnitudes less than the 1:1 year return interval. An estimated 86% of the long-term loading is contributed by these small and moderate storms. In addition, the load from these storms is more likely to be retained within San Leandro Bay, although even for the largest storms, the majority of loads (aside from those discharged directly into the channel leading to Oakland Harbor) will remain initially within San Leandro Bay.

The PMU should benefit from reduced loads in all the local tributaries, with the greatest benefits likely seen for reductions in loads from watersheds discharging to the east side of San Leandro, where the largest loads occur. Any decreases in concentrations from watershed loads should have nearly proportional impacts on ambient concentrations in San Leandro Bay, until or unless San Leandro Bay concentrations are reduced to nearly as low as Central Bay ambient concentrations.

San Leandro Bay represents a different scenario from the Emeryville Crescent due to the presence of two known highly contaminated properties, with substantial masses of PCBs in soil and downstream sediment, immediately upstream of the PMU. The General Electric (GE) property has recently been nearly completely capped, and the Union Pacific Railroad (UPRR) site is scheduled for cleanup in the next two years. Cleanup of these properties, especially GE, could significantly accelerate the recovery of San Leandro Bay.

3) How should we monitor to detect the expected reduction?

A preliminary field study in 2016 yielded a great deal of valuable information on the current distribution of PCBs in sediment and fish in San Leandro Bay, providing a baseline for future monitoring and valuable information on the attributes of these different indicators of contamination.

Long-term monitoring should track multiple lines of evidence. Continued sampling of sport fish and prey fish should be conducted periodically to evaluate the state of impairment, but less frequent (~decadal scale) monitoring of abiotic matrices should also be conducted. Periodic surface sediment sampling (e.g., every 5 years, coincident with biota sampling) and core sampling at longer intervals (greater than a decade) should be conducted. A third line of evidence should be near-field monitoring as immediately downstream of major management actions as possible.

Annual monitoring of topsmelt at key sites would be valuable in monitoring long-term interannual trends in response to changes in tributary loadings. Given the major management actions on the GE and UPRR contaminated properties, monitoring of the downstream food web response in the next few years would be of particular interest.

Shiner surfperch could be cost-effectively sampled on a five-year cycle as part of RMP Bay-wide sport fish monitoring. Given the management actions at GE and UPRR, annual monitoring of shiner at San Leandro Main Bay for the next 5-10 years should also be considered.

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. The Emeryville Crescent was the first PMU to be studied (Davis et al. 2017). San Leandro Bay (Figures 1-1 and 1-2) 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.

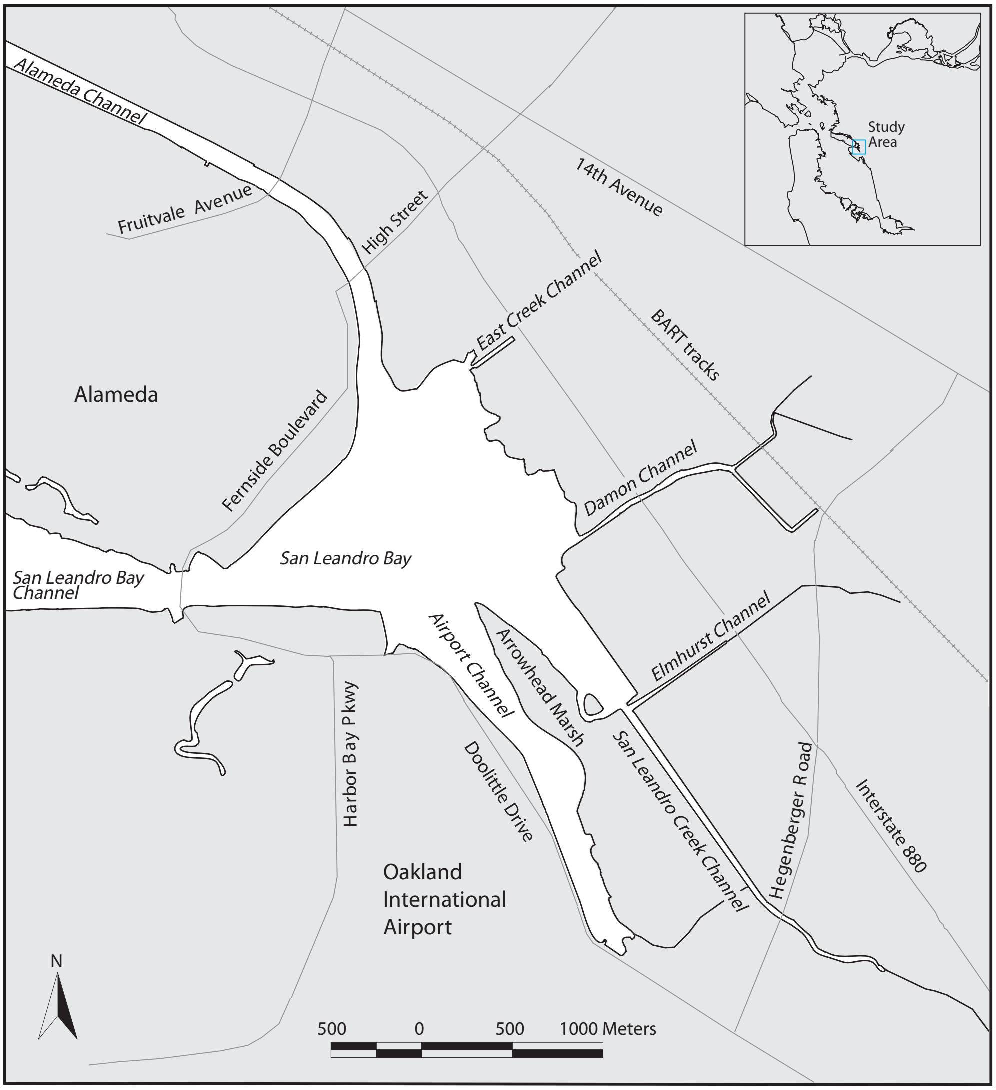


Figure 1-2. San Leandro Bay at low tide, March 2014. Marsh, intertidal mudflat, and subtidal areas are visible.

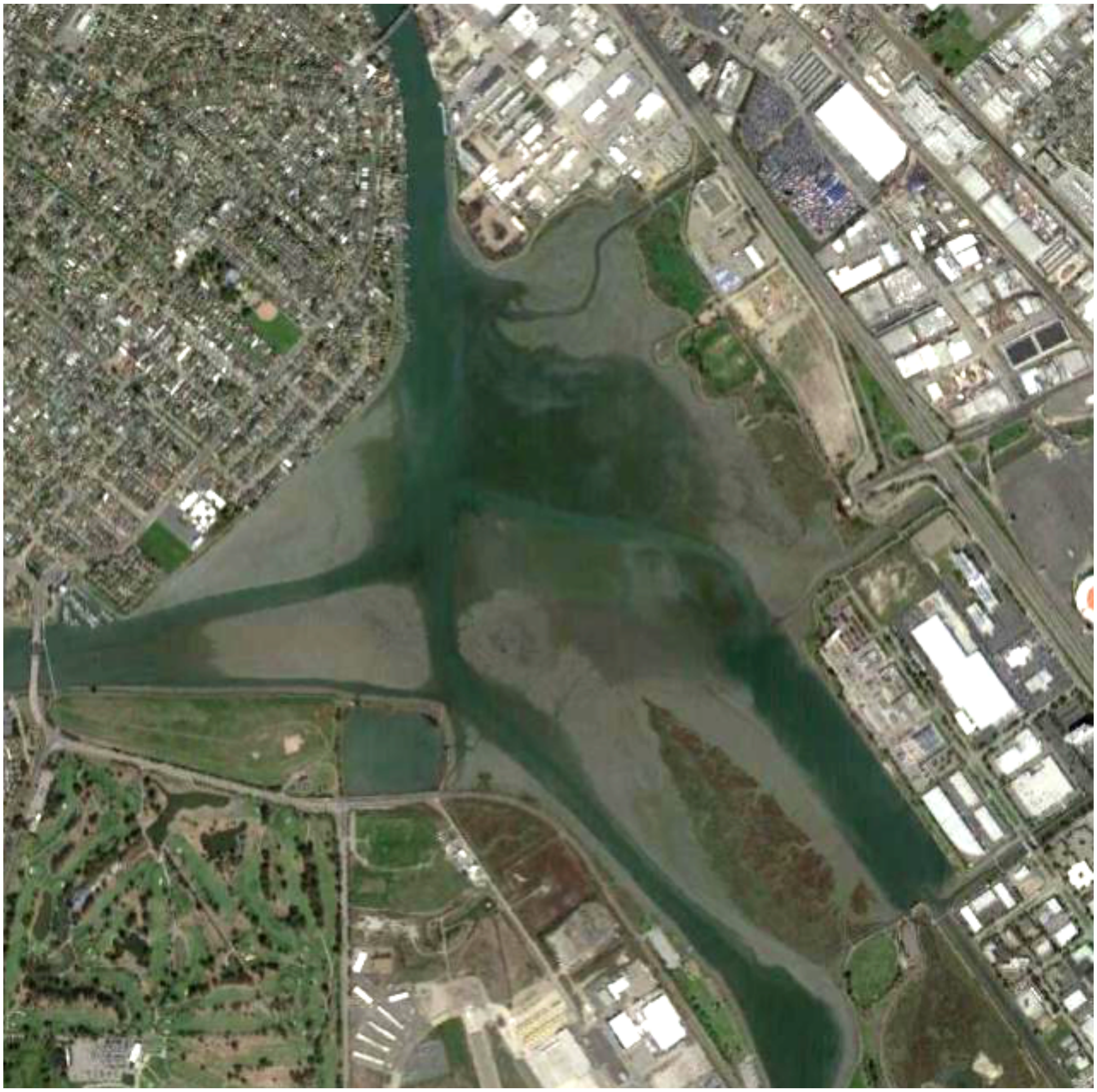
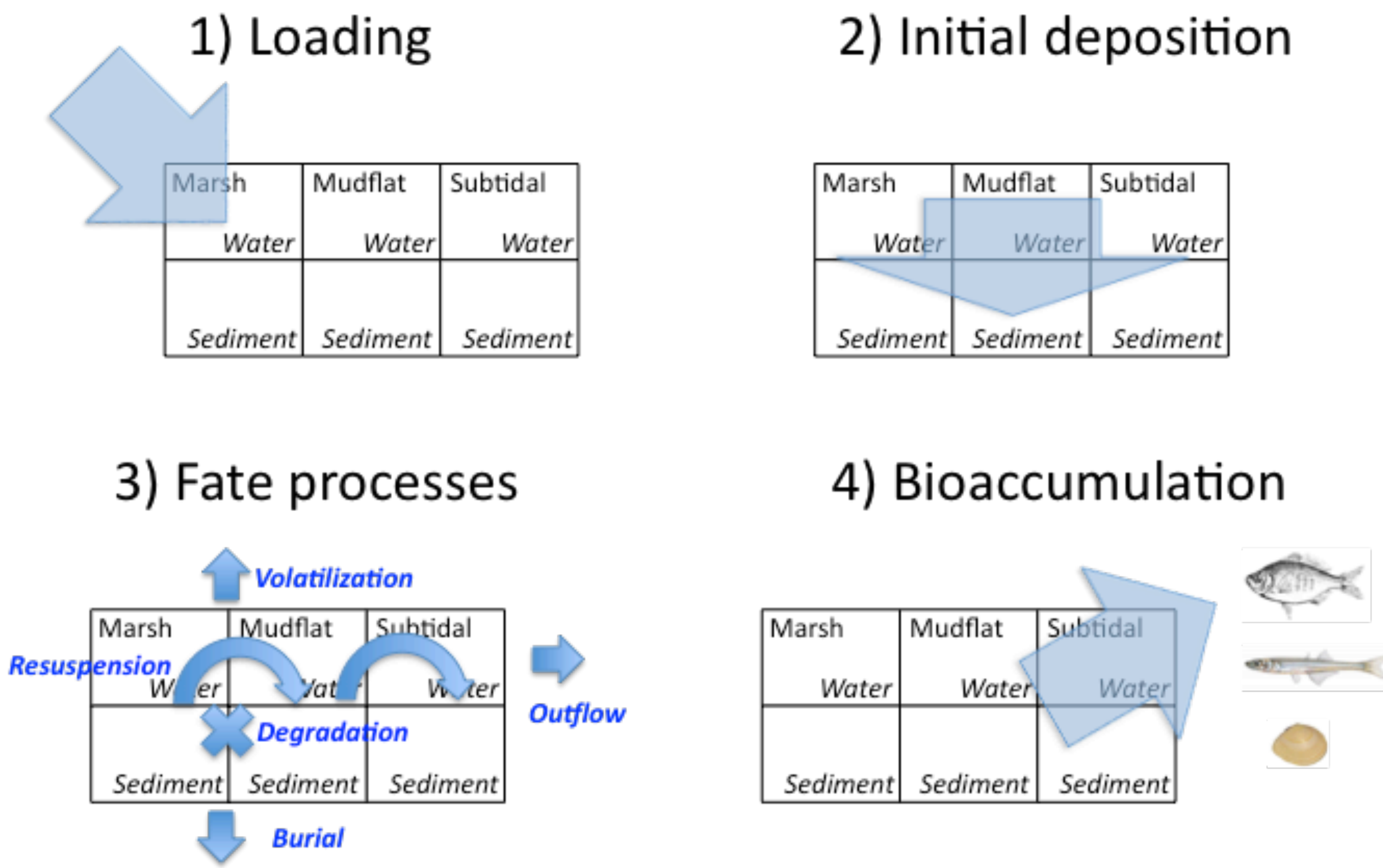


Figure 1-3. Overall conceptual model.



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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.

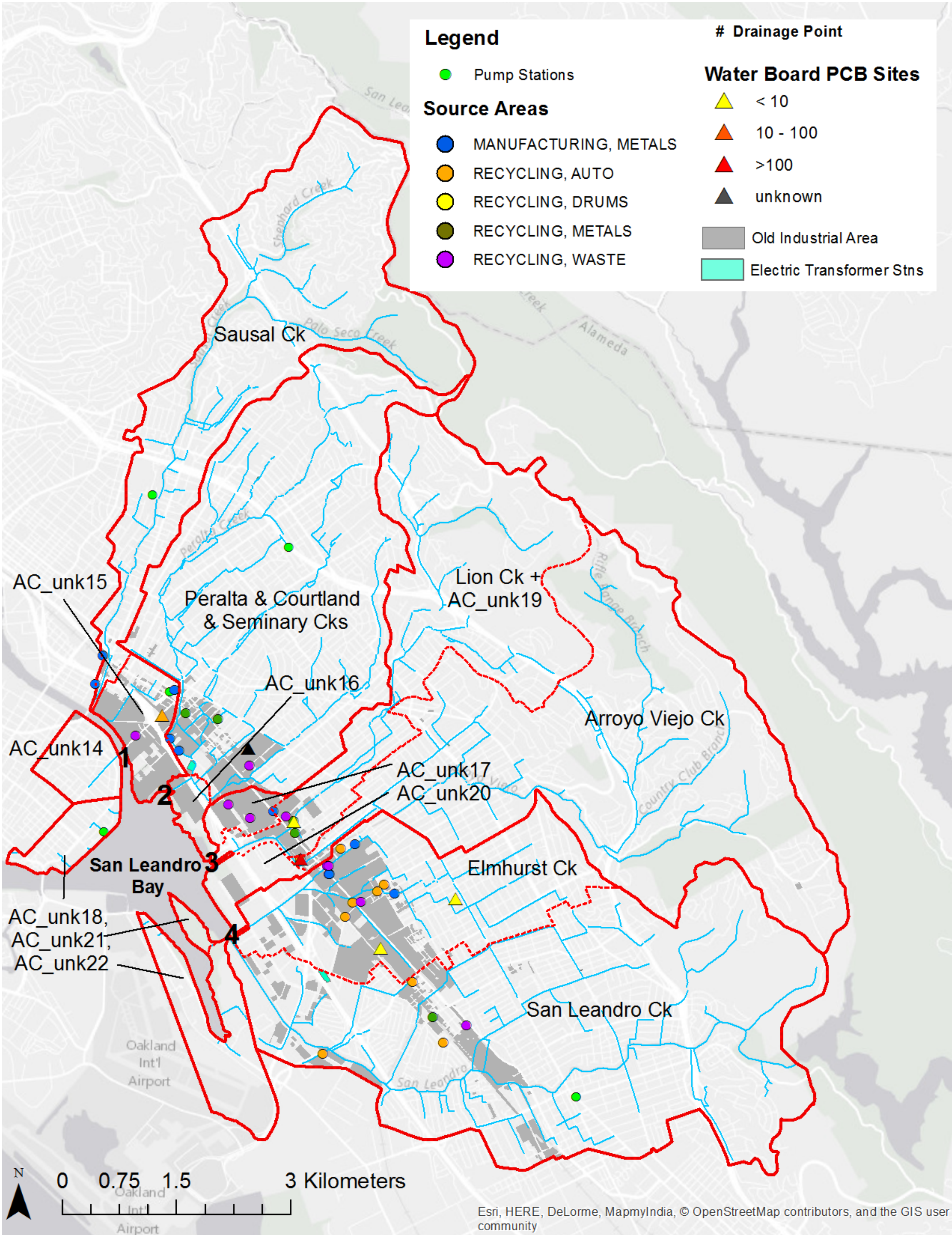

Figure 2-1. Main tributary watersheds to the San Leandro Bay PMU.

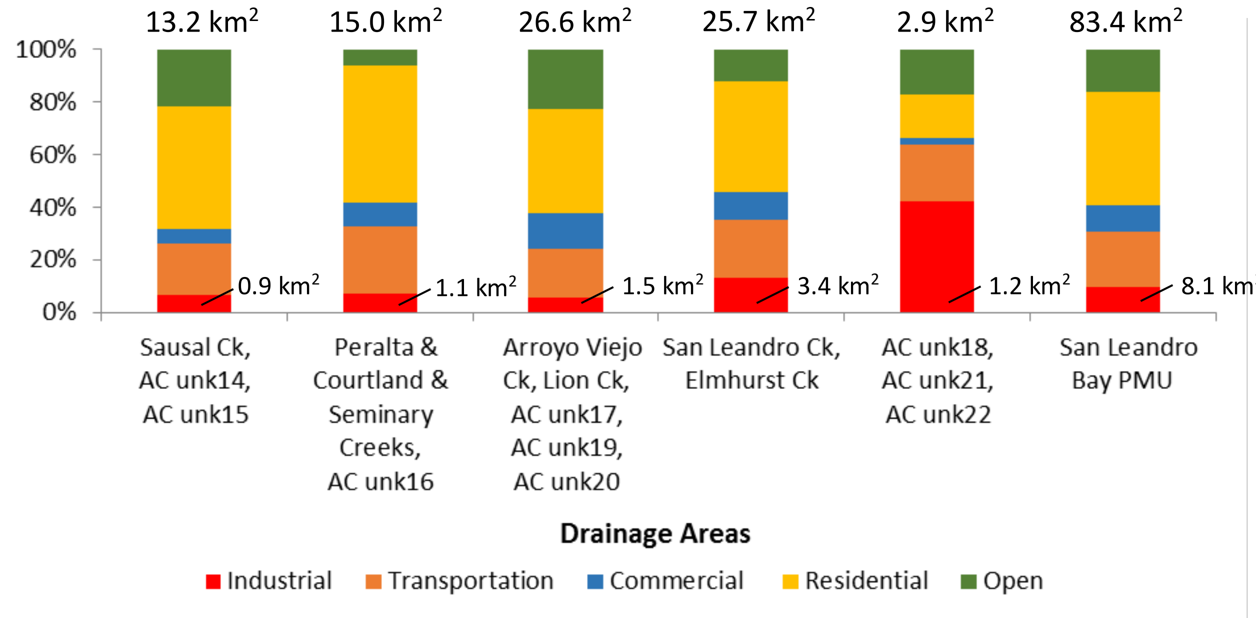

Figure 2-2. Land use in the San Leandro Bay PMU watersheds.

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 multi-year datasets for runoff and PCB concentrations from the SLB PMU subwatersheds, PCB export was estimated using the Regional Watershed Spreadsheet Model (RWSM; Wu et al., 2017). The RWSM applies Bay Area-specific 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. Two highly elevated sites are part of the RWSM calibration dataset and serve to raise the Bay Area-specific region coefficients, but it cannot be substantiated whether the San Leandro Bay drainage area should be higher than the regional average coefficients. Two prominent source locations do exist in the watershed, one of which is likely having a significant influence on loads to the PMU. In lieu of a means to quantify these source contributions, they are discussed qualitatively in Section F of this report.

The RWSM estimates average annual flow volumes of 26.6 Mm^3 (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. This best estimate is derived from applying the optimally calibrated coefficients[1] for PCBs using the RWSM. 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 (km^2)	Total Runoff Volume (Mm^3)	PCB Load - Low Estimate (g)	PCB Load - Best Estimate (g)	PCB Load - High Estimate (g)	PCB Yield -Best Estimate (ug/m^2)
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

[1] An automatic calibration approach was developed to calibrate the PCB model and provide an estimate of uncertainty around the calibrated coefficients (EMCs). The approach was based on a constrained optimization method (“Complex Method”, Box 1965). Functionally, this was done by 1) randomly sampling concentrations for each land use group within their lower and upper bounds and multiplying this with runoff volumes to get estimated loads; 2) deriving simulated EMCs from the estimated loads normalized by the total volume; and 3) running the Complex Method to search for the optimal combination of EMCs that minimized the difference between observed and simulated EMCs for all calibration watersheds simultaneously.

To quantify the uncertainty associated with the data and the calibration process, a Monte Carlo procedure was employed to calibrate the models to a distribution of observed data, rather than a single average or median concentration. A log normal distribution was found to be appropriate for this stormwater data. The procedure invokes the Complex Method in a number of iterations (100) to repeatedly calibrate the models to a range of observed concentrations sampled from the pre-determined distribution. The distribution of simulated EMCs that were produced by all iterations was then established.

The 25th percentile, median, and 75th percentile of calibrated EMCs were then used to estimate a range of PCB and Hg loads for individual watersheds and the whole region.

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 a 1:1 year, 24 hr return interval storm;
iii. the load for a 1:5 year, 24 hr return interval storm; and
iv. the load for a 1:10 year, 24 hr 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. All storm recurrence intervals with a 24 hr duration.

	Low	High
% 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 1:1 Year, 24 hr Storm (g)		Estimated Load from a Single 1:5 Year, 24 hr Storm (g)		Estimated Load from a Single 1:10 Year, 24 hr Storm (g)	
				Low	High	Low	High	Low	High
Sausal Ck, AC unk14, AC unk15	136	10.3	8.2	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	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	10.8	12.2	22.2	23.6	27.1	28.5
San Leandro Ck and Elmhurst Ck	350	13.6	21.0	16.1	18.2	33.3	35.4	40.6	42.7
AC unk18, AC unk21, AC unk22	91	31.2	5.5	4.2	4.7	8.6	9.2	10.6	11.1
Total for Margin Unit	986	11.8	59	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.

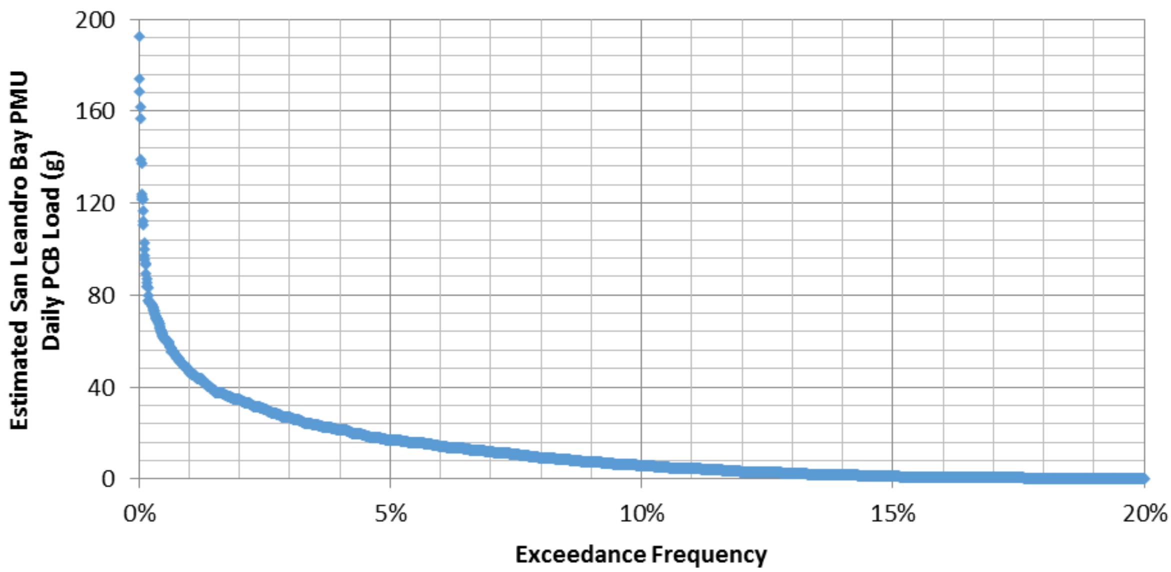

Figure 2-3. Exceedance frequency of estimated daily SLB PCB loads over a 40-year time period (WY 1971 – 2010).

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	Estimated % Dissolved based on: % 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).

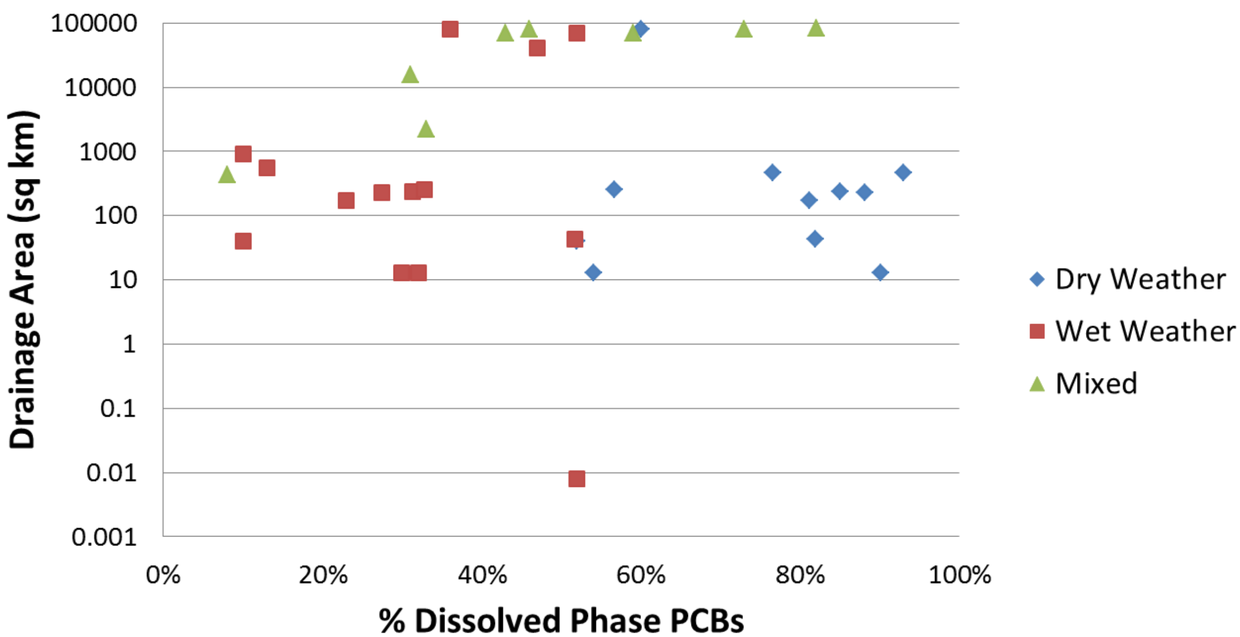

Figure 2-4. Summary graph of literature review case examples. Studies include: Steuer et al., 1999; Foster et al., 2000a, 2000b; Verbrugge et al., 1995; Marti and Armstrong, 1990; Quemerais et al., 1994; Howell et al., 2011; Hwang and Foster, 2008; Tlili et al., 2012; Ko and Baker, 2004; Gomez-Gutierrez 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. It should be noted that these estimates lack specific quantification of the load contributions from the known source areas in the PMU (see Section F for further discussion). 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 (24 hr duration) 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 (24 hr) 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.

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

			Annual PCB loads (g) transported during different flow and partitioning characteristics									
Watershed	Total Area (km^2)	Total Runoff Volume (Mm^3)	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
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.

f. Existing Data and 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).

In addition to the MRP requirements, two major clean-up efforts are currently underway in the San Leandro Bay watershed. First, the California Department of Toxic Substances Control (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) (Figure 2-5). This location was formerly a transformer and electrical equipment facility from the mid-1920s until nearly 2000. Surface soil samples at this site measured up to 11,000,000 µg/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 (UPRR) site at 701 73rd Avenue just east of the Coliseum in Oakland (pers. comm. Janet O'Hara, SFBRWQCB) (Figure 2-5). This location was formerly a rail station and then an auto salvage yard. Soil samples at this site measured up to 3,000,000 µg/kg, and sediment samples collected in the adjacent channel ranged up to 3300 µg/kg (GHD 2017). Clean-up of this site is expected to take place in the next two years (pers. comm. Sara Ziff, EPA).

Figure 2-5. Major clean-up sites (approximate location at red stars) in the watershed draining to San Leandro Bay, and PCB concentrations in sediment (µg/kg) for select samples.

In August 2016, sediment samples were collected in channels downstream of each of these clean-up sites. Figure 2-5 shows the concentrations of select sediment samples downstream of the clean-up sites. Sediment PCB concentrations were particularly high in East Creek Channel, downstream of the GE site and Peralta, Courtland, and Seminary Creeks. The congener profiles in East Creek Channel were dominated by congeners indicative of Aroclor 1260, except for the site furthest from the Creek mouth (ECM100m) which was dominated by Aroclor 1254. A primary use of Aroclor 1260 was in electrical transformers, which were processed at the GE facility. Concentrations in Damon Channel downstream of the UPRR site on Arroyo Viejo Creek were not as high, and were dominated by congeners indicative of Aroclor 1254. Aroclor 1254 had a wider variety of uses than Aroclor 1260, including use in capacitors, hydraulic fluids and vacuum pumps, as plasticizers (including in sealants and caulking), and other uses.

The same sediment concentration patterns were seen in the Daum et al. (2000, Figure 2-7): concentrations were generally very high downstream of the GE site and not as high downstream of (with the exception of one sample collected directly adjacent to) the UPRR site. In both the Daum et al. study and 2016 study, elevated concentrations were also present in Elmhurst Creek, though the source or sources in this watershed are unknown.

Stormwater data collected in a single storm event in 2017 along each tributary to San Leandro Bay also corroborate these patterns (Gilbreath et al. 2018). There are three channels that drain into East Creek Channel: Peralta, Courtland and Seminary creeks. PCB concentrations on suspended sediment particles in stormwater samples collected from those three channels measured 180, 2600, and 400 µg/kg. The highest concentration (2600 µg/kg) was collected in Courtland Creek downstream of the GE plant. Consistent with the pattern of sediment concentrations, suspended sediment concentrations collected downstream of UPRR measured just 48 µg/kg in stormwater runoff. And finally, also similar to the sediment results, Elmhurst Creek had an elevated concentration of 220 µg/kg. The empirical EMC or load from one storm for these tributaries were similar to the "best" estimate for the RWSM regional model.

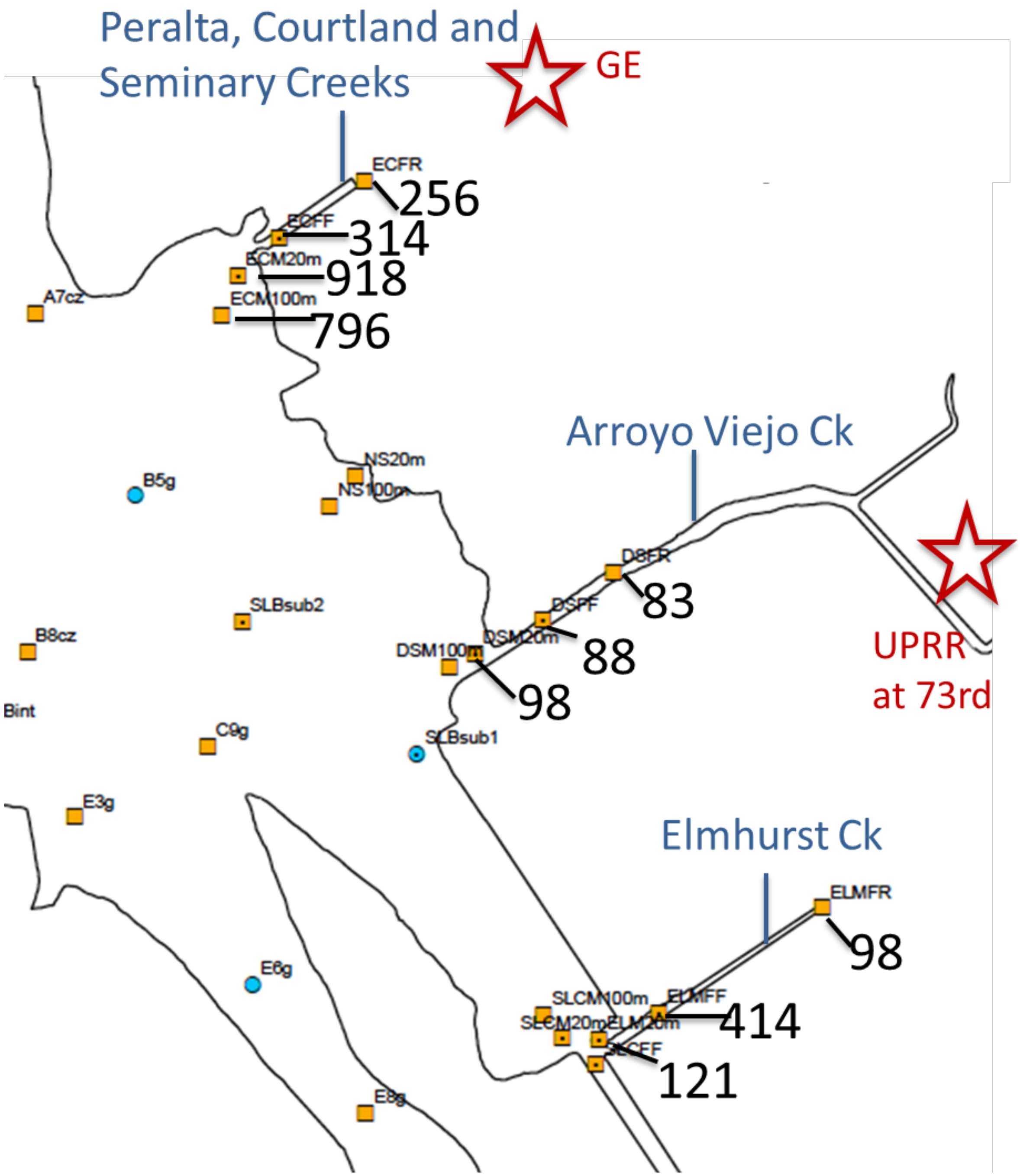

Figure 2-6. Major clean-up sites (approximate location at red stars) in the watershed draining to San Leandro Bay, and PCB concentrations in sediment (ug/kg) for select samples.

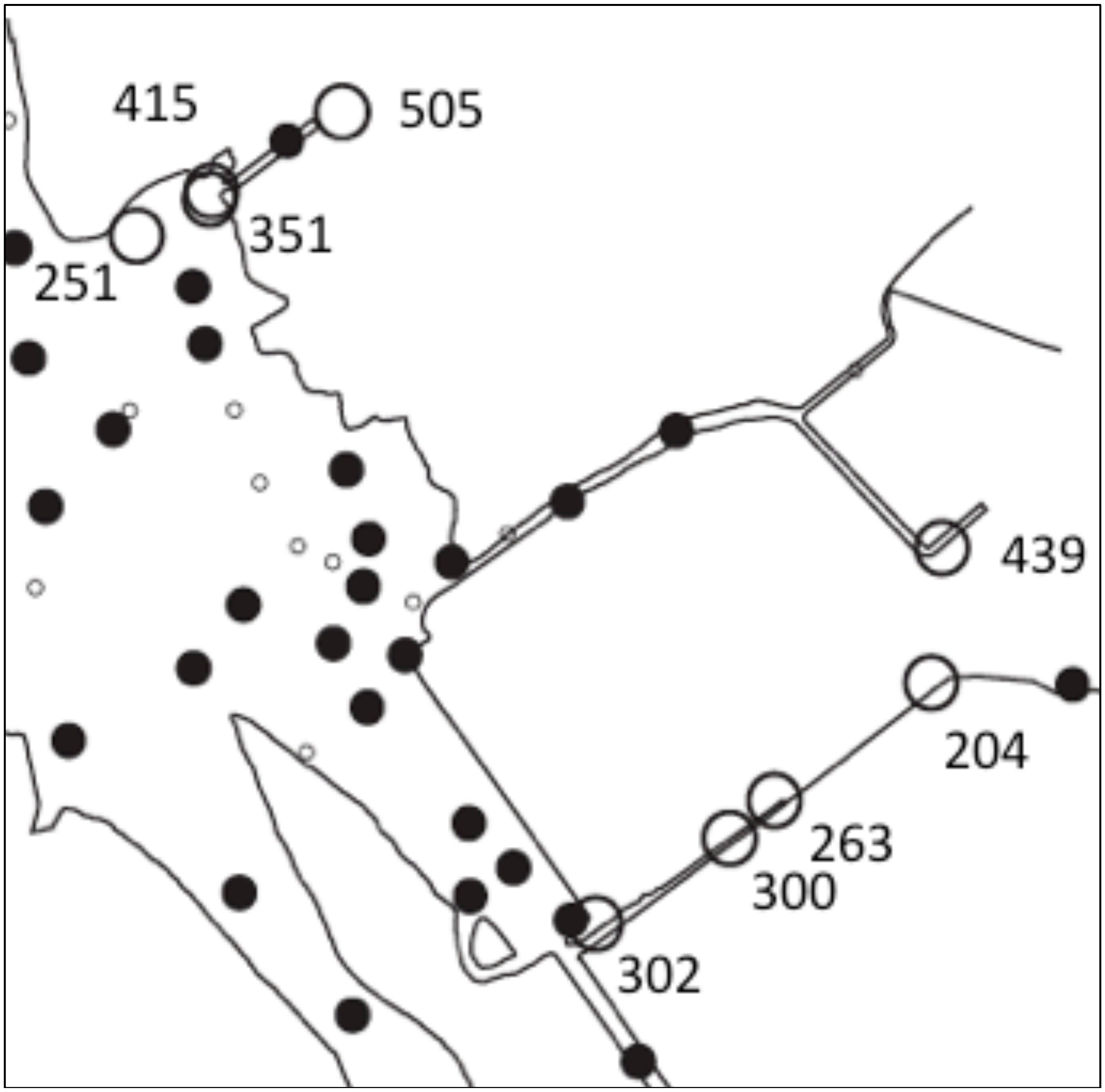

Figure 2-7. PCB concentrations (ug/kg) in sediment collected in 1998 (Daum et al. 2000).

Of the two clean-up sites, General Electric is likely to have a much greater influence on load export to the PMU. The highest concentrations sampled in soil on that site are greater than those sampled at the UPRR location. Conceptually this makes sense: PCB handling and usage was a primary activity at the GE location. Even with the majority of the site now capped, drainage off the property may still be functioning as a continuing source to the channel. Planned sampling in WY 2019 and WY 2020 should provide an estimate of ongoing elevated loading, if any. Contaminated sediment stored in the channels downstream of the property is likely also contributing to continued loading to East Creek Channel and San Leandro Bay. In addition to the concentration patterns, the congener profiles of the suspended and bed sediment samples in East Creek Channel are consistent with the GE property being an important source of PCBs to sediment in East Creek Channel.

On the contrary, the former UPRR site (and then auto salvage yard) appears likely to have a more limited influence on PCB loading to the PMU relative to the former GE site. Concentrations of PCBs found on the site and in the adjacent channel are lower (GHD, 2017). PCBs would have only been ancillary to the activities by these businesses. GHD (2017) also summarize what the more extensive sediment data for the channel downstream of the site show (i.e., more concentrations that are not that high). It is likely that significant loading from this site to the PMU is only intermittent, when more areas with higher soil and sediment concentrations are mobilized.

In summary, two major clean-up efforts are currently underway, and investigations to determine if there are additional source properties in the watershed are ongoing. It is promising that these efforts will serve to substantially reduce PCB loads to the PMU over a long time period. In light of management actions currently in an early phase of a longer-term effort, the challenge with quantifying the impact of PCB loading from the source areas before and after cleanup, 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%.

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 tested and is now implementing two remote sampling techniques that help to reduce the field effort and costs required for each individual sample. Each of these monitoring protocols is tailored to suit specific questions and needs (Table 2-8). These same monitoring designs will be explored or adapted for measuring trends in storm water concentrations and loads in response to management efforts as part of the Trends Strategy (Wu et al., 2018; Wu and McKee, in review).

Short Term Data Gathering

The main near-term data weaknesses associated with the loading estimates are the lack of long-term monitoring data during storms in any of the San Leandro Bay subwatersheds apart from Pulgas Pump Station South (Flow and PCBs for two WYs) that would allow for relative ranking of pollution pathways between each of the subwatersheds and help to provide a better calibration for the loads estimates generated by the RWSM. If there was also better flow data available, a better calibration of the RWSM for hydrology could also be achieved. Another major weakness is the lack of information on PCBs in relation to particle size or in the dissolved fraction. 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 we would get some idea of how variable the relationships between flow and PCBs and dissolved or particulate phase may be 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 storms could be completed for the highest priority locations and analysis performed to determine dissolved concentrations, concentrations on several grainsizes, as well as whole water concentrations.

Long-term Monitoring

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 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 2-9) is, are the uncertainties associated with the planning level modelling effort within the PMU resolved by obtaining continuous (at scales of minutes) estimates of flow and PCB load over wet season or multiple wet season timescales? And even if this would be useful data, is taking the time and effort to obtain it from the highest priority attending subwatersheds going to change our understanding of the processes of pollutant uptake and biological impact in San Leandro Bay? If the San Leandro Bay watershed ends up having a lot of focused management effort aimed at PCBs or redevelopment more generally, is baseline data suitable for determining long term trends in storm water concentrations and loads needed or are data for trends analysis best collected in the Slough system itself? These questions need to be reconciled as we learn more about San Leandro Bay. 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 indicated in Table 2-10, dynamic simulation models can be used to estimate loads and trends (Wu et al., 2018). 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. In addition, the RMP is moving ahead with model development as a component of the small tributaries loads trends strategy (STLS_T) (Wu et al., 2018; Wu and McKee in review), that will also benefit from improved calibration data. The minimum monitoring method suitable for input to and calibrating a dynamic simulation model that is illustrated in Table 2-8 is the wet weather single-storm discrete sampling protocol coupled with stage and flow measurement. Obviously, as more storm and years of data were collected, a greater accuracy would be achieved (Table 2-10 – left to right) but with gradually diminishing returns. In relation to trends validation, we recommend at least one loading station that is representative of the range of land uses and the types of management being considered. Such a loading station should be reoccupied for a minimum of 5 wet seasons over a minimum of 10 years (long enough for land use, redevelopment and management implementation to take effect). For the best power to detect a trend, flow and concentration data should be collected during four storms a year using a discrete sampling design to capture 16 samples (Melwani et al., 2018). Such data would be suitable for local calibration of the regional trends model being developed through the RMP (Wu and McKee, in review). To support trends evaluation, detailed accounting of management effort would also be needed, ideally on a watershed by watershed basis, but at very least, in the one watershed where the trends monitoring station is set up.

Table 2-10. Monitoring protocols available to support characterization of concentrations, phase distribution, particle ratios, or PCB loadings during storms.

Data uses	Name of protocol					
	Remote sampler (Walling tube/ Hamlin	Wet weather single storm reconnaissance (composite)	Wet weather single storm reconnaissance (discrete) coupled with flow measurement	Wet weather multi-storm composite) coupled with flow measurement	Wet weather multi-storm discrete) coupled with flow measurement	Wet weather multi-storm discrete) coupled with flow and turbidity measurement
	Relative level of effort					
	Low	Medium	Medium-high	High	Very high	Very very high
Field measured trends	Maybe	Maybe	Maybe	Yes (lower certainty)	Yes (lower certainty)	Yes (high certainty)
Relative PMU sub-watershed rankings	Yes	Yes	Yes	Yes	Yes	Yes
Quantification of PCB concentrations on sediment size fractions	Yes	Yes (but care must be made not to exceed 6-hour hold times)	Yes	No (samples likely to exceed 6-hour hold time)	Yes	Yes
Quantification of dissolved phase		Lower certainty (and care must be made not to exceed 6-hour hold times)	Lower certainty	No (samples likely to exceed 6-hour hold time)	High certainty	High certainty
Support for RWSM to estimate loads				Calibration only	Calibration only	Calibration and verification
Measured storm specific loads			Yes	Yes	Yes	Yes
Support for dynamic model (e.g. SWMM or HSPF) to estimate continuous total loads estimates and trends			Calibration and verification	Calibration and verification	Calibration and verification	Calibration and verification
Measured wet season loads			Yes (lower certainty)	Yes (lower certainty)	Yes (lower certainty)	Yes (high certainty)

Measured continuous loads estimates and trends				Yes (lower certainty)	Yes (lower certainty)	Yes (high certainty)

h. 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, only very limited stormwater data were available for the San Leandro Bay PMU watersheds (several of these watersheds were sampled in a single storm event in WY 2017) and therefore load estimation is entirely dependent on the RWSM. One aspect of PCB loading into the PMU that is important but not well captured in the limited 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 is 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.

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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.

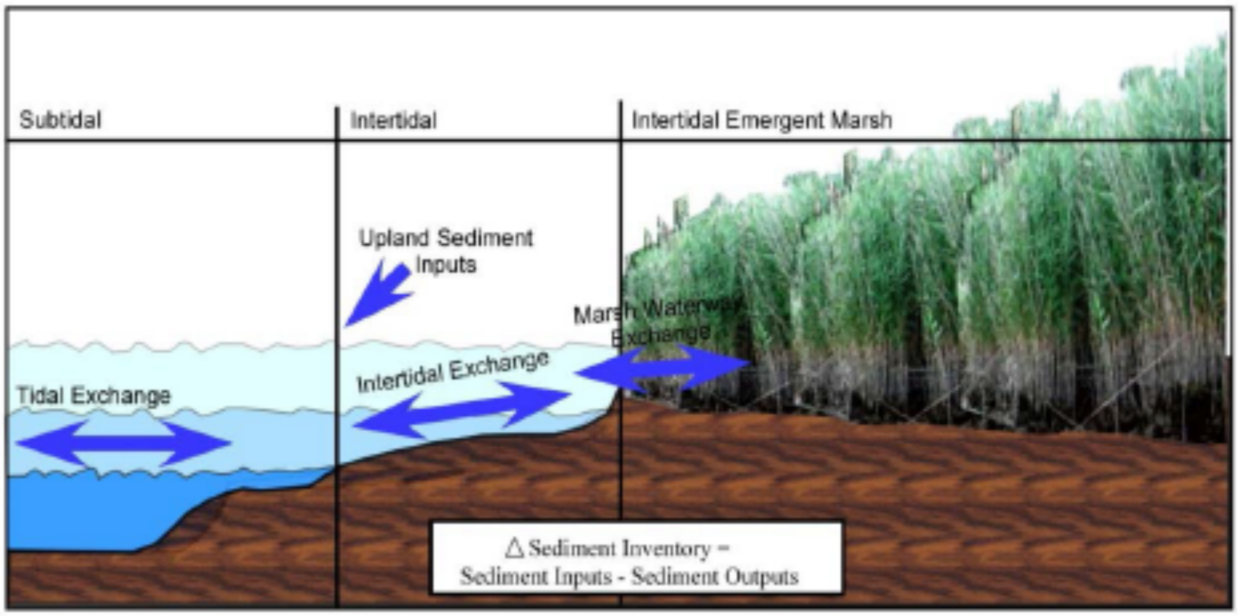

Figure 3-1. General conceptual illustration of margin sediment fate

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.

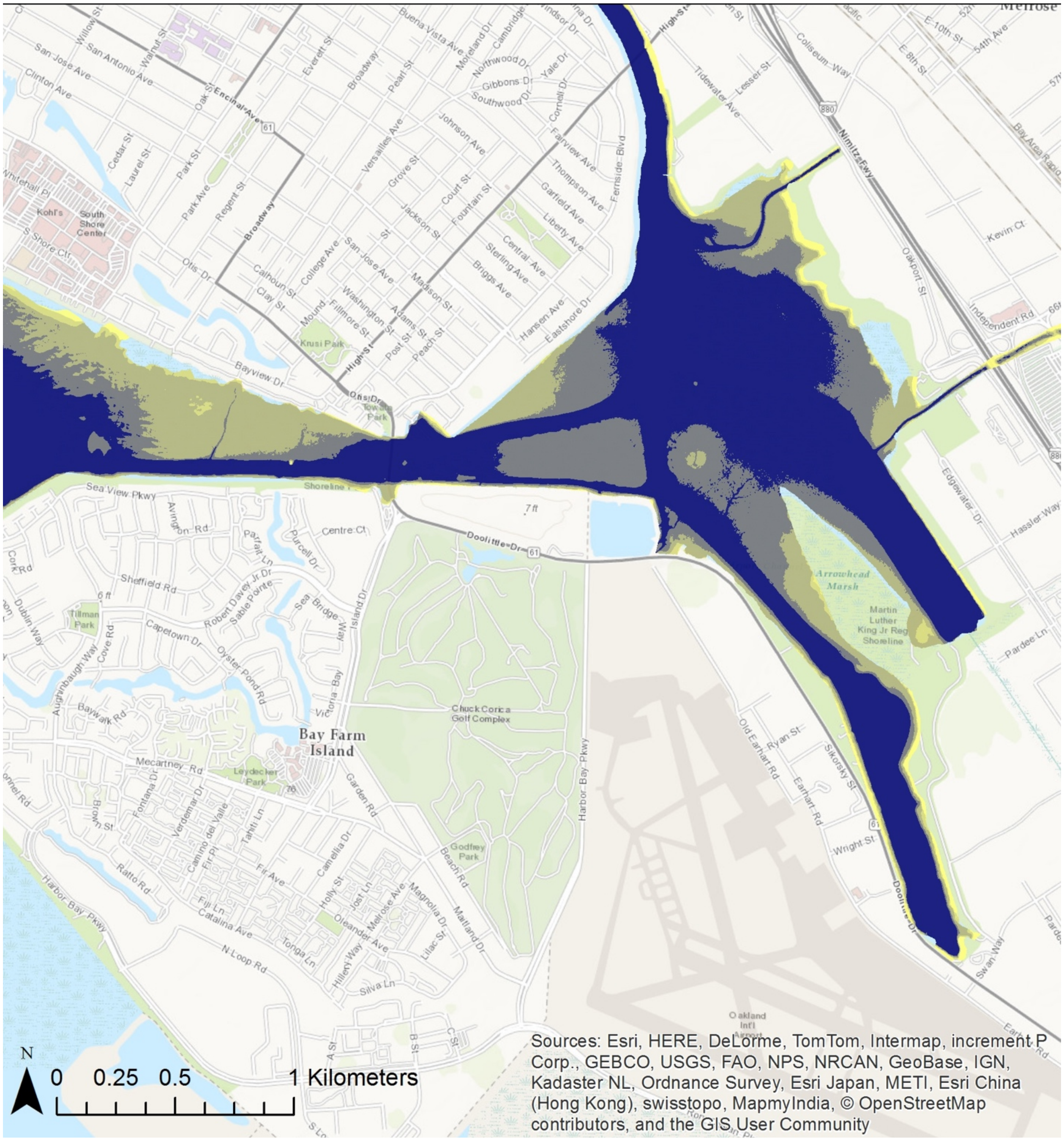

Figure 3-2. Tidal datums in San Leandro Bay. MLLW, MLW, MSL, MHW, and MHHW indicated by colored contours, from darkest (blue) to lightest (yellow), respectively.

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.

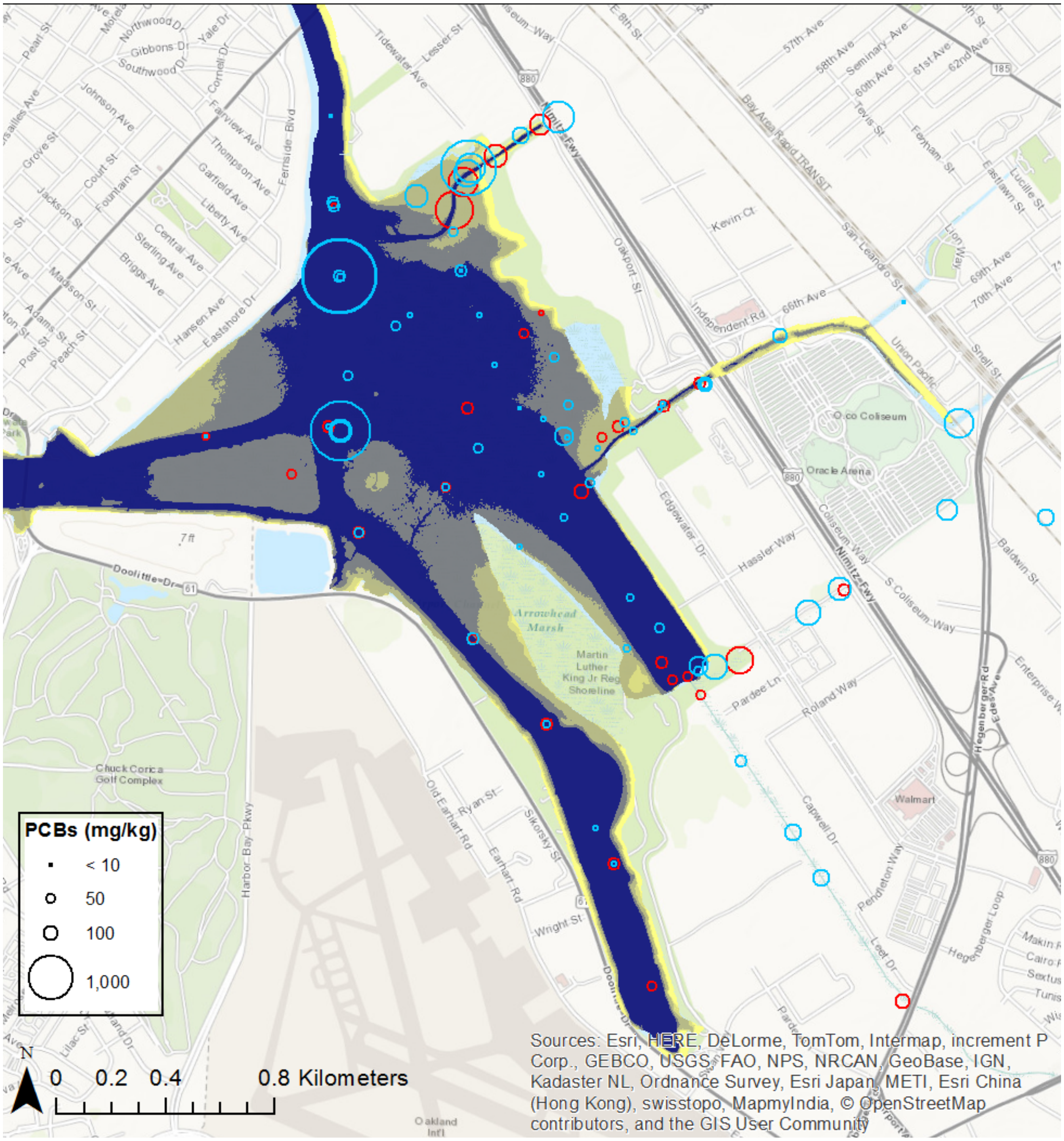

Figure 3-3. Bubble plot of sediment PCB concentration distributions in and around San Leandro Bay (from Daum et al., 2000 in blue, and summer 2016, in red).

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.

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. In general, velocities in the intertidal zone at the edges of SLB are much lower than in the central portion (Figure 3-4), 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).

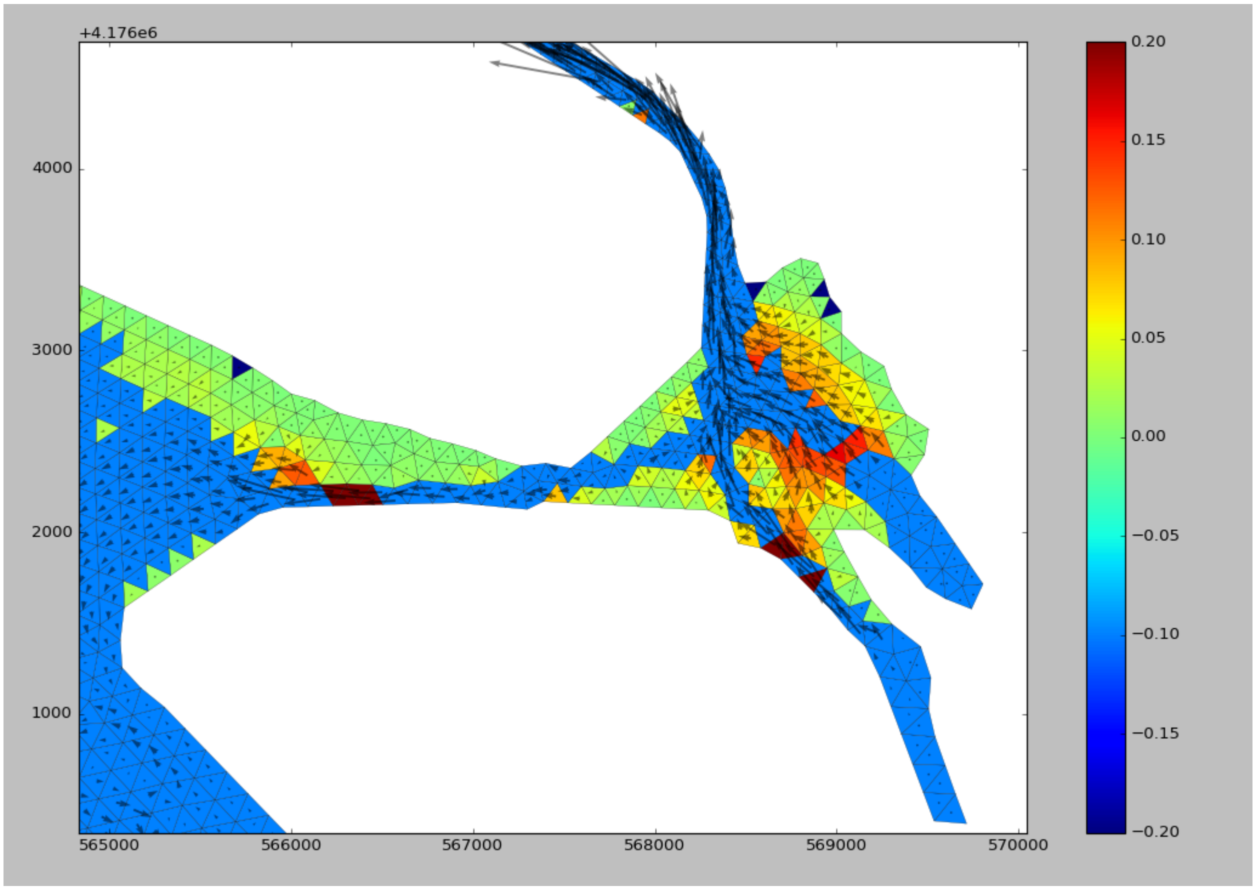

Figure 3-4. Flow velocities and direction on ebb tide around San Leandro Bay. Velocities on colored legend shown in m/s.

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 40^{th} 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.

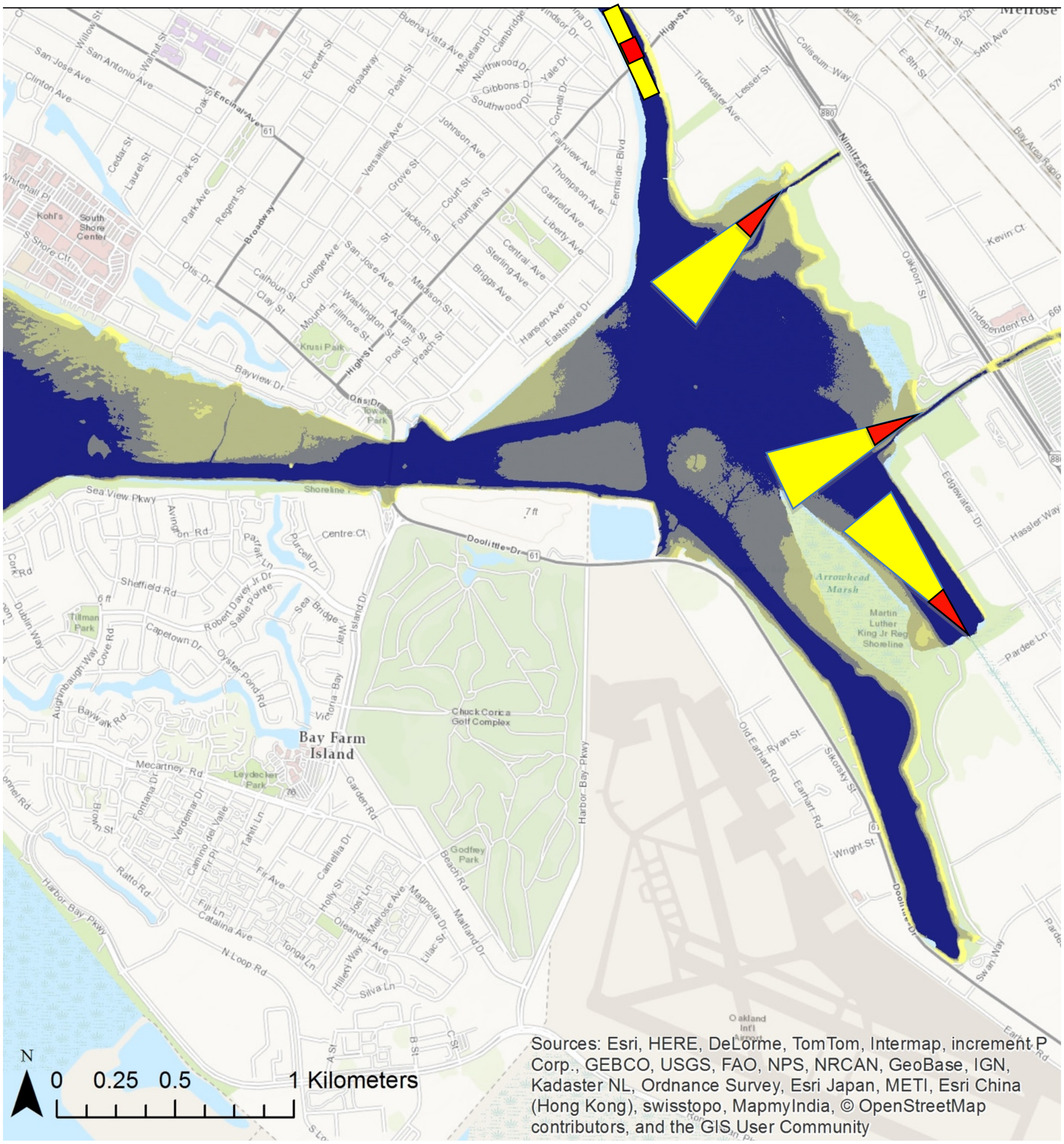

Figure 3-5. Hypothesized short-term deposition zones at high tide. Yellow triangles represent 1 hour settling areas for each area. Red triangles indicate fast settling (0.1 hour) areas. The zone affected by discharge from Area 1 has no direction at high slack, so is pictured as a band rather than a conical 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. SLB can be broken up into three zones, the vegetated intertidal 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 require empirical data or separately devise a simple box model of contaminant fate. 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.

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 combining with BPTCP and other studies) to minimize concerns over inter-lab variation. Although there are inaccuracies to having selected only one congener to represent "Total PCBs", fate predictions based on the physico-chemical properties of select lighter and heavier congeners are explored and 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 major 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.

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. Another 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.

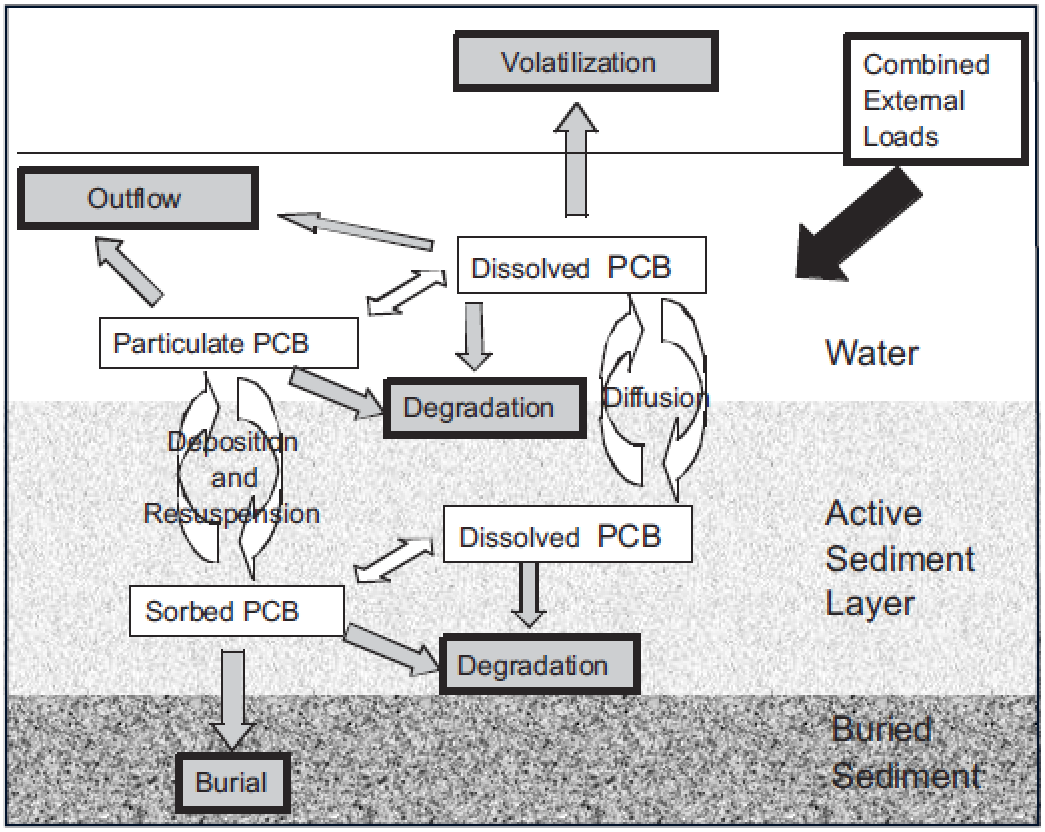

Figure 4-1. PCB Fate Conceptual Model (from Davis, 2004)

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.

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	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 slower 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 surface sediment, 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 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 per year based on surface 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.

The persistence of highly contaminated areas for SLB suggests high ongoing loading rates to maintain locally elevated concentrations, slower loss processes than captured in the current parameterization of the simple box model, or both. For example, adjusting the suspended sediment concentration up or down increases and decreases the export rate respectively; two-fold lower SSC roughly doubles the system response time, and raises the final steady state to roughly the same point as a doubled loading rate. Similarly, higher ambient water PCB concentrations in adjacent areas (e.g., Oakland Harbor, Coast Guard Island) would provide less of a sink of PCBs, and yield slower net export (or if high enough, net import to SLB) and a higher final steady state. Therefore a good local quantification of the suspended sediment pool available for tidal export, as well as PCB concentrations in adjoining water bodies 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 model of sediment resuspension across the intertidal zone may be needed to better 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. Loading processes are modeled as 0^{th} order inputs (independent of the model box concentration), while losses and exchanges of PCBs are modeled as first order (directly proportional to box concentrations). With constant 0^{th} order input rates and 1^{st} order loss rates, the residual mass can be explicitly calculated for any time point. Total PCB mass in the modeled system (the SLB water column and mixed sediment layer, with >99% of the mass in the sediment layer) is calculated at regular intervals starting from various initial states, plotting their progression towards a final steady state.

Although annual loads are not truly constant due to climatic variability and gradual changes in the landscape, 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 independent of the initial inventory, as would be expected. These mass budget model results suggest ongoing loading rates at the median "best" estimate described in Section 2 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, various processes may also need to be explicitly mechanistically modeled or otherwise approximated through additional adjustment factors to get more accurate predictions.

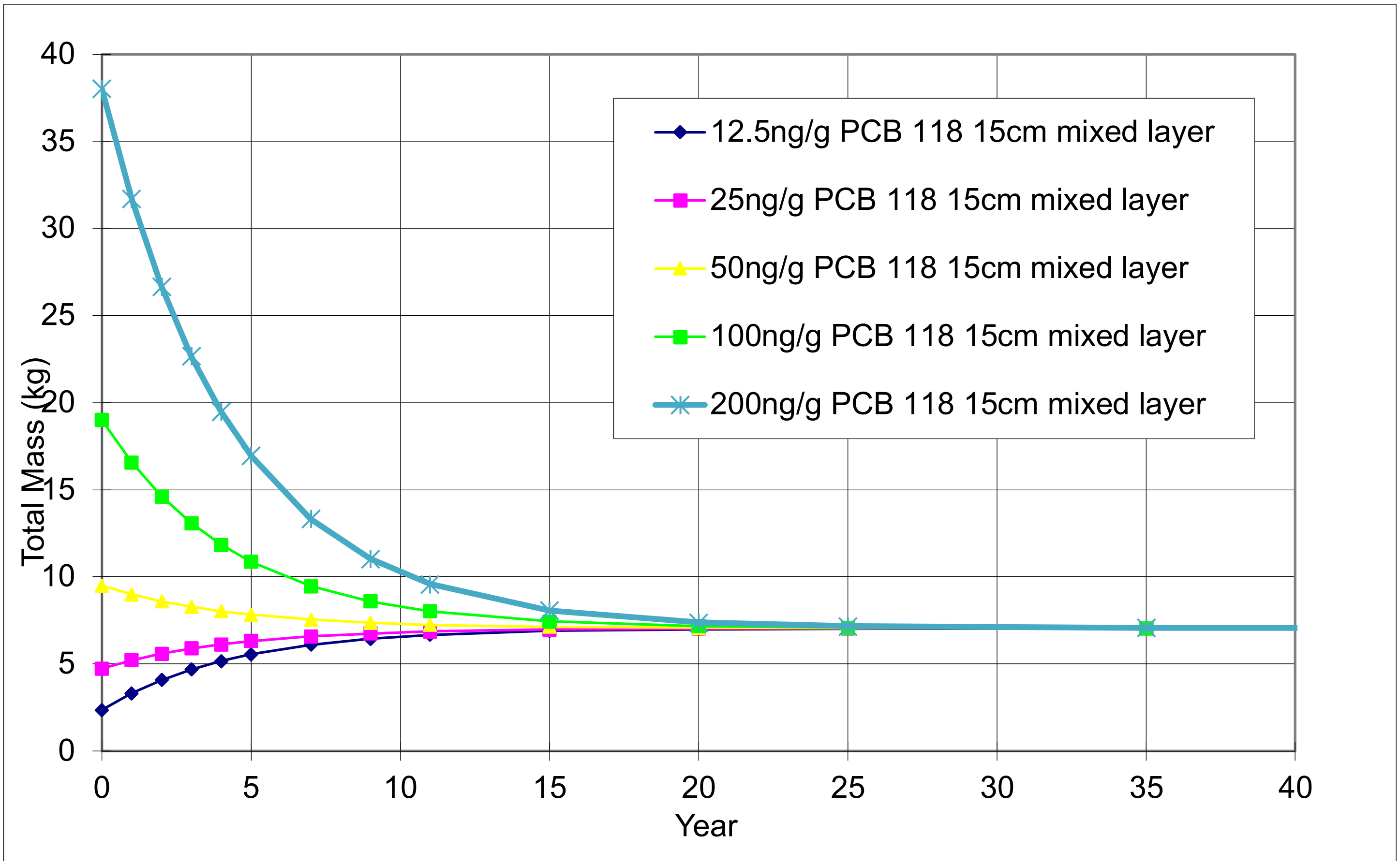

Figure 4-2. Recovery trajectories from differing starting concentrations, constant watershed and Bay loading, other parameters from open Bay 1 box PCB model (15 cm mixed layer, Bay SSC, 1 m/day settling, no burial, etc.). The y-axis is the total mass of PCBs in the modeled volume of SLB (the water column and mixed layer of sediment). Around 35 ng/g sediment concentration would be supported at steady state with current watershed and Bay loads continually entering SLB indefinitely.

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. Conversely, higher loads are also possible, as the base case (1x) load is based on a regionally calibrated loading model. The high loading case described in Section 2 (the 2x load case in Figure 4-3), represents the loads generated using the 75th percentile of regionally estimated annual PCB release rates for the reported land uses around SLB. Some watersheds could yield higher loads, conceivably even the 4x higher rate that the simple mass budget model suggests would maintain SLB at steady-state PCB concentrations near their 1998 values. Good local measurements of incoming loads are thus very important for projecting long-term fate and for measuring the effectiveness of loading reduction efforts in various margin areas.

Although actual changes in watershed loads are not likely to occur all at T=0 (starting from the 1998 initial conditions) 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.

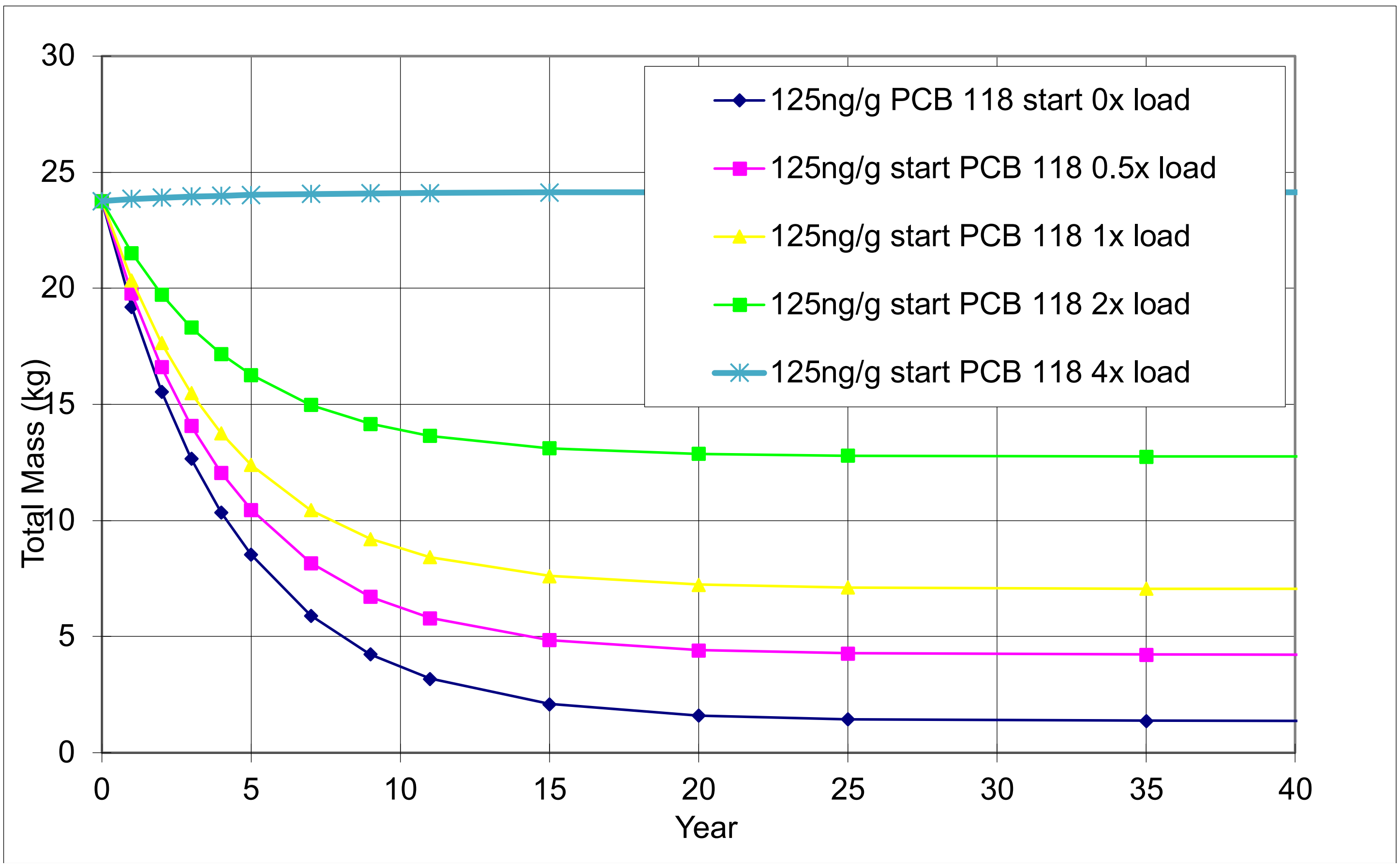

Figure 4-3. Trajectories with 125 ng/g starting concentration, differing watershed (WS) loads, other parameters same as in Figure 4-2. The y-axis is the total mass of PCBs in the modeled volume of SLB (the water column and mixed layer of sediment). In the base (1x = 986 g/yr) load case, WS load is 4x the tidal load from the Bay (the 0x WS load case, where the only new PCB inputs come from SF Bay ambient waters).

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). Although the high (2x above the base case) loading rate described in Section 2 would not by itself yield steady-state concentrations unchanged in SLB since 1998, those high loads represent a regionally derived 75th percentile, and loads in individual watersheds could potentially be even higher (or conversely, lower than the “low” 25th percentile load estimate). A loading rate 4x the base case estimate would be sufficient to maintain modeled concentrations at their 1998 values. In addition, there may be combined effects; a high load estimate (~2x higher than the base case) combined with other changes in model parameters (such as reduced tidal exchange or lower SSC) could yield steady state projections similar to the 4 x loading case, with nearly no change in SLB concentrations.

Given the large tidal exchange relative to total volume, changes to parameters affecting SSC and net 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). The two-fold increases and decreases in SSC and net tidal exchange explored represent considerable uncertainties in model parameters that could be better constrained with more site-specific data. 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 states, the half-response times increase to about 4.5 years, nearly 50% slower response. Increases in SSC or tidal exchange have an opposite effect, for example, doubling of SSC decreasing the final steady-state concentration nearly two-fold, and the half-response time shrinking about 50%.

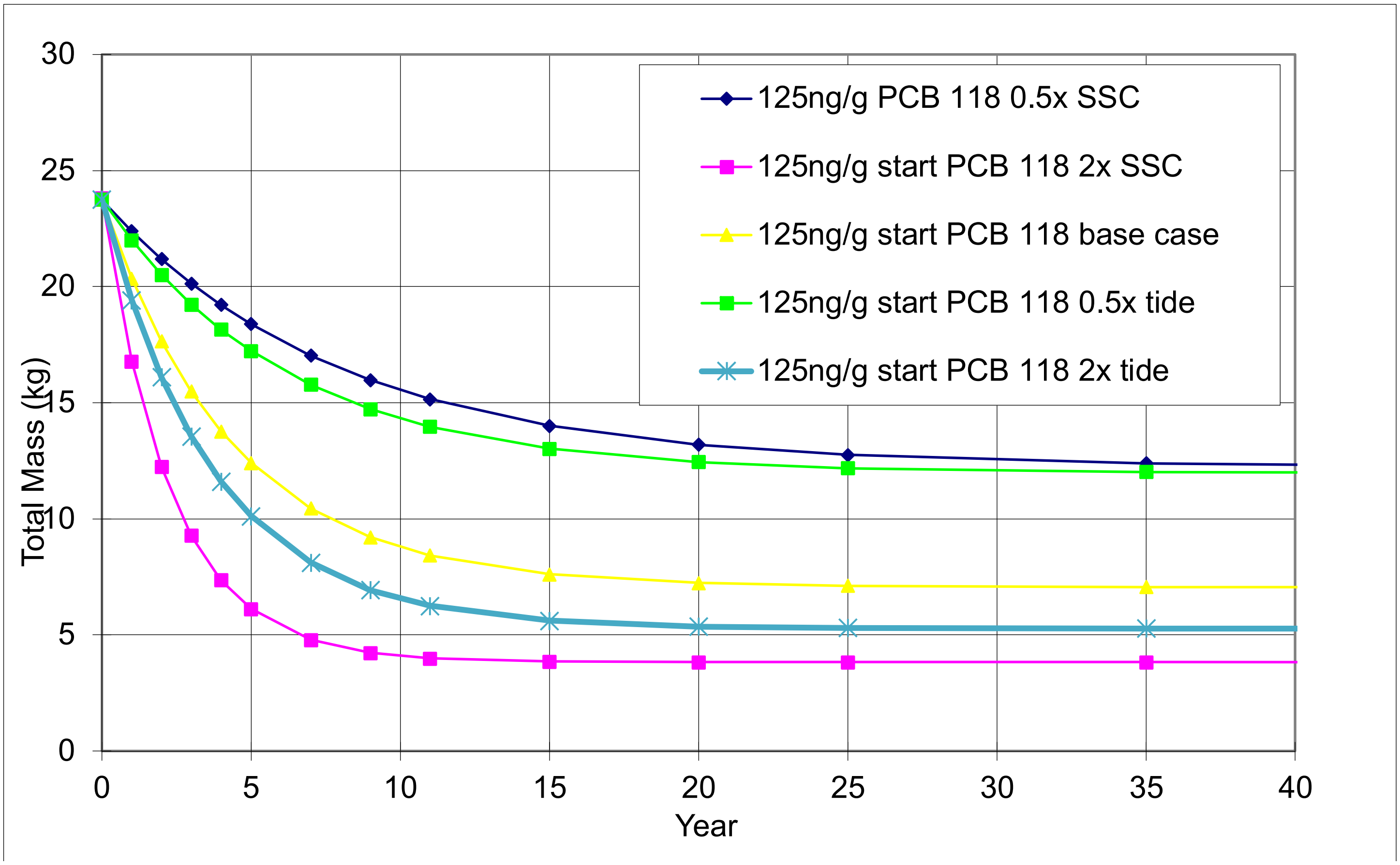

Figure 4-4. Trajectories under base case loads, with different SSC and tidal export parameterization. The y-axis is the total mass of PCBs in the modeled volume of SLB (the water column and mixed layer of sediment). Adjustments halving the exchanged tidal volume (0.5x tide) and the mass of suspended sediment (0.5x SSC) reduce PCB loss rates from SLB, slowing the system response time, and raising the final steady state mass and concentration.

Similar to the case for Emeryville Crescent, other factors affecting the sediment layer fate such as burial and erosion rates, and degradation rates, had small impacts on long-term fate due to their slow rates, 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. The mass of PCBs in the water column in equilibrium with sediment (and thus mass lost via tidal exchange) is dependent only on the sediment PCB concentration and not the mixed layer thickness. Thus tidal losses for thin mixed layer thicknesses are large relative to the initial inventory, but the losses decrease as the sediment concentrations do. In contrast, thicker mixed layer scenarios maintain high loss rates until their concentrations are in turn decreased.

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. Comparison to Emeryville Crescent mass budget

A mass budget was previously calculated for the Emeryville Crescent (Davis et al., 2017), with qualitatively similar behavior and uncertainties as in the SLB mass budget presented here due to identical model structure. However, the predicted recovery response in Emeryville Crescent was slightly faster, due to different system characteristics, primarily larger tidal prism relative to volume, and lower expected concentrations in incoming water from adjacent water bodies. Although the water coming into Emeryville past Treasure Island, and coming into SLB through the Bay Farm Island inlet, would be expected to have similar Central Bay open water ambient concentrations, water coming back into SLB would have a greater proportion of returning (more contaminated) flow. In SLB, much of the water entering from the Oakland Harbor side would have just exited SLB on the previous tide, and would be less mixed with open Bay water, as well as having potential internal sources of contaminants such as the area around Coast Guard Island, where high PCB concentrations previously found in sediment could contribute additional load, keeping SLB concentrations higher. This latter factor (contamination from Coast Guard Island areas) was not explicitly included in the SLB mass budget, but could contribute to the apparent slower recovery than anticipated in the model (little to nearly no change observed in the recent sampling, discussed in more detail in the next section).

Another major difference is that SLB is much more enclosed than Emeryville Crescent, with relatively narrow channels for entry and exit, and Arrowhead Marsh separating the two sides, so a multi box model may be more accurate. Cleaner Central Bay water entering SLB would first have to come in from the west via a narrow channel, then travel past Arrowhead Marsh to the east side, and finally exit to the north. Some of that cleaner entering water might also have a chance to exit before dispersing and mixing much with the more contaminated areas on the eastern shores of SLB where the main PCB sources are, so net PCB export would be further reduced from expectations derived using a simple uniformly mixed box model. SLB is also relatively well protected, surrounded by land in nearly all directions, so effects from waves originating in the open Bay would be minimal. In contrast, although Treasure Island, Yerba Buena Island, and the Bay Bridge may shield Emeryville Crescent from some of the waves coming through the Golden Gate and from southern Central Bay, its wide entrance leaves it directly open to swells originating from the northwest (Sausalito and Angel Island area). Emeryville Crescent has not previously been sampled extensively like SLB has, so it will be difficult to verify whether these factors potentially affecting transport within these PMUs have real observable influence, but conceptually, Emeryville Crescent at least appears more suitable to model as a single well-mixed box.

d. 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 (although as noted before the application of a multi box model to SLB may yield more accurate results). 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).

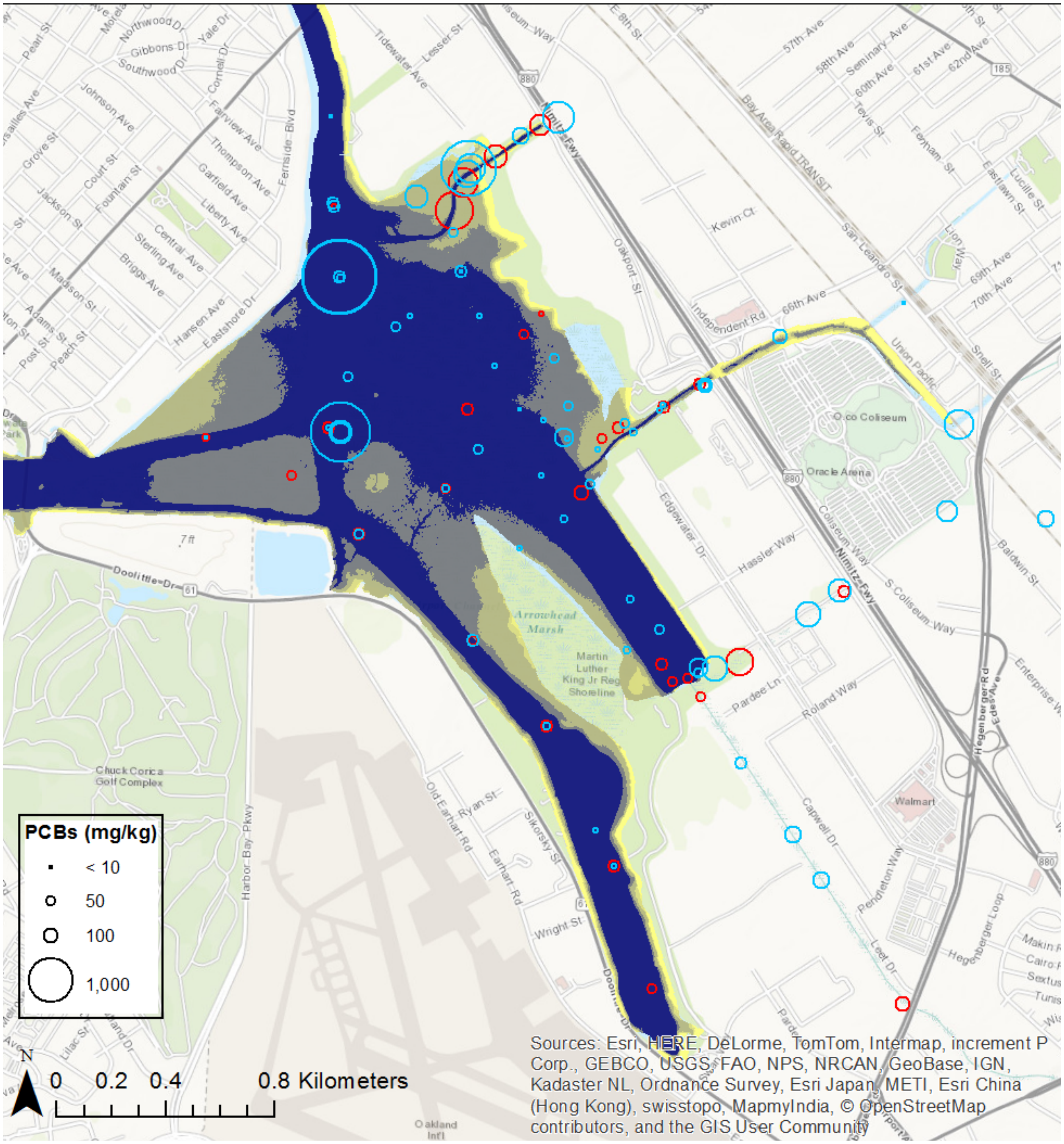

Figure 4-5. Bubble plot of PCB concentrations (mg/kg dry weight) in SLB sediment, from Daum et al. (2000) (blue) and summer 2016 (red).

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 between the earlier and current studies, with concentrations in some cases seemingly higher. The simple mass budget model as currently parameterized has many uncertainties in loading rates and other modeled variables, and differences in analytical methods may have obscured potential changes, or in some cases even seeming to cause increased concentrations over time. The base case 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 base case current loads within about 10 years, but even if the model is inaccurately parameterized and the system response is overall 4x slower, we would expect at least a small change in the nearly 20 years since the prior study, if the incoming sediment and water are notably less contaminated than those already in SLB.

The base case estimate for current loads for the model suggests a steady state ambient concentration supported 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 analytical method for PCBs in archived RMP Status and Trends sediment samples). The Daum results even using a two-fold upward adjustment factor to roughly match the current method would start at 250 ng/g (above the 200 ng/g top line in Figure 4-2). However, 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 using the base case estimate of current loads.

The uniform box handling of the area likely contributes, as changes in loading are instantly propagated; PCBs in external loads, newly exchanged water, the remaining water column, and the mixed sediment layer are modeled as virtually instantly (within the modeled daily rates) in equilibrium. This accelerates both projected export and import fluxes of PCBs and/or cleaner sediment. A more spatially detailed 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 uncertainty 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. Similarly, using open Bay water PCB concentrations for tidal flows entering SLB may underestimate the tidal loads; waters entering from Oakland Harbor and Coast Guard Island to the north may already be contaminated by past and current PCB inputs, slowing the rate of loss and increasing the final steady state PCB mass (relative to using open Bay concentrations in the base case). 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 helpful to generate more accurate estimates 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. The average equilibrium concentrations predicted for SLB using an adjustment factor of 25% unequilibrated 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 slower decrease in PCBs over time, and a higher steady state under current loads, may be a closer representation of current flux. A 0.25x (four-fold lower) SSC scenario, with even slower export, might even be warranted, with an even greater net effect of lowered export rate, slower recovery, and a higher steady state concentration under the base case of current loads. Combined with higher loads than estimated in the base case, a scenario with effectively no detectable change is possible.

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 only moderate sensitivity 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 similar or higher PCB 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 that 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.

However, even using steady state values for SSC half as high as the base case, the predicted half response times are less than 10 years, so neither the one box simplification, nor the use of open Bay SSC values alone can explain the relative lack of reduction in SLB concentrations of PCBs. Thus another likely at least partial explanation for the apparent lack of progress, is that loads from the tributaries entering SLB are greater than we are estimating for the base case. Loading 4 times higher than the base case (the top line in Figure 4-3) by itself would result in no change in ambient PCBs in SLB over the past 20 years, without changing any other model parameters. Somewhat higher loads, combined with other model parameter changes such as lower average SSC, could also result in similar outcomes of negligible progress. Although the current loads estimates suggest a high estimate only two-fold higher than the base case "best" estimate, additional uncharacterized loads could explain higher than expected loads. The potential influence of the large masses of PCBs directly upstream from contaminated sites (UPRR, GE, 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.

Professor Dick Luthy's group (Stanford University) conducted a pilot study in SLB to examine sediment porewater profiles of PCBs to compare to grab surface sediment concentrations, as well as provide a longer term integrated indicator of overlying water concentrations (Appendix A2). Passive samplers were inserted into the sediment at locations near selected sites in the 2016 sampling campaign (some of which were also sampled in 1998, reported in Daum et al., [2000]): a sampler at G4g, in the lagoon near Oakland Airport, was selected to reflect a more dispersed signal, away from known large or moderate new watershed loads; another was placed where high concentrations were previously found, in East Creek, near the 2016 ECM20m station (East Creek mouth ~20m site), but in the center of the channel rather than off the channel axis, as the passive samplers operate most predictably when consistently wet/submerged; lastly one was placed near the SLBsub1 site (near where Damon Slough enters the sediment borrow pit next to Arrowhead Marsh , sampled in the 2016 study, but nearer shore (shallow enough that the sampler could be manually inserted from a small kayak, ~1m depth at low tide), The Luthy group also took shallow cores at those locations at the time of deployment. Samplers were retrieved about a month later, and analyzed at Stanford.

The results of the study with passive samplers roughly parallel those from the surface sediment grabs collected in the SFEI effort (which were nearby, but not exactly the same points) and sediment cores collected by the Luthy group at the time of deployment (which were exactly co-located). The East Creek site was highest in sediment PCBs analyzed by the Luthy group, ~200 ug/kg dw PCBs, with the SLBsub1 site averaging about half that, and the G4g site about half again (~50 ug/kg dw). Passive sampler results (indicating near-bottom water and porewater concentrations) were ordered similarly, with ECM20m highest, and G4g lowest, but relative differences between sites varied with position in the overlying water or subsurface depth. Sediment grabs collected by SFEI also followed the same rank order, but the ECM20m concentration was about double, SLBsub1 about the same, and G4g slightly higher than concentrations found by the Stanford researchers. The sites were not exactly co-located as noted before, so the differing concentrations are not particularly surprising. Nonetheless, the qualitative agreement in ranking among the reported values confirms the observed spatial variations.

Nonetheless, despite suggestions in the subtidal zone that concentrations are fairly stable, and inputs continue at similar or even higher concentrations than sediments already in

SLB, there is also evidence that reductions in loading should eventually show benefit. The wetland adjacent to Damon Slough was one of the locations sampled in a 2005-2006 coring study (Yee et al., 2011). Although the section nearest the surface in that study (Figure 4-6) had concentrations similar to current subtidal concentrations in SLB (~60 ug/kg dw), deeper sections going back in time show a rapid rise to a maximum around 170 ug/kg dw, and two other sections with >100 ug/kg dw, before dropping down to background concentrations in pre-industrial sections (<1 ug/kg dw, essentially absent; although pre-industrial sediments should hypothetically have zero PCBs, the little detected is possibly from cross-contamination in sampling and lab analytical procedures, or a minute amount of transport via porewater), Thus going forward in time, the core sections reflect a major increase in PCB usage and releases during industrialization around World War II and later, followed by a nearly three-fold drop following their banning in the late 1970s. The pattern in the Damon Slough wetland core suggests that the effects of management are reflected in the receiving water body, when the changes are large.

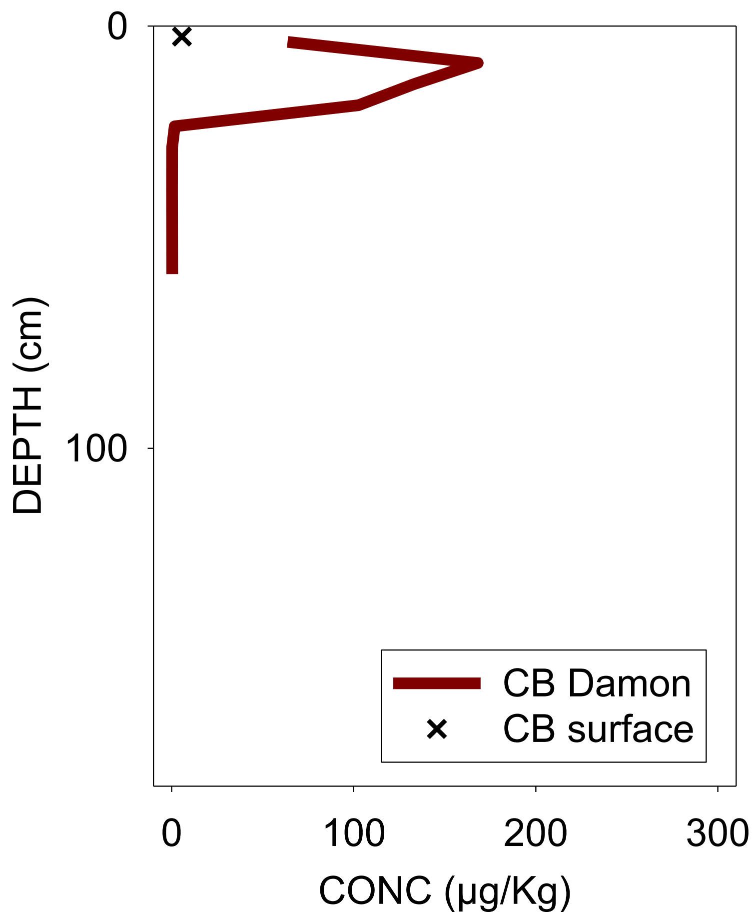

Figure 4-6. Plot of PCB concentrations in Damon Slough wetland core, from Yee et al., (2011) collected ca. 2005. The (x) symbol indicates Central Bay average open water sediment concentrations at that time.

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, for large changes in loading 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. The large decrease in PCBs in the wetland core by Damon Slough from their maximum concentrations provide some evidence of response on decadal scales, at least in the near-field of some expected major loading pathways.

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 long-term ambient concentrations; as long as PCB concentrations in incoming loads are greater than those in the ambient Bay, ambient concentrations in water and sediment will remain elevated. Thus efforts to reduce PCB loads will be beneficial until loads 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.

References

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5. Bioaccumulation

a. Background and General Concepts

The conceptual model for PCBs in the Emeryville Crescent (Davis et al. 2017b) provided a review of concepts that are generally important in regard to monitoring PCB bioaccumulation in Central Bay margin areas. PCB exposure in Bay species at higher trophic levels occurs primarily through the diet. An understanding of biota life histories (diet, feeding strategy, movement, and lifespan) and the structure of the food web is therefore essential to understanding the current and future influence of tributary PCB loads on impairment of beneficial uses in San Leandro Bay.

The food web for San Leandro Bay is largely similar to that described for the Crescent. One major difference between these two margin areas, however, is that many more data are available on the species present in San Leandro Bay and their PCB concentrations. The overall dataset is based on a series of historical studies, which was then bolstered by an intensive RMP sampling effort in 2016 (Davis et al. 2017a), which included analysis of gut contents of topsmelt, shiner surfperch, white croaker, and northern anchovy (Jahn 2018).

The following studies have contributed to the overall dataset on the San Leandro Bay food web and PCB bioaccumulation.

- RMP sport fish sampling (most recently summarized in Sun et al. [2017]) has sometimes included sampling of shiner surfperch in San Leandro Bay, specifically in 1997 and 2000.
- In 2000, piggybacking on RMP sport fish sampling in San Leandro Bay, a detailed food web study was conducted (Roberts et al. 2000) to support development of the food web model that provided part of the foundation for the PCBs TMDL (SFBRWQCB 2008). This multi-faceted study included an evaluation of the benthic community, gut contents of three sport fish species (shiner surfperch, white croaker, and jacksmelt), and measurement of PCB concentrations in sediment, water, benthos, zooplankton, fish, and fish gut contents.
- Jahn (2008) examined gut contents of shiner surfperch collected from San Leandro Bay in 2007, as part of a broader study of gut contents of shiner surfperch, white croaker, topsmelt, and Mississipi silverside from locations throughout the Bay.
- Greenfield and Allen (2013) reported on sampling of PCBs in topsmelt and Mississippi silverside from 33 sites in 2007 and 2010. This included one sample of silverside collected at the mouth of East Creek Channel in 2010. In addition, this study generated a robust dataset on PCBs in these species from sites throughout the Bay (including 15 probabilistic sites), which is a valuable frame of reference for interpreting the latest San Leandro Bay sampling in 2016.

- The intensive RMP sampling in 2016 included analysis of PCBs and ancillary parameters in sediment at 30 stations, water at three stations, and fish at nine stations (Davis et al. 2017a). The fish species analyzed for PCBs were topsmelt and shiner surfperch. As mentioned above, Jahn (2018) examined gut contents of the fish species that were collected. In addition, a concurrent study by Stanford University employed passive samplers to assess dissolved PCBs in water and pore water at three sites.

Based on the studies listed above, including the most recent diet information from Jahn (2018), a simplified summary of the San Leandro Bay food web focusing on species of importance in PCB impairment is presented in Figure 5-1.

b. Evaluation of Bioaccumulation Indicators for San Leandro Bay

Prey Fish

RMP prey fish sampling from 2005-2010 established Mississippi silverside (*Menidia audens*) and topsmelt (*Atherinops affinis*) as valuable indicator species for evaluating spatial patterns of mercury and PCB contamination on the Bay margins (Greenfield and Jahn 2010, Greenfield and Allen 2013, Greenfield et al. 2013a,b). The sampling effort targeting these two species provided thorough coverage of the Bay, with topsmelt occurring more frequently at sites in Central Bay (Figures 5-2 and 5-3). Given budget constraints, PCBs were only measured at a subset of the total number of prey fish stations sampled (Figure 5-4). Even with this limited dataset, however, Greenfield and Allen (2013) were able to establish a correlation between PCB concentrations in silverside and topsmelt and concentrations at nearby RMP sediment sampling locations. These biosentinel species can therefore be linked, via sediment, to PCB exports from local watersheds.

Davis et al. (2017b) presented a detailed summary of the many other characteristics that make silverside and topsmelt valuable indicators of PCB contamination on the Bay margins. These include:

- importance in the food web as prey for piscivorous fish and bird species throughout the Bay, and resultant linkage to impairment;
- diets dominated by epibenthic invertebrates that feed on surface sediment and filter feed, making them a potential leading indicator of changes in PCB concentrations on recently deposited sediment particles;
- a strong signal of contamination (high PCB concentrations);
- site fidelity on the Bay margins, with a hypothesized higher site fidelity in silverside, and the potential to show variation at the within-PMU scale;
- temporal integration over discrete one year periods because the fish collected are primarily less than one year old; and
- ease of collection.

The 2016 San Leandro Bay Study provided an opportunity to test these concepts with data from a thorough sampling of topsmelt from eight sites.

Topsmelt

Presence in San Leandro Bay

The 2016 study established topsmelt as the key prey fish indicator for San Leandro Bay. The sampling plan targeted both silverside and topsmelt for collection, with a preference for silverside based on the hypothesis presented in Davis et al. (2017b) that they may have more site fidelity for the mouths of the PMU tributaries. Silverside had also been collected previously in RMP sampling of San Leandro Bay: twice in 2010 at the mouth of San Leandro Creek Channel (as part of a seasonal sampling effort – Figure 5-3) and once at the mouth of East Creek Channel in 2010 (Figure 5-4). Davis et al. (2017a) found topsmelt in abundance at eight sites throughout San Leandro Bay, but no silverside were collected. While silverside may occasionally be present in San Leandro Bay, it appears that topsmelt are more reliably present and a better species to target for development of long-term time series. Future sampling should continue to target both of these species, however, as they are both valuable indicators and as a safeguard against interannual variation in their presence in San Leandro Bay.

Signal Strength

Consistent with prior prey fish monitoring, topsmelt exhibited a strong PCB accumulation signal in San Leandro Bay in 2016 (Davis et al. 2017a). On a wet weight basis, sum of PCB (52 congeners reported by the lab) concentrations in 24 composite samples of topsmelt from eight stations ranged from 107 ppb to 304 ppb. The median concentration was 177 ppb, and the mean was 185 ppb. Station means ranged from 111 ppb at San Leandro Channel Road to 244 ppb at Alameda Channel (Figure 5-5). As a frame of reference, the San Francisco Bay-wide mean PCB concentration (sum of 40 congeners) in shiner surfperch (the sport fish species with the highest mean and a no consumption advisory) in 2014 was 90 ppb. The 2016 median and mean concentrations in topsmelt were also higher than the 2016 median (161 ppb) and mean (164 ppb) concentrations in shiner surfperch from San Leandro Bay (the shiner surfperch data are discussed further below).

Lipid weight values provide a more precise comparison of bioaccumulation differences among species, locations, and over time. Lipid weight concentrations in 2016 San Leandro Bay topsmelt samples ranged from 4800 to 12600 ppb, with a median of 7400 and a mean of 7500 ppb. Station means ranged from 5200 ppb at San Leandro Channel Road to 8700 ppb at Alameda Channel (Figure 5-5). These topsmelt concentrations were high relative to the general distribution of concentrations in shiner surfperch for San Francisco Bay: the lipid weight Bay-wide mean for shiner surfperch in 2014 was 3900 ppb. The tospmelt concentrations were also almost as high as the lipid weight PCB concentrations in shiner surfperch in San Leandro Bay in 2016 (mean of 8900 ppb – the shiner surfperch data are discussed further below).

The 2016 topsmelt values were also high relative to the San Francisco Bay-wide distribution of prior prey fish data. The Greenfield and Allen (2013) study included sampling of 16 probabilistic sites in 2010 to characterize ambient concentrations, with a combined mean for topsmelt and silverside of 3500 ppb (and a median of 2600 ppb), much lower than the San Leandro Bay mean. Greenfield and Allen also sampled 13 sites in 2010 that were targeted based on an expectation of elevated PCB exposure. The 2016 topsmelt median (7400 ppb) was higher than the median for topsmelt and silverside at the Greenfield and Allen targeted sites (6900 ppb), but the 2016 mean (7500 ppb) was lower than the Greenfield and Allen targeted mean (12100 ppb) due mainly to the influence of two sites with very high values in 2010.

Only one prey fish sample in San Leandro Bay was analyzed prior to the 2016 study. Greenfield and Allen (2013) measured a concentration of 16200 ppb lipid weight in a Mississippi silverside sample collected at the mouth of East Creek Channel. This value was higher than the highest sample in 2016 (12600 ppb), and the 2016 mean for East Creek Channel (7400 ppb). With only one sample from 2010, it is unclear whether the difference between the sample from 2010 and the 2016 samples is indicative of real interspecific or temporal variation.

Spatial Integration

The 2016 study provided an unprecedented opportunity for a detailed evaluation of spatial variation in PCB accumulation in prey fish at a sub-PMU scale.

Statistically significant spatial variation in topsmelt PCB concentrations was observed (Figure 5-5), suggesting that this species can also be an indicator of within-PMU spatial patterns. Within-site variance was generally low, owing in large part to the inclusion of 20 fish in each of three composite samples per site, and this led to greater power to detect differences among sites. An analysis of variance was performed on the lipid weight data, using Welch's ANOVA (which accommodates unequal variances), and a Games-Howell post-hoc test. High variance at Alameda Channel and Bay Farm prevented detection of differences between these sites and the others, but many differences were detected among the other sites. San Leandro Channel Road had the lowest lipid weight mean concentration, and was significantly lower than every other site except for Alameda Channel and Bay Farm. Elmhurst Channel had the second highest lipid weight mean (after Alameda Channel), and was significantly higher than all sites except Airport Lagoon and the two high-variance sites (Alameda Channel and Bay Farm). Significant variation among sites on a very fine spatial scale was observed at the mouths of Elmhurst Channel and San Leandro Channel, which meet at the southeast corner of San Leandro Bay. These sampling sites were only approximately 100 meters apart, but the mean concentration at San Leandro Channel Mouth was 5900 ppb, while the Elmhurst Channel mean was 8300 ppb. Concentrations were even lower further up San Leandro Channel at the San Leandro Channel Road site (5200 ppb). Concentrations at Damon Slough and Elmhurst Channel were similar (7900 and 8300 ppb, respectively). Concentrations at Airport Lagoon were expected to potentially be relatively low based on the sediment concentrations observed there by Daum et al. (2000) and the relative geographic isolation of this site from the others, but the mean there was intermediate (6500 ppb).

The spatial pattern of PCBs in topsmelt showed a general correspondence with the pattern of PCBs in sediment (Figures 5-6 and 5-7), providing further evidence of topsmelt having high enough site fidelity to indicate spatial variation within San Leandro Bay. The sediment site closest to each fish collection site was selected for the correlation analysis, with the exception of Airport Lagoon where two sites were used because the fish collection site was in the middle of the two sediment sites (Figure 5-6). This relationship was based on comparison of topsmelt PCBs in lipid weight compared to sediment PCBs on an organic carbon basis. East Creek Channel Mouth was a distinct outlier, with a very high sediment concentration but a moderate topsmelt PCB concentration.

In addition to the capacity to indicate within-PMU variation, the 2016 topsmelt PCB concentration data also indicate that this species is clearly an appropriate indicator for San Leandro Bay as a whole. This conclusion is based on their capacity to indicate within-PMU variation, as well as the uniform elevation of SLB sites relative to the ambient average in Greenfield and Allen (2013).

PCB congener profiles in topsmelt were fairly constant across all samples, indicating a dominant contribution by Aroclor 1254, with a significant contribution also from Aroclor 1260. The San Francisco Bay-wide dataset generated by Greenfield and Allen (2013) showed that prey fish are capable of showing variation in exposure to different Aroclors, with several sites dominated by Aroclor 1260, and Stege Marsh dominated by Aroclors 1242 and 1248. The uniformity of the topsmelt congener profiles was a little surprising, given the observed spatial variation in topsmelt concentrations (indicating site fidelity, as discussed above) and the indication of a greater contribution of Aroclor 1260 in the sediment collected in East Creek Channel at stations ECM20, ECFF, and ECFR (i.e., from within 20 m of the Creek mouth and at two stations upstream in the Creek itself). However, the station 100 m from the mouth of East Creek Channel (ECM100) had an unusually strong Aroclor 1254 signal, and the topsmelt samples collected from this area were consistent with a mix of the sediment profile at ECM20 and ECM100. The San Leandro Bay silverside sample collected by Greenfield and Allen at the mouth of East Creek Channel was at almost exactly the same location as the 2016 topsmelt sample, and also had the same congener profile dominated by Aroclor 1254.

Topsmelt gut contents also showed signs of variation among sites within San Leandro Bay (Jahn 2018), but these observations are snapshots representing recent consumption and may not be indicative of persistent spatial patterns. Gammarid amphipods were the major portion of topsmelt diet at all but two sites (Alameda Channel and San Leandro Creek Channel Road). At Alameda Channel chain diatoms were the dominant prey item. At San Leandro Creek Channel Road a group of age 1+ fish were included in the sample, and macroalgae were the principal food item in these older fish (Jahn [2018] concluded that it is probable that topsmelt switch to herbivory after their first year). Since this ontogenetic dietary shift would affect PCB accumulation, sampling of topsmelt as a PCB indicator should focus on young-of-the-year fish. Most of the topsmelt caught in 2016 were young-of-the-year fish.

Potential as a Leading Indicator

Consistent with prior studies, the gut content analysis in 2016 indicated that topsmelt primarily feed on epibenthic invertebrates (gammarid amphipods). Species identified included *Grandidierella japonica*, *Americorophium stimpsoni*, *Laticorophium baconi*, and *Ampithoe valida*. These species were all classified as filter and surface deposit feeders by Luthy et al. (2011). It thus appears that topsmelt in San Leandro Bay consume primarily small epibenthic invertebrates that are exposed to PCBs via surface sediment or suspended sediment, making this species a potential leading indicator of changes in PCB concentrations on particles that are exported from the PMU watersheds.

If topsmelt sampling focuses on young-of-the-year fish, as it should given the probable shift to herbivory in age 1+ fish, then these fish are providing a discrete index of exposure in the year they were sampled. This narrow temporal integration will enhance the value of this species as a leading indicator of change in the concentrations of PCBs on particles entering San Leandro Bay.

Sport Fish

Shiner Surfperch

Shiner surfperch are the most important biosentinel for PCB contamination in the Bay, due to their explicit role as an indicator species for the PCB TMDL, the no-consumption advisory issued by OEHHA for surfperch in the Bay, and their excellent attributes as an indicator of spatial patterns and temporal trends. Shiner surfperch have been sampled at multiple locations throughout the Bay in every round of RMP sport fish sampling, and have been collected in the Oakland Harbor area in every round as well (Figure 5-8) (and Oakland Harbor has consistently had the highest PCB concentrations of any of the RMP sampling locations).

Presence in San Leandro Bay

Shiner surfperch are reliably present in San Leandro Bay, but not throughout this whole area. Oakland Harbor area monitoring included collection of shiner surfperch in the Alameda Channel area in 1994, 1997, and 2000, and in the area between the mouths of Damon Slough and Elmhurst Channel in 2000 (Figure 5-8). In the 2016 study, four areas were trawled, but shiner were only obtained at San Leandro Main Bay and Airport Lagoon – no shiner were collected at Alameda Channel or Bay Farm. Based on the limited information available, San Leandro Main Bay (between the mouths of Damon Slough and Elmhurst Channel) appears to be a viable site for long-term monitoring.

Signal Strength

Sampling in San Francisco Bay (Sun et al. 2017) and throughout the state (Davis et al. 2012) has demonstrated that shiner surfperch has the capacity to accumulate high PCB concentrations. Davis et al. (2012) also showed that shiner surfperch can have concentrations that are quite low when they are present in cleaner locations (e.g., 3 ppb in Tomales Bay in 2009). Shiner surfperch consistently have mean concentrations that are among the highest of any species in San Francisco Bay. In the latest San Francisco Bay sampling, the Bay-wide mean for shiner was 90 ppb. As mentioned above, Oakland Harbor has consistently exhibited the highest shiner concentrations of all of the San Francisco Bay sampling locations. The Oakland Harbor mean in 2014 was 220 ppb.

The 2016 sampling of shiner surfperch in San Leandro Bay continued to indicate a strong contamination signal, though significantly lower than that observed in the 2000 sampling by Roberts et al. (2002). In 2016, wet weight sum of PCB concentrations in 6 composite samples of shiner surfperch from two sites ranged from 119 ppb to 208 ppb. The median concentration was 161 ppb, and the mean was 164 ppb. Station means were 145 ppb at Airport Lagoon and 183 ppb at San Leandro Main Bay (Figure 5-5). Roberts et al. (2002) sampled the San Leandro

Main Bay location, and observed a wet weight mean concentration of 288 ppb. In 2016 the wet weight mean at San Leandro Main Bay was 174 ppb. The lipid-normalized means from San Leandro Main Bay also suggest a decrease, from 12,700 ppb in 2000 to 9000 ppb in 2016 (p=0.02, t-test).

Spatial Integration

Like silverside and topsmelt, shiner surfperch have been proven to be excellent spatial indicators in RMP sport fish sampling, showing patterns that match patterns in sediment contamination. Even with a low cost design (three composites of 20 fish at each location), shiner surfperch results have consistently indicated statistically significant differences among RMP sampling locations – in 2009, all five locations were significantly different from each other (Davis et al. 2011). Limited information is available, however, on whether shiner surfperch site fidelity is sufficient to allow detection of spatial differences at the sub-PMU scale in a setting like San Leandro Bay.

The hypothesis that shiner could show differences at this scale was tested in the 2016 study. Due to the apparent absence of shiner from Alameda Channel and Bay Farm, the 2016 spatial evaluation was limited to a comparison of two locations: San Leandro Main Bay and Airport Lagoon. The mean concentrations were similar at these two sites, and the intra-site variance was high, so there was not a significant difference between them (Figure 5-5). In addition, the PCB congener profiles at these two sites was virtually identical, dominated by congeners representative of Aroclor 1254 with a secondary contribution from Aroclor 1260 (similar to the profile described above for topsmelt). In contrast to the PCB concentrations and congener profiles, gut contents at these two sites were somewhat different, with a greater contribution of clams and caprellids at San Leandro Main Bay, and a greater contribution of polychaetes at Airport Lagoon. The shiner at San Leandro Main Bay, however, were a bit older and larger than those at Airport Lagoon, potentially confounding the site comparison. Overall, these results suggest either that shiner site fidelity is not sufficient to distinguish differences at this scale, or that exposure in these two parts of San Leandro Bay is similar. The topsmelt data from these areas also suggested that PCB exposure in these two areas is not that different. The shiner data suggest that monitoring one of the two sites would be sufficient for long-term monitoring. San Leandro Main Bay is the logical choice given its proximity to watershed PCB inputs and the existence of historic data at that site.

Potential as a Leading Indicator

A reliance on prey that feed on suspended particles or surface sediment deposits may lead to a quicker response to reductions in PCB concentrations on particles exported from the watershed. Available information on shiner surfperch diet indicate a large degree of reliance on surface deposit and filter feeders, but with a significant contribution of polychaetes, some of which are subsurface deposit feeders.

Jahn (2008) reached the general conclusion, based on his own analysis of shiner surfperch gut contents along with the earlier results from Roberts et al. (2002), that shiner surfperch consume mainly small benthic and epibenthic crustaceans, sometimes adding in, or even switching to, major portions of polychaetes and clams. Jahn's 2016 study (Jahn 2018) yielded results that are consistent with this characterization. At both San Leandro Bay Main and Airport Lagoon, gammarid amphipods were the main prey items, constituting about 50% of the diet by volume. Caprellid amphipods contributed another 10% at Airport Lagoon. The other major prey items were bivalves (20% at Airport Lagoon) and polychaetes (16% at San Leandro Main Bay). The shiner surfperch diet therefore appears to be dominated by surface sediment and suspension feeding prey, which would make them responsive, though perhaps not quite as responsive as topsmelt due to the consumption of some subsurface deposit-feeding prey, to reduced concentrations in particles exported by the watershed.

Unlike topsmelt, the shiner typically collected in RMP sampling are generally age 1 or older. Jahn (2018) noted that shiner surfperch perch bear live young in June that grow very rapidly, and fish <90 mm total length in August are probably age-0. The samples from both sites in 2016 were therefore a mix of age 0 and older fish. The target size range for shiner in RMP sport fish sampling is 100-150 mm. The shiner samples typically collected therefore represent PCB exposure over multiple years. This is in contrast to topsmelt, for which sampling can focus on age-0 fish that provide narrower temporal integration and therefore should be a more sensitive leading indicator of change.

c. Future Monitoring Recommendations

The 2016 San Leandro Bay field study provided an opportunity to gather a great deal of valuable information on PCBs in the San Leandro Bay food web, including data on PCB concentrations in prey fish, shiner surfperch, surface sediment, and water (both through analysis of whole water samples and of passive samplers), and diet information from gut content analysis of topsmelt and shiner surfperch. This information provides an excellent baseline for long-term trend monitoring, and also provides the key input data needed for development of an improved and updated food web model for this area.

Based on the results from this survey, the following elements and approaches are recommended for long-term bioaccumulation monitoring.

- Prey fish - Annual monitoring of topsmelt at key sites would be valuable in monitoring long-term interannual trends in response to changes in tributary loadings. Given the major management actions on contaminated properties in the East Creek Channel and Damon Slough watersheds (GE and UPRR, respectively), monitoring of the downstream food web response in the next few years would be of particular interest. The 2016 field study results indicated that sites at East Creek, Damon Slough, Elmhurst, San Leandro Channel Mouth, San Leandro Channel Road, and Airport Lagoon would provide an array that would allow tracking of general and localized trends in food web PCBs. After an initial period (perhaps 5 - 10 years) that firmly establishes a baseline and characterizes interannual variation and the presence or absence of trend, a power analysis could be conducted to determine whether a reduced frequency would optimize use of monitoring resources. Sampling of topsmelt as a PCB indicator should focus on young-of-the-year fish (<90mm TL).

- Shiner surfperch - Shiner surfperch could be sampled on a five-year cycle as part of RMP Bay-wide sport fish monitoring. Leveraging the Bay-wide sport fish monitoring would save costs associated with planning, data management, and reporting, and would provide an extended dataset for comparison. The sampling could perhaps be limited to the one site at San Leandro Main Bay, but if it is performed at such a low frequency, it might be valuable to continue sampling the Airport Lagoon location to provide better information on site variation and trends throughout San Leandro Bay. Given the management actions at GE and UPRR, annual monitoring of shiner at San Leandro Bay Main for the next 5-10 years should also be considered.

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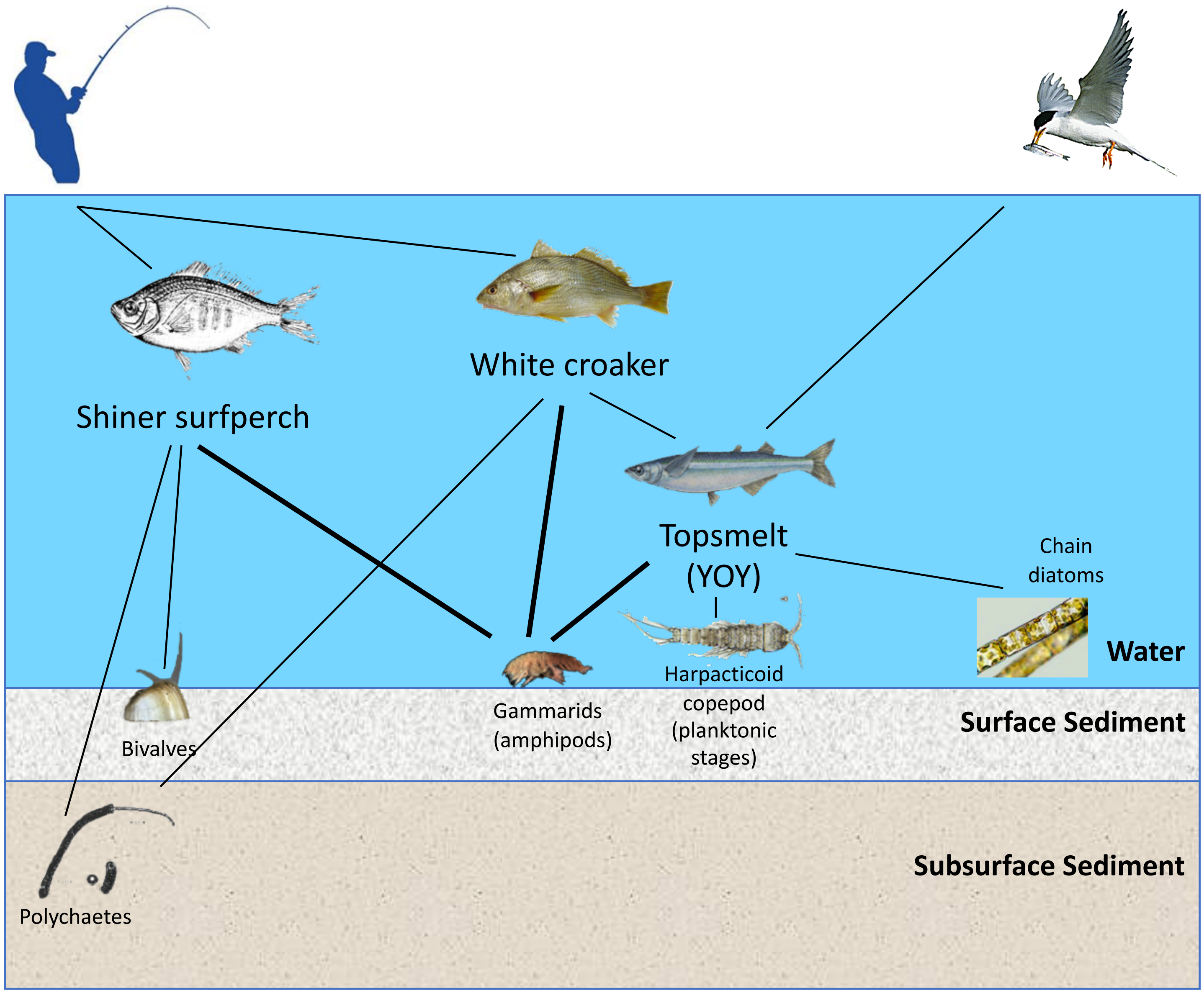


Figure 5-1. Schematic of the San Leandro Bay food web for species of interest. Bold lines indicate dominant pathways.

Figure 5-2. Locations where Mississippi silverside were collected in RMP prey fish sampling, 2005-2010: a) whole Bay and b) enlarged view of Central Bay.

Figure 5-3. Locations where topsmelt were collected in RMP prey fish sampling: a) whole Bay and b) enlarged view of Central Bay.

Figure 5-4. PCB concentrations (sum of 40 congeners, ng/g wet weight) measured in a) Mississippi silverside (including a sample from the mouth of East Creek Channel in San Leandro Bay) and b) topsmelt in RMP prey fish sampling.

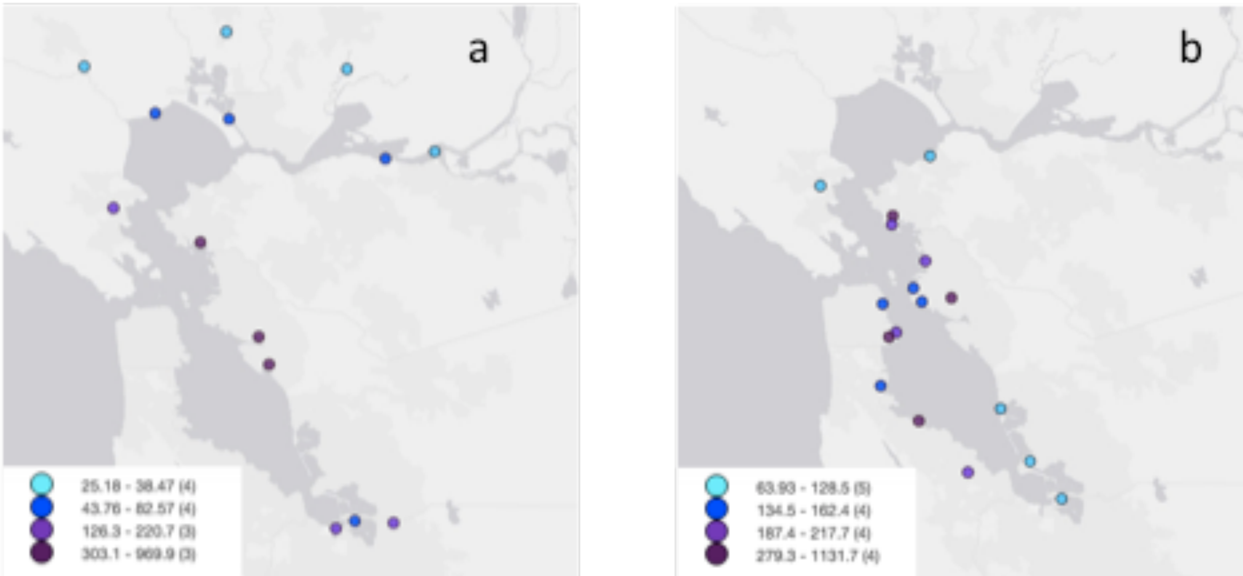
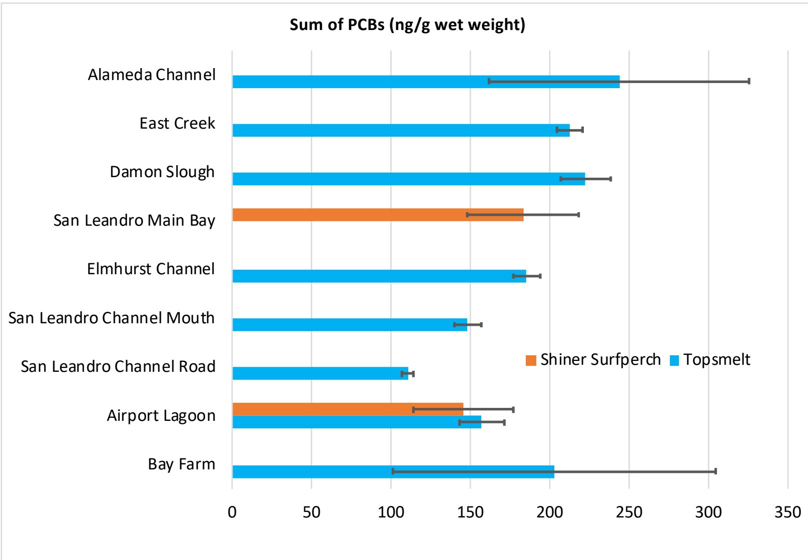
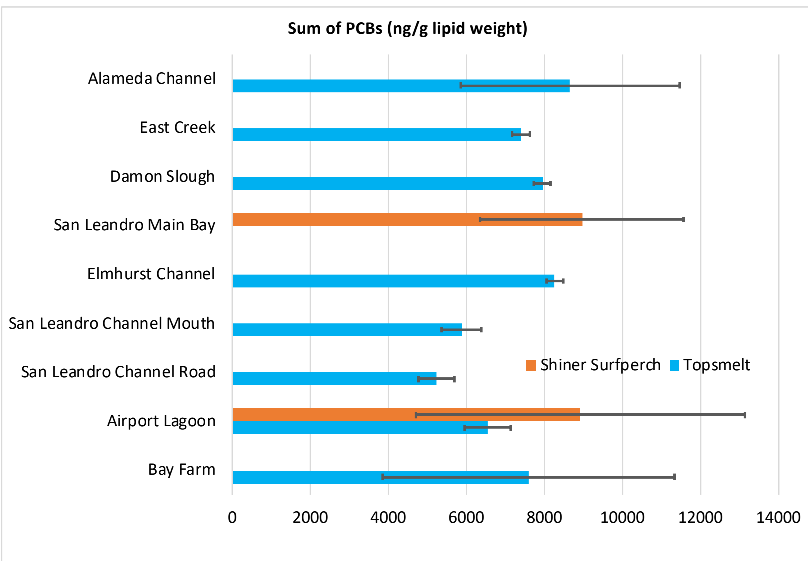
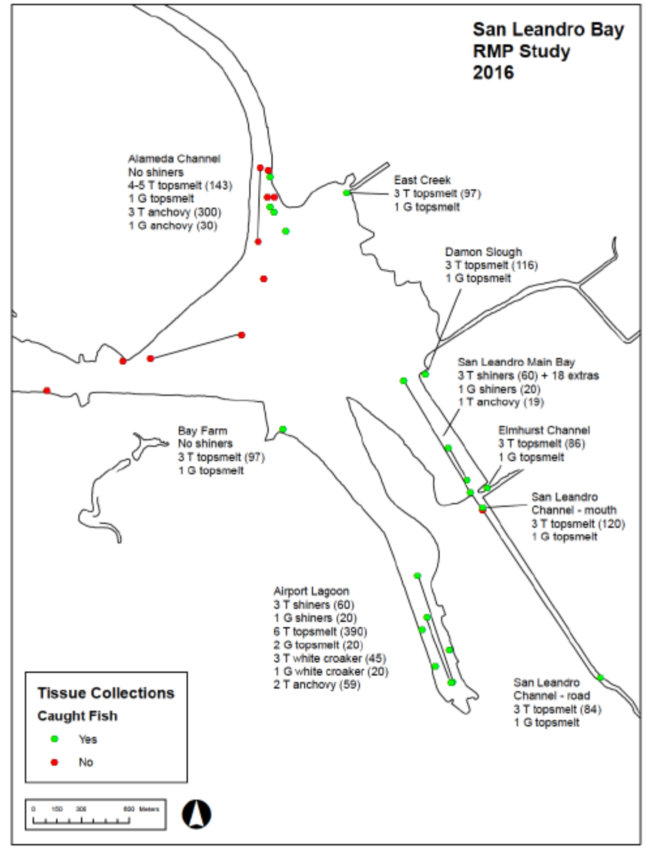


Figure 5-5. PCB concentrations (wet weight in top left, lipid weight in bottom left) in topsmelt and shiner surfperch in San Leandro Bay, 2016. Bars represent means, error bars represent 2 times the standard error. Sampling locations shown in the panel on the right. Multiple comparisons from ANOVA on the lipid weight data on bottom right.







Multiple Comparisons

* different at p<0.05

	Alameda	East Creek	Damon	Elmhurst	SL Cr Mouth	SL Cr Road	Airport Lagoon	Bay Farm
Alameda	-							
East Creek		-		*	*	*		
Damon			-		*	*	*	
Elmhurst		*	*	-	*	*		
SL Cr Mouth		*	*	*	-	*		
SL Cr Road		*	*	*	*	-	*	
Airport Lagoon			*			*	-	
Bay Farm								-

Figure 5-6. Sediment sites used in correlating topsmelt and sediment PCB concentrations.

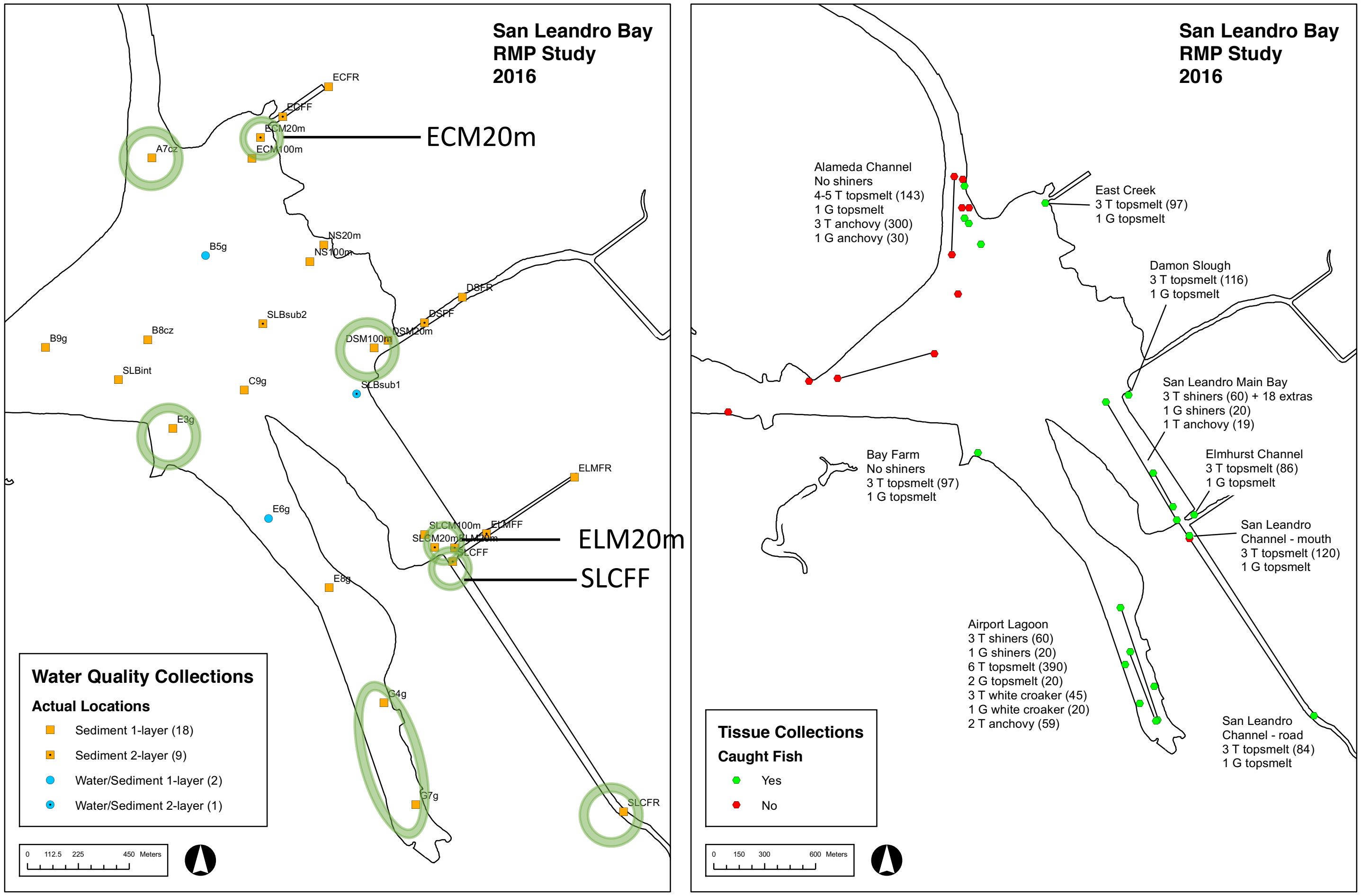


Figure 5-7. PCB concentrations in topsmelt (sum of 52 congeners, ng/g lipid) versus PCB concentrations (sum of 208 congeners, ng/g OC) in sediment in San Leandro Bay in 2016. Data from Davis et al. (2017b).

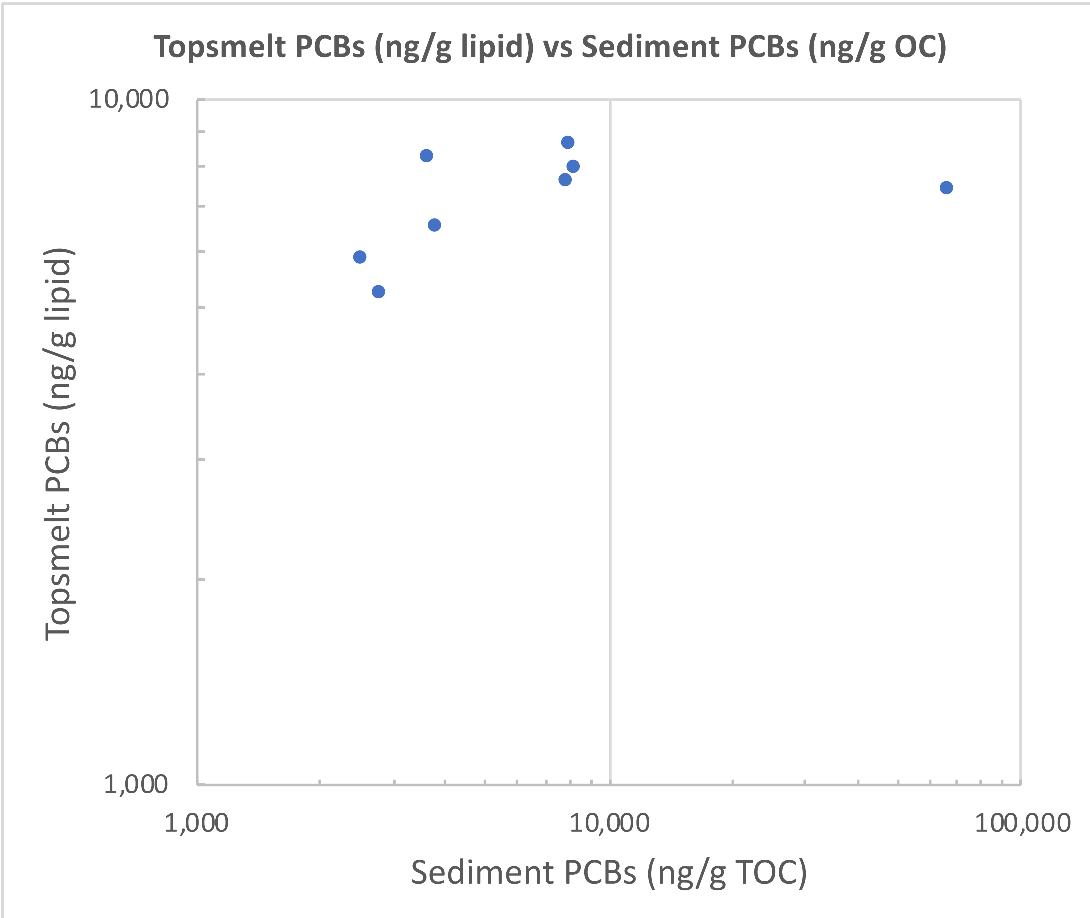


Figure 5-8. Shiner surfperch sampling locations in the Oakland Harbor area, 1994-2014.

6. Answers to the Management Questions

a. Can we expect a decline in any compartment of the PMU in response to projected load reductions in the PMU watershed?

The simple mass budget model suggests that conceptually we would expect to eventually see changes in both water and sediment compartments, 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. The response would be proportional to the change in loading. Evidence of responsiveness was observed in the wetland sediment core profile at Damon Slough (Yee et al. 2011), which indicated a substantial reduction in PCBs between the 1970s and the early 2000s. However, a comparison of the results of extensive sampling of San Leandro Bay surface sediment in 1998 by Daum et al. (2000) and in 2016 as part of the present study suggest a lack of reduction over this more recent 18 year period. This latter finding suggests that continuing inputs, with smaller reductions than those following the PCB phaseout and ban in the 1970s, are slowing the recovery of San Leandro Bay from PCB contamination.

Significant cleanup actions have been taken (at GE) or are in process and scheduled for completion in the next two years (UPRR). The portion of loads coming from these or other specific properties has not been quantified, but at least conceptually, these cleanups should also lead to lower concentrations in San Leandro Bay. Effects are likely to be most apparent in relatively unmixed depositional sites in the nearfield of the incoming loads (e.g., the Damon Slough wetland site noted before), with slower and smaller changes in the wider area. With more total sediment mass and mixing of sediments, the inertia of existing inventory in the large SLB subtidal area will tend to buffer and mute any response, making detection more difficult.

Changes in surface sediment concentrations would lead to similar changes in PCB exposure in the food web. A significant amount of food web transfer of PCBs to species of interest occurs through benthos that are surface deposit feeders and filter feeders that can be expected to respond relatively quickly to reductions in ambient surface concentrations, which may in turn respond relatively quickly to reductions in tributary inputs.

b. How should tributary loads be managed to maximize PMU recovery?

Recovery of San Leandro Bay from PCB contamination would be maximized by pursuing a load reduction strategy that encompasses any remaining older industrial areas in the PMU watersheds. Old industrial represents around 3% of the watershed area, but the Regional Watershed Spreadsheet Model estimates that this land use category contributes 48% of the PCB load. PCB loads from contaminated areas in the lower watershed should be reduced as much as possible without impacting sediment supply from cleaner upper watershed areas, in order to provide diluting sediment. 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 region-wide conceptual model and supporting data from sampled watersheds indicating relatively low PCB yields from residential and open spaces should also apply here.

Management attention should focus on loads from storms with magnitudes less than the 1:1 year return interval. An estimated 86% of the long-term loading is contributed by these small and moderate storms. In addition, the load from these storms is more likely to be retained within San Leandro Bay, although even for the largest storms, the majority of loads (aside from those discharged directly into the channel leading to Oakland Harbor) will remain initially within San Leandro Bay.

The PMU should benefit from reduced loads in all the local tributaries, with the greatest benefits likely seen for reductions in loads from watersheds discharging to the east side of San Leandro, where the largest loads occur. Any decreases in concentrations from watershed loads should have nearly proportional impacts on ambient concentrations in San Leandro Bay, until or unless San Leandro Bay concentrations are reduced to nearly as low as Central Bay ambient concentrations.

San Leandro Bay represents a different scenario from the Emeryville Crescent due to the presence of two known highly contaminated properties, with substantial masses of PCBs in soil and downstream sediment, immediately upstream of the PMU. The GE property has recently been nearly completely capped, and the UPRR site is scheduled for cleanup in the next two years. Cleanup of these properties, especially GE, could significantly accelerate the recovery of San Leandro Bay.

c. How should we monitor to detect the expected reduction?

A preliminary field study yielded a great deal of valuable information on the current distribution of PCBs in sediment and fish in San Leandro Bay, providing a baseline for future monitoring and valuable information on the attributes of these different indicators of contamination.

Long-term monitoring should track multiple lines of evidence. Continued sampling of sport fish and prey fish should be conducted periodically to evaluate the state of impairment, but less frequent (~decadal scale) monitoring of abiotic matrices should also be conducted to ensure that there are not biological factors (e.g., shifts in diet) confounding the detection of real improvements in the loads and degree of contamination. Periodic surface sediment sampling (e.g., every 5 years, coincident with biota sampling), archived for a long period, with less frequent lab analysis, and/or core sampling at longer intervals (greater than a decade, which only will contribute ~3cm/decade if net sedimentation keeps up with sea level rise) should be conducted. A third line of evidence should be near-field monitoring as immediately downstream of major management actions as possible. If PCB metrics (suspended sediment PCB concentration, total loads [normalized for a given water year type or event size, etc.]) show no evidence of change in the near-field, the prospects of finding any signals further downstream inevitably diminish.

Annual monitoring of topsmelt at key sites would be valuable in monitoring long-term interannual trends in response to changes in tributary loadings. Given the major management actions on contaminated properties in the East Creek Channel and Damon Slough watersheds (GE and UPRR, respectively), monitoring of the downstream food web response in the next few years would be of particular interest. The 2016 field study results indicated that sites at East Creek, Damon Slough, Elmhurst, San Leandro Channel Mouth, San Leandro Channel Road, and Airport Lagoon would provide an array that would allow tracking of general and localized trends in food web PCBs.

Shiner surfperch could be sampled on a five-year cycle as part of RMP Bay-wide sport fish monitoring. Leveraging the Bay-wide sport fish monitoring would save costs associated with planning, data management, and reporting, and would provide an extended dataset for comparison. The sampling could perhaps be limited to the one site at San Leandro Main Bay, but if it is performed at such a low frequency, it might be valuable to continue sampling the Airport Lagoon location to provide better information on site variation and trends throughout San Leandro Bay. Given the management actions at GE and UPRR, annual monitoring of shiner at San Leandro Main Bay for the next 5-10 years should also be considered.

Appendix 1.

Methods for Characterizing Temporal Dynamics of Loading into the PMU

To better understand how the flow of storm water, suspended sediments, and PCBs interact with or flush through the PMU, estimates of temporal variation were needed. Estimated annual average loads were devolved into the following relevant storm periods or return intervals:

i. The load delivered during summer and winter non-storm flow
ii. The loads for a 1:1 year, 24 hour return storm
iii. The load for a 1:5 year, 24 hour return storm
iv. The load for a 1:10 year, 24 hour return storm

Recurrence Interval Method – Method 1

Three reference watersheds in which we have multiple years of continuous loads estimates, and which are small and highly urbanized, similar to the PMU watersheds (including Z4LA, Sunnyvale East Channel and North Richmond Pump Station) were selected for analysis to estimate the proportion of load that is delivered in each of the storm periods. Because all three reference watersheds have some characteristics similar to the PMU watersheds, the results of all three reference watersheds are reported here and these results help to form an estimated range for the PMU watersheds.

Using NOAA Atlas 14 (http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html), precipitation magnitude, duration, and frequency estimates were identified for each of the three reference watersheds. Storm events during the continuous records for each watershed were isolated and then characterized for return interval (RI) using the NOAA Atlas 14 magnitude-duration-frequency tables. Total PCB loads for each of the isolated storm events were summed and the relationship between PCB load (as a percentage of the total annual climatically adjusted load) and RI was graphed (Figure A1-1). These linear regression relationships were applied to the RIs of interest to estimate the percentage of the average annual load that was transported for each storm recurrence. The low and high percentage estimates for the three stations were used to produce the low and high range of load transport for each storm recurrence in the PMU watersheds (Tables A1-1 and A1-2).

APPENDIX 1

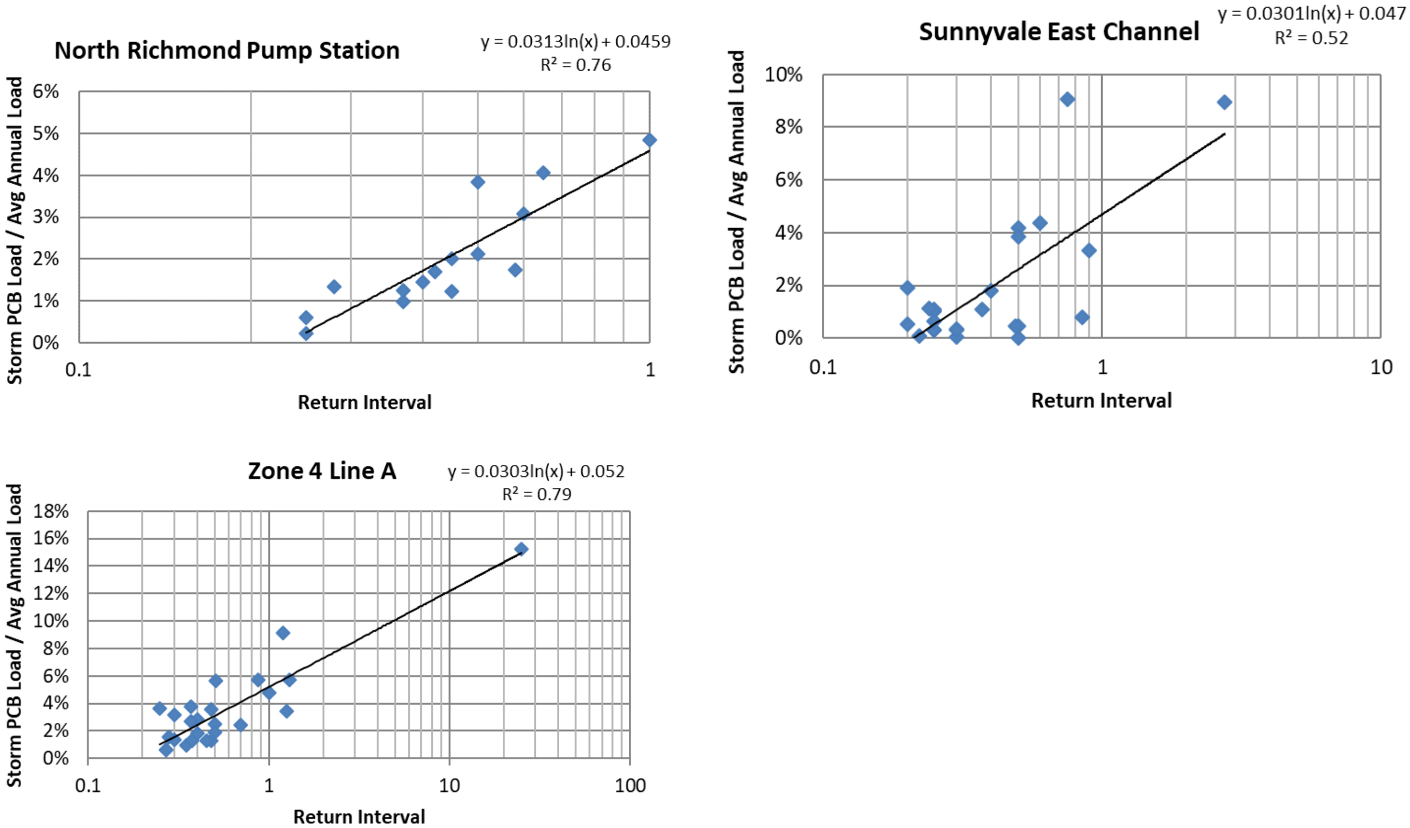


Figure A1-1. PCB loads (as a percentage of the total annual climatically adjusted load) transported in individual storm events as a function of storm return interval.

APPENDIX 1

Table A1-1. PCB loads transported annually and for select return interval storms (load as a percentage of the average annual load) in reference watersheds. All storm recurrence intervals with a 24 hr duration.

	Area (km^2)	Long Term (40 year) Avg Annual Load (g)	Long Term (40 year) Avg Annual Yield (g/km^2)	Summer and winter non-storm flow PCB load	% of load in 1:1 yr storm	% of load in 1:5 yr storm	% of load in 1:10 yr storm
Sunnyvale East Ch	15.19	134	9.4	NA	4.7%	9.5%	11.6%
Z4LA	4.17	14.6	3.5	5%	5.2%	10.1%	12.2%
N Richmond PS	1.96	11.4	5.8	7%	4.6%	9.6%	11.8%

Table A1-2. PCB loads transported for select return interval storms (load as a percentage of the average annual load) in reference watersheds. All storm recurrence intervals with a 24 hr duration.

	Low	High
% 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%

Continuous Loads Method – Method 2

To support mass budget calculations for the PMU watersheds 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 PMU. Two continuous datasets were explored to form the foundation of these daily loads estimates: USGS San Lorenzo at San Lorenzo daily flows (WYs 1987-2015) and Western Regional Climate Center Oakland Museum gauge daily rainfall (WYs 1971-2010) (Figures A1-3 and A1-4). Because there were no suitable data in the PMU watersheds, we used data collected in Zone 4 Line A (Gilbreath and McKee, 2015) to estimate the distribution of concentration and load variability around the mean and then applied that to the mean loads estimated above for the PMU watersheds. To do this, a three-step process was applied.

1) The daily rainfall for the respective gauge was plotted against daily PCB loads in Zone 4 Line A (Z4LA) for WYs 2007-2010. Zone 4 Line A is a small urban watershed in Hayward which was monitored extensively in WYs 2007-2010, and has an associated continuous PCB loading record (Gilbreath and McKee, 2015).
2) The resulting regression equation was applied to the entire rainfall record to estimate PCB loads for Z4LA for the entire record duration.
3) The percentage that each daily load represented relative to the total load was calculated and then applied to the estimated annual PCB loads for the PMU, resulting in an estimated daily PCB load.

USGS San Lorenzo daily flows as a potential continuous dataset was considered instead of rainfall as a surrogate in this method, however, when plotted with daily PCB loads at Z4LA, we found that the Z4LA daily PCB load transport and San Lorenzo flow characteristics exhibit a bi-modal relationship. This is probably due to the artificial daily time-step (many storms occur overnight and so would be represented on two days, e.g. Figure A1-5) and because San Lorenzo Creek flows over a longer duration than Z4LA. The relationship between Z4LA daily PCB load and Oakland Museum daily rainfall was much stronger (Figure A1-6), and therefore was used in combination with the 30-year record from Oakland Museum between (WYs 1981-2010) to estimate a 30-year record of daily PCB loads in the PMU (see Figure A1-7 for exceedance frequency of this dataset).

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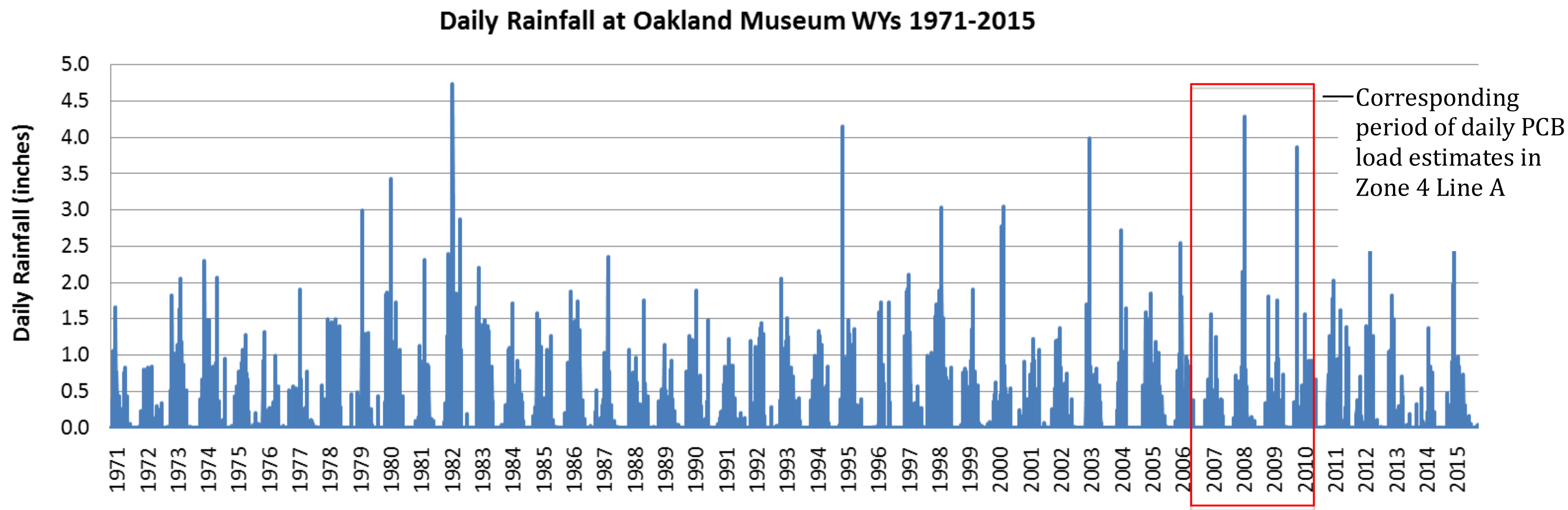

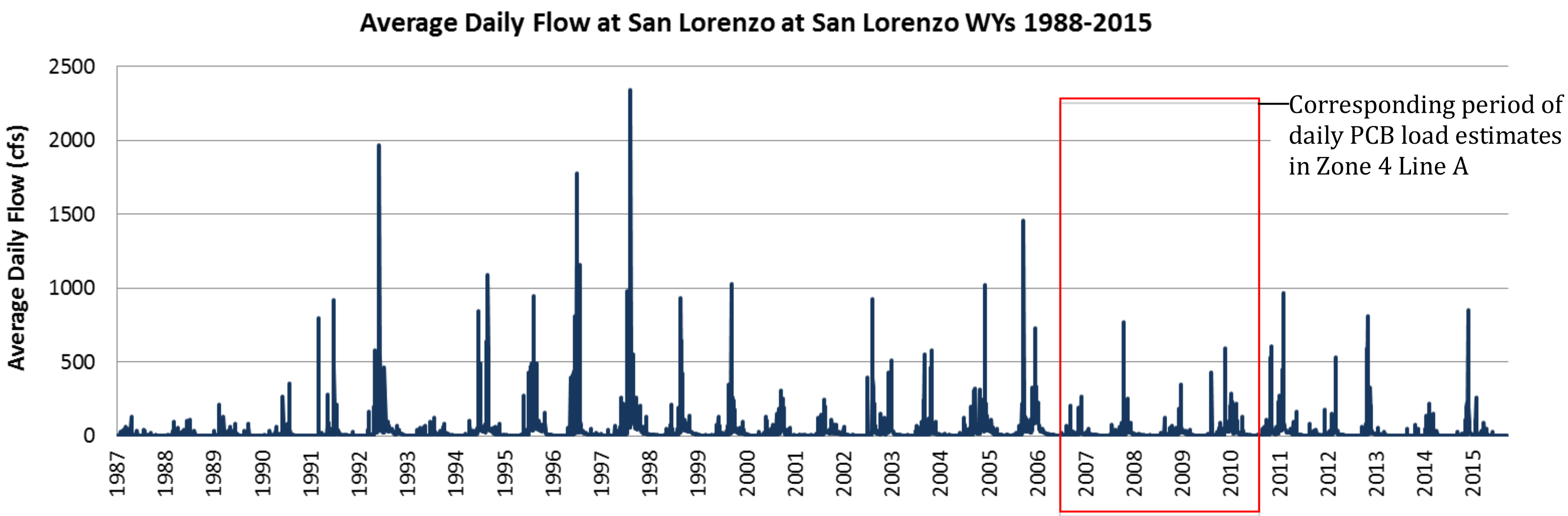

Figure A1-3. Long-term time series of a) rainfall at Oakland Museum and b) flow at USGS San Lorenzo at San Lorenzo.

APPENDIX 1

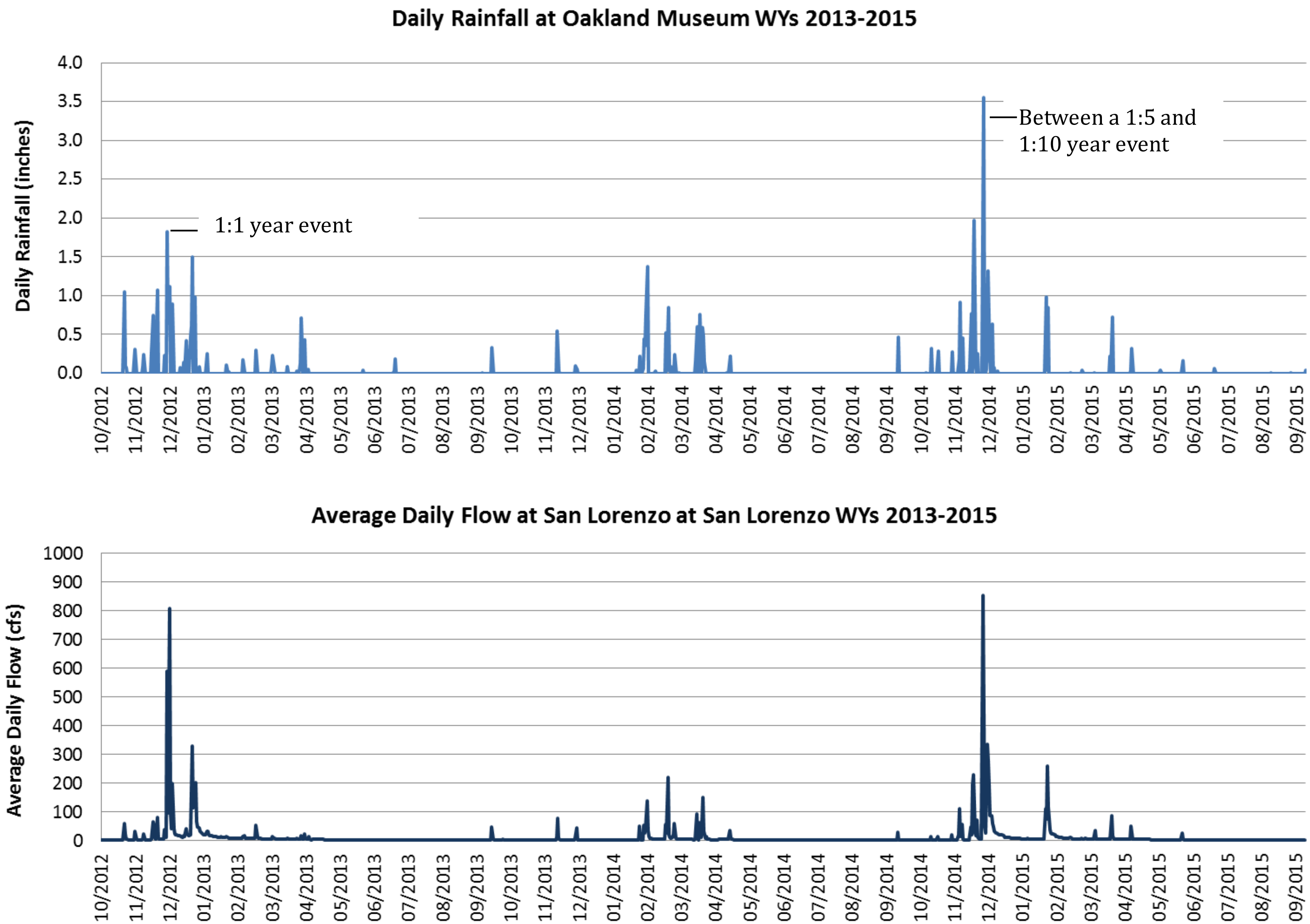

Figure A1-4. Three year time series of a) rainfall at Oakland Museum and b) flow at USGS San Lorenzo at San Lorenzo.

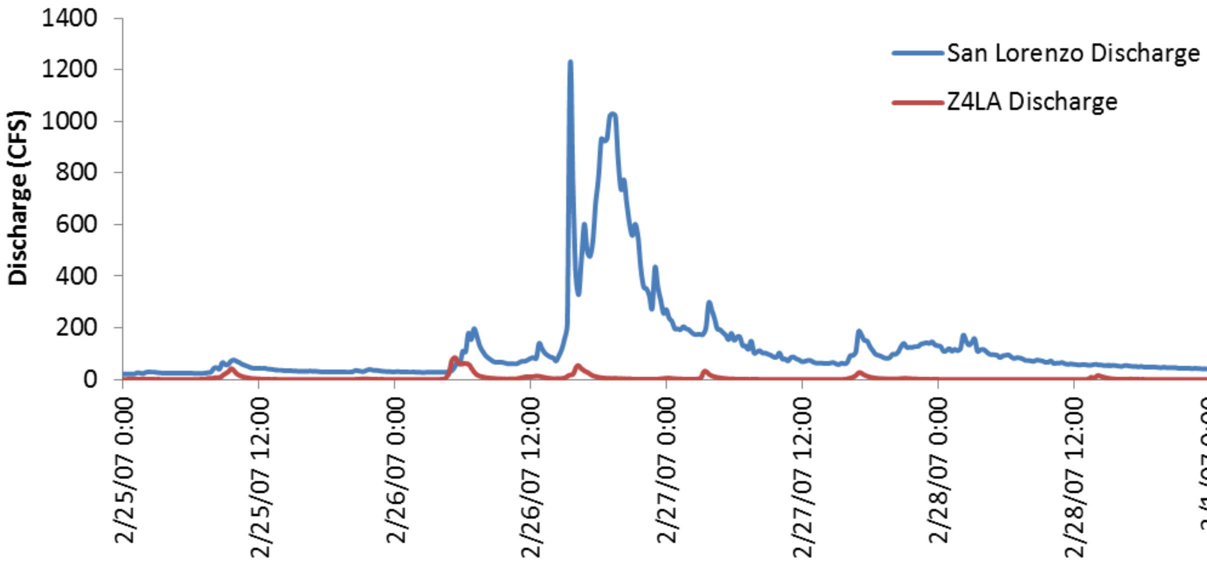

Figure A1-5. Discharge during a WY 2007 storm series at USGS Gauge San Lorenzo at San Lorenzo and Zone 4 Line A, showing how storm-driven discharges at Z4LA are flashy whereas discharge at San Lorenzo is more likely to occur over more than a single day, leading to a poor correlation between San Lorenzo daily discharge and Z4LA daily PCB load.

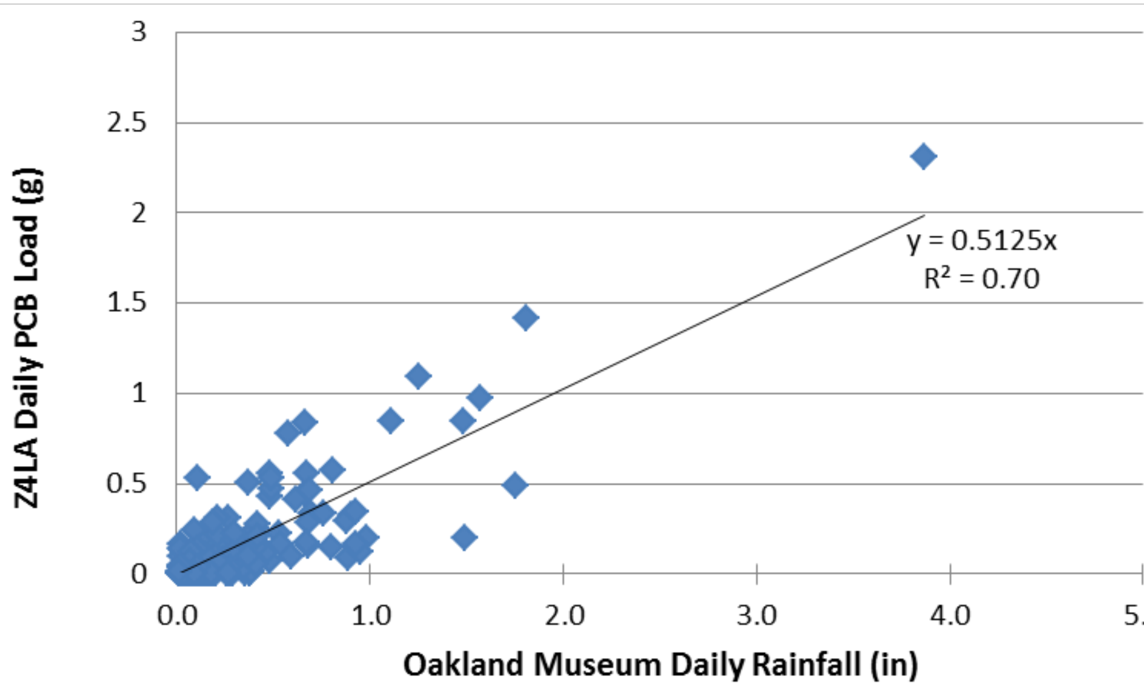

Figure A1-6. Daily PCB loads at Zone 4 Line A during the study period in that watershed (WYs 2007-2010, with some gaps) plotted against daily rainfall at WRCC Oakland Museum rain gauge. The relationship between Z4LA daily PCB load and Oakland Museum daily rainfall was selected as the basis for estimating long term daily loads exported from the PMU watersheds.

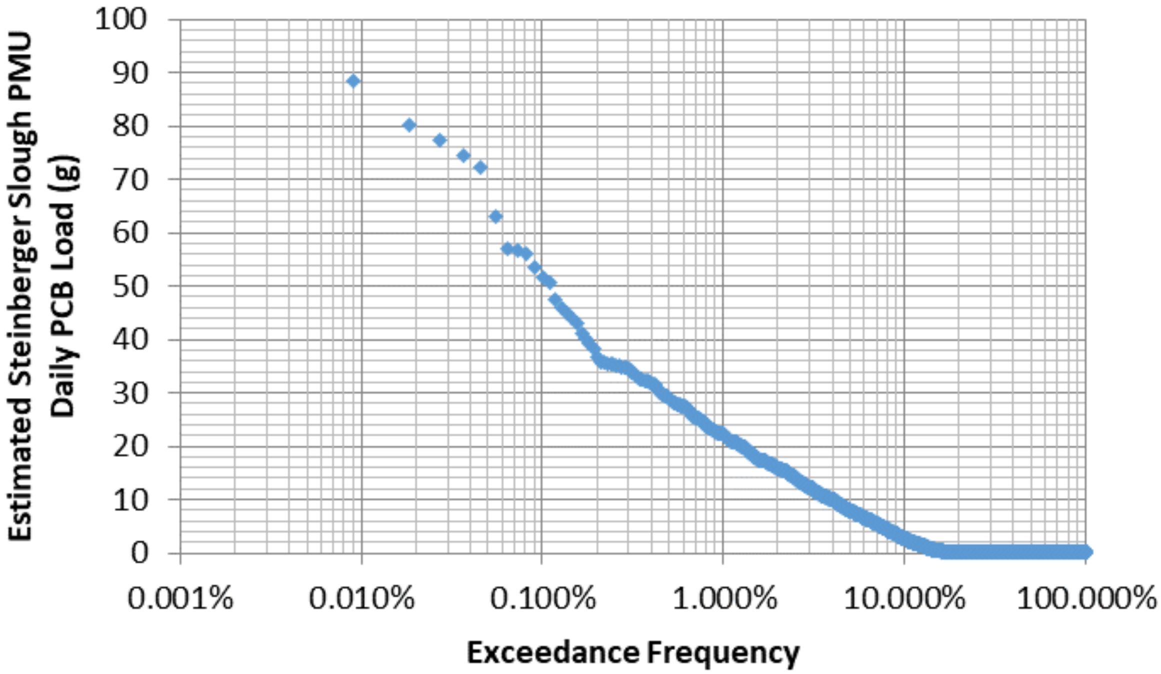

Figure A1-7. Exceedance frequency of estimated daily PMU PCB loads over a 30-year time period (WY 1981 – 2010).

Comparison between Method 1 and Method 2

A comparison was made between the loads estimate methods (the "recurrence interval method" generated by finding the percentage of load transported during specific storm types at reference watersheds, and the "continuous loads method" generated by using a long-term, continuous rainfall record) to ensure that the results generally corroborate one another. By selecting days from the 30-year continuous rainfall record at Oakland Museum which met the 24-hour recurrence interval values for the 1:1 year event, the 1:5 year event, and 1:10 year event, the daily loads estimated for those dates were compared to the load estimates for those storm types generated using the recurrence interval method (Table A1-3). The two methods produce similar results; although the recurrence interval method results suggest overall less load transport during these select larger storm types than does the continuous loads method. A better estimate of return frequency of loads or the distribution of loads over time relative to climatic variation can only be obtained with empirical observations of PCB concentrations in the watershed during winter storms over a number of years.

Although storm events larger than the 1:1 year event can transport a significant portion of the PCB load for any given year, events of that size occur infrequently. By identifying representative 1:1, 1:5 and 1:10 year events in the long-term continuous loads dataset, it's possible to estimate the percentage of long term PCB load delivered to the PMU during the dry season and more frequent smaller storm events versus less frequent but larger events. Based on the continuous loads method, it is estimated that 92% of the long-term PCB load to the PMU is transported during the dry season and storm events smaller than the 1:1 storm.

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Table A1-3. Summary comparison of the two methods for estimating loads in the PMU watersheds.

	% of average annual load transported - Recurrence Interval method	% of average annual load transported - Continuous loads method	% of long-term load transported during storms smaller than the select event - based on Continuous loads method
1:1 year event	4-5 %	8%	92%
1:5 year event	9-10 %	14%	97%
1:10 year event	11-12 %	16%	98%

Methods of Estimating Partitioning of PCB Exports from the Watersheds

Little is known regionally about the proportion of PCBs on varying grain size fractions. To our knowledge, there have been only two studies that explore the PCB partitioning in the region. The first study was done by Yee and McKee (2010), who carried out a settling experiment to estimate the portion of PCB loads that were in different size fractions. The outcome of this simple apportionment exercise was to make some first order estimates for PCBs in each of three size fractions: <0.25 µm, 25-75 µm, and >75 µm.

Table A1-4. The fraction of PCB mass in different grain size fractions. Study: Yee and McKee, 2010.

Sample/site	PCB (ng/L)	%<25um incl. dissolved	%25-75 um	%>75 um
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%

A second study included data collected more recently by BASMAA through the CW4CB project. In this study, PCBs passing through a 10 um filter and total PCBs were both measured, the difference of which represented the portion larger than 10 µm. In this study, on average 15% of the mass was in the dissolved phase or on particles smaller than 10 µm.

APPENDIX 1

Table A1-5.

Site	PCBs (ng/L)	% <10 μm	% >10 μm
PUL-3-I-EV4	273	2%	98%
LAU-1-I-EV5	8.52	25%	75%
LAU-4-I-EV3	1.99	16%	84%
LAU-4-I-EV5	28.0	9%	91%
LAU4-I-EV9	3.75	5%	95%
LAU-3-I-EV3	5.15	25%	75%
LAU-3-I-EV6	10.0	25%	75%
LAU3-I-EV7	8.73	2%	98%
ETT-TW2-I-EV3	24.3	11%	89%
ETT-TW2-I-EV4	39.1	14%	86%
ELC-B1-I-EV3	3.02	34%	66%
Range	2 - 273	2% - 34%	66% - 98%
Average	37	15%	85%

PCBs in the Dissolved Fraction

In the absence of any data for the PMU watersheds or other Bay Area small, urban tributaries, the dissolved proportion of PCBs was evaluated using two approaches. The first approach involved a literature review of dissolved PCBs in other surface runoff studies and provides general context for the likely range of dissolved PCBs under different flow conditions, while the second approach involved manipulation of PCB and SSC data from Bay Area tributaries and resulted in estimates of dissolved phase PCBs for the PMU watersheds.

Literature Review

PCBs have a high affinity for sorption to suspended sediment and organic matter in stormwater runoff. In tributaries and storm drains of watersheds contaminated by PCBs, mobilization of PCB residues by erosion and leaching of particulate material is often the dominant transport mechanism (Steuer et al., 1999; Foster et al., 2000a, 2000b; Verbrugge et al., 1995; Marti and Armstrong, 1990; Quemerais et al., 1994). In contrast to the expected preferential sorption of PCBs to particulate phases, several studies have measured higher proportions in the dissolved fraction in water samples with low suspended particulate concentrations (Chevreuil et al., 1990; Marti and Armstrong, 1990), low organic carbon content (Jiang et al., 2000), and/or in samples with PCB homolog patterns similar to Aroclor 1242/1248 (Marti and Armstrong, 1990).

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. It is therefore unsurprising that when data from studies are stratified between dry and wet weather conditions, the data points representing dry weather sample collection have higher overall proportions of dissolved PCBs (Figure A1-8, 52-93% versus 10-52% for wet weather sampling).

Samples collected from the water column and bed sediment of contaminated tributaries and storm drains of Bay Area watersheds typically have PCB congener patterns indicative of high-molecular weight Aroclors 1254 and 1260 (KLI 2001, Johnson et al., 2000, Leatherbarrow et al., 2002), and therefore are expected to be primarily associated with suspended particulate material transported during storm events. Ettie St. samples collected from the water column in WY 2011 (McKee et al., 2012) were also dominated by indicators for Aroclors 1254 and 1260, however the Ettie St. samples were comprised of greater proportions of the Aroclor 1242 and 1248 congeners than most other watersheds in the study, suggesting that a larger portion of the total PCBs may be in the operationally defined dissolved phase than is otherwise typical for the Bay Area.

Figure A1-8. 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.

Bay Area PCB Data to Estimate Dissolved Phase

The second approach used to estimate dissolved phase PCBs in the PMU watersheds involved graphing the available regional data (for each watershed in which we had sufficient data, referred to hereafter as the “RMP wet weather watersheds”) on total concentrations of PCBs in stormwater against the simultaneously collected suspended sediment concentrations. Only sample pairs of PCBs and SSC were used in which the collection was done when flow and SSC were low. The intercept of the linear regression equations that results was used to estimate the average dissolved phase concentration for each watershed. The estimated average dissolved phase concentration was then compared to the flow-weighted mean concentration of PCBs for the watershed and the proportion, or percentage, dissolved was calculated (Table A1-6).

These estimates of dissolved-phase PCBs were plotted against the % imperviousness and the % old industrial area in the each of the RMP wet weather watersheds (Figures A1-9 and A1-10). We anticipated the percentage in dissolved phase to be greater for more impervious watersheds due to lower SSC concentrations in these watersheds. We also anticipated that the dissolved proportion could be greater in watersheds with more old industrial area, where there is greater possibility of colloidal and liquid sources of PCBs. Using the relationships between PCBs and % imperviousness and % old industrial, dissolved phase PCBs in the PMU watersheds were then estimated.

Table A1-6. Estimates of dissolved phase PCBs for well-sampled watersheds (in white).

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%		

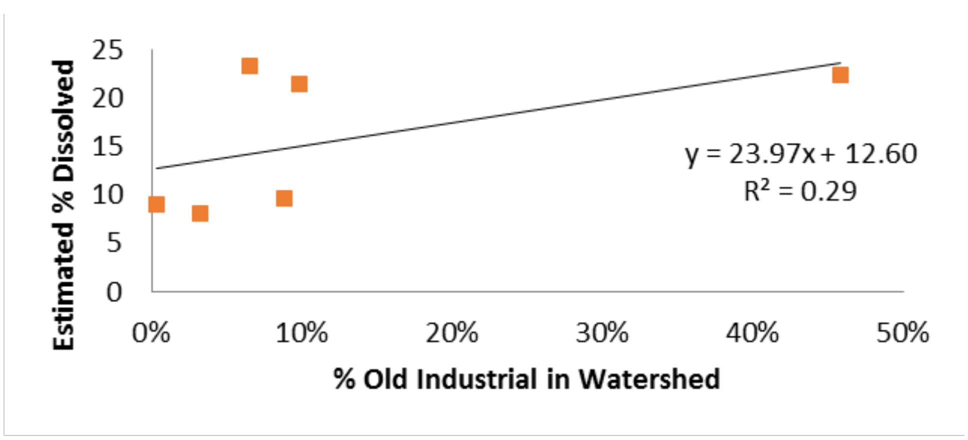


Figure A1-9. Estimated percentage of dissolved phase PCBs as a function of the percentage of old industrial area in well-sampled watersheds.

APPENDIX 1

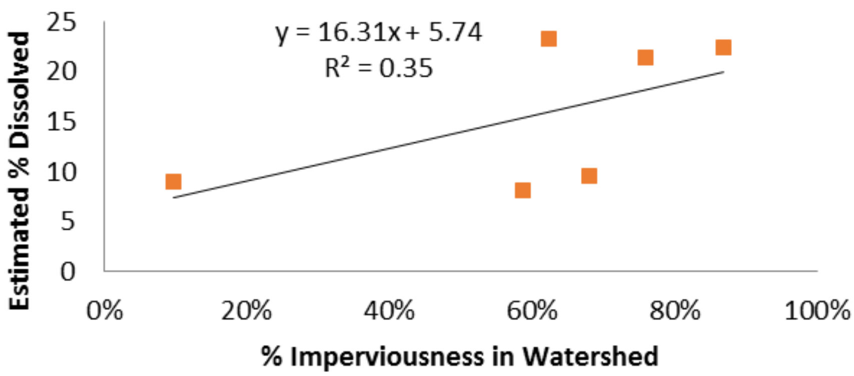
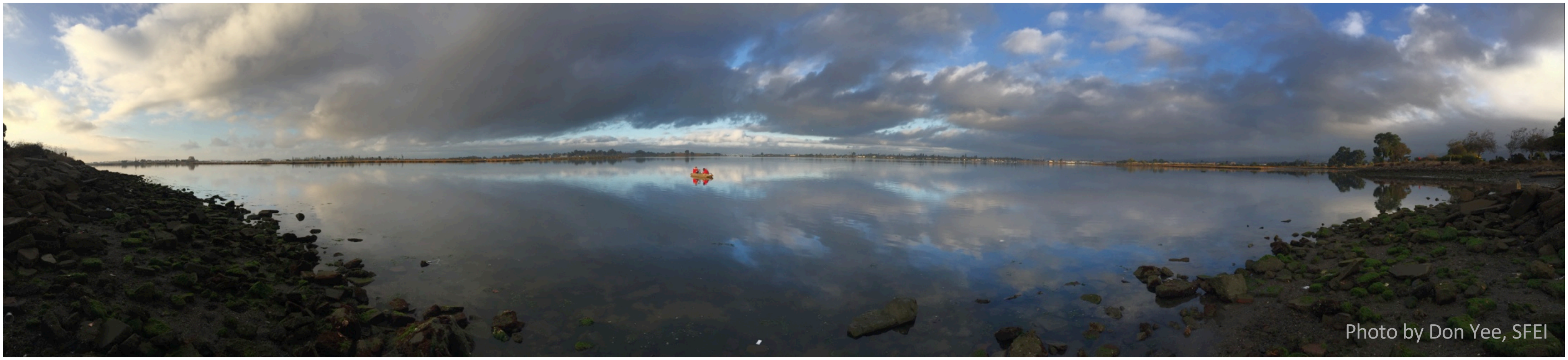


Figure A1-10. Estimated percentage of dissolved phase PCBs as a function of the percentage of imperviousness in well-sampled watersheds.

This method of estimating dissolved phase is not valid for periods of dry weather or non-storm flow. 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 recommend applying the median value from the literature (81%) for non-storm flow periods in the Steinberger slough watersheds.

APPENDIX 2



SAN LEANDRO BAY PCB PASSIVE SAMPLING:
RESULTS (FEB 13, 2017)

SFEI | AQUATIC SCIENCE CENTER

SAN FRANCISCO ESTUARY INSTITUTE & THE AQUATIC SCIENCE CENTER

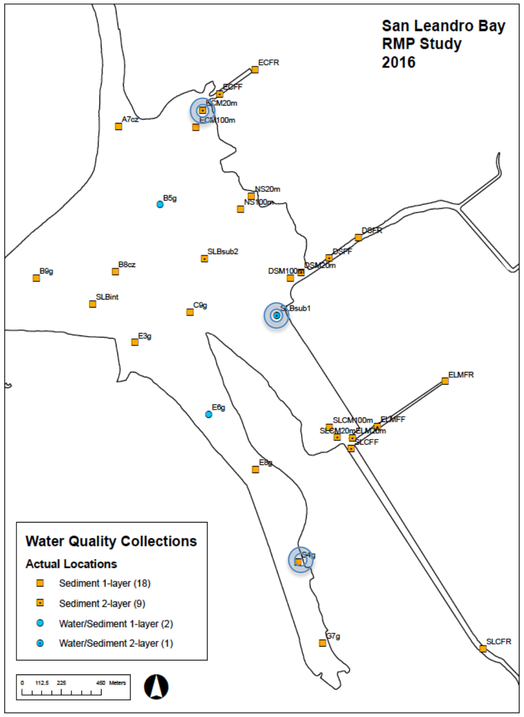
Results Memo, Feb 13, 2017

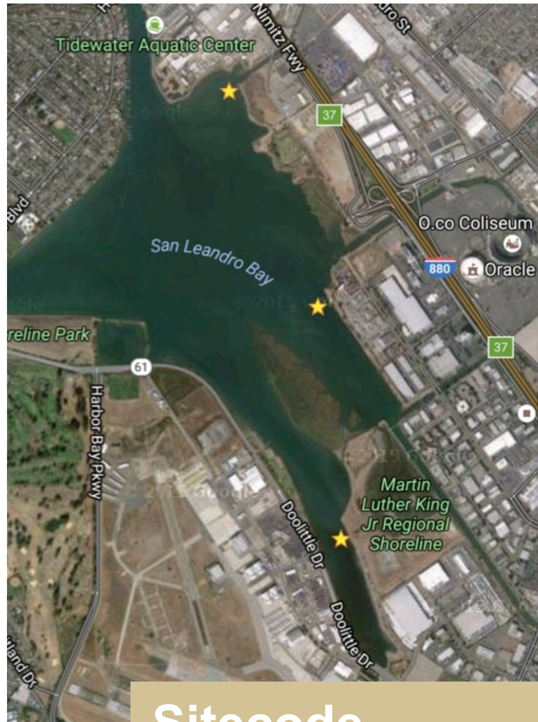
Stanford University

Sampling Activities

- Participants: Dr. Don Yee (SFEI)
  Dr. YeoMyoung Cho, Conrad Pritchard (Stanford)
- Field activities:
  - PE passive sampling (Sep 18 2016 - Oct 15 2016, 27 days)
  - Sediment core sampling

SAMPLING LOCATIONS



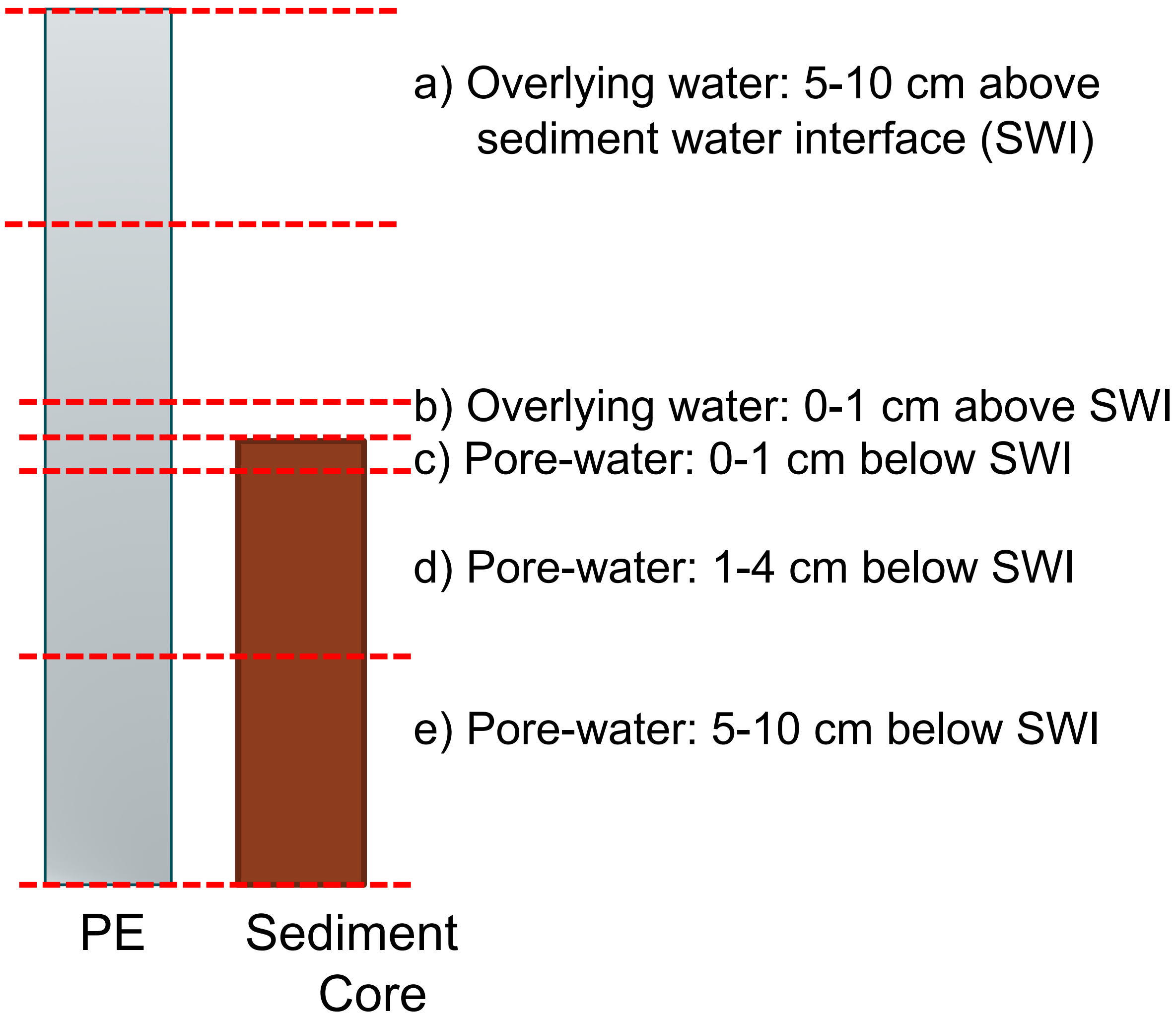


WGS84

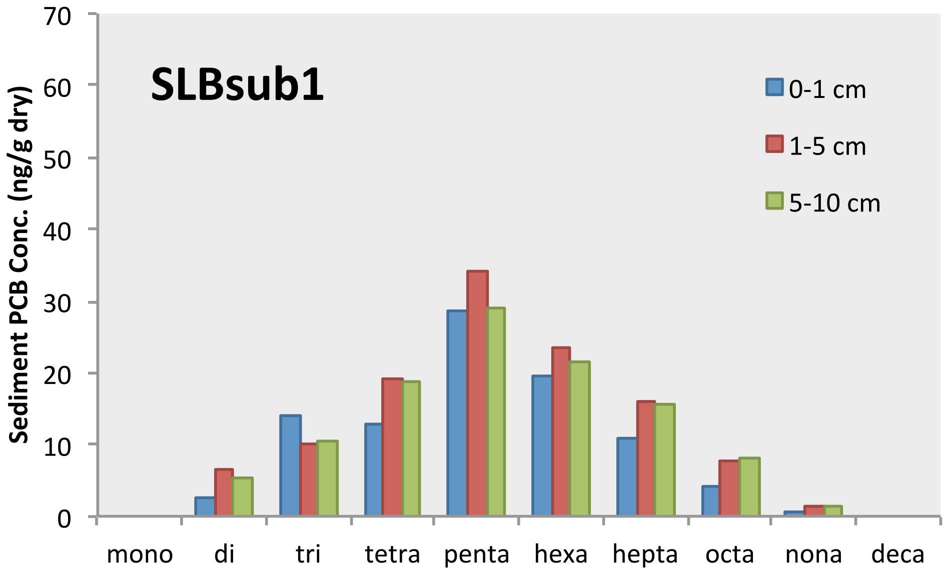
Sitecode		Lat (N)	Long (E)
G4g	Target	37.73683	-122.21135
	Actual	37.736885	-122.21133
SLBsub1	Target	37.7491	-122.21308
	Actual	37.749427	-122.212770
ECM20m	Target	37.75922	-122.21822

POST-PROCESSING

- PE sampler into subsamples
- PCB uptake in PE subsamples compared to PCB conc. of sediment core subsections



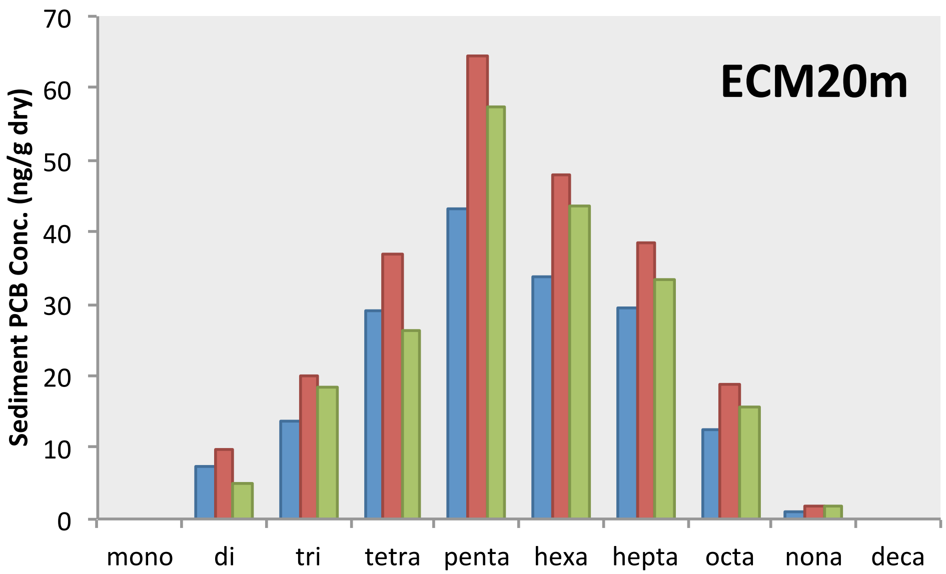
Sediment PCB Concentration

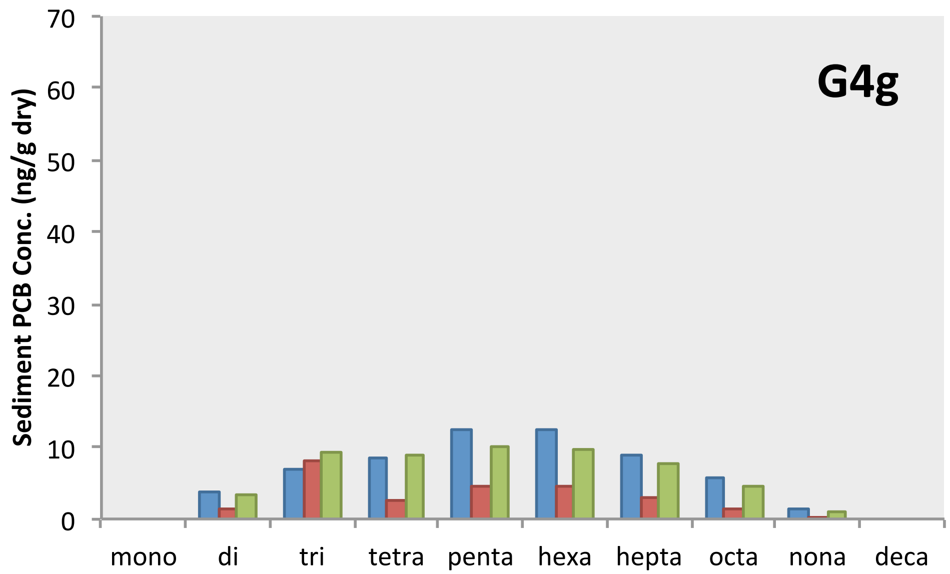


Sediment PCB conc. (µg/kg dry)

Depth	0-1 cm	1-5 cm	5-10 cm
SLBsub1	93	119	110
ECM20m	170	238	202
G4g	60	26	55

- ECM20m > SLBsub1 > G4g (t-test, p<(
- Penta > Hexa > Hepta ~Tetra-CBs





Stanford University

PE PCB UPTAKE

Depth	Overlying Water 10-5 cm	Overlying Water 1-0 cm	Pore-water 0-1 cm	Pore-water 1-5 cm	Pore-water 5-10 cm
SLBsub1	143	195 ± 40	224	217 ± 2	175 ± 15
ECM20m	256 ± 52	251	309 ± 91	240 ± 1	282 ± 15
G4g	89	103 ± 43	152 ± 11	106 ± 30	81

SWI

PE PCB Conc. (ng/g PE)

- ECM20m > SLBsub1 > G4g (t-test, $p>0.05$)
- Penta > Tetra > Hexa > Tri-CBs
- Similar uptakes from overlying water and pore-water

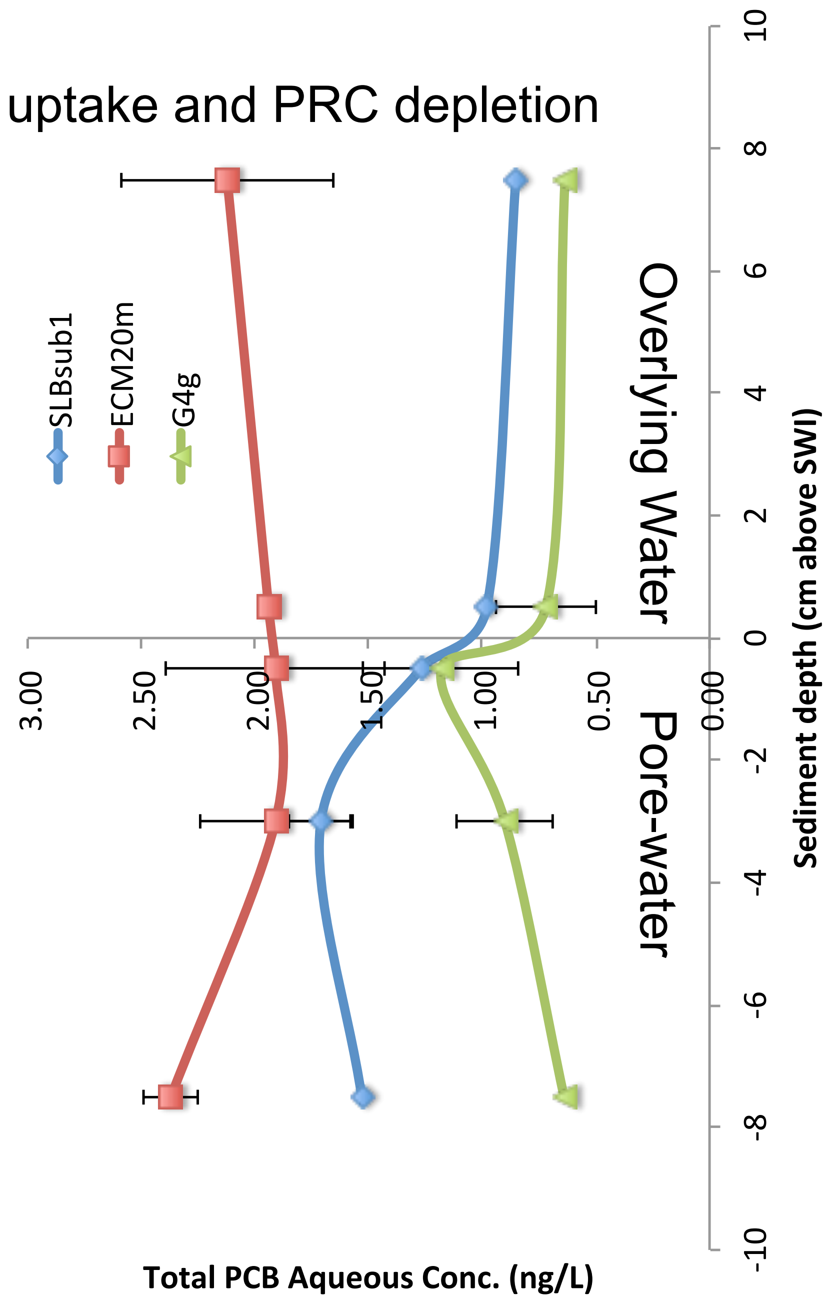
Aqueous PCB Concentration

- Aq. PCB conc.s were calculated using PE PCB uptake and PRC depletion

	Overlying Water		Pore-water		
Depth	**10-5 cm**	**1-0 cm**	**0-1 cm**	**1-5 cm**	**5-10 cm**
SLBsub1	0.85	0.98 ± 0.01	1.27	1.71 ± 0.14	1.53 ± 0.01
ECM20m	2.12 ± 0.47	1.94	1.91 ± 0.48	1.91 ± 0.33	2.37 ± 0.12
G4g	0.64	0.72 ± 0.22	1.18 ± 0.34	0.90 ± 0.21	0.64

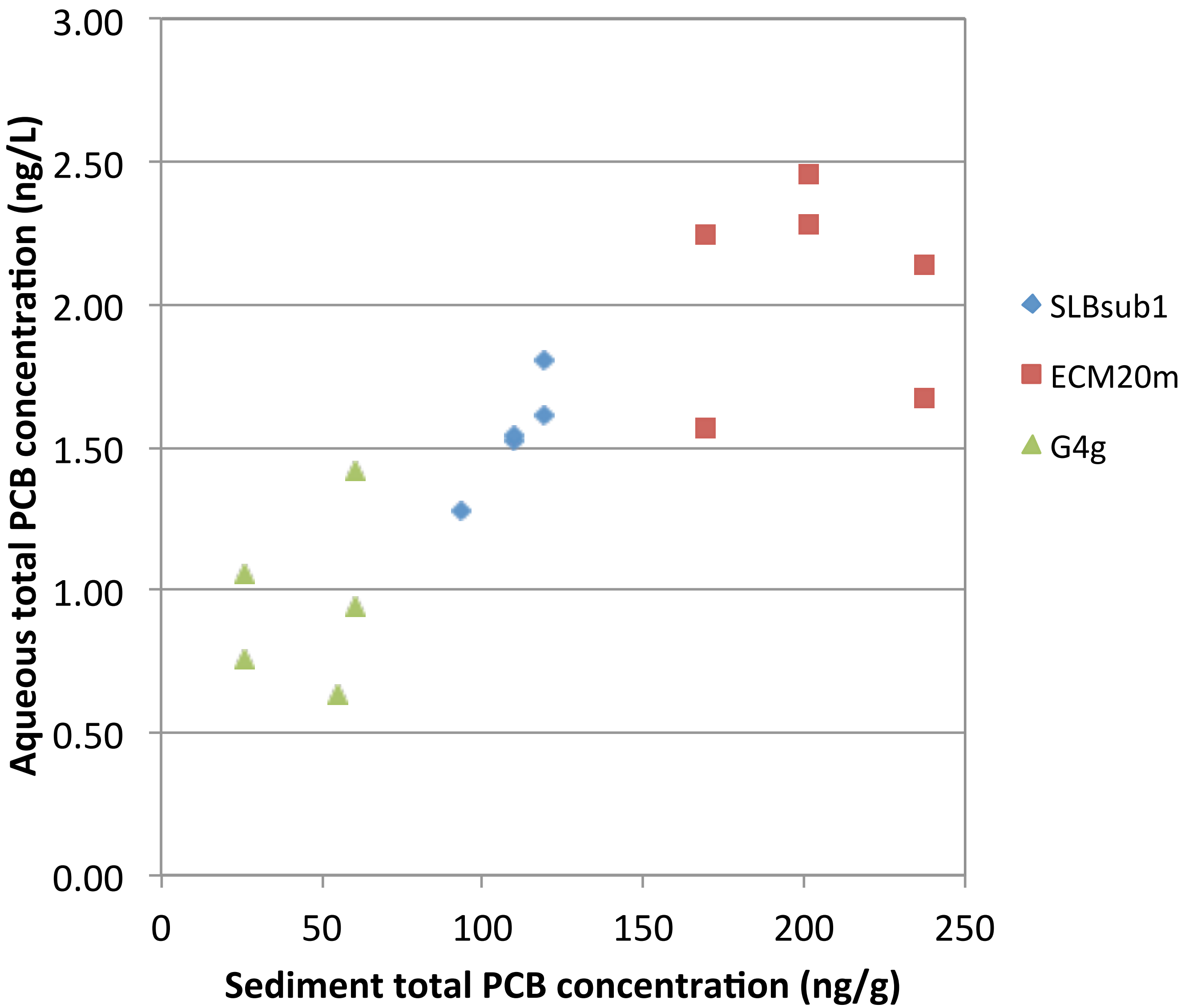
Aqueous PCB Conc. (ng/L)

SWI

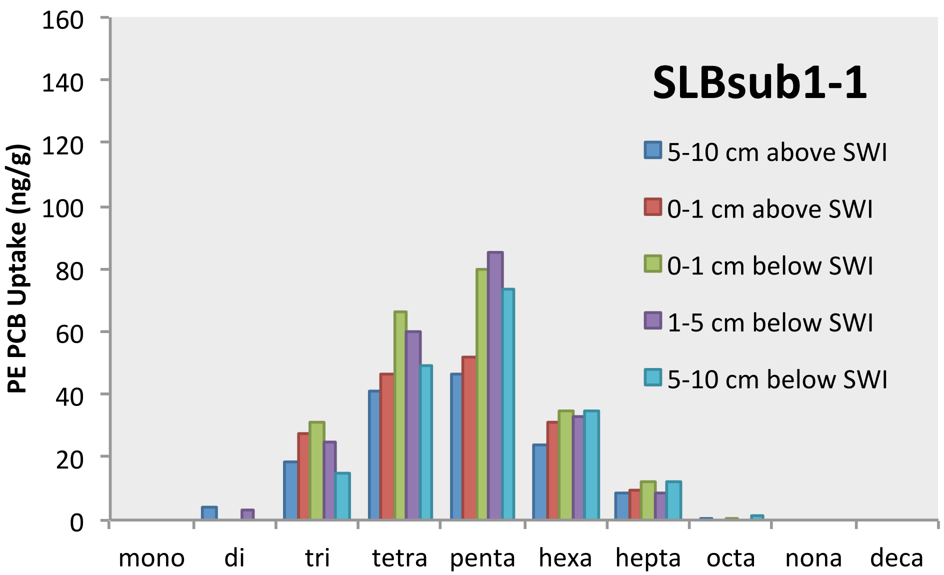


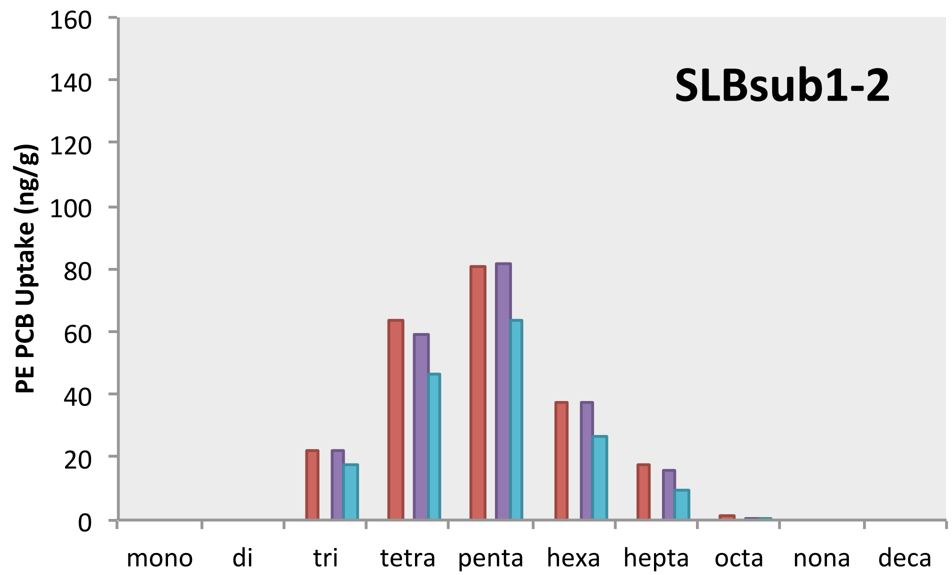
- ECM20m > SLBsub1 > G4g (t-test, p>0.05)
- Penta > Tetra > Hexa ~ Tri-CBs

Sediment vs. Pore-water PCB Concentrations

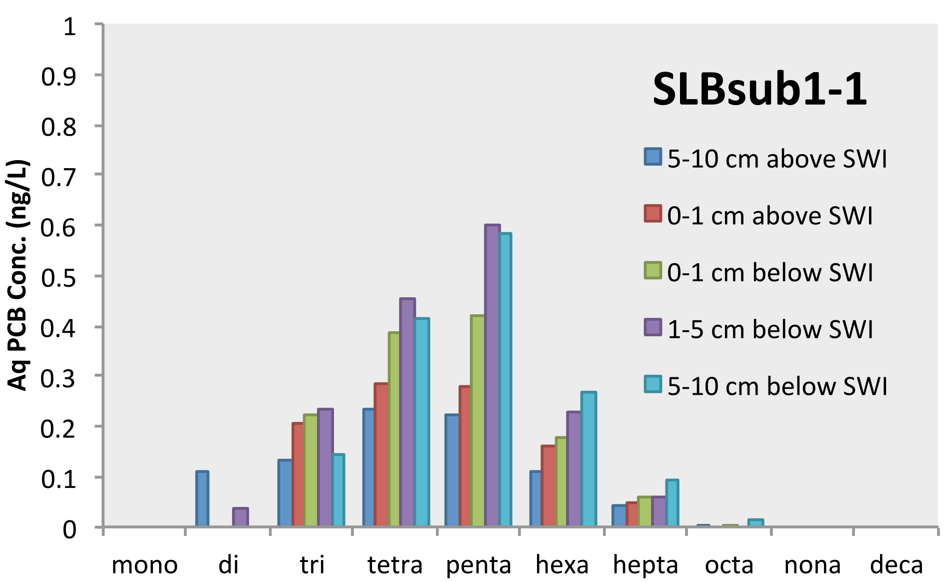


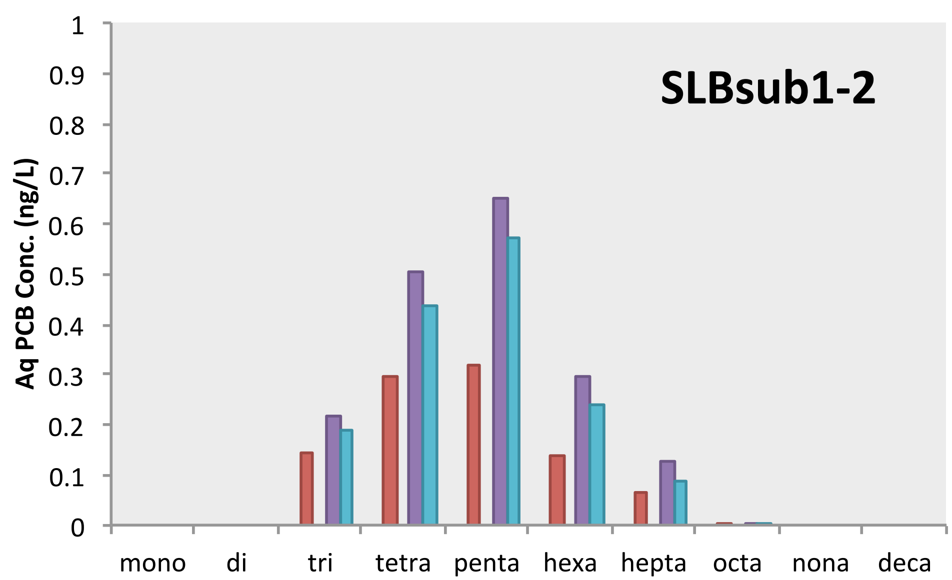
SLBsub1 (PE Uptake and Calc. Aq. Conc.)



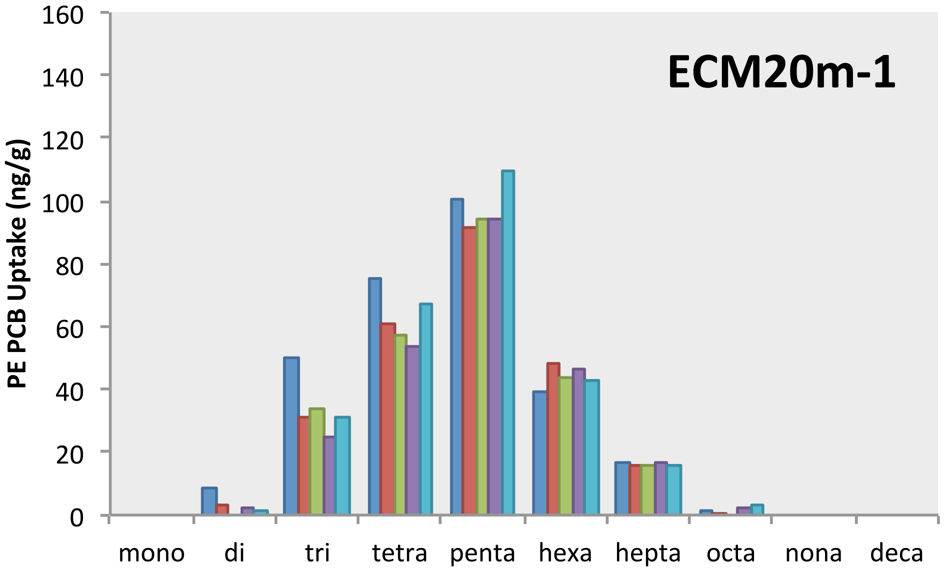


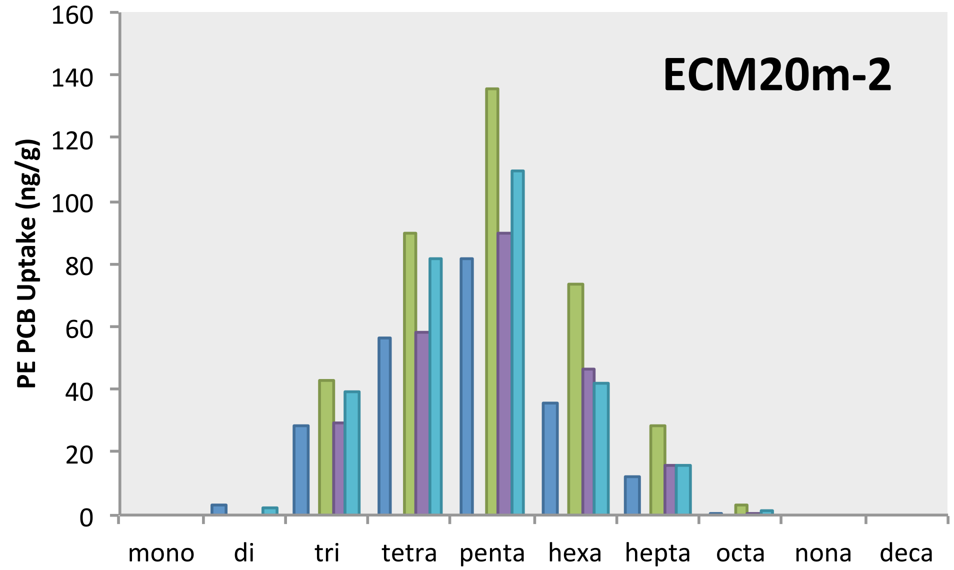
Data with low SS recovery not included





ECM20m (PE Uptake and Calc. Aq. Conc.)





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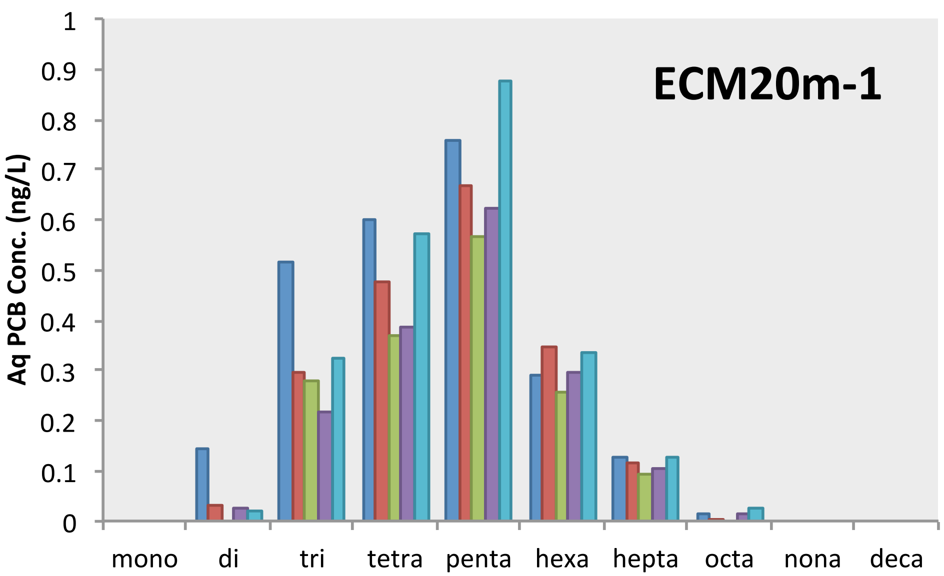
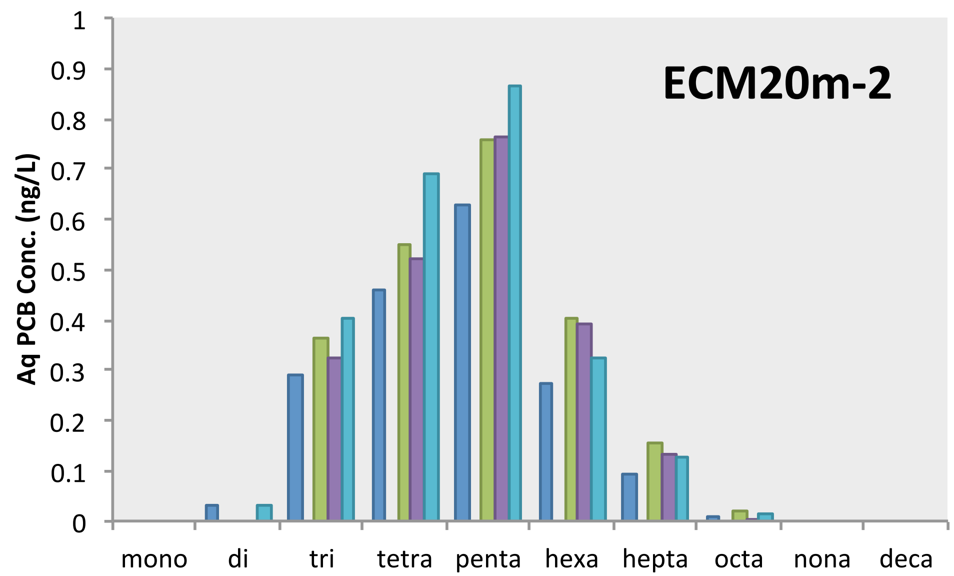
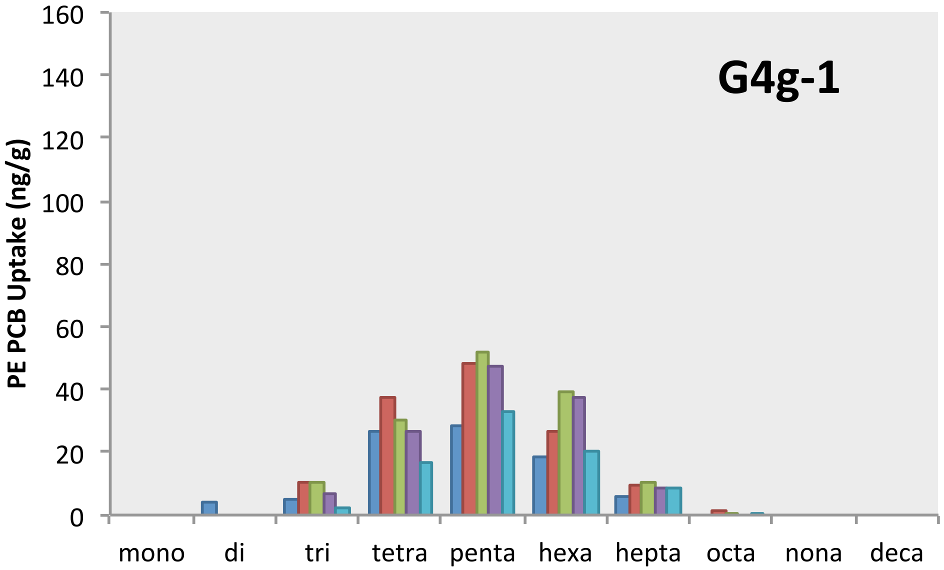
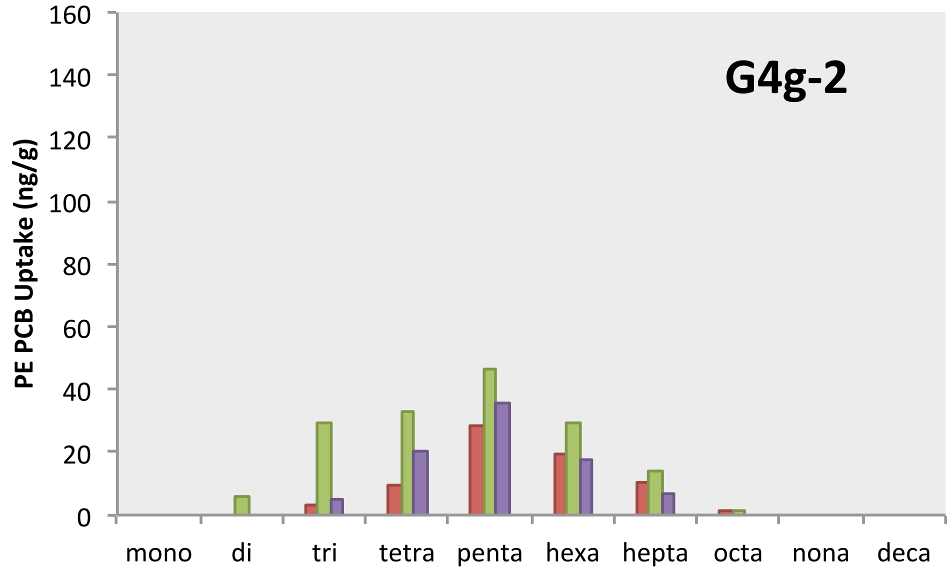


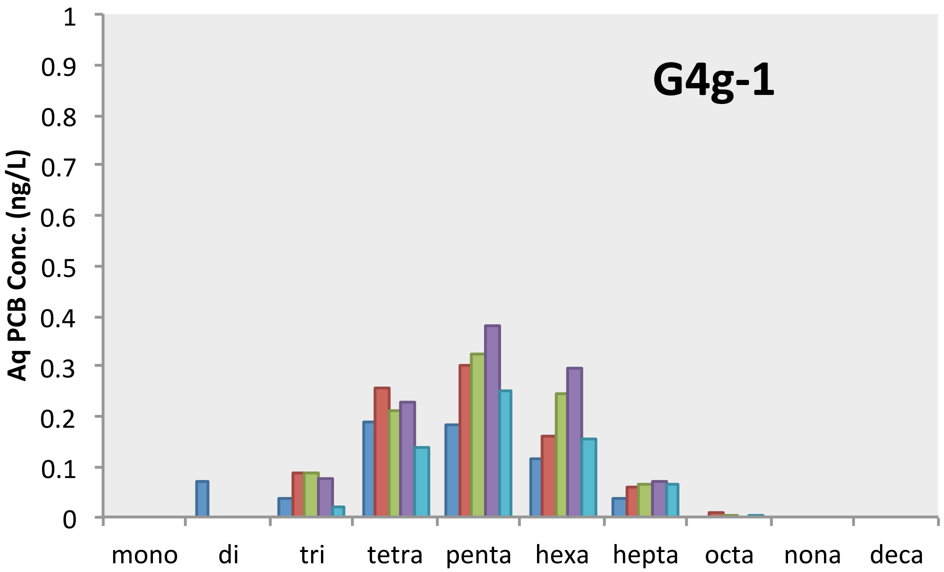


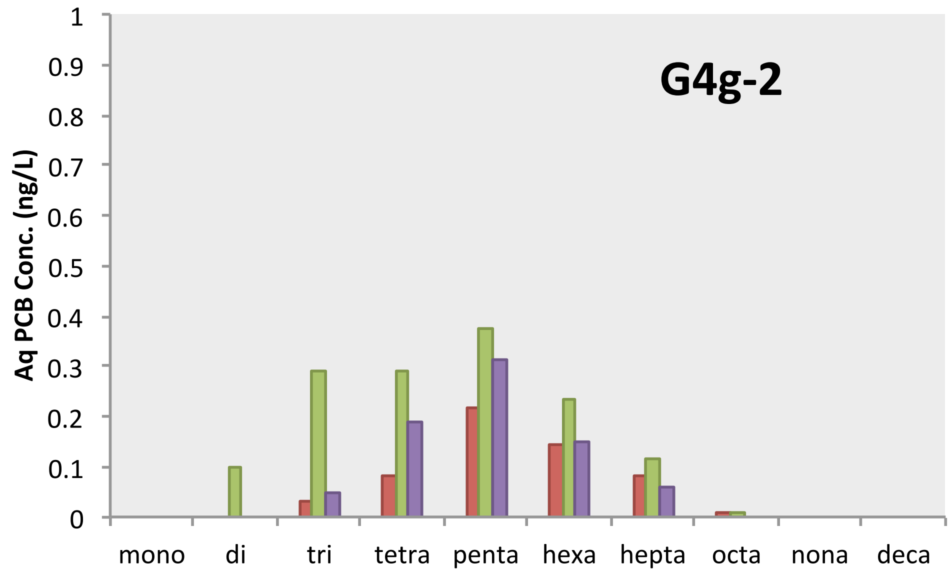
G4g (PE Uptake and Calc. Aq. Conc.)





Data with low SS recovery not included





SUMMARY

- Spatial variance of PCBs in sediment and aqueous phase among sampling sites
- Sediment PCBs are 26-238 ppb
- Aqueous PCBs (overlying water and pore-water) are 0.6-2.4 ng/L
- ECM20m is the most contaminated, G4g is the least
- Correlation between sediment PCB conc. and aqueous pore-water PCB conc.