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Summary and Evaluation of Bioaccumulation Tests for Total Polychlorinated Biphenyls (PCBs) Conducted by San Francisco Bay Dredging Projects

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Suggested Citation:
Mendez, M.; Grosso, C.; Lin, D.; 2021. Evaluation of Bioaccumulation Tests for Total Polychlorinated Biphenyls (PCBs) Conducted by San Francisco Bay Dredging Projects. SFEI Contribution #1092. San Francisco Estuary Institute, Richmond, CA.

CONTRIBUTION #1092 / October 2022

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Executive Summary

The Dredged Material Management Office (DMMO) is responsible for annually approving dredging and disposal of millions of cubic yards of sediment to maintain safe navigation in San Francisco Bay. Dredged sediment is characterized for physical, chemical, and biological characteristics to ensure sediment disposed of in the Bay or at beneficial use locations does not cause adverse environmental impacts. Bioaccumulation thresholds and total maximum daily loads (TMDLs) have been established for several contaminant classes, including PCBs, and are used by the DMMO to determine whether sediment contaminant levels trigger subsequent bioaccumulation testing. Sediment with contaminant concentrations above any TMDL levels cannot be disposed of within the Bay but may be further evaluated for upland reuse and ocean disposal. The objective of this study was to evaluate PCB bioaccumulation data from navigational dredging projects to assess the existence of correlations between sediment chemistry and bioaccumulation test results. The motivation for this study was to determine whether the current PCB bioaccumulation trigger is effective in differentiating sediment bioaccumulation concerns. The DMMO may use the results of this study to inform evaluation requirements for PCBs, particularly in support of modifying the terms of the Long-term Management Strategy for San Francisco Bay (LTMS) programmatic Essential Fish Habitat (EFH) agreement concerning PCB bioaccumulation testing.

The first part of this study focused on compiling the necessary paired datasets for bioaccumulation and chemistry results from the continuously growing DMMO database. Since 2015, all dredging project testing data have been collated into this database to allow for searchable and downloadable data (overall the database contains data from 1995 to present). The database undergoes continual improvements by the DMMO and the San Francisco Estuary Institute (SFEI), with funding from the San Francisco Bay Regional Monitoring Program (RMP), for quality assurance and ease of access by users. As several recent studies with PCB bioaccumulation testing have not yet been uploaded to the database, two of these reports were manually uploaded, and there is ongoing work to upload the remaining studies. The DMMO requires testing of the same 40 PCB congeners historically monitored by the RMP (RMP 40), which are summed for each sample. The upper and lower bounds in the PCB sums were calculated by substituting non-detects (NDs) with either zero or half the method detection level (MDL) to determine the potential effect of NDs on the outcome. The chemistry and bioaccumulation data were paired to produce a dataset of 101 matching data points for each bioaccumulation test species (polychaetes and bivalves).

There were extensive NDs within the dataset, with 40% of individual congener results noted as ND and 60% for bioaccumulation testing results. The large amount of NDs increased the uncertainty in quantification and characterization of PCB distributions within the test results. Bivalve bioaccumulation results ranged from ND to 36 ppb. Polychaete bioaccumulation results ranged from ND to 33 ppb. The results (sum of 40 PCBs) for both species showed no statistical difference in the average of bioaccumulation test results for sediment below the bioaccumulation trigger (BT, sum of

PCB in sediment < 18 ppb), sediment between the BT and TMDL limit (29.5 ppb), and above the TMDL limit. There was a non-statistical difference among these three bins, with results above the TMDL limit exhibiting higher concentrations of PCBs in tissue than the tissue results between the BT and TMDL limit and below the bioaccumulation trigger. This suggests the current BT is not a useful criterion to differentiate sediment chemistry where adverse bioaccumulation risk may be of concern. The DMMO may use these findings to evaluate whether bioaccumulation testing for results between the BT and TMDL limit should be reevaluated. We also provide additional steps that can refine this data synthesis, although the value of the additional steps may be limited based on the DMMO’s experiences with reported bioaccumulation studies. Additionally, ongoing DMMO database improvements will continue to improve the quality of the available dataset.

1. Introduction

In and around San Francisco Bay, millions of cubic yards of sediment are dredged yearly to maintain safe navigation and marine operations throughout the Bay. The Dredged Materials Management Office (DMMO) is an interagency group under the Long-term Management Strategy for Dredged Material in SF Bay (LTMS) responsible for evaluating routine dredging projects to ensure their execution in an economically- and environmentally-sound manner. The DMMO comprises the San Francisco Bay Conservation and Development Commission (BCDC), San Francisco Bay Regional Water Quality Control Board (SFBRWQCB), State Water Resources Control Board (SWRCB), California State Lands Commission (CSLC), San Francisco District U.S. Army Corps of Engineers (USACE), and Region 9 of the U.S. Environmental Protection Agency (USEPA).

Routine dredging projects are systematically reviewed to evaluate whether exposure to disposed sediment, or to the post-dredging surface sediment (often referred to as the “z-layer”), has the potential to cause unacceptable adverse environmental impacts, including via bioaccumulation and food web transfer. If bioaccumulative contaminants are detected at elevated levels in dredged sediment, the contaminants are evaluated using a conservative screening-level hazard assessment approach (discussed below) that considers contaminant concentrations in the sediment and in the tissues of laboratory-exposed marine invertebrates from bioaccumulation studies. Those project-specific results are then used to estimate potential trophic transfer to fish using a bioaccumulation model.

The LTMS and DMMO have established dredged sediment chemistry thresholds for seven different contaminant classes for determining whether sediment contaminant levels are elevated to the extent that bioaccumulation testing will be required for the dredged material to be disposed in an unconfined open water disposal site in the Bay. These contaminant classes are polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dichlorodiphenyltrichloroethane and metabolites (DDTs), chlordanes, dieldrin, dioxins/furans, and mercury. Bioaccumulation testing thresholds for total PCBs and total PAHs are based on ambient sediment concentrations from the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP). The current bioaccumulation testing threshold for PCBs is 18 ppb dw (Table 1).[1]

If bioaccumulation testing thresholds are exceeded, bioaccumulation analysis with benthic organisms is required to determine the bioavailability of the contaminant and the potential for negative impacts to benthic invertebrates if dredged sediment is disposed of at in-Bay sites (or the San Francisco Deep Ocean Disposal Site, SF-DODS). Bioaccumulation testing evaluations are typically conducted with the polychaete *Nereis virens,* and the bivalve *Macoma nasuta*, in 28-day exposures as a general indication of bioavailability from the sediment into the food web.

[1] Dredged material testing thresholds are summarized here: https://www.sfei.org/projects/dmmo-ambient-sediment-conditions

The San Francisco Bay has a known legacy of PCB contamination with direct negative impacts to the Bay environment including health risks to humans and wildlife. In 2008, the SFBRWQCB adopted a Total Maximum Daily Load (TMDL) for PCBs in San Francisco Bay (SFBRWQCB 2008), establishing a plan for reducing impairment from elevated PCB concentrations. The TMDL Implementation Plan calls for the control of internal sources of PCBs within the Bay (including dredging) and management of risks to consumers of fish from the Bay. Dredged sediment with measured PCB levels above the TMDL limit may not be disposed of in the Bay with the current TMDL limit for PCBs is 29.5 ppb dw (Table 1). The TMDL limit is an ambient-based threshold, which rely on currently available ambient sediment concentrations from the RMP monitoring program data over a running 13-year period to derive an appropriate threshold (Yee and Trowbridge, 2016). The TMDL for PCBs includes a target tissue concentration for sport fish of 10 ppb (wet weight) (Table 1).

Table 1. Relevant thresholds for PCBs in San Francisco Bay.

TMDL Fish Tissue Target	10 ppb ww
2012 EFH Bioaccumulation Trigger	18 ppb dw
2016 TMDL In-Bay Disposal Limit	29.5 ppb dw

The current framework for evaluating bioaccumulation impacts from PCBs in dredged sediment is based on the LTMS Management Plan (2001) and the subsequent programmatic Essential Fish Habitat (EFH) agreement with the National Marine Fisheries Service (NMFS; 2011, 2015). Dredged sediment is analyzed for PCBs and other contaminants on an ongoing or periodic basis, with the remaining residual sediment (“z-layer” or post-dredge surface sediment) examined if warranted based on the results of overlying sediment chemical analysis. This analysis is used to identify sediment suitable for disposal at specific sites within the Bay, for reuse at upland sites around San Francisco Bay, or for ocean disposal. The regulatory assessment for bioaccumulative compounds like PCBs, as outlined below, is sequential. It begins with assessments of sediment, with those exceeding the bioaccumulation trigger (BT), an ambient-based threshold, requiring further analysis of bioaccumulation in benthic organisms and fish:

1. **If sediment concentrations are below the BT:**
   In-Bay sediment disposal of dredged sediment is acceptable.[2]
2. **If sediment concentrations are above the BT but below the TMDL in-Bay disposal limits:**
   Detected compounds are evaluated using a risk assessment approach that requires sediment bioaccumulation tests and analyses to determine whether in-Bay disposal is acceptable.[3]

[2] Dredged material testing thresholds are summarized here: https://www.sfei.org/projects/dmmo-ambient-sediment-conditions
[3] For all target bioaccumulating compounds except mercury

3. **If sediment concentrations exceed TMDL in-Bay disposal limits:**
   In-Bay disposal is not allowed. (Additional evaluation is required to consider acceptability for ocean disposal).

Prior to 2012, bioaccumulation testing for mercury in dredged sediment was also required following similar steps as those described above for PCBs. After 2012, the DMMO no longer required bioaccumulation testing for mercury above the previously established bioaccumulation testing threshold of 0.33 mg/kg dw. This decision was based on a review of bioaccumulation testing results from maintenance dredging projects in the San Francisco Bay conducted between 2001-2012. The review of sediment and tissue data (n = 50 sediment samples with mercury concentrations between 0.33 and 0.5 mg/kg dw) found little bioavailability of mercury from the sediment tested, and little or no increase in mercury bioavailability with increasing sediment concentration (Ross, 2012). Further, because sediment exceeding 0.5 ppm is prohibited from in-Bay disposal by current TMDL requirements, the DMMO no longer requires bioaccumulation testing for mercury (Kendall and Brush, 2012). NMFS concurred with the results of the mercury analysis. As a result, dredged sediment with mercury concentrations below the TMDL limit has been cleared for possible disposal at in-Bay locations, and dredgers and the DMMO have not spent time and money on mercury bioaccumulation testing.

The motivation for this study was to conduct similar analyses of the PCB bioaccumulation data to that done previously for mercury. Similar to the process for mercury, analysis of PCBs data can provide needed information to evaluate the efficacy of the current PCB bioaccumulation testing threshold. The results of this review may be used to support reassessing these thresholds and the need for costly bioaccumulation testing. This study is the first step in this evaluation, focusing on the synthesis of available PCB bioaccumulation tests results submitted to the DMMO. The dataset was subsequently analyzed to evaluate the quality of sediment and tissue data as well as compared to results from RMP fish monitoring efforts and fish concentrations and relevant PCBs thresholds. These thresholds include bioaccumulation trigger levels, TMDL limits for sediment (and aquatic resources and wildlife), and toxicity reference values (TRVs) for benthic organisms.

2. Methods

2.1 Download PCB Sediment Chemistry and Bioaccumulation Data from DMMO Database

The DMMO has compiled dredging project testing data from approximately 1995 into a database (DMMO Database) to allow data to be more readily searched and downloaded. The DMMO Database contains a significant amount of data. Since 2017, the RMP has been providing significant support to host, manage, and update the DMMO Database. The version of the DMMO Database used for this analysis was downloaded on February 10, 2022. Several DMMO sampling analysis reports (SARs) with relevant PCB bioaccumulation data had not yet been added to the DMMO Database at the start of this effort. Therefore, the first step was to check which SARs had been submitted to the DMMO website (www.dmmosfbay.org) but not yet uploaded to the DMMO Database. We added two SARs to the DMMO Database as part of this study.

The next step involved extracting the relevant PCB sediment chemistry and bioaccumulation test results and relevant metadata (e.g., study name, study location, unique sample name, sample location, sampling date, method detection limit (MDL, reporting limit (RL), data qualifier flags) from the DMMO Database. This included identifying relevant studies and data that had paired sediment and bioaccumulation testing data for the RMP 40 PCB congeners.

While we initially tried to link the two datasets using queries within the DMMO Database (currently stored in Microsoft Access), this ended up being too restrictive and failed to match all the data due to small errors or inconsistencies in the metadata parameters. Therefore, we downloaded the datasets separately from the DMMO Database and manually confirmed the matching of results.

2.2 Calculate Sum of PCBs from Sediment and Bioaccumulation Data

We focused our data analysis on the sum of 40 PCB congeners historically reported for the RMP, with their coeluters in cases where the congeners were not individually isolated and quantified. The RMP reported congeners represent those commonly most abundant in PCB technical mixtures, such as Aroclors, and most likely to be present at ambient concentrations.

Where studies reported multiple samples under the same sample ID, the record with the greatest concentration was used.[4] A particular challenge with examining the PCB data in the DMMO Database was the widespread occurrence of non-detects (ND) for individual congeners. Examining the entire DMMO database (including z-layer results), there were over 26,000 individual sediment PCB results across 118 studies with about half noted as ND and over 8,900 bioaccumulation testing results in 31 studies with 63%

[4] While we considered taking the average of reported replicates, there was significant uncertainty in this approach due to a significant number of ND.

noted as ND. This result is not unexpected as most of the dredged material the DMMO evaluates is from sediment that is removed annually and unless a nearby source of PCBs is present, is expected to be well below the PCB trigger thresholds. The DMMO target reporting limit for each RMP 40 PCB congener is set at 0.5 ppb dw. However, the method detection limit (MDL) values varied widely among the SARs by over two orders of magnitude. While ND is acceptable for DMMO evaluations, the significant presence of ND introduces uncertainties in our efforts to quantify and characterize chemical distributions as was the goal of this study.

For this study, we calculated the sum of RMP 40 for each sample, and treated NDs in two ways. First, we substituted all results with no quantified result and “non-detect flags” or “J flags” (indicates an estimated concentration when the value is less than the calculated RL, but greater or equal to the MDL) with half the detection limit. When MDLs were not available, the result was noted as the MDL. We then calculated the sum of PCBs after substituting ND and J flags with zero to explore the impacts of high MDLs on the calculated sum of PCBs. When substituting half the MDL for unquantified, flagged results, calculated sum of PCBs could lead to overestimations. This was particularly relevant for calculation of sums where many or all of the individual reported congeners were ND, which occurred frequently in the DMMO data.

2.3 Linking Sediment Chemistry and Bioaccumulation Data

The resulting summed sediment and tissue results were subsequently matched using five important data identifiers: date of study, study ID, study name, station name, and sample IDs. This caused a particular challenge as nuances (i.e., anything that does not exactly match) across studies in the DMMO Database led to errors in matching. Several studies required manual verification (by looking at the original reports) to ensure samples were accurately matched. The version of the DMMO Database used in the present study included 30 studies from 2011-2021, which included 13,079 sediment and 8,478 bioaccumulation testing results. Roughly, 40% of sediment results and 60% of bioaccumulation results were reported as NDs with MDL median and max of 0.22 and 12 ppb (dw), and 0.10 and 2.8 ppb (ww), respectively. For studies with multiple results per sediment sample, the maximum result and subsequent metadata were used to match to the bioaccumulation data. Overall, 101 matching data points for each species (polychaetes and bivalves) from bioaccumulation tests were identified and summarized in Appendix A. Samples from “z-layers,” which are located below the planned dredging depth, were not included in this analysis since there were no associated bioaccumulation tests.

3. Results

The synthesized data represent bioaccumulation tests conducted with sediment containing sum of PCBs ranging from below detection limits to 174 ppb and associated bioaccumulation test results for bivalves (n = 101) and polychaetes (n = 101). This provided sample results distributed across the sediment range from below the BT, between the BT and TMDL limit, and above the TMDL limit (Table 2). Bivalve bioaccumulation results ranged from non-detect to 36.4 ppb ww (with ND = zero). Polychaete bioaccumulation results ranged from non-detect to 32.9 ppb ww (with ND = zero).

Table 2. Summary of Sediment and Bioaccumulation Test Results Used in Evaluation. Sediment chemistry results are based on ppb dw. Bioaccumulation test results are based on ppb ww. Sum of PCBs for sediment and tissue are based on non-detect results substituted with zero to avoid the influence of high detection limits.

Sum of PCBs range in Sediment	Number of Tissue Exposures*	Bivalve Average (Minimum - Maximum)	Polychaete Average (Minimum - Maximum)
Sediment < 18 ppb	n = 43	2.7 (ND-16.9)	6.9 (ND-40)
18 < Sediment < 29.5 ppb	n = 22	3.1 (ND-10.2)	7.2 (ND-22.9)
Sediment > 29.5 ppb	n = 36	8.2 (ND-36.4)	10.3 (ND-32.9)

*These bins are based on the sum of PCBs in sediment where non-detects are substituted with zero.

These test results were graphed to explore trends between the sediment chemistry and bioaccumulation test results (Figures 1, 2, 3, and 4, and 5). When looking at the overall dataset, we do not see a clear, visually observable correlation between sediment chemistry and bioaccumulation in bivalves (Figures 1 and 2) or polychaetes (Figures 3 and 4). This is also apparent in Figures 5 and 6, where paired sediment-tissue results are sorted in increasing order of sediment chemistry; as sediment PCB concentration increased, we did not see a similar trend in the tissue results. The bioaccumulation results (for both bivalves and polychaetes) for sediment chemistry between the BT and TMDL limit are within the range of bioaccumulation results from sediment chemistry below the BT (Table 2). Each dataset was checked for normality using the Shapiro-Wilks test, with the data below the BT and above TMDL limit not exhibiting normality while data between the BT and TMDL limit did exhibit normality. We used a Mann-Whitney U test, used when a dataset does not have a normal distribution, to compare the bioaccumulation test results associated with sediment below the BT and sediment between the BT and TMDL limit. This analysis indicated these datasets were not statistically different ($p = 0.48$ and $p = 0.62$ for bivalves and polychaetes). This suggests no statistically significant difference in bioaccumulation for sediment below the BT and between the BT and TMDL limit.

A comparison of the bioaccumulation test results for sediment above the TMDL limit to the other two bins did indicate a higher average concentration in bioaccumulation results (8.2 ppb ww for bivalves and 10.3 ppb ww for polychaetes), indicating an increase in bioaccumulation from sediment with PCB levels above the TMDL limit. A Mann-Whitney U Test indicated that the datasets above TMDL limit and below TMDL limit were not statistically different ($p = 0.18$ and $p = 0.136$ for bivalves and polychaetes, respectively). The three highest sediment chemistry results were associated with the highest bioaccumulation test results. The highest bioaccumulation test results were below 50 ppb.

DMMO uses Toxicity Reference Values (TRVs) as a conservative screening tool to efficiently evaluate whether observed invertebrate test organism body burdens could indicate adverse ecological effects on benthic organisms in situ. While currently, there are no published standard TRVs for the Bay, the DMMO currently uses a TRV value of 162 ppb for PCBs, based on a previous study that applied the DMMO's methodology for selecting TRVs from the USACE's Environmental Residue-Effects Database (ERED) (Lin and Davis, 2018). Benthic bioaccumulation tissue values represented in the data are below this TRV PCB values currently used by the DMMO.

The RMP recently reported San Francisco Bay sport fish PCB concentrations with shiner surfperch having the highest concentration among measured species. For fish collected in 2019, the median concentration for shiner surfperch was 200 ppb ww, and 50 ppb ww for white croaker (Buzby et al. 2021). Overall, 10 of the 16 species monitored had an average concentration above the SFBRWQCB's numeric target of 10 ppb ww (Buzby et al. 2021). It is important to note graphed data are for benthic organism bioaccumulation levels and are not directly comparable to fish tissue concentrations. Further modeling would be to predict fish tissue concentrations from benthic organism concentrations to compare to either the fish TMDL limit or Bay fish concentrations. DMMO requires such trophic trace modeling on an individual project basis when sediment results exceed the BT, and the project proposes in-Bay disposal. Modeling considers site-specific bioaccumulative factors in sediment (organic carbon content) and tissue (lipid content) to inform the model output.

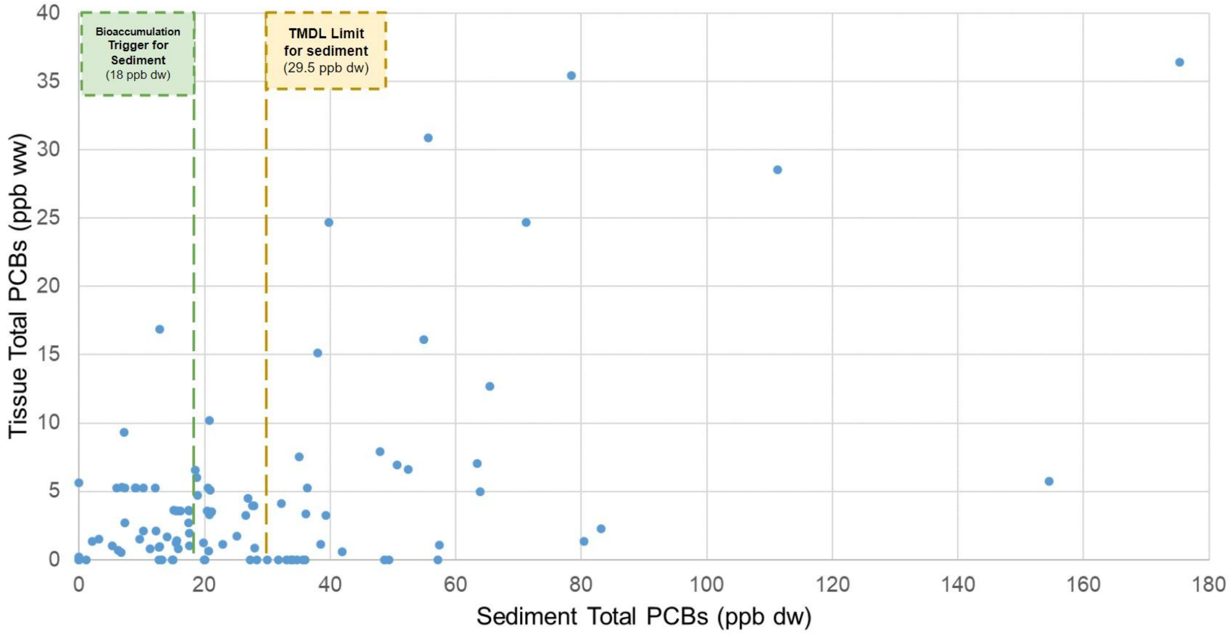

Figure 1. Matched bivalve bioaccumulation testing results for sum of PCBs (RMP 40) for studies conducted in San Francisco Bay, where ND = zero.

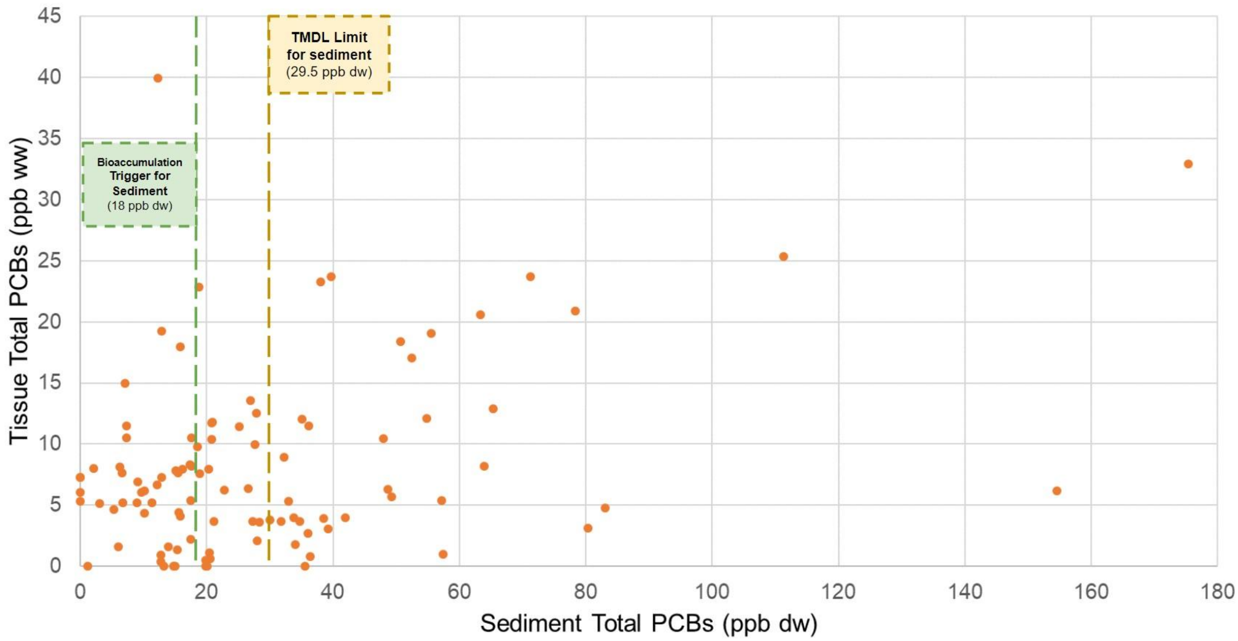

Figure 2. Matched polychaete bioaccumulation testing results for sum of PCBs (RMP 40) for studies conducted in San Francisco Bay, where ND = zero.

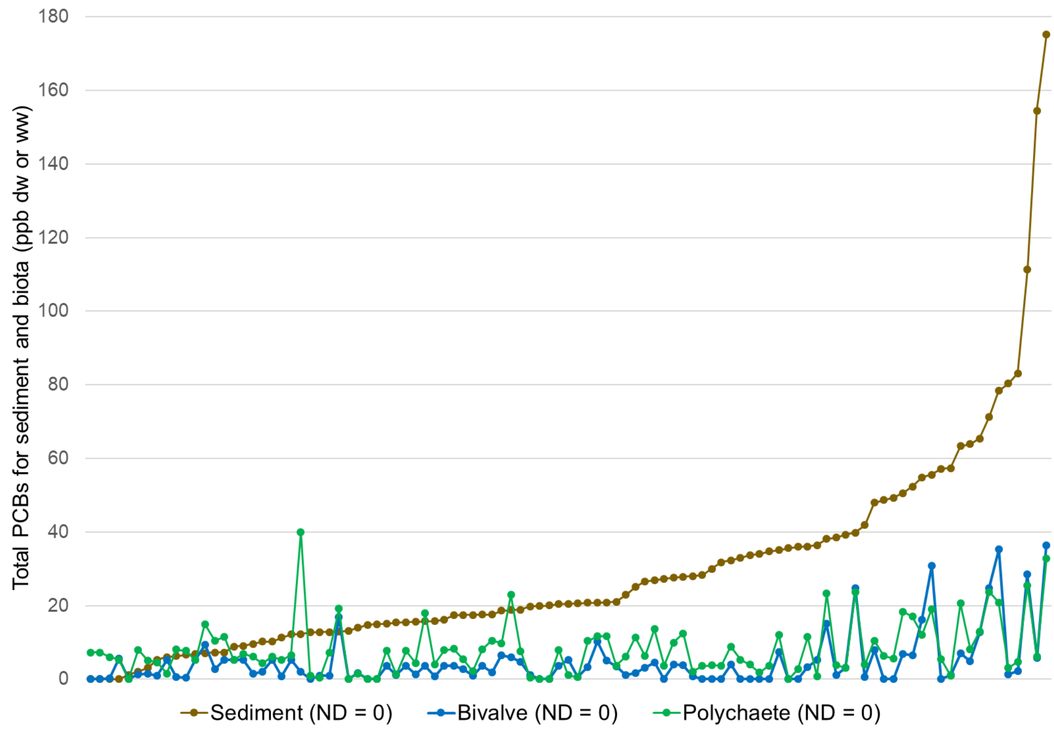

Figure 3. Sum of PCBs in sediment (ppb dw) with the matched sum of PCBs in bivalves and polychaete bioaccumulation results (ppb ww). Sum of PCBs are calculated by substituting the non-detect congeners with zero. Results are ranked in order of increasing sediment PCB concentration.

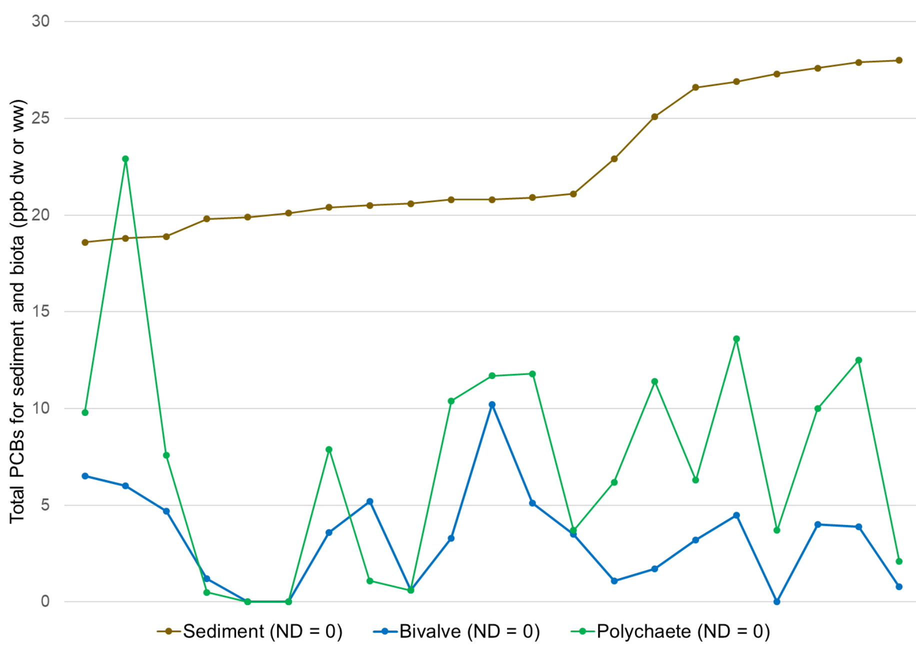

Figure 4. Sum of PCBs in sediment from 18-29.5 ppm range with the matched sum of PCBs in bivalves and polychaete bioaccumulation results. Sum of PCBs are calculated by substituting the non-detect congeners with zero. Results are ranked in order of increasing sediment PCB concentration.

4. Conclusion

We synthesized and analyzed the PCB bioaccumulation test results. There were significant challenges in synthesizing the data for analysis. This included differences in how the ND, MDLs, and RLs were reported, which had to be cleaned up prior to analysis. This engendered a source of uncertainty in this data analysis. Ongoing DMMO and RMP efforts to improve the quality of available metadata will improve the accuracy of future analysis that require linking bioaccumulation test results and sediment chemistry.

This synthesis showed that there was not a measurable increase in bioaccumulation from tests associated with sediment below the BT and sediment between the BT and TMDL limit. Bioaccumulation test results from sediment above the TMDL limit were elevated compared to bioaccumulation test results from sediment below the TMDL limit, but differences were not statistically significant due to uncertainty in the quantified tissue and sediment concentrations. The use of two different analysis methods, where NDs were replaced with zero or half the MDL, illustrated an impact of the prevalence of NDs on tissue concentration results and on sediment concentration results to a lesser extent. These results suggest that the PCB bioaccumulation trigger may not be effective in differentiating sediment bioaccumulation concerns.

With over half the bioaccumulation test results reported as ND, and with MDLs spanning two orders of magnitude, there is significant uncertainty in further bounding the bioaccumulation test results range and evaluating meaningful differences in the different sediment concentration bins. Additional steps can be taken to refine the data analysis presented in this study, although the value of these additional steps may be limited considering the additional costs that would be associated. 1) Improved analytical methods with significantly lower detection limits would provide better quantification of sediment and tissue results. For example, the RMP target MDLs for PCB congeners are in the range of 10^{-4} ug/kg dw (ppb) for sediment and 10^{-3} ng/g dw (ppb) for bivalve tissue to meet the data quality objectives for the RMP (Yee et al., 2019). 2) Further evaluation of bioaccumulation modeling done to predict higher trophic level fish concentrations from ingestion of benthic organisms in the range of the bioaccumulation data synthesized in this study.

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Appendix: Supplementary Information

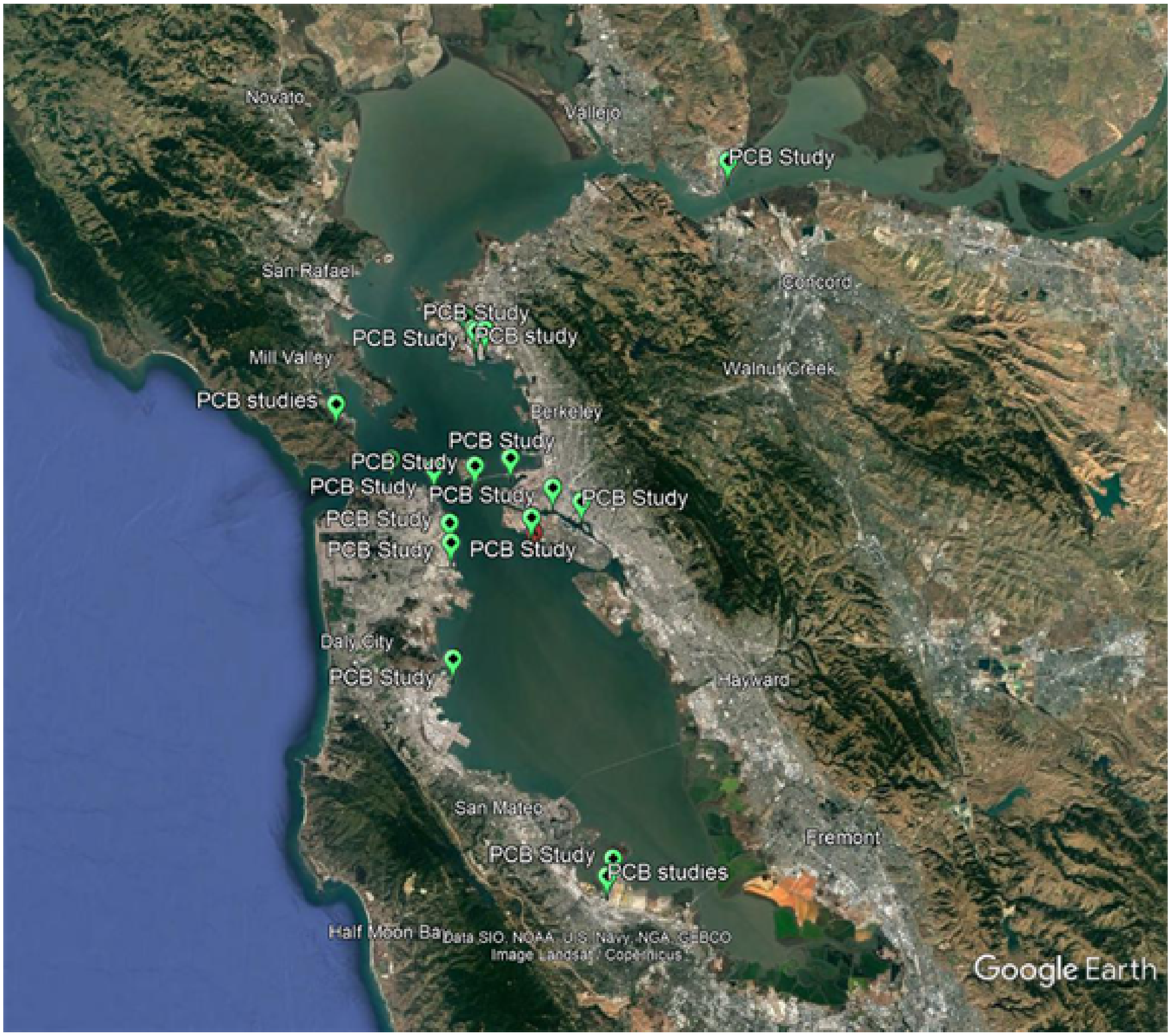


Figure A1. Spatial representation of 30 dredging projects used in this study.

Table A1. Matched bioaccumulation testing results for the 30 studies included in this project. Each matrix includes results where the non-detects (and "J flags") were treated as zero or half of the method detection limit (or reporting limit). All sediment results are in ug/kg dw; all tissue results are in ug/kg ww. For samples with replicates, only the highest value of sample replicates is shown here. Sediment, bivalve, and polychaete samples were matched annually based on date of study, study ID, study name, station name, and sample IDs. For caveats to the table, please refer to the Methods section.

		Sediment		**Bivalves**		**Polychaetes**	
Study Name	**Sample ID**	**Sediment PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Sediment PCB Concentration of RMP 40 Samples (ND = 0)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 0)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 0)**
Blu Harbor Maintenance Dredging 2018	BH-DU1-COMP	175.4	175.3	36.8	36.4	33.5	32.9
	BH-DU2-COMP	111.5	111.3	28.9	28.6	25.9	25.4
Clipper Yacht Club 2013	CYH-B1-Comp	155	154.5	7.4	5.8	7.8	6.2
Clipper Yacht Club 2016	CYH-B2-ST-Comp	26.7	21.1	7.5	3.5	8.4	3.7
Clipper Yacht Harbor 2015	CYH-B3-Comp	27.6	26.9	5.6	4.5	14.6	13.6
Marina Bay Yacht Harbor Entrance Channel 2017	EC-DU1	64.7	63.9	6.2	5	9.6	8.2
	EC-DU2	49.1	48	9	7.9	11.8	10.5
Oakland Inner and Outer Harbor Channels Operations	OAK-2017-6	28.2	20.8	10.2	10.2	11.7	11.7

		Sediment		Bivalves		Polychaetes	
Study Name	**Sample ID**	**Sediment PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Sediment PCB Concentration of RMP 40 Samples (ND = 0)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 0)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 0)**
Phillips 66 Richmond Marine Terminal 2014	P66-Comp	24.6	22.9	3.4	1.1	7.9	6.2
Port of Oakland Berths 22,25/26/57/59,60/63 2012	B22-Comp	21.8	12.8	5	1	10	7.3
	B25-26-Comp	20.8	12.3	5.6	2.1	41.1	40
	B60-63-Comp	23.8	18.8	8.9	6	24.4	22.9
Port of Oakland Berths 60-63 2016	B60/63-COMP	36.9	36.1	4.7	3.3	12.5	11.5
Port of Redwood City 2021	PRC-W1/2	8.6	5.3	2.6	1	6	4.6
	PRC-W3/4	13	10.2	3.5	2.1	5.7	4.3
Port of Redwood City 2015	PRC-DU1-Comp	57.8	57.4	5.4	1.1	5.9	1
Port of Redwood City 2018	PRC-DU1-Comp	40.3	39.3	4.6	3.2	4.5	3.1
	PRC-DU2-Comp	84.3	83.1	3.7	2.3	6.1	4.8
	PRC-DU3-Comp	18	15.6	2.9	1.4	5.9	4.4
	PRC-DU4-Comp	19.9	17.5	4.1	2.7	6.7	5.4
	PRC-DU5-Comp	28.5	26.6	4.6	3.2	7.6	6.3
Port of Redwood City Marina & F-Dock 2013-14	F-COMP	28.5	28	3	0.8	4	2.1
	MA-COMP	51.8	50.6	8.2	6.9	19.2	18.4
	MB-COMP	64.1	63.4	8.3	7.1	21.4	20.6

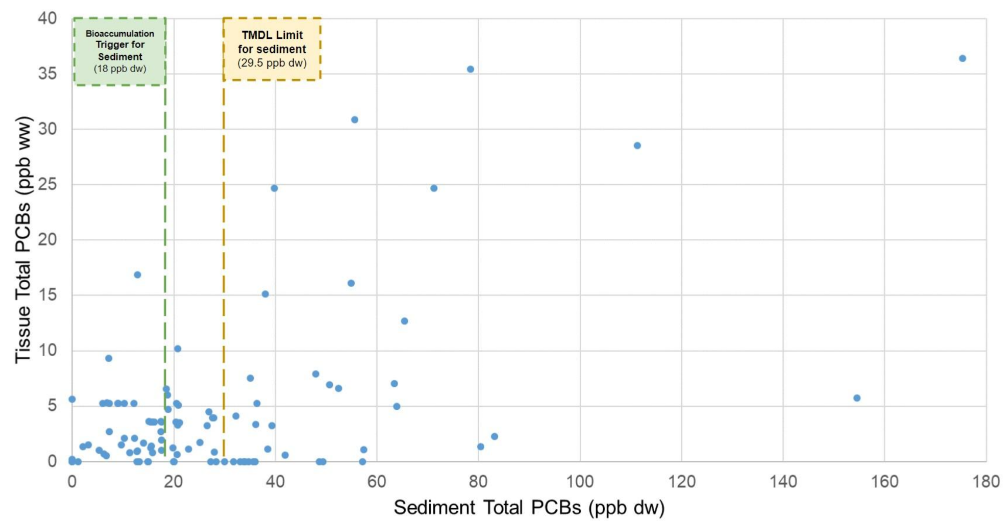
		Sediment		Bivalves		Polychaetes	
Study Name	**Sample ID**	**Sediment PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Sediment PCB Concentration of RMP 40 Samples (ND = 0)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 0)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 0)**
Port of Richmond Terminals 7 and 8 2016	PR-DU1-Comp	23.3	20.8	4.5	3.3	11.3	10.4
	PR-DU2-Comp	20.7	17.6	3.2	1.9	11.4	10.5
Port of San Francisco Central Basin Pier 70 2015	CB1-DU1-A-Comp	31.5	30	20	0	21.8	3.8
	CB1-DU5-B-Comp	36.8	36	20	0	20.7	2.7
	CB1-DU7-B-Comp	35.1	33.8	20	0	22	4
	CB2-DU2-A-Comp	29	27.3	20	0	21.7	3.7
	CB2-DU6-B-Comp	30	28.3	20	0	21.6	3.6
	CB3-DU3-A-Comp	33.3	31.8	20	0	21.7	3.7
	CB3-DU8-B-Comp	35.7	34.7	20	0	21.7	3.7
	CB4-DU4-A-Comp	42.9	41.9	20.1	0.6	21.5	4
	CB4-DU9-B-Comp	39.3	38.5	20.1	1.1	21.9	3.9
Port of San Francisco Pier 27 2011	B27-DU3B-COMP	55.4	35.6	20	0	20	0
	B27-DU3M-COMP	30.1	15	20	0	20	0
	B27-DU3T-COMP	20.3	1.2	20	0	20	0
Port of San Francisco Pier 80, Islais Creek Channel	80B-3A-C	28.1	20.6	4.5	0.6	4.6	0.6
	80B-3B-C	26.1	19.8	4.8	1.2	4.4	0.5
	80C-06-C	20.2	12.7	4.1	0	4.7	0.9
	ICA-05-C	20.3	14	5.2	1.7	5.3	1.6

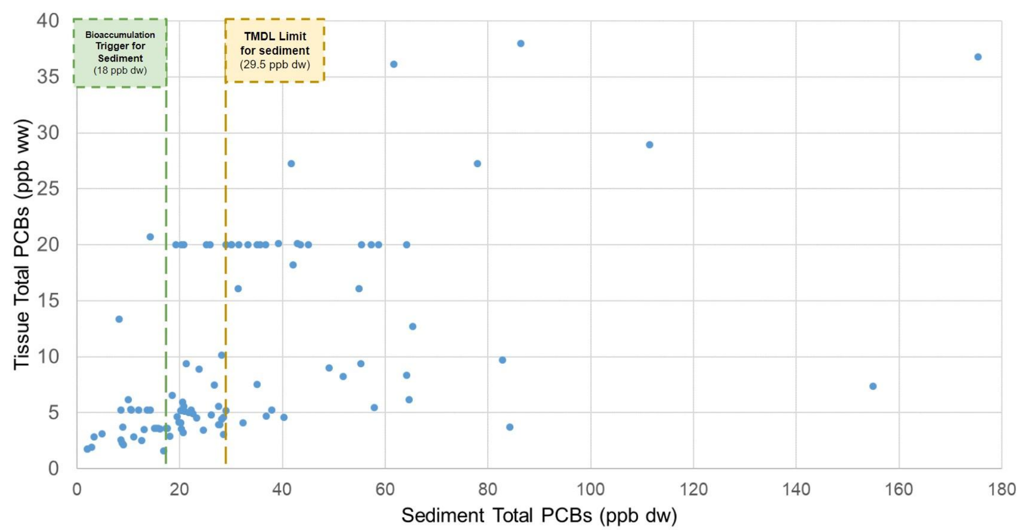
		Sediment		Bivalves		Polychaetes	
Study Name	**Sample ID**	**Sediment PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Sediment PCB Concentration of RMP 40 Samples (ND = 0)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 0)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 0)**
	ICC-4A-C	22.6	15.4	4.9	1.2	4.9	1.3
	ICC-4B-C	19.5	12.8	4.6	0.9	4.3	0.4
Port of San Francisco Piers, Islais Creek 2014	ICC-DU01-COMP	25.2	19.9	20	0	20	0
	P92-DU05-COMP	25.9	20.1	20	0	20	0
	P94-DU07-COMP	20.8	14.8	20	0	20	0
	P96-DU08-COMP	19.3	13.2	20	0	20	0
Redwood City Harbor 2018	RED-2018-1	15.1	15.1	3.6	3.6	7.8	7.8
	RED-2018-10	16.2	16.2	3.6	3.6	7.9	7.9
	RED-2018-2	17.4	17.4	3.6	3.6	8.3	8.3
	RED-2018-3	15.5	15.5	3.6	3.6	7.7	7.7
	RED-2018-4	15.8	15.8	3.6	3.6	17.9	17.9
	RED-2018-5	17.6	17.6	3.6	3.6	8.2	8.2
	RED-2018-6	20.4	20.4	3.6	3.6	7.9	7.9
	RED-2018-7	27.9	27.9	3.9	3.9	12.5	12.5
	RED-2018-8	27.6	27.6	4	4	10	10
	RED-2018-9	32.3	32.3	4.1	4.1	8.9	8.9
Richmond Inner Harbor 2015	RIH-2015-1-COMP	10	8.9	6.2	5.3	6.3	5.2
	RIH-2015-2-COMP	4.9	3.1	3.1	1.5	6.3	5.1
	RIH-2015-3-COMP	11	9.6	2.8	1.5	7.4	6.1

		Sediment		Bivalves		Polychaetes	
Study Name	**Sample ID**	**Sediment PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Sediment PCB Concentration of RMP 40 Samples (ND = 0)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 0)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 0)**
	RIH-2015-4-COMP	12.6	11.3	2.5	0.8	6.6	5.2
	RIH-2015-5-COMP	8.9	7.3	3.7	2.7	11.4	10.5
	SF-10-REF-COMP	3.4	2.1	2.8	1.3	9.4	8
Richmond Upper Inner Harbor 2018	RIH-2018-10-Com	54.9	54.9	16.1	16.1	12.1	12.1
	RIH-2018-6-Comp	20.9	20.9	5.1	5.1	11.8	11.8
	RIH-2018-7-Comp	18.6	18.6	6.5	6.5	9.8	9.8
	RIH-2018-8-Comp	35.1	35.1	7.5	7.5	12.1	12.1
	RIH-2018-9-Comp	65.4	65.4	12.7	12.7	12.9	12.9
San Francisco Marina West Basin 2011	B2-4-NB-COMP-2	57.3	49.3	20	0	24.2	5.7
	B2-4-NB-COMP-3	43.5	33	20	0	23.8	5.3
	B2-4-SB-COMP-1	58.7	48.7	20	0	25.3	6.3
	B2-4-SB-COMP-2	64.2	57.2	20	0	24.4	5.4
South San Francisco Ferry Terminal Dredging Project 2018	B2-4-SB-COMP-3	45	34	20	0	21.3	1.8
	DU-1-Comp	29	25.1	5.2	1.7	13.7	11.4
	DU-2-Comp	55.3	52.4	9.4	6.6	18.9	17
US Coast Guard Island Integrated Support 2014	CGI-2013-1-4-L	42.1	38.1	18.2	15.1	28	23.3
	CGI-2013-1-4-U	77.9	71.3	27.2	24.7	28.9	23.7
	CGI-2013-4U	41.7	39.8	27.2	24.7	28.9	23.7
	CGI-2013-5-8-L	8.2	7.1	13.3	9.3	20.8	15

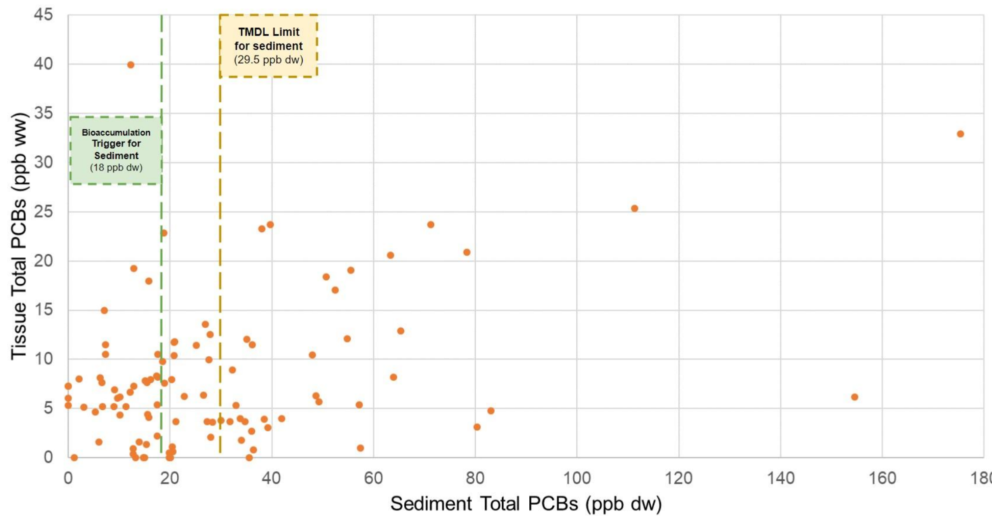
		Sediment		Bivalves		Polychaetes	
Study Name	**Sample ID**	**Sediment PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Sediment PCB Concentration of RMP 40 Samples (ND = 0)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 0)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 0)**
	CGI-2013-5-8-U	86.3	78.4	38	35.4	30	20.9
	CGI-2013-9-12-L	14.3	12.9	20.7	16.9	24.2	19.2
	CGI-2013-9-12-U	61.7	55.6	36.1	30.9	25.7	19
USACE Redwood City Harbor 2011	RED-2-Comp	31.4	0	16.1	5.6	16	5.3
USACE Redwood City Harbor 2014	RED-2014-1	22.2	20.5	5.2	5.2	3.2	1.1
	RED-2014-2	10.6	7.3	5.2	5.2	12.8	11.5
	RED-2014-3	12	9.1	5.2	5.2	8.4	6.9
	RED-2014-4	14.3	12.2	5.2	5.2	8	6.6
	RED-2014-5	10.4	6.8	5.3	5.3	6.9	5.2
	RED-2014-6	13.7	10.2	5.2	5.2	7.5	6.2
	RED-2014-7	37.9	36.4	5.2	5.2	3	0.8
	SF-10-REF	8.6	6	5.2	5.2	3.4	1.6
USCG Aspen Mooring and Approach SAR 2018	Alcatraz-COMP	2	0	1.8	0	8.3	7.3
	COMP A	9	6.7	2.1	0.5	8.7	7.7
	COMP B	2.9	0	1.9	0.2	7.2	6
	COMP C	20.6	18.9	5.9	4.7	8.5	7.6
USCG SBB Dredging 2018	Alcatraz-COMP	2	0	1.8	0	8.3	7.3
	SBB-COMP	8.8	6.3	2.3	0.7	9.1	8.1

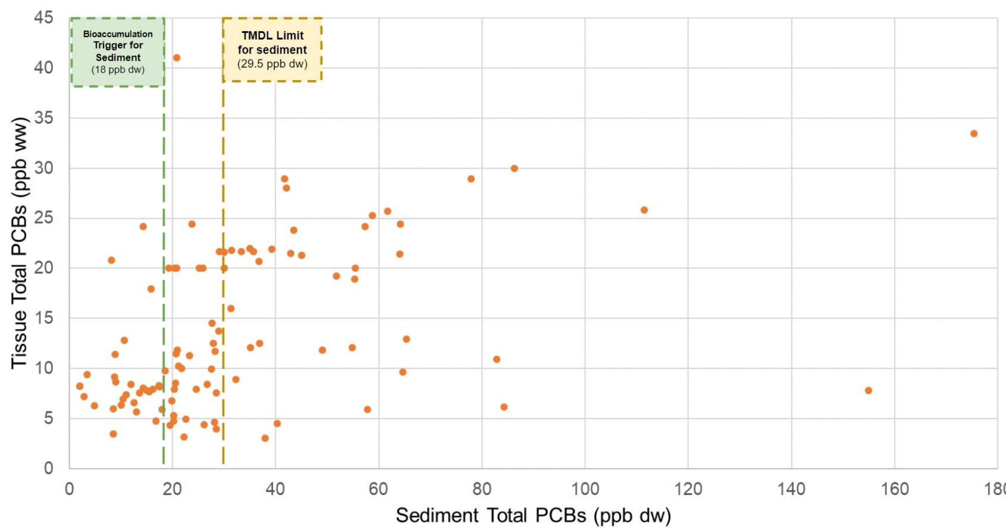
		Sediment		Bivalves		Polychaetes	
Study Name	**Sample ID**	**Sediment PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Sediment PCB Concentration of RMP 40 Samples (ND = 0)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Bivalves PCB Concentration of RMP 40 Samples (ND = 0)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 1/2 MDL)**	**Polychaetes PCB Concentration of RMP 40 Samples (ND = 0)**
Valero Refinery Terminal 2015	VRC-DU2-Comp	16.9	15.8	1.6	0.8	4.7	4.1
WETA Central Bay O&M Facility 2012	WETA-DU1-Comp	21.2	17.5	9.4	1	10.2	2.2
	WETA-DU2-Comp	82.9	80.4	9.7	1.3	10.9	3.1





Figures A2 and A3. Matched bioaccumulation testing results (for bivalves) for sum of PCBs (RMP 40) for studies conducted in San Francisco Bay. The top figure (Figure A2) uses results where ND are zero while the bottom figure (Figure A3) uses results where ND are half the MDL.





Figures A4 and A5. Matched bioaccumulation testing results (for polycheates) for sum of PCBs (RMP 40) for studies conducted in San Francisco Bay. The top figure (Figure A4) uses results where ND are zero while the bottom figure (Figure A5) uses results where ND are half the MDL.

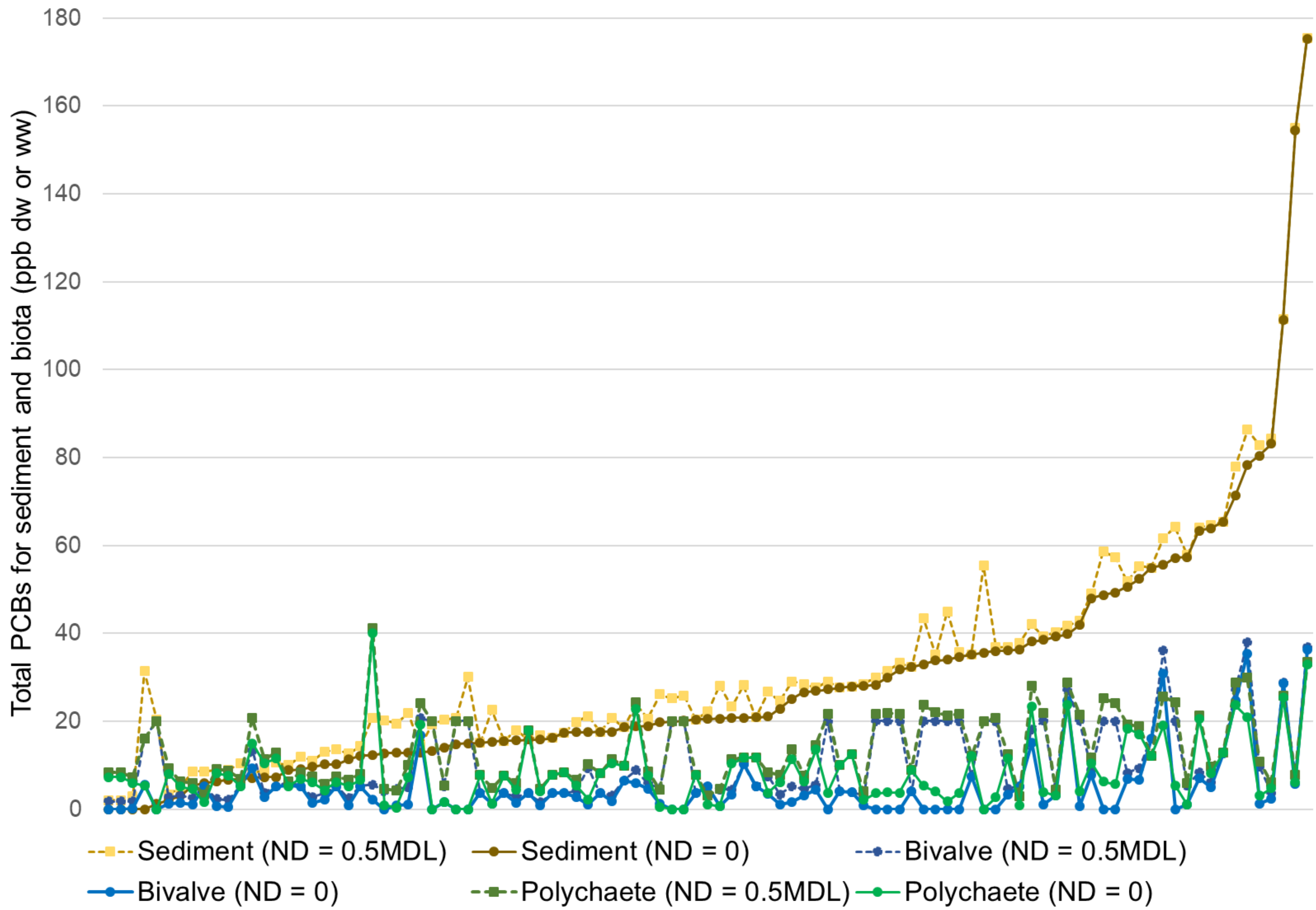


Figure A6. Sum of PCBs in sediment with matched sum of PCBs in bivalves and polychaete bioaccumulation results. Sum of PCBs are calculated by either substituting the non-detect congeners with half the method detection limit or with zero. Results are ranked in order of increasing sediment PCB concentration.

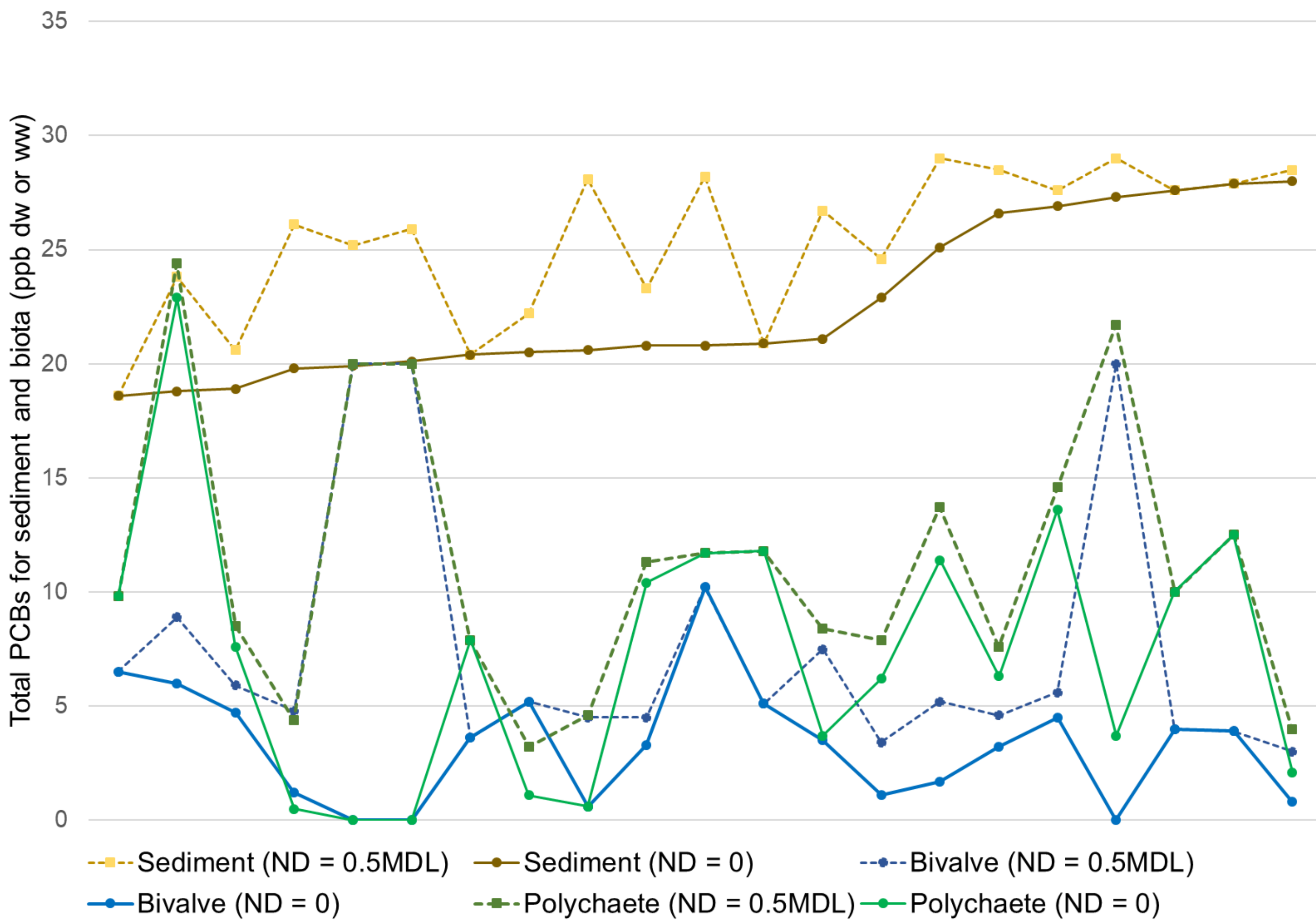


Figure A7. Sum of PCBs in sediment from 18-29.5 ppm with matched sum of PCBs bivalves and polychaete bioaccumulation results. Sum of PCBs are calculated by either substituting the non-detect congeners with half the method detection limit or with zero. Results are ranked in order of increasing sediment PCB concentration.